FUELING THE FUTURE: ON THE ROAD TO THE HYDROGEN ECONOMY

JOINT HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

AND THE

SUBCOMMITTEE ON RESEARCH

COMMITTEE ON SCIENCE

HOUSE OF REPRESENTATIVES

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July 20, 2005

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FUELING THE FUTURE: ON THE ROAD TO THE HYDROGEN ECONOMY

WEDNESDAY, JULY 20, 2005

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY, JOINT WITH
THE SUBCOMMITTEE ON RESEARCH,
COMMITTEE ON SCIENCE,
Washington, DC.

The Subcommittees met, pursuant to call, at 10:00 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Judy Biggert [Chairwoman of the Subcommittee on Energy] and Hon. Bob Inglis [Chairman of the Subcommittee on Research] presiding.

COMMITTEE ON SCIENCE
SUBCOMMITTEE ON ENERGY
SUBCOMMITTEE ON RESEARCH

JOINT HEARING

U.S. HOUSE OF REPRESENTATIVES

Fueling the Future: On the Road to the Hydrogen Economy

Wednesday, July 20, 2005
10:00 a.m. to Noon
2318 Rayburn House Office Building (WEBCAST)

Witness List

Mr. Douglas Faulkner
Acting Assistant Secretary for Energy Efficiency and Renewable Energy at the Department of Energy

Dr. David Bodde
Director of Innovation and Public Policy at Clemson University's International Center for Automotive Research.

Mr. Mark Chernoby
Vice President for Advanced Vehicle Engineering at the DaimlerChrysler Corporation

Dr. George Crabtree
Director of the Materials Science Division at Argonne National Laboratory

Dr. John Heywood
Director of the Sloan Automotive Laboratory at the Massachusetts Institute of Technology

HEARING CHARTER

SUBCOMMITTEE ON ENERGY, JOINTLY WITH THE SUBCOMMITTEE ON RESEARCH COMMITTEE ON SCIENCE U.S. HOUSE OF REPRESENTATIVES

Fueling the Future: On the Road to the Hydrogen Economy

WEDNESDAY, JULY 20, 2005
10:00 A.M.–12:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

1. Purpose

On Wednesday, July 20, 2005, at 10:00 a.m., the Energy and Research Subcommittees of the House Science Committee will hold a joint hearing to examine the progress that has been made in hydrogen research since the launch of the President's Hydrogen Initiative and the next steps the Federal Government should take to best advance a hydrogen economy.

2. Witnesses

Mr. Douglas Faulkner is the Acting Assistant Secretary for Energy Efficiency and Renewable Energy at the Department of Energy (DOE).

Dr. David Bodde is the Director of Innovation and Public Policy at Clemson University's International Center for Automotive Research (ICAR).

Mr. Mark Chernoby is Vice President for Advanced Vehicle Engineering at the DaimlerChrysler Corporation.

Dr. George Crabtree is the Director of the Materials Science Division at Argonne National Laboratory.

Dr. John Heywood is the Director of the Sloan Automotive Laboratory at the Massachusetts Institute of Technology.

3. Overarching Questions

The hearing will focus on the following overarching questions:

1. What progress has been made toward addressing the principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel since the Administration announced its hydrogen initiatives, FreedomCAR and the President's Hydrogen Fuel Initiative? What are the remaining potential technical "showstoppers?"
2. What are the research areas where breakthroughs are needed to advance a hydrogen economy? How has DOE responded to the report by the National Academy of Sciences (NAS) calling for an increased emphasis on basic research? How is DOE incorporating the results of the Basic Energy Sciences workshop on basic research needs for a hydrogen economy into the research agenda for the hydrogen initiative?
3. The NAS report suggested that the research agenda should be developed with future policy decisions in mind. How has DOE increased its policy analysis capabilities as recommended by the NAS? How will the results of that analysis be applied to the research agenda?

4. Overview

- In his 2003 State of the Union speech, President Bush announced the creation of a new Hydrogen Fuel Initiative, which built on the FreedomCAR initiative announced in 2002. Together, the initiatives aim to provide the technology for a hydrogen-based transportation economy, including production of hydrogen, transportation and distribution of hydrogen, and the vehicles that will use the hydrogen. Fuel cell cars running on hydrogen would emit only water vapor and, if domestic energy sources were used, would not be dependent on foreign fuels.

- Industry is participating in the hydrogen initiatives, and has invested heavily in hydrogen technology, particularly the automobile manufacturers and oil companies. The FreedomCAR program is a partnership between Ford, GM, DaimlerChrysler, and the Federal Government, and the President's Hydrogen Fuel Initiative expanded that partnership to include major oil companies such as Shell and BP, and merchant producers of hydrogen like Air Products and Chemicals, Inc. Although exact amounts of industry investment are proprietary, GM alone is estimated to have spent over $1.5 billion, and other automakers have invested similar amounts.
- The National Academy of Sciences (NAS) recommended changes to the hydrogen initiatives in its 2004 report, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* The report particularly stressed the need for a greater emphasis on basic, exploratory research because of the significant technical barriers that must be overcome. DOE has responded by expanding the hydrogen program into the Office of Science, and has requested $33 million for fiscal year 2006 (FY06) to fund basic research efforts in DOE's Office of Science.
- In addition, the NAS report noted that DOE needs to think about policy questions as it develops its research and development (R&D) agenda: "Significant industry investments in advance of market forces will not be made unless government creates a business environment that reflects societal priorities with respect to greenhouse gas emissions and oil imports.. . .The DOE should estimate what levels of investment over time are required—and in which program and project areas—in order to achieve a significant reduction in carbon dioxide emissions from passenger vehicles by mid-century." DOE has expanded its hydrogen policy and analysis efforts to be able to answer questions like those posed by the NAS, but the analytical work is still in progress, and available results are still preliminary.
- Even with the most optimistic of assumptions, it will take some time for hydrogen vehicles to compose a significant part of the automobile fleet. The NAS estimates that sales of hydrogen vehicles will not be significant enough for the full benefits of a hydrogen economy to be realized at least until 2025.
- During the transition to a hydrogen economy, many of the technologies being developed for hydrogen vehicles, such as hybrid systems technology and advanced lightweight materials could be deployed in conventional automobiles to provide reduced oil dependence and emissions. Without the proper incentives, vehicle improvements are likely to continue to be used to increase performance, rather than improving fuel economy, as they have been for the past twenty years. The Environmental Protection Agency estimates that if today's vehicles had the same weight and acceleration as cars did in 1987, they would get 20 percent better gas mileage due to technology improvements.

5. Background

What are the technical challenges?

Major advances are needed across a wide range of technologies for hydrogen to be affordable, safe, cleanly produced, and readily distributed. The production, storage and use of hydrogen all present significant technical challenges. While the research effort at DOE has produced promising results, the program is still a long way from meeting its goals in any of these areas.

Hydrogen does not exist in a usable form in nature, and has to be produced from something else, such as coal or natural gas. But one goal of using hydrogen is to reduce emissions of carbon dioxide. If hydrogen is to be produced without emissions of carbon dioxide, then the technology to capture and store carbon dioxide while making hydrogen must improve significantly. The other main goal of using hydrogen is to reduce the use of imported energy. Today most hydrogen is produced from natural gas, but in order to supply the entire transportation sector significant imports of natural gas would be required. Other possible means of producing hydrogen, including nuclear energy and renewable energy sources, are inherently cleaner than coal, but are far from affordable with existing technology.

Another major hurdle is finding ways to store hydrogen, particularly on board a vehicle. Hydrogen is a small molecule with properties that make it difficult to store in small volumes and in lightweight materials. The American Physical Society argued in its 2004 report on hydrogen, *The Hydrogen Initiative,* that a new material would have to be discovered in order to meet the FreedomCAR goals.

The NAS estimated that fuel cells themselves would need a ten- to twenty-fold improvement before fuel cell vehicles become competitive with conventional technology. Large improvements have been made since the report has been released, but additional improvements are still needed. DOE estimates that roughly a five-fold decrease in cost will be required, while at the same time increasing performance and durability. Current fuel cells wear out quickly, and lifetimes are far short of those required to compete with a gasoline engine. Small-scale distributed hydrogen production also needs improvement, and the NAS report recommended increased focus in that area because it may be among the first hydrogen-related technologies to be deployed.

What are the non-technical challenges, in the policy and regulatory areas?

Since many of the benefits of a hydrogen economy, such as reduced greenhouse gas emissions, are not currently accounted for in the marketplace, it will be difficult for hydrogen vehicles to compete with conventional technology. Even if all the technical challenges are met, and industry has the capability to produce hydrogen vehicles that are competitive with conventional vehicles, a successful hydrogen economy is not guaranteed. First, the transition to a hydrogen economy will require an enormous investment to create a new infrastructure. Changes in regulation, training and public habits and attitudes will also be necessary. Estimates of the cost of creating a fueling infrastructure (replacing or altering gas stations and distribution systems) alone are in the hundreds of billions of dollars. DOE is initiating an effort to better understand the economics and influences of policy incentives on a possible transition to hydrogen.

How are the Hydrogen Initiatives funded?

The FreedomCAR and the Hydrogen Fuel Initiative are expected to cost $1.7 billion over five years from FY03 to FY08. The President called for $358 million across DOE for these programs in the FY06 request, an increase of $48 million, 16 percent over levels appropriated for the initiatives in FY05. However, this increase comes at a time when R&D programs in the other energy efficiency and renewable energy programs are seeing decreasing requests overall, by $74 million, 10 percent to $692 million. Unless additional funding is provided to renewable energy and energy efficiency programs at DOE in general, the projected further increases in the FreedomCAR and Hydrogen Fuel Initiative will likely result in more cuts to other efficiency and renewable programs.

	FY04 appropriation (in millions)	**FY05 appropriation (in millions)**	**FY06 Request (in millions)**	**$ Change from FY05 Level**	**% Change from FY05 Level**
Hydrogen Fuel (EERE only)	$145	$169	$183	$14	8%
FreedomCAR	$150	$160	$184	$24	15%
HFI and FreedomCAR (without duplications)	$232	$254	$283	$29	11%
Fossil Energy	$5	$17	$22	$5	29%
Nuclear Energy	$6	$9	$20	$11	124%
Office of Science	$0	$29	$33	$3	11%
Total DOE Hydrogen	$243	$309	$358	$48	16%
DOT	$1	$1	$2	$2	328%
Grand Total	$243	$310	$360	$50	16%

Technology Background

What is a Fuel Cell?

Central to the operation of the hydrogen-based economy is a device known as a fuel cell that would convert hydrogen fuels to electricity. In cars, these devices would be connected to electric motors that would provide the power now supplied by gasoline engines. A fuel cell produces electricity by means of an electrochemical reaction much like a battery. There is an important difference, however. Rather than using up the chemicals inside the cells, a fuel cell uses hydrogen fuel, and oxygen extracted from the air, to produce electricity. As long as hydrogen fuel and oxygen are fed into the fuel cell, it will continue to generate electric power.

Different types of fuel cells work with different electrochemical reactions. Currently most automakers are considering Proton Exchange Membrane (PEM) fuel cells for their vehicles.

Benefits of a Hydrogen-based Economy

A hydrogen-based economy could have two important benefits. First, hydrogen can be manufactured from a variety of sources, including natural gas, biofuels, petroleum, coal, and even by passing electricity through water (electrolysis). Depending on the choice of source, hydrogen could substantially reduce our dependence on foreign oil and natural gas.

Second, the consumption of hydrogen through fuel cells yields water as its only emission. Other considerations, such as the by-products of the hydrogen production process, will also be important in choosing the source of the hydrogen. For example, natural gas is the current feedstock for industrial hydrogen, but its production releases carbon dioxide; production from coal releases more carbon dioxide and other emissions; and production from water means that pollution may be created by the generation of electricity used in electrolysis. Production from solar electricity would mean no pollution in the generation process or in consumption, but is currently more expensive and less efficient than other methods.

6. Witnesses Questions

The witnesses have been asked to address the following questions in their testimony:

Mr. Douglas Faulkner:

- What progress has been made toward addressing the principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel since the Administration announced its hydrogen initiatives, FreedomCAR and the President's Hydrogen Fuel Initiative? What are the remaining potential technical "showstoppers?"
- What are the research areas where breakthroughs are needed to advance a hydrogen economy? How has DOE responded to the report by the National Academy of Sciences (NAS) calling for an increased emphasis on basic research? How is DOE incorporating the results of the Basic Energy Sciences workshop on basic research needs for a hydrogen economy into the research agenda for the hydrogen initiative?
- The NAS report suggested that the research agenda should be developed with future policy decisions in mind. How has DOE increased its policy analysis capabilities as recommended by the NAS? How will the results of that analysis be applied to the research agenda?
- How is DOE conducting planning for, and analysis of, the policy changes (such as incentives or regulation) that might be required to accelerate a transition to hydrogen? What other agencies are involved in planning for, or facilitating, such a transition?

Mr. Mark Chrenoby:

- What criteria does DaimlerChrysler consider when making investment decisions regarding its portfolio of advanced vehicle research and development programs? What factors would induce DaimlerChrysler to invest more in the development of hydrogen-fueled vehicles? What do you see as a probable timeline for the commercialization of hydrogen-fueled vehicles? What about the other advanced vehicle technologies DaimlerChrysler is currently developing, such as hybrid vehicles and advanced diesel engines?
- What do you see as the potential technology showstoppers for a hydrogen economy? To what extent is Daimler relying on government programs to help solve those technical challenges?
- How are automakers using, or how do they plan to use, the advanced vehicle technology developed for hydrogen-fueled vehicles to improve the performance of conventional vehicles?

Dr. David Bodde:

- What progress has been made toward addressing the principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel since the Administration announced its hydrogen initiatives, FreedomCAR and the President's Hydrogen Fuel Initiative? What are the remaining potential technical "showstoppers?"

- What are the research areas where breakthroughs are needed to advance a hydrogen economy? How has DOE responded to the report by the National Academy of Sciences (NAS) calling for an increased emphasis on basic research? How is DOE incorporating the results of the Basic Energy Sciences workshop on basic research needs for a hydrogen economy into the research agenda for the hydrogen initiative?
- Is the current balance between funding of hydrogen-related research and research on advanced vehicle technologies that might be deployed in the interim before a possible transition to hydrogen appropriate? What advanced vehicle choices should the Federal Government be funding between now and when the transition to a hydrogen economy occurs? How are automakers using, or how do they plan to use, the advanced vehicle technology developed for hydrogen-fueled vehicles to improve the performance of conventional vehicles? Are automakers likely to improve fuel economy and introduce advanced vehicles without government support? How will ICAR encourage automakers to introduce technologies to improve fuel economy?
- What role do entrepreneurs, start-up companies, and venture capital investors have to play in accelerating the commercial introduction of advanced hydrogen-fueled vehicles?

Dr. George Crabtree:

- What progress has been made toward addressing the principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel since the Administration announced its hydrogen initiatives, FreedomCAR and the President's Hydrogen Fuel Initiative? What are the remaining potential technical "showstoppers?"
- What are the research areas where breakthroughs are needed to advance a hydrogen economy? How has DOE responded to the report by the National Academy of Sciences (NAS) calling for an increased emphasis on basic research? How is DOE incorporating the results of the Basic Energy Sciences workshop on basic research needs for a hydrogen economy into the research agenda for the hydrogen initiative?
- The NAS report suggested that the research agenda should be developed with future policy decisions in mind. How has DOE increased its policy analysis capabilities as recommended by the NAS? How will the results of that analysis be applied to the research agenda?
- How is DOE conducting planning for, and analysis of, the policy changes (such as incentives or regulation) that might be required to accelerate a transition to hydrogen? What other agencies are involved in planning for, or facilitating, such a transition?

Dr. John Heywood:

- How might the future regulatory environment, including possible incentives for advances vehicles and regulations of safety and emissions, affect a transition to hydrogen-fueled motor vehicles? How could the Federal Government most efficiently accelerate such a transition?
- Is the current balance between funding of hydrogen-related research and research on advanced vehicle technologies that might be deployed in the interim before a possible transition to hydrogen appropriate? What advanced vehicle choices should the Federal Government be funding between now and when the transition to a hydrogen economy occurs? How are automakers using, or how do they plan to use, the advanced vehicle technology developed for hydrogen-fueled vehicles to improve the performance of conventional vehicles? Are automakers likely to improve fuel economy and introduce advanced vehicles without government support?
- What role should the Federal Government play in the standardization of local and international codes and standards that affect hydrogen-fueled vehicles, such as building, safety, interconnection, and fire codes?

Chairwoman BIGGERT. Good morning. I want—the hearing will come to order.

I want to welcome everyone to this joint hearing of the Energy and Research Subcommittees of the House Science Committee. Today, we are going to get a status report on the progress of federal research efforts driving the development of fuel cells and the hydrogen to power them.

This hearing has become something of an annual tradition for the Science Committee. We have had a Full—we have had Full Committee hearings, field hearings, and Energy Subcommittee hearings on this topic. This year, I am pleased that our colleagues in the Research Subcommittee are joining us to examine the contributions of individual researchers and university research activities to the hydrogen and FreedomCAR initiatives.

At this time, it is a privilege for me to recognize my colleague from South Carolina, the Chairman of the Research Subcommittee, Mr. Inglis, for his opening statement.

Chairman INGLIS. Thank you, Madame Chairman.

Good morning. And I am excited about convening this hearing. It is the first on the hydrogen economy this Congress, I believe. And this topic has the potential for being the next "giant leap for mankind." That is certainly our hope.

The way I see it, there are three keys necessary to unlock the door to a full hydrogen economy. The first is commitment. The second is collaboration. And the third is discovery.

We need a commitment from the United States similar to the one that President Kennedy made when he challenged Congress in 1961 to land a man on the Moon before the end of the decade. The President's hydrogen fuel initiative and FreedomCAR are steps in the right direction, and I welcome the testimony on the progress that has been made on these initiatives to date.

Strong public and private collaboration is the second imperative if we are to see real and hopeful ahead-of-schedule success. And in my District, Clemson University is building the International Center for Automotive Research, ICAR, funded in significant part by BMW and Michelin. At ICAR, researchers will do what they do best, industry will do what it does best, and markets will establish the winners and losers. You will hear more about this collaborative effort today from Dr. David Bodde, Director of Innovation and Public Policy at ICAR.

The third key, discovery, is where our greatest challenges lie. That is why it is critically important that we fund basic research supporting the production, storage, and distribution of hydrogen. The development of a hydrogen economy depends on breakthroughs in these areas. At the same time, we should also be pursuing other advanced technologies, such as better batteries, photovoltaic cells that may take us to a new plateau of energy independence.

One of these technologies may turn out to be the "8-track" of the hydrogen economy. Another may be the "cassette player," yet another unknown technology may prove to be the "CD" of automobiles, which, in turn, may be followed by the MP3.

Transition to a hydrogen economy holds great promise on many levels. All along the way, the air will be getting cleaner, the oil pressure could come off the Middle East, entrepreneurs will be making money and employing people, and we will be winning our energy independence.

Admittedly, there are technology and cost challenges ahead of us, but I do not believe them to be insurmountable. In fact, I think we are definitely up to the challenge.

I look forward to hearing from the witnesses on all of these issues, and I thank you, Madame Chairman, for convening your hearing.

[The prepared statement of Chairman Inglis follows:]

PREPARED STATEMENT OF CHAIRMAN BOB INGLIS

Good morning, and thank you Madam Chairman for bringing us together for our first hearing on the hydrogen economy this Congress. I am pleased that we have convened this joint hearing on an issue that I believe has the potential to be the next "giant leap for mankind."

The way I see it, there are three keys necessary to unlock the door to a full hydrogen economy: (1) commitment, (2) collaboration and (3) discovery.

We need a commitment in the U.S. similar to the one we made when President Kennedy challenged Congress in 1961 to land a man on the Moon before the end of the decade. The President's Hydrogen Fuel Initiative and FreedomCAR are steps in the right direction, and I welcome the testimony on the progress that has been made on these initiatives to date.

Strong public and private collaboration is imperative if we are to see real and, hopefully, ahead-of-schedule success. In my district, Clemson University is building the International Center for Automotive Research (ICAR), funded in significant part by BMW and Michelin. At ICAR, researchers will do what they do best; industry will do what it does best; and the markets will establish winners and losers. You will hear more about this collaborative effort today from Dr. David Bodde, Director of Innovation and Public Policy at ICAR.

The third key, discovery, is where our greatest challenges lie. That is why it is critically important that we fund basic research supporting the production, storage and distribution of hydrogen. The development of a hydrogen economy depends on breakthroughs in these areas. At the same time, we should also be pursuing other advanced technologies such as better batteries and photovoltaic cells that may take us to a new plateau of energy dependence. One of these technologies may turn out to be the eight-track of the hydrogen economy. Another may be the cassette player. Yet another yet-unknown technology may prove to be the CD of automobiles, which, in turn, may be followed by the MP3.

The transition to a hydrogen economy holds great promise on many levels. All along the way, the air will be getting cleaner, the oil pressure will be coming off the Middle East, entrepreneurs will be making money and employing people, and we will be winning our energy independence. Admittedly, there are technology and cost challenges ahead of us, but I do not believe them to be insurmountable. In fact, I think we're definitely up to the challenge.

I look forward to hearing from the witnesses on all of these issues.

Chairwoman BIGGERT. Well, thank you, Chairman Inglis.

At last year's hearing on this topic, we closely examined two reports, one prepared by the National Academy of Sciences, the other by the American Physical Society, both of which emphasized the importance of basic research to the long-term success of the President's hydrogen and FreedomCAR initiatives.

I am pleased that President Bush took these recommendations to heart and increased funding in his fiscal year 2006 budget request for the Department of Energy's Office of Science to address some of the fundamental obstacles to greater use of hydrogen and fuel cells. I am anxious to hear how the results of this basic research are being incorporated into the fuel cell and hydrogen technologies under development and how they are shaping the research agenda going forward.

I think that research designed to benefit the Nation significantly in the long-term could benefit us marginally in the near-term, ultimately giving us the greater return on our investments in hydrogen and fuel cell research. We couldn't ask for more in this era of tight budgets. We have a diverse panel of witnesses today representing some exceptional institutions engaged in all kinds of hydrogen and fuel research.

[The prepared statement of Chairman Biggert follows:]

PREPARED STATEMENT OF CHAIRMAN JUDY BIGGERT

This hearing will give this committee another opportunity to get an update on the work underway at the Department of Energy as part of the President's Hydrogen Fuel and FreedomCAR initiatives. I also want to thank the witnesses for being so generous with their time, and for agreeing to share with us their insight and expertise on the topics of fuel cells and hydrogen.

I have a keen interest in both the fuel cell and hydrogen initiatives that the President announced in 2002 and 2003 respectively. My district is, of course, home to Argonne National Laboratory, which has a strong fuel cell R&D program. My district also is home to small businesses like H2Fuels and various auto parts suppliers, corporations like BP, and research organizations like the Gas Technology Institute. In short, I have the privilege to represent a region that has much to contribute to the continued development of fuel cells and the hydrogen needed to fuel them.

As I've said many times before, I do not believe that affordable energy and a clean and safe environment are mutually exclusive. America has the ingenuity and the expertise to meet our future energy demands and promote energy conservation, and we can do so in environmentally responsible ways that set a standard for the world. Most importantly, America now has the motivation perhaps like no other time since the oil crisis of the '70's - to find newer and better ways to meet our energy needs.

There clearly are many compelling reasons to work towards our shared vision of a hydrogen economy. Today, we will hear testimony not only about the progress DOE has made already in hydrogen research but also about those research questions—both basic and applied—that remain as questions yet to be solved. While we want to know about any potential scientific or technical "showstoppers," we also want to know whether there are any new problems that have been identified as a result of on-going research. We will hear testimony about how DOE is incorporating the results of basic research needs for a hydrogen economy into the research agenda for the hydrogen initiative. Finally, we will hear how the Department's hydrogen research agenda has been modified to account for anticipated future policy decisions, as suggested by the National Academy of Sciences.

It is clear that the vision of a hydrogen economy is a tremendously challenging endeavor. But, it is also clear that it will take us many years to reach our goal. Once they become available, hydrogen vehicles will require a number of years until they compose a significant part of the automobile fleet. The NAS estimates that sales of hydrogen vehicles will not be significant enough for the full benefits of a hydrogen economy to be realized at least until 2025. In light of that, we need to next ask, "Are we working to meet our goals in the best way that we can?"

I would also observe that during the transition to a hydrogen economy, many technologies developed for hydrogen vehicles—such as hybrid systems technology and advanced lightweight materials—could be deployed in conventional automobiles to provide reduced oil dependence and emissions. Congress and the Administration need to understand whether we can design proper incentives so that those technologies are deployed for improving the fuel economy of conventional automobiles, rather than continuing an exclusive focus on ever increasing performance, as has been the norm for the past twenty years. We need to next ask, "Are we getting *all* the benefits we can from our investment in hydrogen research?"

Our job at this hearing is to look at what we've learned in our initial research efforts, and to gain insight into whether we have an appropriately balanced research effort. I look forward to hearing more about how the DOE is moving the Nation ever-closer to realizing the promise and potential of fuel cells and hydrogen.

Thank you.

Chairwoman BIGGERT. But before we hear from them, I want to recognize the Ranking Member of the Energy Subcommittee, Mr. Honda from California, for his opening statement.

Mr. HONDA. Thank you, Madame Chair, and I do appreciate the Chair's work in putting this hearing together.

At a Full Committee hearing held earlier this year, we heard about two reports, which suggested that resources should be directed away from demonstration projects and towards more basic R&D because there are significant technical barriers to overcome.

I agree that there are many technical barriers to be overcome, but I also note that demonstration programs have served to help us identify some of those technical barriers.

I hope that the witnesses can comment on the role that the—that investments made in demonstration projects by other agencies can play in helping the Department of Energy's work to make hydrogen feasible. For example, the Santa Clara Valley Transportation Authority's Zero-Emission Bus program is funded by a transit sales tax, the Federal Transit Administration, the California Energy Commission, and the Bay Air Quality Management District.

It will be useful to know whether DOE is able to work with programs like this to gain knowledge about the infrastructure needs and identify potential technical obstacles that we will need to overcome.

Finally, we must remember that hydrogen is not an energy source, it is an energy carrier. We cannot afford to look at only the hydrogen piece of the puzzle. We must figure out where we are going to get that hydrogen.

I hope that the witnesses will discuss whether we are doing the necessary work to develop the electricity-generating infrastructure that will clearly be necessary to provide the fuel for hydrogen vehicles.

I look forward to this hearing and hope that the witnesses can address some of these concerns. And I yield back the balance of my time.

[The prepared statement of Mr. Honda follows:]

PREPARED STATEMENT OF REPRESENTATIVE MICHAEL M. HONDA

Chairman Inglis, Chairwoman Biggert, Ranking Member Hooley, thank you all for holding this hearing today to receive updates on the progress that is being made in addressing technical barriers to the use of hydrogen in vehicles.

At a Full Committee hearing held earlier this year, we heard testimony about two reports which suggested that resources should be directed away from demonstration projects and towards more basic R&D because there are significant technical barriers to overcome.

I agree with the conclusion that there are many technical barriers to be overcome, and I look forward to hearing from the witnesses their thoughts on the breakthroughs they believe will need to be made in order to overcome these barriers.

But I also note that prior demonstration programs have served to help to identify some of the very technical barriers that an increased emphasis on research would aim to overcome. I fear that we might miss more obstacles until after we have made significant investments of time and resources if we stop working on demonstration projects.

I hope that the witnesses can comment on the role that investments made in demonstration projects by other agencies can play in helping the Department of Energy's work to make hydrogen feasible. For example, the Santa Clara Valley Transportation Authority's Zero Emission Bus program is funded by a transit sales tax, the Federal Transit Administration (FTA), the California Energy Commission (CEC), and the Bay Area Air Quality Management District.

It will be useful to know whether DOE is able to work with programs like this to gain knowledge about infrastructure needs and identify potential technical obstacles that we will need to overcome.

Finally, we must remember that hydrogen is not an energy source, it is an energy carrier. We cannot just look at the hydrogen piece of the equation, assuming that an infinite supply of fuel will be available for vehicles if only we can make those vehicles.

Where is the energy going to come from to produce hydrogen? Converting natural gas is one option, but supplies of that fuel are already limited.

Barring that, a switch to hydrogen vehicles looks like it will also require a commensurate increase electricity generating capacity to supply the fuel. I hope the witnesses will discuss whether we are undertaking the necessary efforts to address this critical piece of the puzzle.

I look forward to this hearing, and hope the witnesses can address some of these concerns. I yield back the balance of my time.

Chairwoman BIGGERT. Thank you, Mr. Honda.

Any additional opening statement submitted by the Members may be added to the record.

[The prepared statement of Mr. Costello follows:]

PREPARED STATEMENT OF REPRESENTATIVE JERRY F. COSTELLO

Good morning. I want to thank the witnesses for appearing before our committee to examine the progress that has been made in hydrogen research since the launch of the President's Hydrogen Initiative. A greater reliance on hydrogen requires modification of our existing energy infrastructure to ensure greater availability of this new fuel source. Making the transition to a hydrogen economy will require an enormous investment to create a new infrastructure. It is my understanding that the Department of Energy is initiating an effort to better understand the economics and influences of policy incentives on a possible transition to hydrogen. Since the President's Initiative has left many questions unanswered, I am hopeful our witnesses here today will provide more insight into the funding and technology challenges facing the Hydrogen Initiative.

I agree that a hydrogen-based economy could have important benefits that could help relieve our dependence on foreign oil. First, hydrogen can be manufactured from a variety of sources, such as coal. I strongly support the President's Integrated Sequestration and Hydrogen Research Initiative, entitled FutureGen, which is a coal-fired electric and hydrogen production plant. The prototype plant will serve as a large-scale engineering laboratory for testing and will expand the options for producing hydrogen from coal.

As the Administration begins to consider locations for the new plant, I would hope they would consider Southern Illinois. I have led the effort to locate FutureGen in Illinois, including leading a bipartisan effort in the House to secure funding for the project. The region is rich in high-sulfur coal reserves and the Coal Center at Southern Illinois University Carbondale (SIU–C) has been doing extensive work with hydrogen and coal. The geology of the region is well suited to the carbon-trapping technology to be developed and Illinois is home to oil and gas reserves and deep saline aquifers that can permanently sequester carbon dioxide.

I have been tracking this issue closely since its inception and I am anxious to see the Department's program plan. This Administration has touted FutureGen as one of the most important climate change technologies at our disposal and heightened its international visibility to extraordinary levels and I am committed to working with my colleagues and the Administration to move forward on a path that is technically, financially, and politically viable.

I again thank the witnesses for being with us today and providing testimony to our committee.

[The prepared statement of Ms. Jackson Lee follows:]

PREPARED STATEMENT OF REPRESENTATIVE SHEILA JACKSON LEE

Let me thank Chairwoman Biggert and Ranking Member Honda of the Energy Subcommittee as well as Chairman Inglis and Ranking Member Holley of the Research Subcommittee for holding this joint hearing on the future of hydrogen energy. Clearly, hydrogen technologies hold great potential; however we do not know how long it will be before hydrogen can represent a significant portion of our fuel consumption. I hope this hearing will shed some light on the path that we must take to make the potential of hydrogen into a reality.

In his 2003 State of the Union speech, President Bush announced the creation of a new Hydrogen Fuel Initiative, which built on the FreedomCAR initiative announced in 2002. Together, the initiatives aim to provide the technology for a hydrogen-based transportation economy, including production of hydrogen, transportation and distribution of hydrogen, and the vehicles that will use the hydrogen. Fuel cell cars running on hydrogen would emit only water vapor and provide environmental benefits in addition to being an alternative source of energy.

However, as I stated we must make this potential in to a reality and we are not yet at that point. The National Academy of Sciences (NAS) recommended changes to the hydrogen initiatives in its 2004 report, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* The report particularly stressed the need for a greater emphasis on basic, exploratory research because of the significant technical barriers that must be overcome. The Department of Energy (DOE) has responded by expanding the hydrogen program into the Office of Science, and has requested $33 million for fiscal year 2006 (FY06) to fund basic research efforts in DOE's Office of Science.

The fact is that even with the most optimistic of assumptions, it will take some time for hydrogen vehicles to compose a significant part of the automobile fleet. The NAS estimates that sales of hydrogen vehicles will not be significant enough for the full benefits of a hydrogen economy to be realized at least until 2025. But, this should not be a deterrent to developing hydrogen technology, instead it should serve as incentive for the scientific community to move towards this technology that holds so much promise.

While in this transition to a hydrogen economy, many of the technologies being developed for hydrogen vehicles, such as hybrid systems technology and advanced lightweight materials could be deployed in conventional automobiles to provide reduced oil dependence and emissions. Without the proper incentives, vehicle improvements are likely to continue to be used to increase performance, rather than improving fuel economy, as they have been for the past twenty years. In fact the Environmental Protection Agency estimates that if today's vehicles had the same weight and acceleration as cars did in 1987, they would get 20 percent better gas mileage due to technology improvements. I sincerely hope that we use our resources to improve gas mileage and make hydrogen technology a reality for the American public.

Thank you.

[The prepared statement of Mr. Carnahan follows:]

PREPARED STATEMENT OF REPRESENTATIVE RUSS CARNAHAN

I am pleased that we are holding this very important hearing this morning.

The U.S. Federal Government often serves the role of jump-starting research in fields that cannot be immediately lucrative, yet provide American citizens the promise of improved health, efficiency, or lifestyle. We again find ourselves in this role, and we must do our best to advance a hydrogen economy in this country.

I am particularly interested in the FreedomCAR program that partners with DaimlerChrysler. As we recognize the potential of FreedomCAR and the hydrogen initiative, I am excited about the promise that developments in this field may provide for many of my constituents who are employees of Chrysler.

Furthermore, I would like to recognize the good research being conducted at the University of Missouri on the Plug-In Hybrid Power System Partnership for Innovation, a research project that will examine how regenerative fuel cell systems, which produce high hydrogen and oxygen pressures, will be designed, fabricated and then demonstrated in the laboratory.

Thank you for your willingness to join us, Mr. Faulkner, Dr. Bodde, Mr. Chernoby, Dr. Crabtree and Dr. Heywood. I am eager to hear your testimony.

Chairwoman BIGGERT. And at this time, I would like to introduce all of the witnesses and thank you for coming before us this morning.

First off, we have Mr. Douglas Faulkner. He is the Acting Assistant Secretary for Energy Efficiency and Renewable Energy at the Department of Energy. There is a lot of energy in there. Dr. David Bodde, Director of Innovation and Public Policy at Clemson University's International Center for Automotive Research. And thank you. Mr. Mark Chernoby, Vice President for Advance Vehicle Engineering at the DaimlerChrysler Corporation. Thank you. And Dr. George Crabtree, Director of the Materials Science Division at Argonne National Laboratory, a familiar place. And Dr. John Heywood, Director of the Sloan Automotive Laboratory at the Massachusetts Institute of Technology. Welcome.

As the witnesses probably know, spoken testimony will be limited to five minutes each, after which the Members will have five minutes each to ask questions. This is Wednesday and one of, probably, our busiest days, so we are going to be pretty strict on the time, if you can keep it to five minutes.

We will begin with Mr. Faulkner. And the fact that there are two Committees here, we expect a lot of questions.

So we will begin with Mr. Faulkner.

STATEMENT OF MR. DOUGLAS L. FAULKNER, ACTING ASSISTANT SECRETARY, ENERGY EFFICIENCY AND RENEWABLE ENERGY, DEPARTMENT OF ENERGY

Mr. FAULKNER. Thank you.

Madame Chairman, Mr. Chairman, Members of the Subcommittees, I appreciate the opportunity today to testify on the Department's hydrogen program.

Since President Bush launched the Hydrogen Fuel Initiative over two years ago, we have made tremendous progress. We have implemented valuable feedback from the National Academy of Sciences and the Department's Basic Energy Sciences Workshop and are already seeing results. In fact, as we speak, the Academy is completing its biannual review of the program and will publish its findings in coming weeks.

The Academy called for us to improve integration and balance of activities within the relevant offices of the Department of Energy's Renewables, Nuclear, Fossil, Science, prioritizing the efforts within and across program areas, establishing milestones, and go/no-go directions. We have done this. In the Hydrogen Posture Plan, we have identified strategies and milestones to enable a 2015 industry commercialization decision on the viability of hydrogen and fuel cell technologies. Each office has, in turn, developed a detailed research plan, which outlines how the high-level milestones will be supported. We are now implementing these research plans, and we are making tangible progress.

The Department competitively selected over $510 million in total federal funding for projects to address critical challenges. Of these projects, the Office of Science announced 70 new competitively selected projects, $64 million over three years. Topics include new materials for hydrogen storage and development of catalysts at the nanoscale, all recommended by the Basic Energy Sciences Workshop. Sixty-five projects were initiated on hydrogen production and delivery, funded at $170 million over four years. And the results here are already promising.

We believe we can meet our goal of $2 to $3 gallon of gasoline equivalent, which is independent of the production pathway. The basic research component of the program is especially valuable to long-term concepts, such as photoelectrochemical hydrogen production. I would also like to underscore that our ultimate hydrogen production strategy is carbon-neutral and emphasizes resource diversity.

We launched a Grand Challenge focusing on materials discovery and development of hydrogen storage, one of the critical technologies for the hydrogen economy. We established a National Hydrogen Storage project at over $150 million over five years, including three Centers of Excellence with multi-disciplinary teams of university, industry, and federal laboratories.

Closely coordinated with the new Office of Science Research, our activities address the Academy's recommendation to shift toward more exploratory work as well as to partner with a broader range of academic and industrial organizations. We are already seeing results from this work, too.

Recent progress in materials discovery allows hydrogen to be stored at low temperature—low pressures and modest temperatures. We need both fundamental understanding and engineering solutions to address key issues, like charging and discharging hydrogen at practical temperatures and pressures.

To address fuel cell cost and durability, a new $75 million solicitation will soon be released, complementing the current $17.5 million solicitation on new membrane materials as well as existing efforts. Results are already being achieved.

As highlighted by Secretary Bodman in earlier Congressional testimony, this high-volume cost of automotive fuel cells was reduced from $275 per kilowatt to $200 per kilowatt. And the Office of Science has initiated new basic research projects on nanoscale catalysts and membrane materials for fuel cell design and applications.

Through better techniques for fabricating electrodes and new strategies for improved durability, we believe the targets we have set are achievable. We must keep sight of our ultimate goal to transfer research to the real world, and we have complemented our research efforts with a learning demonstration activity. We conduct research on safety codes and standards working with the Department of Transportation, standards development organizations, and other organizations. We are also creating a road map now with the Department of Commerce and other federal agencies for developing manufacturing technologies to bridge the continuum from basic research to commercialization. That effort will help attract new business investment, create new high-technology jobs, and build a competitive U.S. supply base.

The Academy also recommended a systems analysis and integration activity. We are developing that capability. Analysis of various scenarios for hydrogen production delivery are underway. These efforts will be valuable in providing rigorous data and potential guidance for policy decisions in future years.

Madame Chairman, Mr. Chairman, the DOE hydrogen program is committed to a balanced portfolio. We do not do stand-alone test tube research, but rather we have an integrated effort of basic, applied, and engineering sciences. This Committee, in particular, has been instrumental in providing valuable guidance to us.

This completes my prepared statement. I would be happy to answer any questions you have.

[The prepared statement of Mr. Faulkner follows:]

PREPARED STATEMENT OF DOUGLAS L. FAULKNER

Madam Chairman and Members of the Subcommittee, I appreciate the opportunity to testify on the Department of Energy's (DOE or Department) Hydrogen Program activities which support the President's Hydrogen Fuel Initiative. Today I will provide an overview and status update of the Hydrogen Program's accomplishments and plans.

Over two years ago, in his 2003 State of the Union address, President Bush announced a $1.2 billion Hydrogen Fuel Initiative over FY 2004—2008 to reverse America's growing dependence on foreign oil by developing the hydrogen technologies needed for commercially viable fuel cells—a way to power cars, trucks, homes, and businesses that could also significantly reduce criteria pollutants and greenhouse gas emissions. Since the launch of the Initiative, we have had many accomplishments on the path to taking hydrogen and fuel cell technologies from the laboratory to the showroom in 2020, following an industry commercialization decision in 2015. The Department's Program encompasses the research and development (R&D) activities necessary to achieve the President's vision, including basic research, applied research and technology development, and learning demonstrations that are an extension of our research. These activities benefit from detailed planning efforts conducted by the Department, and the National Academies study and the Office of Science Basic Research Needs for the Hydrogen Economy workshop, in which two other speakers today, Dr. Bodde and Dr. Crabtree, have made major contributions. I will talk about progress in these areas as we continue on the road to solving the technical barriers that stand between us and this vision of a new energy future.

Hydrogen Vision and Overview

As a nation, we must work to ensure that we have access to energy that does not require us to compromise our security or our environment. Hydrogen offers the opportunity to end petroleum dependence and to virtually eliminate transportation-related greenhouse gas emissions by addressing the root causes of these issues. Petroleum imports already supply more than 55 percent of U.S. domestic petroleum requirements, and those imports are projected to account for 68 percent by 2025 under a business-as-usual scenario. Transportation accounts for more than two-thirds of the oil use in the United States, and vehicles contribute to the Nation's air quality problems and greenhouse gas emissions because they release criteria pollutants and carbon dioxide.

At the G8 Summit earlier this month, President Bush reiterated his policy of promoting technological innovation, like the development of hydrogen and fuel cell technologies, to address climate change, reduce air pollution, and improve energy security in the United States and throughout the world. The Department's R&D in advanced vehicle technologies, such as gasoline hybrid electric vehicles, will help improve energy efficiency and offset growth in the transportation fleet in the near- to mid-term. But, for the long-term, we ultimately need a substitute to replace petroleum. Hydrogen and fuel cells, when combined, have the potential to provide carbon-free, pollution-free power for transportation.

Hydrogen will be produced from diverse domestic energy resources, which include biomass, fossil fuels, nuclear energy, solar, wind, and other renewables. We have planned and are executing a balanced research portfolio for developing hydrogen production and delivery technologies. The Department's hydrogen production strategy recognizes that most hydrogen will likely be produced by technologies that do not require a new hydrogen delivery infrastructure in the transition to a hydrogen economy, such as distributed reforming of natural gas and of renewable liquid fuels like ethanol and methanol. As research, development, and demonstration efforts progress along renewable, nuclear, and clean coal pathways, a suite of technologies will become available to produce hydrogen from a diverse array of domestic resources. These technologies will be commercialized as market penetration grows and demand for hydrogen increases.

The economic viability of these different production pathways will be strongly affected by regional factors, such as feedstock or energy source availability and cost, delivery approaches, and the regulatory environment so that each region will tailor its hydrogen infrastructure to take advantage of its particular resources. Our ultimate hydrogen production strategy is carbon-neutral and emphasizes diversity. During the transition, net carbon emissions on a well-to-wheels basis, from vehicles running on hydrogen produced from natural gas would be 25 percent less than gasoline hybrid vehicles and 50 percent less than conventional internal combustion engine vehicles. Natural gas is not a long-term strategy because of import concerns and the demands of other economic sectors for natural gas. In the long-term, in a hydrogen economy using renewables, nuclear, and coal with sequestration, near-zero carbon light duty vehicles are our goal. I want to emphasize that hydrogen from coal will be produced directly from gasification, not coal-based electricity. This is consistent with technology currently under development for carbon capture and sequestration.

My testimony today will specifically address the Subcommittees' questions:

1. What progress has been made toward addressing the principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel since the Administration announced its hydrogen initiatives, FreedomCAR and the President's Hydrogen Fuel Initiative? What are the remaining potential technical "showstoppers?"

Progress and Accomplishments

Since the President launched the Hydrogen Fuel Initiative, we have made tremendous progress. The Department has developed a comprehensive technology development plan, the *Hydrogen Posture Plan,* fully integrating the hydrogen research of the Offices of Energy Efficiency and Renewable Energy; Science; Fossil Energy; and Nuclear Energy, Science, and Technology. This plan identifies technologies, strategies, and interim milestones to enable a 2015 industry commercialization decision on the viability of hydrogen and fuel cell technologies. Each Office has, in turn, developed a detailed research plan which outlines how the high-level milestones will be supported.

We are now implementing these research, development, and demonstration plans:

- Using FY 2004 and FY 2005 appropriations and contingent upon future appropriations over the next three years, the Department competitively selected over $510 million in projects ($755 million with cost-share) to address critical challenges such as fuel cell cost, hydrogen storage, hydrogen production and delivery cost, diverse ways of producing hydrogen, as well as research for hydrogen safety, codes and standards.
- Of this total, 65 projects are for hydrogen production and delivery, funded at $107 million over four years. These include hydrogen production from renewables, distributed natural gas, coal, and nuclear sources.
- We initiated three Centers of Excellence and 15 independent projects in Hydrogen Storage at $150 million over five years. The Centers include 20 universities, nine federal laboratories and eight industry partners, representing a concerted, multi-disciplinary effort to address on-board vehicular hydrogen storage—one of the critical enabling technologies for a hydrogen economy. These activities are closely coordinated with the Office of Science research in hydrogen storage.
- To address fuel cell cost and durability, five new projects were initiated at $13 million over three years. A new $75 million solicitation will be released this fall to address cost and durability of fuel cell systems. This is in conjunction with a $17.5 million solicitation currently open focusing on R&D addressing new membrane materials.
- We established a national vehicle and infrastructure "learning demonstration" project at $170 million over six years, with an additional 50 percent cost share by industry. This effort takes some of the research from the laboratory to the real world, and is critical to measuring progress and to providing feedback to our R&D efforts.
- Most recently, to address basic science for the hydrogen economy, 70 new projects were selected by the Office of Science at $64 million over three years to address the fundamental science underpinning hydrogen production, delivery, storage, and use. Topics of this basic research include novel materials for hydrogen storage, membranes for hydrogen separation and purification, designs of catalysts at the nanoscale, solar hydrogen production, and bio-inspired materials and processes. Such research is important for exploring fundamental science that may be applicable in the long-term and is responsive to the National Academies' report recommending a shift to more exploratory research.

With these new competitively selected awards, the best scientists and engineers from around the Nation are actively engaged. The stage is now set for results.

Technical Progress

Ongoing research has already led to important technical progress.

- As highlighted by Secretary Bodman in earlier Congressional testimony, I am pleased to report that our fuel cell activities recently achieved an important technology cost goal—the high-volume cost of automotive fuel cells was reduced from $275 per kilowatt to $200 per kilowatt. This was accomplished by using innovative processes developed by national labs and fuel cell developers for depositing platinum catalyst. This accomplishment is a major step toward the Program's goal of reducing the cost of transportation fuel cell power systems to $45 per kilowatt by 2010.

- — In hydrogen production, we have demonstrated our ability to produce hydrogen at a cost of $3.60 per gallon of gasoline equivalent at an integrated fueling station that generates both electricity and hydrogen. This is down from about $5.00 per gallon of gasoline equivalent prior to the Initiative.
- — To ensure a balanced portfolio, we must keep sight of our ultimate goal to transfer research to the real world and we have complemented our research efforts with a 'learning demonstration' activity. Most importantly, with the 'learning demonstration' activity we have the key industries that will ultimately have to invest in the hydrogen economy, the auto and energy companies, working together to ensure seamless integration of customer acceptable technology. This activity will evaluate vehicle and refueling infrastructure technologies under real-world conditions and is key to measuring progress toward technical targets and to help focus R&D.

2. What are the research areas where breakthroughs are needed to advance a hydrogen economy? How has the Department of Energy (DOE) responded to the report by the National Academy of Sciences (NAS) calling for an increased emphasis on basic research? How is DOE incorporating the results of the Basic Energy Sciences workshop on basic research needs for a hydrogen economy into the research agenda for the hydrogen initiative?

Starting in FY 2005, the Department of Energy (DOE) Office of Science has been included in the Hydrogen Fuel Initiative in order to focus basic research on overcoming key technology hurdles in hydrogen production, storage, and conversion. The Office of Science-funded research seeks fundamental understanding in areas such as non-precious-metal catalysts, membranes for fuel cells and hydrogen separation, multi-functional nanoscale structures, biological and photoelectrochemical hydrogen production, and modeling and analytical tools.

For example, basic research can help address the critical challenge of hydrogen storage: How do you safely store hydrogen on board a vehicle to enable customer expectations of greater than 300 mile driving range, without compromising passenger or cargo space? The National Academy of Sciences recommended "a shift. . .away from some development areas towards more exploratory work" to address issues like storage, stating that "the probability of success is greatly increased by partnering with a broader range of academic and industrial organizations. . ." Through the Department's "Grand Challenge" solicitation, a "National Hydrogen Storage Project" was established to broaden our scope. The new awards in basic research, with an additional $20 million for 17 projects over three years supported by the Office of Science, are integrated into this national project and provide value in developing a fundamental understanding of hydrogen interactions with materials. These multi-disciplinary efforts focused on *materials*-based technology for hydrogen storage, directly address the recommendations from the Basic Energy Sciences workshop on basic research needs for a hydrogen economy. By implementing the NAS recommendations, recent progress in materials discovery and technology allows hydrogen to be stored at low pressures and modest temperatures. Further basic and applied research will lead to better fundamental understanding and engineering solutions to address some of the key storage issues such as charging and discharging hydrogen at practical temperatures and pressures. Rather than 'stand alone' test tube research, we have an integrated effort to address basic, applied, and engineering sciences to develop materials and systems for storing hydrogen.

We face another set of challenges in hydrogen production. In this area, our research efforts are focused on reducing cost, improving energy efficiencies, and ensuring a diversity of pathways based on domestic resources for energy security that do not result in greenhouse gas emissions. Some pathways are further along in development and will be commercially viable sooner than others. For the transition, we envision producing hydrogen from natural gas or renewable liquids such as ethanol, at the fueling point, thus eliminating the need for a dedicated hydrogen distribution network. Centralized hydrogen production from coal with sequestration, biomass, nuclear, and distribution networks can follow later once market penetration justifies the capital investment required. Basic science is critical to understanding materials performance, failure mechanisms, and theoretical technology limits. The basic research component of the program contributes to longer-term concepts such as photocatalytic including biological hydrogen production and direct photoelectrochemical conversion to produce hydrogen. In fact, we have nearly $20 million of federal funding in new projects selected by the Office of Science on solar hydrogen production, membranes for separation and purification, and for bio-inspired materials and processes.

As for fuel cells, key issues are cost and durability. Significant progress has been made by national laboratories as well as industry to reduce the amount of platinum, and hence cost, within the fuel cell electrode. In addition to the targeted activities in fuel cells previously mentioned, the Office of Science has initiated new basic research projects on the design of catalysts at the nanoscale and membrane materials related to fuel cell applications. More effective catalysts, combined with better techniques for fabricating these membrane electrode assemblies and new strategies for improved durability of fuel cells, will enable us to meet the aggressive cost and performance targets we have set for fuel cells. We are also expanding our activities to include manufacturing issues that will help take these new technologies from the laboratory to the marketplace.

3. The NAS report suggested that the research agenda should be developed with future policy decisions in mind. How has DOE increased its policy analysis capabilities as recommended by the NAS? How will the results of that analysis be applied to the research agenda?

I would like to emphasize that this Program is a research effort. However, as stated earlier, in response to the National Academies' recommendation, the Program has established the Systems Analysis and Integration effort to provide a disciplined approach to the research, design, development, and validation of complex systems. A fact-based analytical approach will be used to develop a balanced portfolio of R&D projects to support the development of production, delivery, storage, fuel cell, and safety technologies. Through analysis, the impact of individual components on the hydrogen energy system as a whole will be evaluated and the interaction of the components and their effects on the system will be assessed. Systems Analysis and Integration efforts will be available to examine and understand the cost implications of policy and regulations on technology R&D direction. Analysis of various scenarios for hydrogen production and delivery is critical to the transition plan for developing the infrastructure and carbon-neutral hydrogen resources for a hydrogen economy. The planned analysis efforts will be valuable in providing rigorous data and potential guidance for policy decisions in future years.

4. How is DOE conducting planning for, and analysis of, the policy changes (such as incentives or regulation) that might be required to encourage a transition to hydrogen? What other agencies are involved in planning for, or facilitating, such a transition?

Currently, the focus of the DOE Hydrogen Program is research and development to address key technical challenges. Research and development on the codes and standards necessary to implementing hydrogen and fuel cell technologies will form a scientific and technical basis for future regulations. We are actively working with the Department of Transportation and interface with Standards Development Organizations (SDOs) and Codes Development Organizations (CDOs) on safety, codes and standards.

As part of the Systems Analysis efforts, we have started to model and explore options and pathways to achieve a successful transition to hydrogen. This effort is in collaboration with the Vehicle Technology Office and the overall Energy Efficiency and Renewable Energy modeling efforts. The Energy Information Administration (EIA) is also providing guidance. This work includes the incorporation of rigorous hydrogen production, delivery, and vehicle technology components into the National Energy Management System (NEMS) model architecture, as well development of a more detailed transportation sector model that includes conventional, hybrid, and alternative fuel options. These modeling efforts will also allow us to examine the potential impacts of policy and regulations on the introduction and long-term use of hydrogen.

Now I will talk about our partners and our future plans.

We are working with partners on all fronts to address the challenges to a hydrogen economy. Under the FreedomCAR and Fuel Partnership, DOE is collaborating with the U.S. Council for Automotive Research (USCAR) and five major energy companies to help identify and evaluate technologies that will meet customer requirements and establish the business case. Technical teams of research managers from the automotive and energy industries and DOE are meeting regularly to establish and update technology roadmaps in each technology area.

An Interagency Hydrogen R&D Task Force has been established by the White House Office of Science and Technology Policy (OSTP) to leverage resources and coordinate interrelated and complementary research across the entire Federal Government. In 2005, the Task Force has initiated a plan to coordinate a number of key research activities among the eight major agencies that fund hydrogen and fuel cell research. Coordination topics include novel materials for fuel cells and hydrogen storage, inexpensive and durable catalysts, hydrogen production from alternative sources, stationary fuel cells, and fuel-cell vehicle demonstrations. The Task Force has also launched a website, Hydrogen.gov. In the coming year, the OSTP Task Force plans to sponsor an expert panel on the contributions that nanoscale research can make to realizing a Hydrogen Economy.

Last year, we announced the establishment of the International Partnership for the Hydrogen Economy, or the IPHE. IPHE, which now includes 16 nations and the European Commission, establishes world-wide collaboration on hydrogen technology. The nations have agreed to work cooperatively toward a unifying goal: practical, affordable, competitively-priced hydrogen vehicles and refueling by 2020; and projects involving collaboration between different countries are being proposed and reviewed for selection.

Toward the Hydrogen Future

The Department is looking to the future as well. Just as we have made tremendous progress, we plan to have significant advances to report next year on the R&D projects we have launched through the solicitations I mentioned. The progress will be tracked using performance-based technical and cost milestones that provide clear and quantifiable measures. We will report this progress next year to this Subcommittee, and annually to Congress and to the Office of Management and Budget. In fact, as we speak, the NAS is completing its biennial review of the program. We anticipate more valuable feedback and will have more details to report in the coming months.

For the critical targets, it is important that we verify our progress in a way that is independent and transparent. In Fiscal Year 2006, the major technical milestones will be assessed using a rigorous methodology established by the Hydrogen Program.

— First, in Hydrogen Storage, we will determine the maximum storage potential of cryogenic-compressed hydrogen tanks and the feasibility of this technology towards meeting DOE's 2010 targets.

— Second, in Fuel Cells, we will evaluate fuel cell cost per kilowatt using current materials to determine if $110/kilowatt is feasible towards meeting the 2010 target of $45/kilowatt (assuming high volume manufacturing).

— And third, in Hydrogen Production, we will determine if the laboratory research will lead to $3 per gasoline gallon energy equivalent (gge) using a distributed natural gas reformer system.

In addition to measuring progress, we continue to develop and improve processes to facilitate innovation and to accelerate R&D. For instance, we plan an annual solicitation, starting in 2006, in the critical area of hydrogen storage to complement the Centers of Excellence. This will improve our flexibility to continuously evaluate new ideas and rapidly fund competitively selected projects.

Validation of fuel cell vehicle and hydrogen infrastructure technologies under 'real world' operating conditions is essential to track progress and to help guide research priorities. Technology and infrastructure validation will provide essential statistical data on the status of fuel cell vehicle and infrastructure technologies relative to targets in the areas of efficiency, durability, storage system range, and fuel cost. This activity will also provide information to support the development of codes and standards for the commercial use of hydrogen, and feedback on vehicle and infrastructure safety. Through cost-shared partnerships with the energy industry, Fiscal Year 2006 activities include opening eight hydrogen fueling stations, and validating performance, safety, and cost of hydrogen production and delivery technologies. By 2009, the program is expected to validate fuel cell vehicle durability of 2,000 hours, a 250-mile vehicle range, and full-scale hydrogen production cost of less than $3.00 gge.

In addition, a critical need for lowering the costs of hydrogen and fuel cells is high volume manufacturing processes and techniques. Manufacturing R&D challenges for a hydrogen economy include developing innovative, low-cost fabrication processes for new materials and applications and adapting laboratory fabrication techniques to enable high volume manufacturing. The Hydrogen Program is working with Department of Commerce and other federal agencies to create a roadmap for developing manufacturing technologies for hydrogen and fuel cell systems as part of the President's Manufacturing Initiative. The roadmap will help to guide budget requests in Fiscal Year 2007 and beyond. This work is part of the Interagency Working Group on Manufacturing R&D, which is chaired by OSTP and includes 14 federal agencies. The working group has identified nanomanufacturing, manufacturing R&D for the hydrogen economy, and intelligent and integrated manufacturing systems as three focus areas for the future. Manufacturing R&D for the hydrogen economy will be critical in formulating a strategy to transfer technology successes in the laboratory to new jobs, new investments, and a competitive U.S. supplier base in a global economy.

Successful commercialization of hydrogen technologies requires a comprehensive database on component reliability and safety, published performance-based domestic standards, and international standards or regulations that will allow the technologies to compete in a global market. Initial codes and standards for the commercial use of hydrogen are only now starting to be published. Research will be conducted in Fiscal Year 2006 to determine flammability limits and the reactive and depressive properties of hydrogen under various conditions, and also to quantify risk. Through such efforts, critical data will be generated to help write and adopt standards and to develop improved safety systems and criteria.

Conclusion

Madam Chairman, all the panelists here today will agree that achieving the vision of the hydrogen energy future is a great challenge. The DOE Hydrogen Program is committed to a balanced portfolio, conducting the basic and applied research necessary to achieve this vision. It will require careful planning and coordination, public education, technology development, and substantial public and private investments. It will require a broad political consensus and a bipartisan approach to achieving the President's vision. We appreciate the leadership taken by the Senate, and most recently the House, in establishing Hydrogen and Fuel Cell Caucuses. By being bold and innovative, we can change the way we do business here in America; we can change our dependence upon foreign sources of energy; we can address the root cause of greenhouse gas emissions; we can help with the quality of the air; and we can make a fundamental difference for the future of our children. This committee in particular has been instrumental in providing that kind of leadership over the years, and we look forward to continuing this dialogue in the months and years ahead.

We at the Department of Energy welcome the challenge and opportunity to play a vital role in this nation's energy future and to help address our energy security challenges in such a fundamental way. This completes my prepared statement. I would be happy to answer any questions you may have.

BIOGRAPHY FOR DOUGLAS L. FAULKNER

Douglas Faulkner was appointed by President George W. Bush on June 29, 2001, to serve as the political deputy in the Office of Energy Efficiency and Renewable Energy (EERE). This $1.2 billion research and development organization has over five hundred federal employees in Washington, D.C. and six regional offices, supported by thousands of contractors at the National Renewable Energy Laboratory and elsewhere.

Mr. Faulkner oversees all aspects of EERE's operations in a close partnership with the Office's two career Deputy Assistant Secretaries. He has worked closely with Assistant Secretary David K. Garman to reorganize EERE, replacing an outdated and fragmented organization with what arguably is the most innovative business model ever used in the Federal Government. This has resulted in fewer management layers, fewer but more productive staff, streamlined procedures, stronger project management in the field and lower operating costs overall. These reforms have been recognized as a success by the White House and the National Association of Public Administration.

Mr. Faulkner organized and led an internal management board which completely revamped EERE's biomass programs. Many projects were ended and those funds pooled for an unprecedented solicitation to refocus R&D for new bio-refineries.

Interviews of Mr. Faulkner about renewable energy and energy efficiency have appeared on television and radio and in the print media.

Before assuming his leadership post in EERE, Mr. Faulkner had progressed rapidly through the ranks of the civil service at the Central Intelligence Agency and the Department of Energy. In his over-twenty year career he rose from junior China intelligence analyst to a nationally-recognized leader in bio-based products and a senior policy advisor to the Secretaries of Energy in both Bush Administrations.

Born and raised in central Illinois, Principal Deputy Faulkner received a Bachelor's degree in Asian Studies from the University of Illinois and a Master's degree from the Johns Hopkins University, School of Advanced International Studies. He also attended the University of Singapore as a Rotary Scholar. At these institutions, he studied French and Mandarin Chinese languages. Mr. Faulkner played intercollegiate basketball at home and abroad.

He is involved in his church and community as well as Boy Scouts and youth baseball. Mr. Faulkner was appointed in the early 1990s to two Arlington County, Virginia, economic commissions.

Mr. Faulkner lives in Arlington, Virginia, with his wife and son.

Chairwoman BIGGERT. Thank you very much.

And then, Dr. Bodde, you are recognized for five minutes.

STATEMENT OF DR. DAVID L. BODDE, DIRECTOR, INNOVATION AND PUBLIC POLICY, INTERNATIONAL CENTER FOR AUTOMOTIVE RESEARCH, CLEMSON UNIVERSITY

Dr. BODDE. Thank you, Madame Chairman.

I would like to speak this morning to three basic ideas: first, the importance of recognizing and focusing on the transition from the current infrastructure to a hydrogen infrastructure; second, the need for long-term, fundamental research to resolve five key questions in the hydrogen economy; and third, the importance of enabling entrepreneurs and innovators to take the results of this research and move them into the marketplace and move them into commercial practice.

Let me take those ideas one at a time.

First, the transition is a competitive transition. I think it is helpful to think of three competing infrastructures: first, the internal combustion engine, both spark ignition and compression ignition, and the fuel industries that have built up around that, which are perfectly satisfactory from a consumer point of view, offering mobility services that are reasonably priced and widely available; the next competing infrastructure that is emerging into the market, the hybrid electric vehicle that uses that same fuels infrastructure; and then the third one, the hydrogen fuel cell vehicle, the ultimate competitor that removes oil as the issue in our national life and removes carbon as an environmental issue.

Now if you look at the competitive battle amongst these three, there are some lessons that come out of this look for market share. First, it is a 50-year struggle. It takes a long time to change out these infrastructures. Second, and equally important, that means that all three infrastructures will co-exist during some period during the transition, and that means the hybrid electric vehicle will also be an important contributor, both because of its fuel efficiency and also because it will pioneer some key electric management technologies later useful for the hydrogen fuel cell vehicle. Policies that accelerate this transition will be helpful, will gain more traction, than those that are not cognizant of the transition.

Now what technologies would be useful? Well, one thing that would would be a hydrogen appliance for service stations. This is one of the recommendations that came out of the National Academy of Sciences' report that—I served on that committee, also, advanced technology for hydrogen production with electrolysis, this is for small-scale distributed manufacturing of hydrogen, breakthrough technologies for small-scale performing, and integrated standard fueling station. All of these are needed for a distributed hydrogen production economy that will be part of any transition to hydrogen.

The second key idea is that fundamental research is needed to answer five big questions. And these five questions are: one, can we store hydrogen on board vehicles at near atmospheric pressures? I believe that if we cannot do this, if we have to rely on either cryogenic liquids or high-pressure gas, that this is—comes about as near to be a showstopper for the hydrogen economy as anything that I could think of. And basic research in a variety of areas to accomplish this, I think, is of fundamental importance.

The second major question concerns carbon. Can we capture and sequester the carbon dioxide from hydrogen manufacturing in a societally acceptable way? If the answer is yes, then coal as a feedstock offers a very large and very cost-effective pathway to the hydrogen economy. If the answer is no, then we have to be about very quickly developing alternatives to coal.

And that is the third major question: can we sharply reduce the cost of hydrogen from non-coal resources, in particular, from nuclear, nuclear electricity, both in terms of high-temperature electrolysis of steam and in terms of thermochemical cycles that would chemically produce the hydrogen?

Fourth, fuel cells. We need to have improved fuel cells in order to gain the efficiency on board the vehicle that offsets the inefficiencies from manufacturing hydrogen.

And finally, improved batteries.

Now all of these require broad-based programs, basic research, a wide-scale search for ideas.

The third major idea is enabling entrepreneurship. This is particularly important when the locus of innovation in the motor industry is shifting from the OEM, that is the big three automakers, down toward the suppliers, the tier one, the tier two, the tier three suppliers, and it is becoming a networked pattern of innovation as opposed to a linear pattern of innovation.

Now in many other industries, mature industries, from computers to aerospace, entrepreneurs have become the agents of change and the most important agents of change. It is important that entrepreneurs be enabled, and programs such as the SBIR, STTR, the ATP, the various alphabet soup of technology and entrepreneur support, are quite important for that.

But in addition, the kind of commitment that Congressman Inglis talked about in terms of long-term stability of government policies is very important here, because entrepreneurs seek opportunity, and they seek opportunities that will be stable across the tenure of time that it takes to launch and mature a high-growth, high-technology kind of company.

States and universities have a strong role here, and we at Clemson University are very pleased with our work at the International Center for Automotive Research, called the ICAR. We intend for this institution to be a major player and innovation laboratory in moving technology not only from our own laboratories and the laboratories in South Carolina, but from any place in the world into the entire automotive cluster, not only the major manufacturers but the suppliers as well.

That concludes my statement, Madame Chairman.

[The prepared statement of Dr. Bodde follows:]

PREPARED STATEMENT OF DAVID L. BODDE

Thank you, ladies and gentlemen, for this opportunity to discuss the *Road to the Hydrogen Economy,* a road I believe we must travel if we are to ensure a world well supplied with clean, affordable energy derived from secure sources. I will speak to this from the perspective of motor vehicle transportation and address the questions posed by the Committee within the framework of three basic ideas.

First, research policy should view the hydrogen transition as a marketplace competition. For the next several decades, three rival infrastructures will compete for a share of the world auto market: (a) the current internal combustion engine and associated fuels infrastructure; (b) the hybrid electric vehicles, now emerging on the market; and (c) the hydrogen fueled vehicles, now in early demonstration. We can judge policy alternatives and applied research investments by their ability to accelerate the shift in market share among these competing infrastructures.

Second, and in parallel with the marketplace transition, fundamental research should focus on sustaining the hydrogen economy into the far future. Key issues include: (a) storing hydrogen on-board vehicles at near-atmospheric pressure; (b) sequestering the carbon-dioxide effluent from manufacturing hydrogen from coal; (c) sharply reducing the cost of hydrogen produced from non-coal resources, especially nuclear, photobiological, photoelectrochemical, and thin-film solar processes; (d) improving the performance and cost of fuel cells; and (e) storing electricity on-board vehicles in batteries that provide both high energy performance and high power performance at reasonable cost.

And third, the results of this research must be brought swiftly and effectively to the marketplace. This requires economic policies that encourage technology-based innovation, both by independent entrepreneurs and those operating from the platform of established companies. Clemson University, through its International Center for Automotive Research and its Arthur M. Spiro Center for Entrepreneurial Leadership, intends to become a major contributor to this goal.

In what follows, I will set out my reasoning and the evidence that supports these three basic ideas.

THE HYDROGEN TRANSITION: A MARKETPLACE COMPETITION

Much thinking about the hydrogen economy concerns "what" issues, visionary descriptions of a national fuels infrastructure that would deliver a substantial fraction of goods and services with hydrogen as the energy carrier. And yet, past visions of energy futures, however desirable they might have seemed at the time, have not delivered sustained action, either from a public or private perspective. The national experience with nuclear power, synthetic fuels, and renewable energy demonstrates this well.

The difficulty arises from insufficient attention to the transition between the present and the desired future—the balance between forces that lock the energy economy in stasis and the entrepreneurial forces that could accelerate it toward a more beneficial condition.

In effect, the present competes against the future, and the pace and direction of any transition will be governed by the outcome. Viewing the transition to a hydrogen economy through the lens of a competitive transition can bring a set of "how" questions to the national policy debate—questions of how policy can rebalance the competitive forces so that change prevails in the marketplace.

A Model of the Competitive Transition

The competitive battle will be fought over a half century among three competing infrastructures:[1]

- The internal combustion engine (ICE), either in a spark-ignition or compression-ignition form, and its attendant motor fuels supply chain;
- The hybrid electric vehicle (HEV), now entering the market, which achieves superior efficiency by supplementing an internal combustion engine with an electric drive system and which uses the current supply chain for motor fuels; and,
- The hydrogen fuel cell vehicle (HFCV), which requires radically distinct technologies for the vehicle, for fuel-production, and for fuel distribution.

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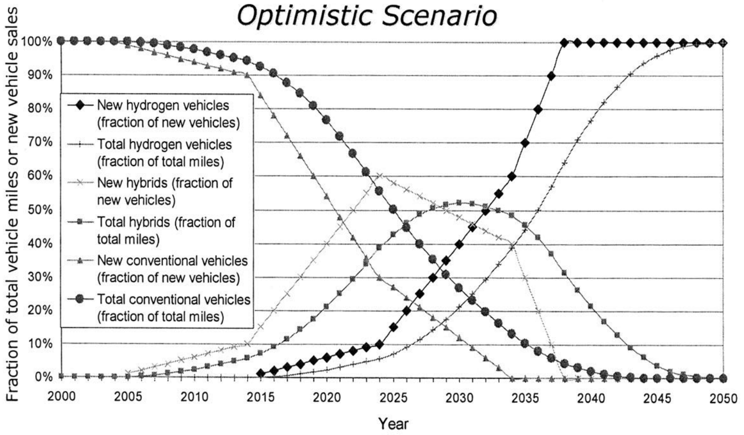
[1] Another concept, the battery electric vehicle (BEV), offers an all-electric drive-train with all on-board energy stored in batteries, which would be recharged from stationary sources when the vehicle is not in operation. I have not included this among the competitors because battery technology has not advanced rapidly enough for it to compete in highway markets. In contrast, BEV have proven quite successful in the personal transportation niche.

Figure 1 shows one scenario, based on the most optimistic assumptions, of how market share could shift among the contending infrastructures (NRC 2004). Several aspects of this scenario bear special mention. First, note the extended time required for meaningful change: these are long-lived assets built around large, sunk investments. They cannot be quickly changed under the best of circumstances. Second, the road to the hydrogen economy runs smoothest through the hybrid electric vehicle. The HEV offers immediate gains in fuel economy and advances technologies that will eventually prove useful for hydrogen fuel cell vehicles, especially battery and electric system management technologies. Although this scenario shows significant market penetration for the HEV, its success cannot be assured. The HEV might remain a niche product, despite its current popularity if consumers conclude that the value of the fuel savings does not compensate for the additional cost of the HEV. Or, its gains in efficiency might be directed toward vehicle size and acceleration rather than fuel economy. Either circumstance would make an early hydrogen transition even more desirable.

Figure 1: COMPETITION FOR MARKET SHARE
Optimistic Scenario



- *Complete replacement of ICE and HEV vehicles with fuel cell vehicles in 2050*

Source: NRC 2004

Any transition to a HFCV fleet, however, will require overcoming a key marketplace barrier that is unique to hydrogen—widely available supplies of fuel. And to this we now turn.

The Chicken and the Egg[2]

Most analyses suggest that large-scale production plants in a mature hydrogen economy can manufacture fuel at a cost that competes well with gasoline at current prices (NRC 2004). However, investors will not build these plants and their supporting distribution infrastructure in the absence of large-scale demand. And, the demand for hydrogen will not be forthcoming unless potential purchasers of hydrogen vehicles can be assured widely available sources of fuel. Variants of this "chicken and egg" problem have limited the market penetration of other fuels, such as methanol and ethanol blends (M85 and E85) and compressed natural gas. This issue—the simultaneous development of the supply side and demand sides of the market—raises one of the highest barriers to a hydrogen transition.

Distributed Hydrogen Production for the Transition

To resolve this problem, a committee of the National Academy of Sciences (NRC 2004) recommended an emphasis on distributed production of hydrogen. In this model, the hydrogen fuel would be manufactured at dispensing stations conveniently located for consumers. Once the demand for hydrogen fuel grew sufficiently, then

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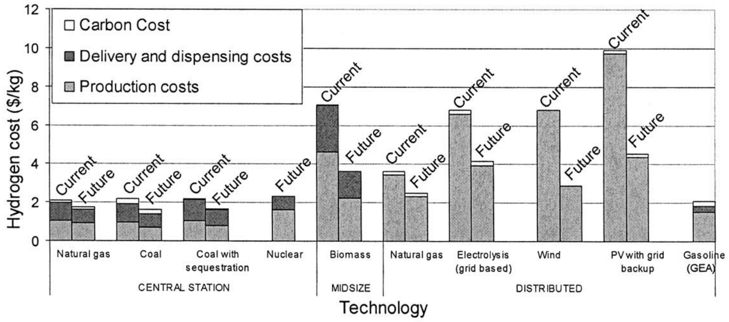
[2] Alternatively framed: "Which comes first, the vehicle or the fuel?"

larger manufacturing plants and logistic systems could be built to achieve scale economies. However, distributed production of hydrogen offers two salient challenges.

The first challenge is cost. Figure 2, below, shows the delivered cost of molecular hydrogen for a variety of production technologies. The "distributed" technologies, to the right in Figure 2, offer hydrogen at a cost between two and five times the cost of the large-scale, "central station" technologies, on the left in Figure 2. Technological advances can mitigate, but not remove entirely, this cost disadvantage.

Figure 2: A SUPPLY CHAIN INFRASTRUCTURE
Delivered H_2 Costs of Alternative Technologies



• *GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency*

Source: NRC 2004

The second challenge concerns the environment. Carbon capture and sequestration do not appear practical in distributed production. During the opening stage of a hydrogen transition, we might simply have to accept some carbon releases in order to achieve the later benefits.

Research to Accelerate a Transition by Distributed Hydrogen Production

A study panel convenienced by the National Academy of Sciences (NAS) recently recommended several research thrusts that could accelerate distributed production for a transition to hydrogen (NRC 2004). These include:

- Development of hydrogen fueling "appliance" that can be manufactured economically and used in service stations reliably and safely by relatively unskilled persons—station attendants and consumers.
- Development of an integrated, standard fueling facility that includes the above appliance as well as generation and storage equipment capable of meeting the sharply varying demands of a 24-hour business cycle.
- Advanced technologies for hydrogen production from electrolysis, essentially a fuel cell operated in reverse, to include enabling operation from intermittent energy sources, such as wind.
- Research on breakthrough technologies for small-scale reformers to produce hydrogen from fossil feedstocks.

The Department of Energy has adopted the NAS recommendations and modified its programs accordingly. It remains too early to judge progress, but in any case these technologies should receive continued emphasis as the desired transition to hydrogen nears. However, progress in research is notoriously difficult to forecast accurately. This suggests consideration be given to interim strategies that would work on the demand side of the marketplace, either to subsidize the cost of distributed hydrogen production while demand builds or to raise the cost of the competition, gasoline and diesel fuels. Such actions would relieve the research program of the entire burden for enabling the transition.

FUNDAMENTAL RESEARCH TO SUSTAIN A HYDROGEN ECONOMY

At the same time that the marketplace transition advances, several high-payoff (but also high-risk) research campaigns should be waged. These include:

- Storing hydrogen on-board vehicles at near-atmospheric pressure;
- Sequestering the carbon-dioxide effluent from manufacturing hydrogen from coal;
- Sharply reducing the cost of hydrogen produced from non-coal resources, especially nuclear, photobiological, photoelectrochemical, and thin-film solar processes;
- Improving the performance and cost of fuel cells; and,
- Storing electricity on-board vehicles in batteries that provide both high energy performance and high power performance at reasonable cost.

On-Vehicle Hydrogen Storage

The most important long-term research challenge is to provide a more effective means of storing hydrogen on vehicles than the compressed gas or cryogenic liquid now in use. In my judgment, failure to achieve this comes closer to a complete "show-stopper" than any other possibility. I believe this true for two reasons: hydrogen leakage as the vehicle fleet ages, and cost.

With regard to leakage, high pressure systems currently store molecular hydrogen on demonstration vehicles safely and effectively. But these are new and specially-built, and trained professionals operate and maintain. What can we expect of production run vehicles that receive the casual maintenance afforded most cars? A glance at the oil-stained pavement of any parking lot offers evidence of the leakage of heavy fluids stored in the current ICE fleet at atmospheric pressure. As high pressure systems containing the lightest element in the universe age, we might find even greater difficulties with containment. With regard to cost, the energy losses from liquefaction and even compression severely penalize the use of hydrogen fuel, especially when manufactured at distributed stations.

The NAS Committee, cited earlier (NRC 2004), strongly supported an increased emphasis on game-changing approaches to on-vehicle hydrogen storage. One alternative could come from novel approaches to generating the hydrogen on board the vehicle.[3] Chemical hydrides, for example, might offer some promise here, such as the sodium borohydride system demonstrated by DaimlerChrysler.

Carbon Sequestration

Domestic coal resources within the United States hold the potential to relieve the security burdens arising from oil dependence—but only if the environmental consequences of their use can be overcome. Further, as shown in Figure 2, coal offers the lowest cost pathway to a hydrogen-based energy economy, once the transient conditions have passed. Thus, the conditions under which this resource can be used should be established as soon as possible. The prevailing assumption holds that the carbon effluent from hydrogen manufacturing can be stored as a gas (carbon dioxide, or CO_2) in deep underground formations. Yet how long it must be contained and what leakage rates can be tolerated remain unresolved issues (Socolow 2005). Within the Department of Energy, the carbon sequestration program is managed separately from hydrogen and vehicles programs. The NAS committee recommended closer coordination between the two as well as an ongoing emphasis on carbon capture and sequestration (NRC 2004).

Producing Hydrogen Without Coal

Manufacturing hydrogen from non-fossil resources stands as an important hedge against future constraints on production from coal, or even from natural gas. And under any circumstance, the hydrogen economy will be more robust if served by production from a variety of domestic sources.

The non-fossil resource most immediately available is nuclear. Hydrogen could be produced with no CO_2 emissions by using nuclear heat and electricity in the high-temperature electrolysis of steam. Here the technology issues include the durability of the electrode and electrolyte materials, the effects of high pressure, and the scale-up of the electrolysis cell. Alternatively, a variety of thermochemical reactions could produce hydrogen with great efficiency. Here the needed research concerns higher operating temperatures (700°C to 1000°C) for the nuclear heat as well as research

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[3] I do not include on-board reforming of fossil feedstocks, like gasoline, among these. These systems offer little gain beyond that achievable with the HEV, and most industrial proponents appear to have abandoned the idea.

into the chemical cycles themselves. In both cases, the safety issues that might arise from coupling the nuclear island with a hydrogen production plant bear examination (NRC 2004).

In addition, hydrogen production from renewable sources should be emphasized, especially that avoiding the inefficiencies of the conventional chain of conversions: (1) from primary energy into electricity; (2) from electricity to hydrogen; (3) from hydrogen to electricity on-board the vehicle; (4) from electricity to mobility, which is what the customer wanted in the first place. Novel approaches to using renewable energy, such as photobiological or photoelectrochemical, should be supported strongly (NRC 2004).

Improved Fuel Cells

The cost and performance of fuel cells must improve significantly for hydrogen to achieve its full potential. To be sure, molecular hydrogen can be burned in specially designed internal combustion engines. But doing so foregoes the efficiency gains obtainable from the fuel cell, and becomes a costly and (from an energy perspective) inefficient process. The NAS Committee thought the fuel cell essential for a hydrogen economy to be worth the effort required to put it in place. They recommended an emphasis on long-term, breakthrough research that would dramatically improve cost, durability, cycling capacity, and useful life.

Improved Batteries

The battery is as important to a hydrogen vehicle as to a hybrid because it serves as the central energy management device. For example, the energy regained from regenerative braking must be stored in a battery for later reuse. Though energy storage governs the overall operating characteristics of the battery, a high rate of energy release (power) can enable the electric motor to assist the HEV in acceleration and relieve the requirements for fuel cells to immediately match their power output with the needs of the vehicle. Thus, advanced battery research becomes a key enabler for the hydrogen economy and might also expand the scope of the BEV.

ENTREPRENEURSHIP FOR THE HYDROGEN ECONOMY

For the results of DOE research to gain traction in a competitive economy, entrepreneurs and corporate innovators must succeed in bringing hydrogen-related innovations to the marketplace. In many cases, independent entrepreneurs provide the path-breaking innovations that lead to radical improvements in performance, while established companies provide continuous, accumulating improvement.[4] The Federal Government, in partnership with states and universities, can become an important enabler of both pathways to a hydrogen economy.

Federal Policies Promoting Entrepreneurship

From the federal perspective, several policies could be considered to build an entrepreneurial climate on the "supply" side of the market. These include:

- Special tax consideration for investors in new ventures offering products relevant to fuel savings. The intent would be to increase the amount of venture capital available to startup companies.
- Commercialization programs might enable more entrepreneurs to bring their nascent technologies up to investment grade. For example, an enhanced and focused *Small Business Innovation Research* (SBIR) program might increase the number of participating entrepreneurs participating in fuel-relevant markets. A portion of the *Advanced Technology Program* (ATP) could be focused in like manner.
- Outreach from the National Laboratories to entrepreneurs might be improved. Some laboratories, the National Renewable Energy Laboratory (NREL) for example, offer small, but effective programs. But more systematic outreach, not to business in general, but to entrepreneurial business, would also increase the supply of market-ready innovations.

On the demand side, any policy that increases consumer incentives to purchase fuel efficient vehicles will provide an incentive for ongoing innovation—provided that the policy is perceived as permanent. Entrepreneurs and innovators respond primarily to opportunity; but that opportunity must be durable for the 10-year cycle required to establish a new, high-growth company.

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[4] See the Appendix: The Process of Innovation and Implications for the Hydrogen Transition for a more complete discussion.

States and Universities as Agents of Innovation/Entrepreneurship

Innovation/entrepreneurship is a contact sport, and that contact occurs most frequently and most intensely within the context of specific laboratories and specific relationships. I will use Clemson's International Center for Automotive Research (ICAR) to illustrate this principle. Most fundamentally, the ICAR is a partnership among the State of South Carolina, major auto makers,[5] and their Tier I, Tier II, and Tier III suppliers. The inclusion of these suppliers will be essential for the success of ICAR or any similar research venture. This is because innovation in the auto industry has evolved toward a global, networked process, much as it has in other industries like microelectronics. The "supply chain" is more accurately described as a network, and network innovation will replace the linear model.

For these reasons, the ICAR, when fully established, will serve as a channel for research and innovation to flow into the entire cluster of auto-related companies in the Southeast United States. We anticipate drawing together and integrating the best technology from a variety of sources:

- Research performed at Clemson University and at the ICAR itself;
- Research performed at the Savannah River National Laboratory and the University of South Carolina; and,
- Relevant science and technology anywhere in the world.

Beyond research, the ICAR will include two other components of a complete innovation package: education, and entrepreneur support. With regard to education, the Master of Science and Ph.D. degrees offered through the ICAR will emphasize the integration of new technology into vehicle design, viewing the auto and its manufacturing plant as an integrated system. In addition, courses on entrepreneurship and innovation, offered through Clemson's Arthur M. Spiro Center for Entrepreneurial Leadership, will equip students with the skills to become effective agents of change within the specific context of the global motor vehicle industry.

With regard to entrepreneur support, the ICAR will host a state-sponsored innovation center to nurture startup companies that originate in the Southeast auto cluster and to draw others from around the world into that cluster. In addition, the ICAR innovation center will welcome teams from established companies seeking the commercial development of their technologies. The State of South Carolina has provided significant support through four recent legislative initiatives. The Research University Infrastructure and the Research Centers of Economic Excellence Acts build the capabilities of the state's universities; and the Venture Capital Act and Innovation Centers Act provide support for entrepreneurs.

None of these elements can suffice by itself; but taken together they combine to offer a package of technology, education, and innovation that can serve the hydrogen transition extraordinarily well.

A CONCLUDING OBSERVATION

Revolutionary technological change of the kind contemplated here is rarely predictable and never containable. Every new technology from the computer to the airplane to the automobile carries with it a chain of social and economic consequences that reach far beyond the technology itself. Some of these consequences turn out to be benign; some pose challenges that must be overcome by future generations; but none have proven foreseeable.

For example, a hydrogen transition might bring prolonged prosperity or economic decline to the electric utility industry depending upon which path innovation takes. A pathway that leads through plug-hybrids to home appliances that manufacture hydrogen by electrolysis would reinforce the current utility business model. A pathway in which hydrogen fuel cell vehicles serve as generators for home electric energy would undermine that model. The same holds true for the coal industry. A future in which carbon sequestration succeeds will affect coal far differently from one in which it cannot be accomplished.

The only certainty is that the energy economy will be vastly different from that which we know today. It will have to be.

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[5] BMW was the founding OEM and most significant supporter of the ICAR.

U.S. National Research Council, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs,* The National Academies Press, 2004.

APPENDIX:[6] THE PROCESS OF INNOVATION AND IMPLICATIONS FOR THE HYDROGEN TRANSITION

At the beginning, it might be helpful to review some general principles regarding technological innovation and how it advances performance throughout the economy. We should begin by understanding technology from the customer perspective—not as a “thing,” but as a service.

Technology Viewed as a Service

Fuels and vehicles have little value in themselves, but enormous utility as providers of mobility services. These valued services include performance vectors like:

- Time saving: will the vehicle travel far enough that the driver does not waste time with frequent refueling?
- Safety: how well does the vehicle protect its occupants, both by its ability to avoid accidents and by its ability to survive them?
- Comfort: can the vehicle mitigate the stress and hassles of road travel for the driver and passengers?
- Image: what does driving this particular vehicle say about its occupants?
- Ancillary services: does the vehicle have enough generating capacity to meet the growing demand for on-board, electricity-based services?

At any time, consumers emphasize some of these performance dimensions while satisficing along others. Consider the consumer preferences revealed by an EPA analysis of automobile performance from 1981 to 2003. Over this period, average horsepower nearly doubled (from 102 to 197 horsepower), weight increased markedly (from 3,201 to 3,974 lbs), and the time required to accelerate from zero to 60 mph dropped by nearly 30 percent. An energy policy that added fuel security to the competitive performance dimensions for road transportation would do much to promote the hydrogen transition.

Technology-based Innovation: Accumulating

Technological innovations can be grouped into two general classes: those that advance performance by *accumulating* incremental improvements, and those that offer *discontinuous* leaps in performance. The term *accumulating* applies to technologies that advance performance along dimensions already recognized and accepted by customers. Each improvement might be incremental, but the cumulative effect compounds to yield markedly improved performance—consider the improvements in processor speed for computers, for example. Auto manufacturers are accustomed to competing along these dimensions, and the cumulative effect can lead to important advances—but only if the technology competition continues long enough for the gains to accumulate. Most of the fuel saving technologies discussed at this hearing are incremental in nature, and so nurturing this kind of innovation could become an important policy goal.

Technology-based Innovation: Discontinuous

In contrast, *discontinuous* technologies introduce performance dimensions quite distinct from what the mainstream customers have come to value, sometimes offering inferior performance along the accustomed dimensions. Because of their inferior mainstream performance, these technologies initially gain traction only in niche markets. With continued use and improvement, however, discontinuous technologies gain adequacy along the original dimensions and then enter the mainstream markets.

Consider the battery electric vehicle (BEV), for example. Many analysts have written off electric vehicles because of their inferior performance in mainstream auto markets—acceleration, range, and recharge time. Yet electric vehicle technologies are emerging in an important niche: the market for personal transportation. This includes golf carts, all-terrain vehicles, touring vehicles for resorts, transportation within gated communities, and so forth. In that market, the chief performance dimensions are convenient access, economy, and ease of use—and style. The current state of electric vehicle technology is adequate for the limited range and acceleration requirements of this niche. But, could electric vehicle technology advance to the point of entry into mainstream markets? Or, could it compete effectively in personal transportation markets in developing countries—say Thailand or China? That is, of course, unknowable. But, please recall that the personal computer was once consid-

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[6] This Appendix draws heavily upon a previous statement prepared for the 9 February, 2005 hearing of the House Science Committee.

ered a hobbyists toy, inherently without enough power to enter mainstream applications.

Discontinuous innovation tends to be the province of the *entrepreneur,* and the companies that such persons found become platforms for the innovations that radically change all markets. Yet entrepreneurs often have low visibility relative to the market incumbents in policy discussions, and their companies are far from household words.[7] This is because the entrepreneurs' story is about the future, not the present; about what could be and not about what is. For that reason, policies that encourage entrepreneurship in technologies relevant to the hydrogen transition should become part of the energy policy conversation.

BIOGRAPHY FOR DAVID L. BODDE

Senior Fellow and Professor: Arthur M. Spiro Center for Entrepreneurial Leadership; Director, Innovation and Public Policy, International Center for Automotive Research, Clemson University. Research and teaching in:

- Intellectual property management
- Markets for new energy technology
- Corporate entrepreneurship
- Next-generation hybrid electric and hydrogen fuel cell vehicles

PREVIOUS PROFESSIONAL EXPERIENCE

University of Missouri–Kansas City, July 1996 to September 2004

Charles N. Kimball Chair in Technology and Innovation at the University of Missouri, Kansas City. Joint appointment as Professor of Engineering and Business Administration.

Midwest Research Institute (MRI), January 1991 to July 1996

Corporate Vice President and President of MRI's for-profit subsidiary, MRI Ventures. Responsible for new enterprise development through cooperative research, new ventures, licenses, and international agreements. Managed technology development consortium of five private companies to commercialize technology from the National Renewable Energy Laboratory (NREL). Worked with Department of Energy and senior NREL management on strategic initiatives for the laboratory.

National Academy of Sciences, April 1986 to January 1991

Executive Director, Commission on Engineering and Technical Systems. Directed research and studies on public and private issues in science and technology.

U.S. Government, March 1978 to March 1986

Assistant Director, Congressional Budget Office, United States Congress. Directed economic analyses of legislation affecting energy, industrial competitiveness, agribusiness, science, technology, and education.

Deputy Assistant Secretary, Department of Energy. Policy research regarding nuclear energy, coal, synthetic fuels, electric utilities, technology transfer and national security. Emphasis on nuclear breeder reactors and nuclear non-proliferation. U.S. delegate to International Nuclear Fuel Cycle Evaluation, which sought an international agreement on plutonium recycle and measures to slow the proliferation of nuclear weapons.

TRW, Inc., January 1976 to March 1978

Manager, Engineering Analysis Office, Energy Systems Planning Division. Built business using systems analysis and engineering studies. Emphasis on application of aerospace technology to energy problems, especially radioactive waste disposal and synthetic fuels.

U.S. Army, 1965 to 1970

Captain. Platoon leader, company commander, and battalion operations officer. Airborne and Ranger qualified. Service as combat engineer in Vietnam (1968–69). Bronze Star, Army Commendation Medals. Remained in the Army Reserve as an R&D officer advising on the management of defense laboratories and nuclear research programs.

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[7] Consider, for example, *Zap!,* a company founded 10 years ago in response to the zero-emissions vehicle market emerging in California. A description can be found at: *http://www.zapworld.com/index.asp*

EDUCATION

Harvard University

Doctor of Business Administration, March 1976. Doctoral thesis on the influence of regulation on the technical configuration of the commercial nuclear steam supply system. Thesis research cited in subsequent books on nuclear energy. Harding Foundation Fellowship.

Massachusetts Institute of Technology

Master of Science degrees in Nuclear Engineering (1972) and Management (1973). Atomic Energy Commission Fellowship. Experimental thesis on irradiation-induced stress relaxation.

United States Military Academy

Bachelor of Science, 1965. Commissioned Second Lieutenant, U.S. Army.

CORPORATE BOARD MEMBERSHIPS

Great Plains Energy

Board member of electric energy company, 1994–present. Chair, Nuclear Committee; Chair, Governance Committee; Member, Audit Committee.

The Commerce Funds

Founding director of family of mutual funds, currently with $2.2 billion assets under management. Growth and Bond Funds achieved Morningstar 5-Star ranking. 1995–present.

PERSONAL BACKGROUND

Grew up in Kansas City, Missouri. Married (since 1967) with four children. Enjoy competitive athletics, especially racquetball and tennis. Frequent backpacker, amateur historian, bad poet, and worse musician. Publications in technology management, energy, and policy.

Chairwoman BIGGERT. Thank you very much, Dr. Bodde.

Mr. Chernoby.

STATEMENT OF MR. MARK CHERNOBY, VICE PRESIDENT, ADVANCED VEHICLE ENGINEERING, DAIMLERCHRYSLER CORPORATION

Mr. CHERNOBY. We are going to shift a little bit and use some visual aids to support my conversation, so go ahead to the next slide, please.

[Slide.]

I want to thank the Chairs and the distinguished Members of the House Committee for this opportunity to appear before you today.

I am going to briefly describe DaimlerChrysler's involvement in the Administration's hydrogen initiative, what we are trying to do to advance the overall hydrogen economy, and then as well as some of the specific questions raised today.

Mr. Chairman, you mentioned three keys. You mentioned commitment, collaboration, and discovery. And as I go through these slides, I am going to try and point that out.

In the slide you see before you now, what I am trying to describe is DaimlerChrysler, we have been working on fuel cell technology for over 10 years. We have poured a billion dollars into different technologies for fuel cells that run on different fuel sources. We are committed. We have now centered, in the past few years, all of our work on hydrogen as the base fuel for these fuel cell products. And as you can see on the slide with the various pictures, we are attempting to look at products that could be attractive to a broad range of the—of customers, be it heavy buses for certain types of environments all of the way down to the small and compact car.

Next slide, please.

[Slide.]

One of the critical enablers is collaboration. We participate as a member for the United States Council for Automotive Research with our partners at Ford and General Motors. And then most recently, we think it is exceptional to have added partners from BP, ChevronTexaco, ConocoPhillips, Exxon, and Shell, because we truly think the march to a completely new technology, a different way of life in the hydrogen economy is going to truly require collaboration in a pre-competitive environment across these multiple industries. We have got to bring together both vehicle and the infrastructure. And as you see in the center of this slide, the joint partnership and how we work together in certain task teams to understand how these infrastructures interface with the vehicle, what about the fuel, fuel quality, how does that relate to the fuel cell, it has all got to come together in order to realize a successful transition to the hydrogen economy.

Next slide, please.

[Slide.]

At DaimlerChrysler, as Mr. Honda mentioned, we are proud to be a participant in the Department of Energy's demonstration program. We have numerous vehicles that are on the road in the United States already providing information to the Department of Energy. We have also shared information off of these vehicles with the Environmental Protection Agency. And really, there are several key things we are trying to get out of the demonstration product. We are moving from the lab to the road. That is critical. We have already found failure modes and systems to components that we had not seen in the lab environment. And as was mentioned, these now become initiatives and challenges for us to work on both in the research and the development environment as we move forward. So it is critical, when you are moving from a technology, like the internal combustion engine that we have on the road for well more than 50 years, we understand how that affects the environment. With the new technology, we have to develop that understanding. That is why we are participating in three different environments. And DaimlerChrysler, outside of this demonstration project, we have vehicles around the world in a multitude of environments. And as you can see, our demonstration vehicles range from the small vehicle, the F-cell, up to the large sprinter, because these two types of vehicles clearly operate in different environments between the commercial and more of the daily use. So we absolutely think the demonstration fleet is providing very valuable data to feed the codes and standards efforts as well as helping us find new barriers and challenges we need to overcome to bring this product to a reality.

Next slide, please.

[Slide.]

There was a question raised about, you know, what does DaimlerChrysler do. What do we focus on in order to make decisions on where we put our research funds and how much research funds get placed against a certain topic?

As you can see on the slide, we basically look at five key factors. I would like to tell you there is a perfect math formula that with algebra you can just plug in the numbers and say this is where you put your money. Unfortunately, the world and life isn't that easy.

We do look at probability of technical success, the probability of commercial success in the market, the value from a customer perspective, how does it fit with our business strategy, and then what strategic leverage does it provide the company. All of these factors, any type of research that we do, are calibrated, assessed, and then with that assessment, we look at, all right, how are we going to prioritize our funding and our people resource over a said time period.

Next slide, please.

[Slide.]

There was a question raised about how do we see the fuel cell vehicle, the infrastructure coming together in terms of time in transitioning to truly the hydrogen-based economy for this transportation sector.

At DaimlerChrysler, we think we are—we project we are going to go through four different phases. Right now, we have moved from basically what we call market preparation. That is basically setting up the infrastructure, setting up the vehicles in the lab environment, and getting ready to put some vehicles actually on the road that are fit for daily use. Fit for daily use, I have to qualify, only in certain environments. As an example, we have had severe challenges with cold start, so you will find many of the vehicles around the world aren't necessarily in extremely cold environments.

We think we are going to go through two more stages before this finally becomes the reality. We are going to head to a ramp-up stage. That is where we think some of the technological barriers that are facing us through all of this great pre-competitive research are going to be overcome. And we will be able to put a larger fleet in the field. This larger fleet is going to be limited by the growth of the infrastructure. We have got to have both the infrastructure there, the fueling, along with the vehicle to make it work. So we project that will be the next stage.

And then the final stage will actually be commercialization. This is where the—all of the major technical barriers, including cost and value to the customer, and then broad-based movement of the infrastructure have to come together to make it viable to move to large-scale production and then large-scale purchase and use by the customer base.

Next slide, please.

[Slide.]

At DaimlerChrysler, though, we are absolutely convinced, both in the short-term, the near-term, and potentially in the long-term, there is going to be a wide range of technologies that are going to be attractive to the marketplace. We are working on all of them at once, because we believe there is a place for each one of these technologies in the market where they provide maximum value to the customer. As an example, a hybrid provides maximum value to the customer who operates in a city environment. The customer who drives mostly on the highway may be more attracted to a diesel. And so as we transition between now and the hydrogen economy, we are going to keep working on trying to provide a broad-based set of propulsion technologies for the market to enable them to implement them to benefit not only the environment, but energy security, because penetration is what is going to matter. We don't get a benefit from either one of those unless we get market penetration, and so we have got to provide maximum value to the customer.

Next slide, please.

[Slide.]

There are several key technology challenges in front of us to transition to the hydrogen economy. We have—we would summarize them into the fuel cell system itself, durability, cost. We have done some great work in terms of the pre-competitive environment, between academia, government, and industry in overcoming a challenge such as cold start. So that is one behind us, but we have got many more to go. The battery system, as was commented earlier, is a significant challenge as well. And then finally, hydrogen storage, as Dr. Bodde mentioned, is a very significant challenge that we absolutely must find a way to overcome if we expect to have broad-based penetration of the market and not take space away from the customer.

Next slide, please.

[Slide.]

So if we look at the—how we think we are going to transition, obviously, we are very focused at DaimlerChrysler on the near-term in providing both the advanced powertrains and hybrid technology. And then we, obviously, are very committed to a transition to an H2 fuel cell vehicle and then the ultimate infrastructure and economy that is going to come together with the broad-based focus on zero emissions, ultimate low energy consumption for the environment, and then finally the concept of energy self-sufficiency and energy security that comes along with it.

Next slide, please.

[Slide.]

I think that is it.

Thank you, and I would be happy to answer any questions you may have.

[The prepared statement of Mr. Chernoby follows:]

PREPARED STATEMENT OF MARK CHERNOBY

I want to thank the Chairs and distinguished Members of the House Committee on Science for this opportunity to appear today.

I am coming before you today to describe our involvement in the Administration's Hydrogen Initiatives, and what DaimlerChrysler is doing to advance the overall hydrogen economy, as well as, address the questions presented to me by the Subcommittee on Research and the Subcommittee on Energy.

What is DaimlerChrysler doing to advance a hydrogen economy?

DaimlerChrysler has been working on fuel cell technology for transportation utilizing hydrogen for over ten years. We have invested over $1 Billion in R&D and have developed five generations of vehicles (NECAR1, 2, 3, and 4, and the F–Cell). Of all manufacturers, we have the largest world wide fleet of fuel cell cars and buses (100 vehicles) participating in several international demonstration projects in the United States, Europe, and Asia. (See Figure 1: DaimlerChrysler Fuel Cell History)

How does DaimlerChrysler participate in the Administration's Hydrogen Initiatives?

As a member of the United States Council for Automotive Research (USCAR), DaimlerChrysler is a partner in the Department of Energy's (DOE) FreedomCAR and Fuel Partnership along with General Motors and Ford Motor Company, and BP

America, ChevronTexaco Corporation, ConocoPhillips, Exxon Mobil Corporation, and Shell Hydrogen. The recent addition of these five major energy providers has strengthened the Partnership considerably, by providing expertise to solve the infrastructure challenges. DaimlerChrysler has also been working with the DOE since 1993 on advanced automotive technology research. We support the initiative as members on technical teams related to advanced automotive technology, including:

- — Energy Storage
- — Light Weight Materials
- — Advanced Combustion
- — Hydrogen Storage
- — Fuel Cell
- — Codes & Standards
- — Electrical and Electronics
- — Vehicle Systems Analysis

Through these tech teams, we help develop priorities based on future needs and manage a portfolio of research projects directed at a set of Research Goals and Objectives. (See Figure 2: FreedomCAR and Fuel Partnership)

We also are one of four recipients to participate in the DOE Hydrogen and Fleet Demonstration Project. By the end of 2005, we will have 30 vehicles located in three ecosystems (Southern California, Northern California, and Southeastern Michigan) and were the first OEM to provide valuable technical data to the DOE. (See Figure 3: DOE Hydrogen Fleet & Infrastructure Demonstration & Validation Project)

What criteria does DaimlerChrysler consider when making investment decisions regarding its portfolio of advanced vehicle research and development programs?

DaimlerChrysler uses five factors of measurement to determine investment priorities in our advance technology portfolio. They are:

- — Probability of Technical Success
- — Probability of Commercial Success
- — Value
- — Business Strategy Fit, and
- — Strategic Leverage

(See Figure 4: Five Key Investment Factors)

What factors would induce DaimlerChrysler to invest more in the development of hydrogen-fueled vehicles?

Several factors could contribute to inducing DaimlerChrysler to invest more in the development of hydrogen fueled vehicles. Key factors include:

- — Significant technological advances in fuel cells and hydrogen storage/production
- — Major governmental policy support such as incentives, regulatory shifts,
- — Changes in consumer demand and competitive pressure
- — Significant long-term increases in gasoline prices

What do you see as a probable timeline for the commercialization of hydrogen-fueled vehicles?

The current technology is being evaluated in several fleet demonstration projects around the world. The largest is the DOE's program in the United States. These programs include a few hundred vehicles worldwide and several hydrogen fueling stations.

DaimlerChrysler projects that the hydrogen fueled vehicle technologies will evolve in discreet phases driven be the following cadence of events:

- — Breakthrough in basic research
- — Bench/laboratory development
- — "On road" testing and development
- — Parallel manufacturing process development

Within the next 4–6 years, we will enter another phase utilizing technologies that address some of the current deficiencies including durability, range, and cold start, as well as, lower cost. This phase will see vehicle numbers in the low thousands and the beginning of a local infrastructure to support them.

The third phase will require significant vehicle technical breakthroughs in hydrogen storage, fuel cell cost, and a significantly expanded infrastructure. Technological breakthroughs are required in hydrogen storage and fuel cell technology (focused on cost & durability). DaimlerChrysler shares a commitment with our partners in USCAR effort to achieve these gains. It is a challenge to predict a definitive timeline for technological discovery. The vehicle fleet could grow to tens of thousands if significant shifts occur in the infrastructure and value to the consumer. The infrastructure must expand to a much larger scale beyond local support. This will be critical to support the freedom to travel that consumers will demand when we move from a market dominated by local "fleet" customers to the average consumer.

High volume commercialization will require a highly distributed infrastructure capable of delivering cost competitive hydrogen and fuel cell powered vehicles that can compete with other fuel efficient technologies. It is likely that this will require continued government policy support for vehicle and fuel. (See Figure 5: DaimlerChrysler Fuel Cell Strategy)

What about the other advanced vehicle technologies DaimlerChrysler is currently developing, such as hybrid vehicles and advanced diesel engines?

DaimlerChrysler is engaged in a broad range of advanced propulsion technologies. Fuel cell vehicles are a long-term focus of this technology portfolio, which also includes efficient gasoline engines, advanced diesels, and hybrid powertrain systems. (See Figure 6: DaimlerChrysler's Advanced Propulsion Technologies)

DaimlerChrysler is focused on providing the market with the ability to select the advanced propulsion technology that best fits the needs of the individual customer. Each of the short-term technologies optimizes its benefit to the consumer in specific drive cycles (hybrid/city, diesel/highway) and hence its value to the customer.

DaimlerChrysler has developed and implemented technologies that improve the efficiency of the current gasoline propulsion system. We must continue to enhance the gasoline combustion propulsion system since it will be the dominant choice in the market for many years to come. We offer the Multi-Displacement System (MDS) available in the HEMI in seven Chrysler Group vehicles. MDS seamlessly alternates between smooth, high fuel economy four-cylinder mode when less power is needed and V–8 mode when more power from the 5.7L HEMI engine is in demand. The system yields up to 20 percent improved fuel economy.

We are also working on further development of gasoline direct-injection which considerably enhances fuel economy by closely monitoring fuel atomization.

DaimlerChrysler offers four different diesel powertrains in the United States, not including heavy trucks. Advanced diesel technology offers up to 30 percent better fuel economy and 20 percent less CO_2 emissions when compared to equivalent gasoline engines. The diesel provides maximum benefit in highway driving which for many customers is a daily occurrence. Advanced diesel is a technology that is available today and can help reduce our nation's dependency on foreign oil.

Designing more engines to run on Biodiesel is a current objective at DaimlerChrysler. Biodiesel fuel reduces emissions of diesel vehicles, including carbon dioxide, and lowers petroleum consumption. Each Jeep Liberty Common Rail Diesel (CRD) built by DaimlerChrysler is delivered to customers running on B5 biodiesel fuel. Nationwide use of B2 fuel (two percent biodiesel) would replace 742 million gallons of gasoline per year, according to the National Biodiesel Board.

DaimlerChrysler and GM have recently combined efforts to develop a two-mode hybrid drive system that surpasses the efficiency of today's hybrids. The partnership will cut development and system costs while giving customers an affordable hybrid alternative that improves fuel economy. The first use of the system will be in early 2008 with the Dodge Durango.

What do you see as the potential technology showstoppers for a hydrogen economy?

The most significant technology showstoppers that DaimlerChrysler recognizes as challenging the viability of the hydrogen economy include fuel cell durability, on-board hydrogen storage and advanced battery durability performance. Though there are major efforts and investment being put into fuel cell development, the current systems have to make significant gains in life expectancy and extreme operating conditions that the average consumer will demand.

No current on-board hydrogen storage system meets the FreedomCAR and Fuel Partnership targets for cost and performance. To meet customer expectations for driving range, a large amount of hydrogen is required to be stored on-board. Today's compressed hydrogen storage technology has limits in storage density which leads to a compromise in passenger compartment space in order to provide the driving range that consumer's enjoy today. Additionally, the current level of technology for high-pressure storage tanks that are available has associated manufacturing processes that take multiple days per tank. The on-board hydrogen storage tank industry currently does not have the capacity to support even low-volume production levels. Alternative and novel methods of storing hydrogen on-board are critical to the hydrogen economy.

While several advancements have been made in battery technology in recent years, the current level of technology does not support performance requirements for power, energy and durability. (See Figure 7: Technology Showstoppers)

In addition to the technology challenges identified above, the cost challenges are significant barriers. To realize large scale market penetration, we will have to approach the value that customers enjoy with current propulsion technologies.

Even with a viable vehicle, the hydrogen economy will not become a reality without a highly distributed infrastructure. Our Energy Partners in the FreedomCAR and Fuel effort are committed to the research and technology development required to realize this goal. Industry and government will need to work together to develop an implementation plan with financial viability for all entities.

To what extent is DaimlerChrysler relying on government programs to help solve those technical challenges?

DaimlerChrysler realizes that the technical challenges associated with moving towards the hydrogen economy are too great and too costly for any one company to solve. Therefore, we see a benefit in multiple companies working together with government in pre-competitive technology development. Due to the enormity of this transition, DaimlerChrysler actively participates in USCAR with Ford Motor Company and General Motors and in the FreedomCAR and Fuel Partnership along with the other USCAR members as well as the U.S. Department of Energy, BP America, ChevronTexaco Corporation, ConocoPhillips, Exxon Mobil Corporation and Shell Hydrogen. The research required to solve the technical challenges of the hydrogen economy is universally viewed as "high risk" by industry. The research sponsored by DOE through the FreedomCAR and Fuel Partnership provides a forum to pull together some of the best minds and organizations involved in advancement of the hydrogen economy to help address that risk. The development of the hydrogen infrastructure must progress in parallel with fuel cell vehicle technologies. (See Figure 8: Technology Relationship Strategy)

How are automakers using, or how do they plan to use, the advanced vehicle technology developed for hydrogen-fueled vehicles to improve the performance of conventional vehicles?

As stated earlier, DaimlerChrysler is working on a broad portfolio of technologies to improve the efficiency and environmental impact of transportation. In the short-term we continue to improve the internal combustion engine (ICE). In the mid-term we are developing hybrid vehicles utilizing electric drive systems, integrated power modules and advanced batteries. In the long-term fuel cell vehicles with on-board hydrogen storage from a national hydrogen infrastructure will emerge.

The current portfolio of R&D within the DOE's FreedomCAR and Fuel Initiative is focused on the long-term hydrogen vision, but many of the technologies are useful and will mature in the shorter-term as transition technologies. Cost effective, lightweight materials can be applied to vehicles in the short-term to improve fuel efficiency regardless of the propulsion technology. Advanced energy storage and motors will benefit both hybrid and fuel cell vehicles. Novel approaches to hydrogen storage are uniquely required by hydrogen fueled vehicles, but can support stationary and portable applications in the industrial and consumer markets.

It is important to advance and mature many of the aspects of the technology as early as possible. There are many challenges and breakthroughs needed to realize the President's vision of a "Hydrogen Economy."

Figure 1: DaimlerChrysler Fuel Cell History

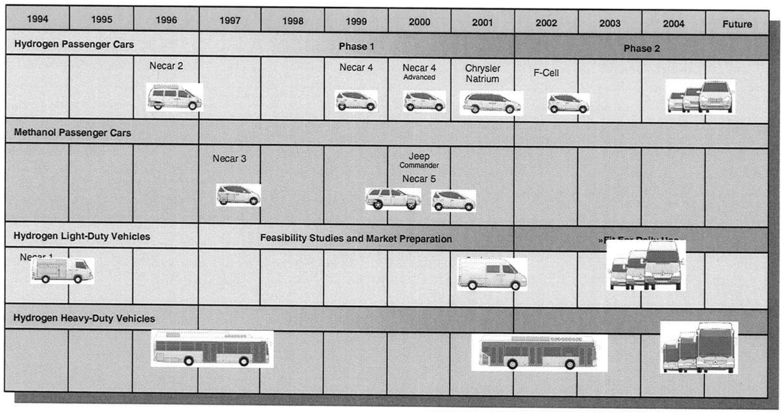


Figure 2: FreedomCAR and Fuel Partnership

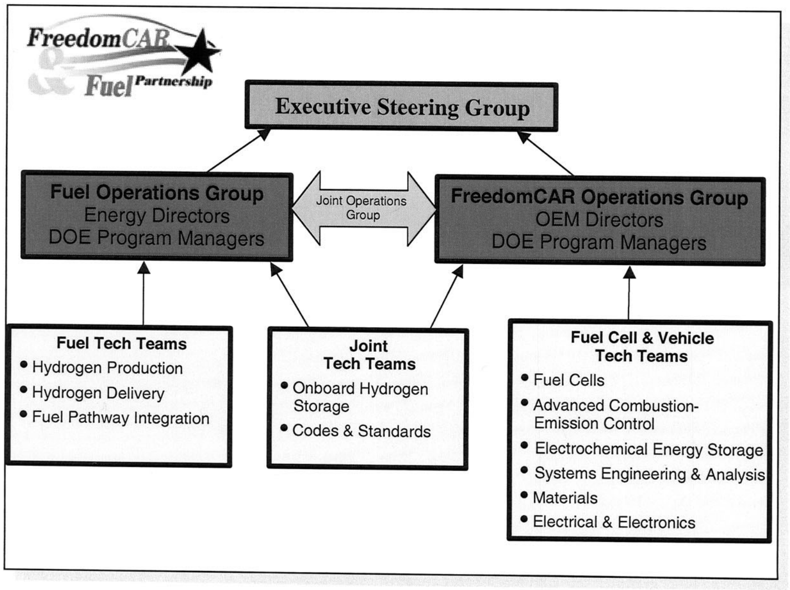
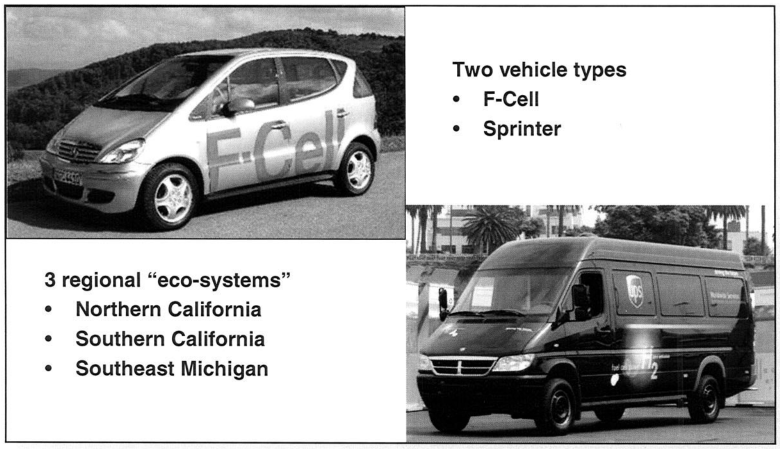


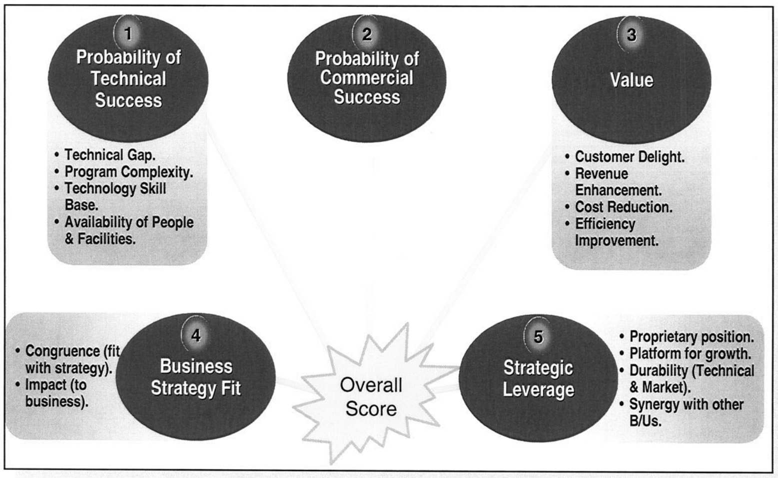
Figure 3: DOE Hydrogen Fleet & Infrastructure Demonstration & Validation Project



Two vehicle types
- F-Cell
- Sprinter

3 regional "eco-systems"
- Northern California
- Southern California
- Southeast Michigan

Figure 4 : Five Key Investment Factors



1 Probability of Technical Success
- Technical Gap.
- Program Complexity.
- Technology Skill Base.
- Availability of People & Facilities.

2 Probability of Commercial Success

3 Value
- Customer Delight.
- Revenue Enhancement.
- Cost Reduction.
- Efficiency Improvement.

4 Business Strategy Fit
- Congruence (fit with strategy).
- Impact (to business).

Overall Score

5 Strategic Leverage
- Proprietary position.
- Platform for growth.
- Durability (Technical & Market).
- Synergy with other B/Us.

Figure 5 : DaimlerChrysler Fuel Cell Strategy

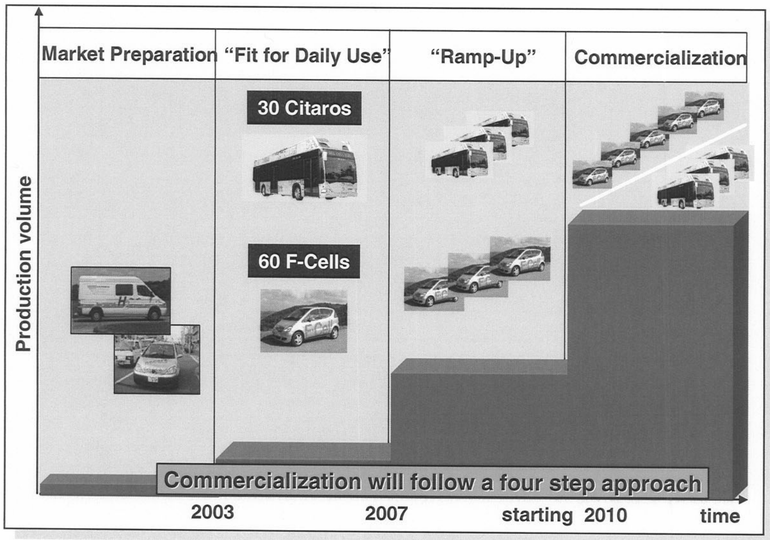
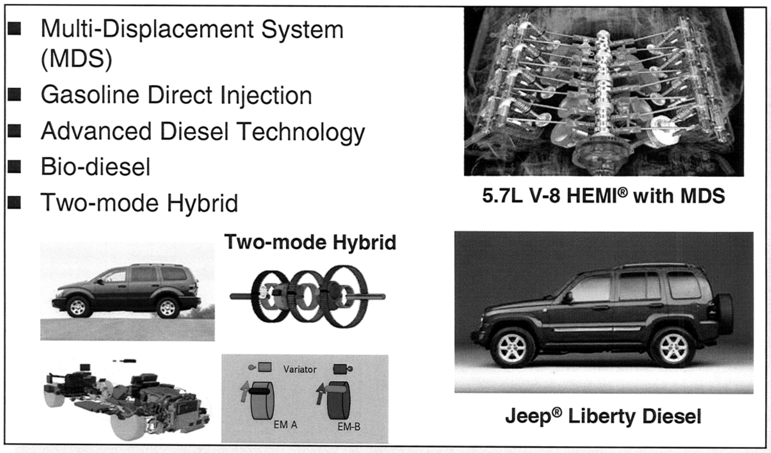


Figure 6 : DaimlerChrysler's Advanced Propulsion Technologies



- Multi-Displacement System (MDS)
- Gasoline Direct Injection
- Advanced Diesel Technology
- Bio-diesel
- Two-mode Hybrid

Figure 7 : Technology Showstoppers

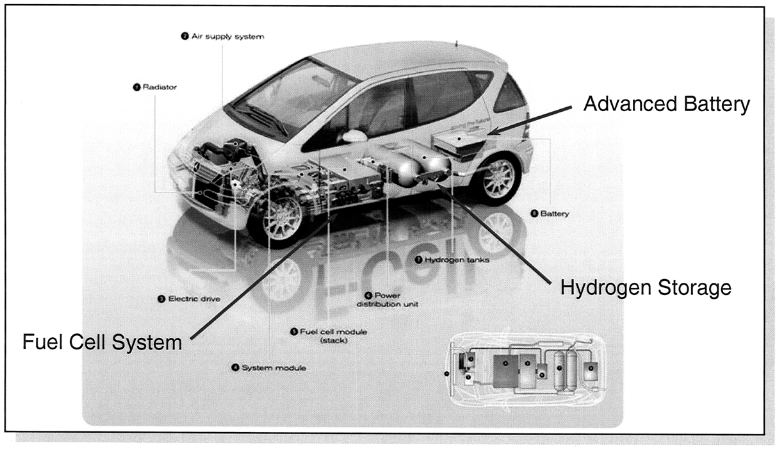
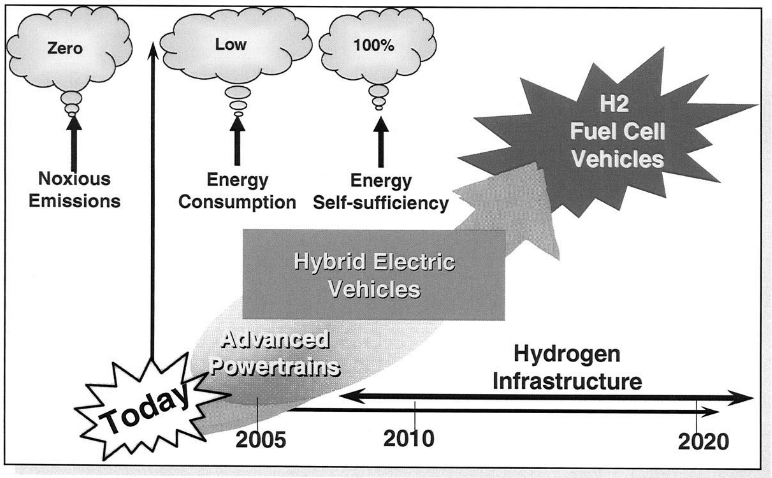


Figure 8 : Technology Relationship Strategy



BIOGRAPHY FOR MARK CHERNOBY

Mark Chernoby is the Vice President of Advance Vehicle Engineering for the Chrysler Group Business Unit at DaimlerChrysler. In this position, he is responsible for engineering Chrysler Group products in the early stages of the program cycle, CAE, Crossfire programs, GEM operation and Government Collaborative Programs. He was promoted to this position in November, 2003.

During his 19 years at Chrysler & DaimlerChrysler, Mark has worked in component, system, and full vehicle engineering. He worked in powertrain component and system engineering for the first nine years of his career. Mark then moved to full vehicle engineering managing the NVH development for Chrysler's products for a period of five years. Mark then had a position responsible for managing all of the functional requirements for a new line of large passenger cars. In has last position, Mark was responsible for the NVH, Crash, and Core Vehicle Dynamics of Chrysler Group Products.

Mark graduated from Michigan State University in 1983 with a B.S. in Engineering, University of Michigan–Dearborn in 1985 with a M.S. in Engineering, and from the University of Michigan in 1990 with a MBA.

Chairwoman BIGGERT. Thank you.

Dr. Crabtree, you are recognized. Turn on your microphone, please.

STATEMENT OF DR. GEORGE W. CRABTREE, DIRECTOR, MATERIALS SCIENCE DIVISION, ARGONNE NATIONAL LABORATORY

Dr. CRABTREE. Is it working?

Yes. Good. Thanks.

Chairman Biggert, Chairman Inglis, Members of the Energy and Research Subcommittees, thank you for the opportunity to testify today and share my thoughts on the hydrogen economy.

I will address the role of basic research in bringing the hydrogen economy to fruition. As background for my testimony, I would like to introduce into the record the report "Basic Research Needs for the Hydrogen Economy" based on the workshop held by the Department of Energy Office of Basic Energy Sciences. This report documents the vision of hydrogen as the fuel of the future and the scientific challenges that must be met to realize a vibrant and competitive hydrogen economy. *(This information appears in Appendix 2: Additional Material for the Record.)*

The enormous appeal of hydrogen as a fuel is matched by an equally enormous set of critical scientific and engineering challenges. Currently, nearly all of the hydrogen we use is produced by reforming natural gas. In a mature hydrogen economy, this production route simply exchanges a dependence on foreign oil for a dependence on foreign gas, and it does not reduce the production of environmental pollutants or greenhouse gases. We must find carbon-neutral production routes for hydrogen with the capacity to displace a large percentage of our fossil fuel use.

The most appealing route is splitting water renewably, because the supply of water is effectively inexhaustible, free of geopolitical constraints, and splitting it produces no greenhouse gases or pollutants. Although some routes for splitting water renewably are known, we do not know how to make them cost-effective, nor do we understand how to adapt them to a diversity of renewable energy sources. The onboard storage of hydrogen for transportation is the second critical basic science challenge. To allow a 300-mile driving range without compromising cargo and passenger space, we must store hydrogen at high density and with fast release times.

Since the 1970s, over 2,000 hydrogen compounds have been examined for their storage capability. None have been found that meet the storage demands. This critical storage challenge cannot be met without significant basic research. We must better understand the interaction of hydrogen with materials and exploit this knowledge to design effective storage media.

The critical challenges for fuel cells are cost, performance, and reliability. High cost arises from expensive catalysts and membrane materials. Performance is limited by the low chemical activity of catalysts and the ionic conductivity of membranes.

Although catalysts have been known for centuries, we still do not understand why or how they work. Our approach to catalysis is largely empirical. We often find that the best catalysts are the most expensive metals, like platinum. The challenge is to understand catalysis on the molecular level and use that understanding to design low-cost, high-performance catalysts targeted for fuel cells.

Membranes are another critical basic research challenge for fuel cells. Currently, fuel cells for transportation depend almost exclusively on one membrane: a carbon-fluorine polymer with sulfonic side chains. Our ability to design alternative membranes is limited by our poor understanding of their ion conduction mechanisms. Significant basic materials research is needed before practical new membrane materials can be found and developed.

These three challenges are critical for the long-term success of the hydrogen economy: production of hydrogen by splitting water renewably, storage of hydrogen at high density with fast release times, and improved catalysts and membranes for fuel cells.

For each of these challenges, incremental improvements in the present state-of-the-art will not produce a hydrogen economy that is competitive with fossil fuels. Revolutionary breakthroughs are needed of the kind that come only from high-risk, high-payoff basic research.

The outlook for achieving such breakthroughs is promising. The recent worldwide emphasis on nanoscience and nanotechnology opens up many new directions for hydrogen materials research. All of the critical challenges outlined above depend on understanding and manipulating hydrogen at the nanoscale. Nanoscience has given us new fabrication tools capable of creating molecular architectures of unprecedented complexity and functionality.

The explosion of experimental techniques to probe matter at ever-smaller link scales and time scales brings new knowledge within our reach. Numerical simulations running on computer clusters of hundreds of nodes can model the atomic processes of water splitting, hydrogen storage and release, catalysis, and ion motion in membranes. These recent scientific developments set the stage for breakthroughs in hydrogen materials science needed for a mature, sustainable, and competitive hydrogen economy.

Thank you.

[The prepared statement of Dr. Crabtree follows:]

PREPARED STATEMENT OF GEORGE W. CRABTREE

Chairmen Biggert and Inglis, and Members of the Energy and Research Subcommittees, thank you for the opportunity to testify today and share my thoughts on the hydrogen economy. I will address the role of basic research in bringing the hydrogen economy to fruition. As background for my testimony, I would like to introduce into the record the report on "Basic Research Needs for the Hydrogen Economy" based on the Workshop held by the Department of Energy (DOE), Office of Basic Energy Sciences. This report documents the vision of hydrogen as the fuel of the future, and the scientific challenges that must be met to realize a vibrant and competitive hydrogen economy.

Let me start my testimony by recalling the energy challenges that motivate the transition to a hydrogen economy. Our dependence on fossil fuel requires that much of our energy come from foreign sources; securing our energy supply for the future demands that we develop domestic energy sources. Continued use of fossil fuels produces local and regional pollution that threatens the quality of our environment and the health of our citizens. Finally, fossil fuels produce greenhouse gases like carbon dioxide that threaten our climate with global warming.

Hydrogen as a fuel addresses all of these issues: it is found abundantly in compounds like water that are widely accessible without geopolitical constraints, it produces no pollutants or greenhouse gases as byproducts of its use, and it converts readily to heat through combustion and to electricity through fuel cells that couple seamlessly to our existing energy networks.

Critical Challenges: Production

The enormous appeal of hydrogen as a fuel is matched by an equally enormous set of critical scientific and engineering challenges. Unlike fossil fuels, hydrogen does not occur naturally in the environment. Instead, hydrogen must be produced from natural resources like fossil fuels, biomass or water. Currently nearly all the hydrogen we use is produced by reforming natural gas. To power cars and light trucks in the coming decades we will need 10 to 15 times the amount of hydrogen we now produce. This hydrogen cannot continue to come from natural gas, as that production route simply exchanges a dependence on foreign oil for a dependence on foreign gas, and it does not reduce the production of environmental pollutants or greenhouse gases. We must find carbon-neutral production routes for hydrogen. The most appealing route is splitting water renewably, because the supply of water is effectively inexhaustible and splitting it produces no greenhouse gases or pollutants. Although some routes for splitting water renewably are known, we do not know how to make them cost-effective, nor do we know how to adapt them to a diversity of renewable energy sources. Splitting water renewably is a critical basic science challenge that must be addressed if the hydrogen economy is to achieve its long-term goals of replacing fossil fuels, reducing our dependence on foreign energy sources, and eliminating the emission of pollution and greenhouse gases.

Critical Challenges: Storage

The on-board storage of hydrogen for transportation is a second critical basic science challenge. To allow a 300-mile driving range without compromising cargo and passenger space, we must store hydrogen at densities higher than that of liquid hydrogen. This may seem a daunting task, but in fact there are a host of materials where hydrogen combines with other elements at densities 50 percent to 100 percent higher than that of liquid hydrogen. Since the 1970s over two thousand hydrogen compounds have been examined for their storage capability; none has been found that meet the storage demands. The challenge is to satisfy two conflicting requirements: high storage capacity and fast release times. High hydrogen capacity requires close packing and strong chemical bonding of hydrogen, while fast release requires loose packing and weak bonding for high hydrogen mobility. This critical storage challenge cannot be met without significant basic research: we must better understand the interaction of hydrogen with materials and exploit this knowledge to design effective storage media.

Critical Challenges: Fuel Cells

The use of hydrogen in fuel cells presents a third critical scientific challenge. Fuel cells are by far the most appealing energy conversion devices we know of. They convert the chemical energy of hydrogen or other fuels directly to electricity without intermediate steps of combustion or mechanical rotation of a turbine. Their high efficiency, up to 60 percent or more, is a major advantage compared to traditional conversion routes like gasoline engines with about 25 percent efficiency. The combination of hydrogen, fuel cells, and electric motors has the potential to replace many of our much less efficient energy conversion systems that are based on combustion of fossil fuels driving heat engines for producing electricity or mechanical motion.

The critical challenges for fuel cells are cost, performance and reliability. High cost arises from expensive catalysts and membrane materials; performance is limited by the low chemical activity of catalysts and ionic conductivity of membranes; and reliability depends on effective design and integration of the component parts of the fuel cell. Although catalysts have been known for centuries, we still do not understand why or how they work. Our approach to catalysts is largely empirical; we often find that the best catalysts are the most expensive metals like platinum. Nature, by contrast, uses inexpensive manganese to split water in green plants and abundant iron to create molecular hydrogen from protons and electrons in bacteria. These natural examples show that cheaper, more effective catalysts can be found. The challenge is to understand catalysis on the molecular level and use that understanding to design low cost, high performance catalysts targeted for fuel cells.

Membranes are another critical basic research challenge for fuel cells. Currently fuel cells for transportation depend almost exclusively on one membrane, a carbon-fluorine polymer with sulfonic side chains. While this membrane is an adequate ion conductor, it requires a carefully managed water environment and it limits the operating temperature of the fuel cell to below the boiling point of water. We need new classes of membrane materials that will outperform the one choice currently available. Our ability to design alternative membranes is limited by our poor understanding of their ion conduction mechanisms. Significant basic materials research is needed before practical new membrane materials can be found and developed.

Meeting the Challenges: Basic Research

The three challenges outlined above are critical for the success of a hydrogen economy:

- Production of hydrogen by splitting water renewably;
- Storage of hydrogen at high density with fast release times; and
- Improved catalysts and membranes for fuel cells.

For each of these challenges, incremental improvements in the present state-of-the-art will not produce a hydrogen economy that is competitive with fossil fuels. Revolutionary breakthroughs are needed, of the kind that come only from high-risk/high-payoff basic research.

The outlook for achieving such breakthroughs is promising. The recent worldwide emphasis on nanoscience and nanotechnology opens up many new directions for hydrogen materials research. All of the critical challenges outlined above depend on understanding and manipulating hydrogen at the nanoscale. Nanoscience has given us new fabrication tools, through top-down lithography and bottom-up self-assembly, that can create molecular architectures of unprecedented complexity and functionality. The explosion of bench-top scanning probes and the development of high intensity sources of electrons, neutrons and x-rays for advanced materials research at DOE's user facilities at Argonne and other national laboratories brings new physical phenomena at ever smaller length and time scales within our reach. Numerical simulations using density functional theory and running on computer clusters of hundreds of nodes can now model the processes of water splitting, hydrogen storage and release, catalysis and ionic conduction in membranes. These scientific developments set the stage for the breakthroughs in hydrogen materials science needed for a vibrant and competitive hydrogen economy.

Significant progress in basic research for the hydrogen economy is already occurring. Basic research on catalysis for fuel cells published in 2005 revealed that a single atomic layer of platinum on certain metal substrates has more catalytic power than the best catalysts now in use; this discovery could significantly reduce the cost and enhance the performance of fuel cells. A new route for splitting water using sunlight was created with the self-assembly of porphyrin nanotubes decorated with gold and platinum nanoparticles. These tiny nanoscale composites have already demonstrated water splitting driven by solar radiation, and they minimize manufacturing cost through their ability to self-assemble. Models of hydrogen storage compounds using density functional theory now predict the density of hydrogen and strength of its binding with unparalleled accuracy. This permits an extensive theoretical survey of potential storage materials, many more than could be practicably fabricated and tested in the laboratory.

Conclusion

The vision of the hydrogen economy as a solution to foreign energy dependence, environmental pollution and greenhouse gas emission is compelling. The enormous challenges on the road to achieving this vision can be addressed with innovative high-risk/high-payoff basic research. The great contribution of basic research to society is the discovery of entirely new approaches to our pressing needs. The phenomenal advances in personal computing enabled by semiconductor materials science and their impact in every sphere of human activity illustrates the power of basic science to drive technology and enhance our daily lives. The challenges for the hydrogen economy in production, storage and use are known. Recent developments in nanoscience, in high intensity sources for scattering of electrons, neutrons and x-rays from materials at DOE's user facilities, and in numerical simulation using density functional theory open promising new directions for basic research to address the hydrogen challenges. The breakthroughs that basic research produces in hydrogen materials science will enable the realization of a mature, sustainable, and competitive hydrogen economy.

Thank you, and I will be happy to answer questions.

BIOGRAPHY FOR GEORGE W. CRABTREE

George Crabtree is a Senior Scientist at Argonne National Laboratory and Director of its Materials Science Division. He holds a Ph.D. in Condensed Matter Physics from the University of Illinois at Chicago, specializing in the electronic properties of metals. He has won numerous awards, most recently the Kammerlingh Onnes Prize for his work on the properties of vortices in high temperature superconductors. This prestigious prize is awarded only once every three years; Dr. Crabtree is its second recipient. He has won the University of Chicago Award for Distinguished Performance at Argonne twice, and the U.S. Department of Energy's Award for Outstanding Scientific Accomplishment in Solid State Physics four times, a notable accomplishment. He has an R&D 100 Award for his pioneering development of Magnetic Flux Imaging Systems, is a Fellow of the American Physical Society, and is a charter member of ISI's compilation of Highly Cited Researchers in Physics.

Dr. Crabtree has served as Chairman of the Division of Condensed Matter of the American Physical Society, as a Founding Editor of the scientific journal *Physica C,* as a Divisional Associate Editor of *Physical Review Letters,* as Chair of the Advisory Committee for the National Magnet Laboratory in Tallahassee, Florida, and as Editor of several review issues of *Physica C* devoted to superconductivity. He has published more than 400 papers in leading scientific journals, and given approximately 100 invited talks at national and international scientific conferences. His research interests include materials science, nanoscale superconductors and magnets, vortex matter in superconductors, and highly correlated electrons in metals. Most recently he served as Associate Chair of the Workshop on Basic Research Needs for the Hydrogen Economy organized by the Department of Energy's Office of Basic Energy Sciences, which is the subject of this hearing.

Chairwoman BIGGERT. Thank you very much, Dr. Crabtree.

Dr. Heywood, you are recognized for five minutes.

STATEMENT OF DR. JOHN B. HEYWOOD, DIRECTOR, SLOAN AUTOMOTIVE LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Dr. HEYWOOD. It is a pleasure to be here to testify before you this morning.

This hearing is focused on hydrogen. I want to spend a couple of minutes developing my understanding of the context within which we ought to think about hydrogen. And that—the critical part of that context is that our U.S. transportation systems' petroleum consumption, first of all, is so large that it is almost beyond our comprehension, and that makes changing what we do extraordinarily difficult. And that consumption is growing at a significant rate. The consumption is already large. Twenty-five years from now, it is projected to be 60 percent higher. Fifty years from now, it is expected to be twice what it is today.

What are our options for dealing with this in a broader way before we focus on hydrogen? And I find it useful to talk about this in two ways, to say there are two pars that we should be pursuing aggressively.

And the first of these is to improve the performance of our mainstream internal combustion engines, transmissions, other vehicle components step by step, and there is a lot of potential for doing that. The challenge is, it costs more, so the price goes up. It goes up a bit if the improvement is small. It goes up more if the improvements are larger. Hybrid vehicle technology is a clear example of that. And to date, the response of the market to somewhat higher cost but more efficient vehicles has not been to reduce fuel consumption. It has largely been traded for higher vehicle—larger vehicle size, higher vehicle weight, and better vehicle performance.

We need to do something with a sense of urgency to reduce our petroleum consumption through these mainstream technology improvements, and we need to reinforce that more broadly within the government by developing a combination of fiscal and regulatory strategies to raise the importance of vehicle fuel consumption in the marketplace so that vehicle buyers and vehicle users are much more aware of their fuel consumption, what it costs them, and what it costs the Nation more broadly.

Now the second path relates to the longer-term, because even with improvements in mainstream technology, without drastic changes in our technology and our vehicles, we will still be dependent on petroleum-like fuels, and the greenhouse gas emissions that come from our transportation sector will still be significant. If we want to get to much lower energy consumption, recognizing that the availability of petroleum is going to decline as this century progresses, we need approaches like hydrogen and fuel cell technology to make—to take the next step.

But our challenge is that big changes in technology, whether it be to hydrogen and fuel cells or to advanced batteries and electricity as the energy carrier, take a long time to have an impact. Yes, we have hydrogen vehicles out there, a limited number already driving around, they cost in the order of $1 million each. In 10 or 15 years, there will be trial fleets, prototypes of what these technologies could be, but the costs will still be substantially above what conventional vehicle costs are.

Our own estimates are that to look at when hydrogen and fuel cells could have a noticeable impact on transportation's energy consumption, we judge that to be at least 40 or 50 years away. That is much longer than most people are willing to acknowledge. And the reason is that most people leave out the time required to build up production facilities for any new technology so that it is both sold and then out there in the in-use vehicle fleet in sufficient quantities driving around to have an impact on transportation's energy consumption.

Let me comment more specifically for a couple of minutes on the government programs that you are here reviewing today.

I think it is important that we have major programs developing hydrogen technology and ideas and the technology needed for a hydrogen infrastructure. But there are alternatives. Hydrogen—success with hydrogen is not guaranteed, and there are alternatives that we are investing in but not with the same sense of commitment and urgency. One is electric vehicles using electricity as the energy carrier, and the critical technology there is advanced energy storage batteries. Another is producing fuels from biomass in energy-efficient ways. Yes, we have programs designed to develop those technologies, but that could be a very important contributor on this longer-term time scale, and we don't understand how we can best do that yet nor what the environmental impacts could well be.

And then we have to think seriously about very different vehicle concepts. I think we have really got to give up on the “living room on wheels” current American vehicle. It has got to be a lot smaller “living room” with much smaller “furniture” in it, because it has to be much lighter, because we cannot continue on this transportation energy growth path that we are now on. And that will take inventiveness in vehicle concepts as well as new materials and new fabrication and assembly processes.

All of these need strong emphasis. The future may not be hydrogen alone. It may be hydrogen plus electricity plus biofuels plus very different vehicle concepts as we move into the middle of this century. And it is our government’s responsibility to invest in the R&D that examines these options and starts to pull them into real life where they could make a contribution.

Let me end by saying that I think our Department of Energy hydrogen program is a substantial program. It is well organized. The DOE people managing this program interact strongly with the auto and energy industries. All of that is essential to producing a good research and advanced development agenda. There is also a strong strategic plan and vision behind that and a concrete set of milestones and deliverables that make this, I think, a very appropriate program on hydrogen.

But our programs that are dealing with improving mainstream technology, engines, transmissions, and other vehicle components, new materials for vehicles, we have these programs, but they don’t have the same scope and intensity, nor do our efforts on advanced batteries. And I offer for your consideration the need to build these other programs up to the point where they are much more aggressively pursuing these parallel opportunities to hydrogen.

Thank you.

[The prepared statement of Dr. Heywood follows:]

PREPARED STATEMENT OF JOHN B. HEYWOOD

It is a pleasure to testify before your committee today on meeting the future energy needs of our U.S. transportation system. I have been working in this area at MIT for the past 37 years doing technical research and broader strategic analysis on how to reduce the environmental impacts and fuel consumption of our transportation vehicles. Summaries of our groups’ relevant recent studies are attached to this testimony.

Our work, and that of others, looking ahead some 10–30 years underlines how important it is that we in the U.S. aggressively pursue two parallel paths related to transportation energy and greenhouse gas emissions. By we, I mean the relevant people in the government, the auto and petroleum industries, the R&D community, and the broader car buying and car using public.

The two paths are:

1. Working effectively to improve current engine and drivetrain technologies, reduce vehicle weight and drag so we significantly reduce vehicle fuel consumption, and to provide incentives to individual light-duty vehicle owners and users to buy such improved technology vehicles and drive them less.
2. Developing the framework and knowledge base for an eventual transition to transportation energy sources, vehicle technologies, and energy consumption rates that offset the expected declining availability and rising cost of petroleum-based fuels, and which on a well-to-wheels and cradle-to-grave basis have low greenhouse gas emissions. This future transportation energy carrier could be hydrogen, it could include electricity, and in part it could be biomass derived fuels.

It is very much in our national interest to pursue both these paths aggressively, and with a real sense of urgency. The only feasible way to impact our steadily growing U.S. petroleum imports and consumption within the next twenty-five years is through reducing the fuel consumption of our U.S. transportation fleet. There are many ways to improve current vehicle technology to increase efficiency, but for most of these, the initial vehicle cost goes up by more than past experience indicates this consumer market will support. There is a strong need, therefore, for the U.S. Government to provide incentives to all the involved stakeholders (including consumers), as soon as possible, to "pull and push" this technology into the marketplace and ensure it is used. I will discuss some of my MIT groups' work on this shortly. However, even these actions will not result in much lower petroleum consumption and very low greenhouse gas emissions from the U.S. light-duty fleet. The importance of these actions is that given the size of our vehicle fleet (some 230 million light-duty vehicle), this is the only way to get off the projected growth from today's light-duty vehicle fleets consumption of 140 billion gallons of gasoline a year (an enormous amount!) to some 1.6 times that (220 billion gallons per year) twenty-five years from now. Whether petroleum resources are available to allow this growth is unclear. While it is likely that "unconventional petroleum" such as gasoline and diesel like fuels made from tar sands, natural gas, and biomass, will increase their contribution, it will still be modest compared to this projected 25-year ahead total.

Thus the primary driver for this first path is to reduce the impact that higher petroleum prices, petroleum availability concerns and shortages, and rising negative balance of payment issues could have on our security, economy, and way of life.

In addition, however, success along this first path will have a significant enabling impact on the second path. It is anticipated by many that by mid-century we will need (in the U.S. and elsewhere) to be on a transition path to much lower vehicle fleet greenhouse gas emissions. If the transportation energy demand in the U.S. at mid-century is as large as many current projections now indicate, then that transition task due to its size, technological difficulty, and likely cost is unbelievably challenging. We are now starting to learn just how challenging that will be. If through improved efficiency and conservation we in the U.S. have cut that energy transition challenge in half, just think how large a difference that will make.

It will not be easy to "cut the challenge in half." Over the last 20–30 years, consumers have bought larger and heavier vehicles, with higher performance, and have thus negated the roughly 30 percent improvement in vehicle fuel efficiency that improvements in engine and transmission efficiencies, reduced drag, and materials substitution have realized. A coordinated set of government actions will be needed to provide the push and pull to realize in-use fuel consumption benefits from future improvements. My group has been analyzing such a coordinated regulatory and fiscal approach. Our assessment is that an integrated multi-strategy approach has the best chance of realizing our objectives, since it shares the responsibility even handedly amongst the major stakeholders—industry and consumers, and each strategy reinforces the others. Gains only will come if we tackle all aspects of the problem simultaneously. Our proposal is to combine on improved version of CAFE regulations to push more fuel-efficient technology into new vehicles with a reinforcing feebate system imposed at time of vehicle purchase (substantial fees for purchasers who buy high fuel-consuming vehicles and rebates for those who buy low fuel consuming vehicles). Such a feebate system could be revenue neutral. To reinforce more fuel-efficient choices at vehicle purchase, taxes on transportation fuels should be steadily increased year by year for the next few decades by some 10 cents per gallon per year. These additional fuel taxes could be used to expand the now depleted Highway Trust Fund revenues to renovate our deteriorating highway systems and provide adequate maintenance. On the fuel side, in parallel, targets and a schedule could usefully be set for steadily increasing the amount of low greenhouse gas emitting biomass-based transportation fuels produced to augment our petroleum-based fuel supply. This would draw the petroleum and alternative fuel industries fully into our national effort. Details of our proposal area given in the attached MIT *Energy and Environment* article, "A Multipronged Approach to Curbing Gasoline Use" June, 2004, and its Bandivadekar and Heywood reference. Such a multi-strategy approach could also provide a transition period so major U.S. market suppliers with different model lineups, and health care and pension legacy costs, would have time to respond appropriately.

Now let me say a few words about the second and longer-term path—working to implement a low greenhouse gas emitting energy stream for transportation. It may be that hydrogen will turn out to be the best of the low greenhouse gas emitting choices we have identified to date. There are, however, other options that warrant substantial federal and industry R&D. The time scales for radical changes in technology to be implemented and have impact are long, much longer than we realize.

My group at MIT is working hard to understand these important time scales better. There are several sequential steps that a new automotive technology must go through before that technology becomes a large enough fraction of the on-the-road vehicle fleet to make a difference. The first step is developing the new technology to the point where it is competitive in the marketplace with standard technology vehicles. While more expensive new-technology more-efficient vehicles can be subsidized, this can only be done to push their introduction up to modest levels. Once market competitive, the production volumes of the new technology components must expand to a significant fraction of total new vehicle production. For engines, for example, this takes one to two decades. For fuel cell hybrid vehicles we estimate this to be 20–30 years. Then the new technology must penetrate the in-use vehicle fleet and be driven significant mileage, which takes almost as long as the production expansion step. Thus for internal combustion engine hybrids the total time to noticeable impact is expected to be some 30-plus years. For hydrogen and fuel-cell hybrids it is likely to be more than 50 years. Hence my emphasis on the first path for nearer-term improvements, and my judgment that any transition to hydrogen on a large scale is many decades away. (See MIT *Energy & Environment* article, “New Vehicle Technologies: How Soon Can They Make a Difference,” March, 2005, attached).

Now, some comments on a transition to hydrogen-fueled vehicles. First, the rationale for attempting such a transition is to significantly reduce greenhouse gas emissions from our transportation systems in the longer-term. Thus the source of the energy used to produce hydrogen is critical. It would have to be either coal or natural gas with effective carbon capture and sequestration, or nuclear power systems which generate both hydrogen and electricity. Electrolysis of water with “renewable electricity” from solar or wind energy does not appear a plausible way to produce hydrogen; it makes much more sense to use renewable electricity to displace coal in the electric power generating sector. Thus not only are there major hydrogen fuel cell technology issues (including cost) to be resolved, there are also major technical and cost challenges in the production, distribution and storage of hydrogen to be resolved as well. Hydrogen produced directly from fossil fuels without carbon sequestration, or from the electric power grid via electrolysis, even when used in fuel cell powered vehicles (which could be significantly more efficient than internal combustion engine powered vehicles), will not save energy nor reduce greenhouse gases.

Are there alternatives that warrant greater federal resources? The above discussion suggests that electric vehicles with advanced high-energy-density batteries recharged with electricity from renewable or low CO_2 electric power systems is one at least partial alternative. Such vehicles would be range limited, but if that range is more than say 200 miles these could be a substantial fraction of the market. Efficiently produced biofuels can also be low net CO_2 emitting and the extent these can contribute is not yet clear. New, much lighter weight, vehicle concepts, may be significantly smaller in size, are also likely to be a significant and necessary long-term option. All of these should be important parts of the U.S. Government’s R&D transportation energy initiatives. While they are part of the Government’s current portfolio, the level of funding, strategic planning, and industry and R&D community involvement should be increased.

Our longer-term list of plausible efficient vehicle technologies and the energy sources that go with them is too short, and the difficulties in realizing these options in the real world are so challenging, that a much larger federal effort on this second path I have been discussing is warranted.

The above discussion broadly to addresses the first two questions asked in the Committee’s letter requesting testimony. Let me now provide a more focused summary of my response.

Question 1: How might the future regulatory environment, including possible incentives for advanced vehicles and regulations of safety and emissions, affect a transition to hydrogen-fueled motor vehicles? How could the Federal Government most efficiently accelerate such a transition?

I have explained how important it is for the U.S. Federal Government through regulatory and fiscal policies to reduce the energy requirements of our total transportation system. Not only would this help reduce our petroleum consumption and thus our oil imports in the nearer-term; it would also make the task of a future hydrogen transition (or more complex mix of low greenhouse gas emitting energy sources and technologies) significantly less challenging.

Question 2: Is the current balance of funding between hydrogen-related research and research on advanced vehicle technologies that might be deployed in the interim before a possible transition to hydrogen appropriate?

What advanced vehicle choices should the Federal Government be funding between now and when the transition to a hydrogen economy occurs? How are automakers using, or how do they plan to use, the advanced vehicle technology developed for hydrogen-fueled vehicles to improve the performance of conventional vehicles? Are automakers likely to improve fuel economy and introduce advanced vehicles without government support?

The government's FreedomCAR and Fuels program is a thoughtfully structured program of significant scale intended to advanced hydrogen fuel and vehicle technologies. It is a partnership between DOE, Ford, DaimlerChrysler, GM and several petroleum companies. Its focus is on applied research with some pre-competitive advanced development. The program plan has had, and continues to have, substantial industry input. DOE cost shares major advanced development projects with the auto companies. The companies involved have substantial programs of their own in these areas, though the details of these programs are largely proprietary. This program approach in my judgment does a reasonable job of using federal funds to encourage the necessary development of new and better ideas, and new knowledge related to hydrogen and its use in transportation.

The FreedomCAR and Fuels Program also supports activities intended to improve the efficiency of mainstream engine and propulsion system technologies. Given the importance of the first pathway I have described, this federal effort should be expanded. Also, efforts on advanced battery research and development, and biofuels should be expanded to better meet their potential importance in the longer-term. The Federal Government must play the role of supporting a broad portfolio of research relevant to transportation energy and transportations greenhouse gas emissions and involve all sectors of the R&D community that can contribute. Our universities, the source of the technical leadership we will need over the next several decades, must be more actively involved.

Question 3: What role should the Federal Government play in the standardization of local and international codes and standards that affect hydrogen-fueled vehicles, such as building, safety, interconnection, and fire codes?

I have not addressed this question directly. Due to the long time scales involved in any transition to hydrogen or other new technologies, this is not as urgent a task as is technology development. However, as is already happening in the FreedomCAR and Fuels Program, work on these issues should be underway with the relevant Standards and Codes organizations, and with the industries involved.

Attachments

Three articles from MIT's Laboratory for Energy and the Environment publication "Energy & Environment":

1. "Vehicles and Fuels for 2020: Assessing the Hydrogen Fuel-Cell Vehicle," March, 2003.
2. "A Multipronged Approach to Curbing Gasoline Use," June, 2004.
3. "New Vehicle Technologies: How Soon Can They Make a Difference?" March, 2005.

energy environment

MIT LABORATORY FOR ENERGY AND THE ENVIRONMENT

MARCH 2003

Vehicles and Fuels for 2020: Assessing the Hydrogen Fuel-Cell Vehicle

Even with aggressive research, the hydrogen fuel-cell vehicle will not be significantly better than diesel and gasoline hybrids in terms of total energy use and greenhouse gas (GHG) emissions by 2020, says a study released by the MIT Laboratory for Energy and the Environment. And while hybrids—vehicles powered by conventional engines supplemented by electric motors—are already appearing on the roads, adoption of the hydrogen-based vehicle will require major infrastructure changes to make fuel-cell cars and hydrogen fuel available. The MIT study involved a systematic and comprehensive assessment of a variety of engine and fuel technologies as they could develop by 2020 with intense research but no real "breakthroughs." An extension of an assessment completed in 2000, this study used far more optimistic assumptions about fuel-cell performance, but key conclusions remained unchanged. If we need to curb GHGs within the next 20 years, improving mainstream gasoline and diesel engines and transmissions and vehicle design and expanding the use of hybrids is the way to go. Singling out hydrogen fuel-cell vehicles for research—the Bush administration's current strategy—has long-term promise but will have little effect by 2020. Such vehicles are efficient and low-emitters on the road, but making the necessary hydrogen fuel from natural gas or gasoline uses substantial energy and emits GHGs that have to be added to road behavior for a "life-cycle" assessment. If dramatically lower GHG emissions are required 30 to 50 years in the future, hydrogen now appears to be the only major fuel option. But the hydrogen must be made from non-carbon sources such as solar energy or from fossil fuels while capturing and sequestering carbon dioxide emissions.

During the past year, the Bush administration has undertaken programs that may devote billions of dollars to developing a passenger vehicle powered by a hydrogen-based fuel cell (FC). Government announcements have deemed that technology to be the best means of reducing energy use and cutting harmful emissions from the transportation sector, which is now responsible for about a third of the nation's GHG emissions. However, some people are concerned that hydrogen FC cars will not enter the fleet in large numbers for decades and that the federal programs are not encouraging work to develop nearer-term fuel-efficient technology options that warrant support.

Researchers in the Laboratory for Energy and the Environment (LFEE) have now released a study that supports that concern. The new study is an extension of *On the Road in 2020*, an assessment released in 2000 in which a team led by Dr. Malcolm A. Weiss and Professor John B. Heywood evaluated new automobile technologies with the potential for lower emissions of GHGs, which are generally believed to contribute to climate change. Using data from a wide variety of sources, they systematically

Onboard and Life-Cycle Energy Consumption Can Be Very Different for New Technologies

Technology	Onboard Consumption	Life-Cycle Consumption
2020 Baseline (see text)	100	100
Hydrogen FC hybrid	31	52
Diesel ICE hybrid	52	56

This figure demonstrates the importance of considering not only the energy used to operate the vehicle on the road ("onboard consumption") but also the energy used in making both the vehicle and the fuel it consumes ("life-cycle consumption"). In terms of onboard energy consumption, the hydrogen fuel cell (FC) hybrid significantly outperforms the diesel internal combustion engine (ICE) hybrid. But that advantage almost disappears in a comparison of life-cycle energy consumption, largely because so much energy is required to make hydrogen fuel from natural gas, the approach assumed in this study.

compared various combinations of fuel and vehicle technologies, assuming the likely state of each technology in 2020 as a result of "diligent" research but without counting on technical breakthroughs.

For each fuel-vehicle combination they calculated energy use and emissions, not just in operating and maintaining the vehicle but also in manufacturing the vehicle, making and delivering the fuel, and ultimately scrapping and recycling the vehicle. Their life-cycle assessment produced no unequivocal winners. The much-touted hydrogen FC hybrid did no better than the diesel internal combustion engine (ICE) hybrid did in terms of energy efficiency and GHG emissions, and the equivalent gasoline engine hybrid was not far behind. Moreover, the hydrogen FC technology would cost more, and its adoption would require major infrastructure changes to make FC vehicles and compressed hydrogen widely available.

On the Road in 2020 received substantial attention from government and industrial groups as well as the press. But some observers—including the researchers themselves—were surprised that the hydrogen FC did not fare better. Could their assumptions about future FC performance have been too conservative?

To find out, Dr. Weiss, Professor Heywood, Dr. Andreas Schafer, and Vinod K. Natarajan repeated the assessment using more optimistic assumptions about certain characteristics of the technology—assumptions closer to what FC advocates cite. The changes focused on sources of "energy losses," which reduce the fraction of the fuel's energy that ends up as electrical energy available for powering the vehicle. The assessment considered two designs incorporating FCs. One is fueled with pure compressed hydrogen gas, which is stored onboard the vehicle; the other is fueled by gasoline, which is converted into hydrogen gas by a "fuel processor" onboard the vehicle. In both designs, energy losses occur within the FC system itself. As the hydrogen is being electrochemically converted into electric power, some of the fuel energy is lost as heat. And some of the generated electricity is diverted from powering the vehicle to running pumps, blowers, and a compressor. In the gasoline-based design, additional significant energy losses occur inside the fuel processor as the gasoline is converted to hydrogen.

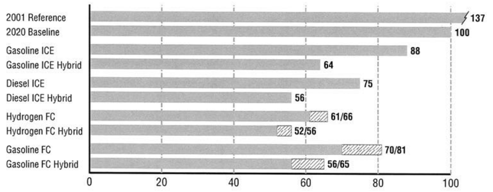
Based on reviews of recent literature and discussions with FC analysts and commercial component and vehicle developers, the researchers identified several advances that were feasible with aggressive development. Accordingly, in the new study they assumed better materials, improved designs, and more efficient operation to reduce the energy losses described above. They did, however, limit the changes to those whose cost looked at least plausible commercially. For example, further increasing the size of the FC or the concentration of platinum catalysts inside it would further increase its efficiency but would result in unrealistically high costs. Analysis showed that the new, more optimistic assumptions about FC performance reduced the previous estimates of fuel consumption onboard the vehicle by a quarter to a third.

The charts below show estimates of life-cycle energy use and GHG emissions for a variety of technologies. All outcomes are compared on a relative scale where 100 is defined as characteristic of a midsize car comparable

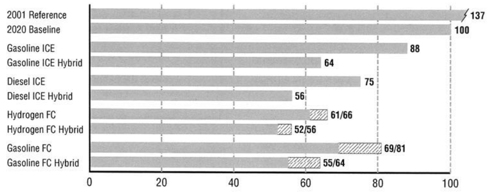
Comparative Assessment of Vehicle Technologies for 2020

- Total energy and greenhouse gas (GHG) emissions from all sources consumed during vehicle lifetime
- GHGs include only CO_2 and CH_4
- Shown as percentage of baseline vehicle energy consumption and GHG emissions
- Total energy and GHG emissions include vehicle operation and production of both vehicle and fuel

Relative Life-Cycle Consumption of Energy



Relative Life-Cycle Emissions of Greenhouse Gases



in capacity and performance to a Toyota Camry in 2020, assuming "evolutionary" changes in the engine, vehicle body, and fuel. All the other vehicles assume more aggressive advances. The hydrogen FC technologies assume that hydrogen is produced by reforming natural gas at local filling stations; it is then compressed for charging vehicle tanks. The gasoline FC technologies assume that gasoline is fed onto the vehicle and converted to hydrogen inside an onboard fuel processor.

The striped extensions on the bars for the four FC technologies require explanation. In each case, the more optimistic outcome—the solid bar—results from assuming that each component of the FC system is separately optimized for maximum performance. However, when engine developers integrate all the components to make a commercial car, they must compromise the performance of some of those components to keep the overall system from being too expensive, heavy, bulky, and so on. The striped extensions represent the outcomes under those less optimistic—but the researchers think more realistic—conditions. In several cases, the loss in performance is considerable.

The charts for both energy consumption and GHG emissions confirm that the 2020 baseline is dramatically better than the 2001 reference and that all the other technologies do even better, some of them significantly. Nevertheless, the hydrogen FC—even with the most optimistic assumptions—still does not beat the diesel ICE hybrid. Incorporating the hydrogen FC into a hybrid system helps, but its performance is still similar to that of the diesel ICE hybrid. (Modest differences are not meaningful because of uncertainties in the results.) The gasoline ICE and gasoline FC hybrids do almost as well. The hydrogen FC is thus not a big winner in terms of either energy use or GHG emissions. The results consistently point to the advantages of both improving ICE technology and using the hybrid approach. Regardless of the propulsion system choice, the hybrid version significantly reduces both energy consumption and GHG emissions, with the gains greater for ICE than for FC designs.

These results raise some obvious questions. First, why did the hydrogen FC technologies not do as well as some expected? A major part of the problem is that people often consider only onboard energy consumption and emissions (during operation of the vehicle on the road). But also taking into account the energy consumption and emissions associated with making and delivering the fuel and making, operating, and disposing of the vehicle dramatically changes the picture.

The table on page 1 demonstrates this effect. The first column shows onboard energy consumption for the hydrogen FC hybrid and the diesel ICE hybrid (both relative to the baseline 2020 vehicle). The former significantly outperforms the latter. The second column shows energy consumption considering the entire life cycle. The diesel ICE does a bit worse than before; but the hydrogen FC does significantly worse, largely because converting the hydrocarbon fuel to hydrogen both consumes energy and generates GHG emissions. (Hydrogen is also much more costly to manufacture and distribute than gasoline or diesel is.) Thus, studies that consider only onboard data give a misleading impression.

Another frequently cited advantage of the hydrogen FC vehicle is that it has no tailpipe emissions of air pollutants. The researchers agree with that claim, but they believe it will be only a small advantage by the year 2020. Current US Environmental Protection Agency mandates on fuels and emissions ensure that by 2010 tailpipe emissions from all new vehicle technologies will be so low that the remaining emissions will not be a significant share of all emissions from all sources. Reducing emissions from other sources is likely to be a more cost-effective way to clean up the atmosphere. The only uncertainty is whether engine designers can develop and introduce diesel technology that cuts emissions of particulates and of nitrogen oxides without incurring large efficiency penalties. However, history suggests that auto manufacturers have usually found a way to meet new regulations that originally seemed too difficult or costly to meet.

Another question is why ICE hybrids did better than some people have predicted. Were the assumptions in the study unrealistically optimistic? According to the researchers, studies with less-positive outcomes tend to focus only on the propulsion system—the engine, transmission, and drive train. In contrast, the MIT assessment also assumed reductions in the weight of the vehicle and in driving resistances—aerodynamic drag and tire rolling friction. Such changes are achievable by 2020 and are significant contributors to improving mileage.

Why does the hybrid approach do so well, regardless of the technology involved? Hybrid designs use both an engine (an ICE or FC) and an electric motor and battery. The electric motor runs the car at low loads such as slow, stop-and-start city driving—conditions under which an ICE is least energy efficient, so the fuel-economy gain is greatest. The electric motor also provides extra power for acceleration and hill climbing, which means the engine can be smaller than otherwise needed to satisfy momentary passing requirements. Also, most hybrid concepts allow the recovery of energy dissipated in braking. Thus, in each case the hybrid vehicle is more efficient than its non-hybrid counterpart.

The researchers caution that they are not discouraging work on developing the hydrogen FC. If auto systems with GHG emissions much lower than the lowest predicted here are required in the long-run future (perhaps in 30 to 50 years or more), hydrogen is the only major fuel option identified to date—but only if the hydrogen is produced without making GHG emissions. Hydrogen has been manufactured on a commercial scale for almost 100 years, mostly from natural gas. Trying to fine-tune existing methods for slightly better efficiency is not the best investment of research time and money. The focus should be on developing the technology and infrastructure for the large-scale production of hydrogen from non-fossil sources of primary energy (nuclear, solar, biomass) or from fossil primary energy with carbon capture and sequestration (see *e-lab*, July–September 2002 and April–September 2001).

While the hydrogen FC does not look promising for the near term, the good news is that several types of technologies have the potential to dramatically reduce energy use and GHG emissions from passenger cars in the next few decades. Already, fuel-efficient ICE hybrids are appearing on the roads, major auto companies are announcing more models to come, and public response is positive.

Malcolm A. Weiss is a senior research staff member in the LFEE. John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of MIT's Laboratory for 21st Century Energy. Andreas Schafer is a principal research engineer in the Center for Technology, Policy, and Industrial Development. Vinod K. Natarajan received his Master's Degree from the Department of Mechanical Engineering in 2002. Further information can be found in the references.

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energy & environment

MIT LABORATORY FOR ENERGY AND THE ENVIRONMENT JUNE 2004

A Multipronged Approach to Curbing Gasoline Use

The key to curbing America's ever-growing appetite for petroleum is not just fuel-efficient vehicles or high gasoline taxes or huge surcharges on gas-guzzling models. It is all of those measures and more, carefully combined into a set of self-reinforcing policies that affects everyone who makes, buys, or uses vehicles and their associated fuels.

This multidimensional approach to tackling the US petroleum consumption problem was outlined by Professor John B. Heywood and graduate student Anup P. Bandivadekar at a March 18 lunchtime seminar hosted by the Laboratory for Energy and the Environment (LFEE).

The United States consumes almost a quarter of the world's petroleum, and current projections suggest that by 2025 it will use 40% more petroleum than it does now (see the table below). About 70% of that petroleum will be imported, and almost three-quarters of it will be used for transportation.

Such tremendous growth in petroleum use has serious environmental implications, Professor Heywood noted. In addition, it sets the stage for possible petroleum system shocks that could disrupt the transportation system on which the US economy and lifestyle depend.

"We've had one or two such shocks, but they were isolated and our economy recovered. What happens if they come more frequently?" Professor Heywood said.

Developing better engine and vehicle technologies and fuels could cut petroleum use and make our transportation system more robust, he said. A recent comprehensive assessment by Professor Heywood, Dr. Malcolm A. Weiss, and others at MIT concluded that even "evolutionary" improvements in "mainstream" gasoline and diesel technologies could yield a 35% reduction in fuel consumption in new vehicles in 20 years—and at moderate cost (see references 2 and 3 in the References section).

But better technology alone may not help. Indeed, over the past 20 years, vehicle efficiency increased by 30%, but any potential fuel savings disappeared because people bought bigger, heavier vehicles and drove them farther and faster.

Fuel Use by Light-Duty Vehicles

	2003	2025 (projected)
Total consumption	**20 million bbl/day**	**28 million bbl/day**
Imported	**55%**	**70%**
Consumed for total transportation	**69% (760 billion liters/yr)**	**73% (1200 billion liters/yr)**
Consumed by light-duty vehicles	**42% (500 billion liters/yr)**	**45% (750 billion liters/yr)**

If the United States is to reduce its rapidly increasing dependence on petroleum, it must focus on its transportation sector, in particular, on light-duty vehicles. In 2003, Americans owned some 230 million cars and light trucks, and close to 90% of all the kilometers they traveled were in those vehicles. As the table shows, without intervention, petroleum used for transportation is going to expand significantly. While most of the percentages in the table do not change dramatically from 2003 to 2025, the absolute quantities consumed jump by as much as 60%. (Sources: US Department of Energy, International Energy Agency.)

According to Mr. Bandivadekar, gains will come only when we tackle all aspects of the problem simultaneously. "A simple way to think about it is that petroleum use and greenhouse emissions depend on how fuel-efficient our vehicles are, how much we drive, and how carbon-intensive our fuel is. We need to target all those pieces of the puzzle," he said.

As an illustration, Mr. Bandivadekar and Professor Heywood looked at the impacts on fuel consumption of increasing fuel efficiency, of reducing vehicle-kilometers traveled, and then of making both of those changes simultaneously. Using a spreadsheet-based model and data from the automotive industry and other sources, they examined four possible scenarios. Those scenarios and the analytical results are presented in the figure on the next page.

The curves in the figure show that tackling two pieces of Mr. Bandivadekar's puzzle—vehicle efficiency and distance traveled—can substantially reduce fuel use by 2035. But those results also demonstrate the difficulty of reducing transportation fuel use significantly in the near future. Climate-change targets are often defined in terms of 1990 levels of consumption. Even with all the changes assumed in the most-aggressive scenario, the estimated consumption in 2035 does not return to 1990 levels—and the researchers believe that the estimates they used in their analysis were optimistic.

What are the best ways to spur the needed changes? To answer that question, the researchers examined all the available policy options—economic incentives such as taxes and subsidies, regulatory actions such as emissions standards and fuel requirements, and public investment, for example, in alternative-fuel development. For each option they asked a series of questions. How much will it cost? Who will have to pay? How will it affect oil consumption, greenhouse-gas emissions, traffic congestion, vehicle-miles traveled? Will it be politically acceptable? Are there major implementation barriers?

Not surprisingly, the answers varied dramatically from policy to policy—and that variation is key to the researchers' proposal. They believe that the key to success is combining a variety of measures so that they work together. For example, one proposal is a "feebate" system in which customers pay an extra fee to buy big gas-guzzlers but get a rebate if they buy small, fuel-efficient models (a measure that can be designed to be revenue-neutral). The feebate system combines well with stricter corporate average fuel economy (CAFE) standards. Auto manufacturers will be required to make smaller, more efficient cars—and that is what their buyers will want. Adding higher fuel taxes to the package will both discourage additional driving and add further incentive for customers to buy fuel-efficient models. Tax credits elsewhere can offset the added fuel costs so vehicle users will feel no extra financial burden.

As an example, Professor Heywood and Mr. Bandivadekar put together a package that combined stricter CAFE standards, feebates, a gasoline tax that increases by about 2¢ per liter per year, and a requirement for increased biomass-derived content in fuels. According to their best estimates, if we enact that package of policies now, petroleum use and carbon dioxide emissions will be 32% lower in 2035 than if we do nothing. The reduction in total distance traveled will be just 15%—not too much of a hardship for transportation users.

Professor Heywood and Mr. Bandivadekar are now gearing up to take their message to the business community and ultimately to Washington. They believe that an integrated policy package will have more chance of implementation than individual proposals have had. Lobbying groups are less likely to be able to defeat a policy package that spreads responsibility broadly.

"This approach will make people realize that it's not my problem or your problem or Detroit's problem—it's everybody's problem, and everybody will have to do something about it," said Mr. Bandivadekar.

The researchers' final warning: don't wait to take action. A few years' delay now will mean a significantly higher level of petroleum use in 20 or 30 years—and a significantly greater problem to be solved by hydrogen fuel cells or whatever technology we come up with for the long term.

"We need to find ways to change attitudes as well as technologies. It's not clear we'll win, but we'd better try," Professor Heywood said.

John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. Anup P. Bandivadekar is a PhD candidate in MIT's Engineering Systems Division. Malcolm A. Weiss is a visiting engineer in the LFEE. This research was supported by the Alliance for Global Sustainability (AGS) and the MIT/AGS Consortium on Environmental Challenges. Further information can be found in reference 1. Information on the comprehensive assessment of vehicle and fuel technologies can be found in references 2 and 3.

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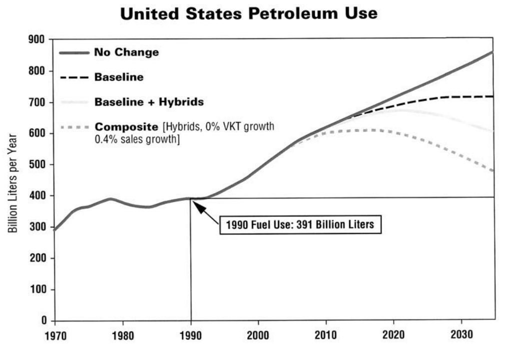

- **No change** – assumes that fuel consumption remains steady at 2008 levels. (Gains from any fuel-efficiency improvements are offset by losses due to higher performance or added vehicle weight or amenities.) Car sales grow at the same rate as population, and each car goes 0.5% farther each year.
- **Baseline** – adds the evolutionary improvements in technology identified in the comprehensive assessment (references 2 and 3). About half of the efficiency improvements translate into reductions in fuel consumption.
- **Baseline + hybrids** – assumes the previous scenario with the gradual addition of gasoline-electric hybrid vehicles into the fleet. By 2035, half of all the new vehicles sold are hybrids.
- **Composite** – adds to the mix a slowing in the growth of both vehicles sold and vehicle-kilometers traveled (VKT). In this scenario, car sales grow only half as fast as population grows, and the distance traveled by each car remains constant at 2008 levels.

energy & environment

MIT LABORATORY FOR ENERGY AND THE ENVIRONMENT

MARCH 2005

New Vehicle Technologies: How Soon Can They Make a Difference?

MIT transportation experts have some pragmatic projections that send a clear warning: we must not be overly optimistic about how quickly changes in vehicle technology can reduce America's staggering consumption of petroleum for transportation.

According to their calculations, it will be some two decades before even moderately improve technology vehicles will be on the roads in sufficient numbers to make a difference. And the much-touted hydrogen fuel cell hybrid vehicle is unlikely to be a common on-road sight for more than 50 years. Given such long lead times, it is imperative that we begin to pursue those changes immediately and aggressively.

For the past year, Professor John B. Heywood and graduate student Anup P. Bandivadekar have been examining how various government policies may affect long-term US petroleum use and emissions (see *energy & environment,* January–June 2004). Among those policies are regulations that encourage development of improved and new technologies for vehicles and fuels.

Time Scales for New Vehicle Technologies to Affect US Transportation Energy Use

	Vehicle Technology			
Implementation Phase	Gasoline Direct-Injection Spark-Ignition Boosted Downsized Engine	High Speed Direct-Injection Diesel with Particulate Trap, NO_x Catalyst	Gasoline Spark-Ignition Engine/ Battery-Motor Hybrid	Fuel Cell Hybrid Vehicle, Onboard Hydrogen Storage
Market competitive vehicle	~ 5 years	~ 5 years	~ 5 years	~ 15 years
Penetration across new vehicle production	~ 10 years	~ 15 years	~ 20 years	~ 25 years
Major fleet penetration	~ 10 years	~ 10–15 years	~ 10–15 years	~ 20 years
Total time required	~ 20 years	~ 30 years	~ 35 years	~ 55 years

Timetable shows MIT estimates of how long it will take for four new vehicle technologies to be on the road in sufficient numbers to affect total US energy consumption for transportation. In the first phase, the technology must become market competitive in performance, convenience, and cost. In the second, it must become more than 35% of all the new vehicles manufactured. In the third, it must become responsible for more than 35% of total US miles driven. The total times (even allowing for overlap in the phases) demonstrate that new vehicle technology is far from a "quick fix" for America's enormous appetite for transportation energy.

According to a comprehensive life-cycle assessment by Dr. Malcolm A. Weiss, Professor Heywood, and their colleagues, these improved and new vehicle and fuel technologies promise to be far more energy efficient than today's vehicles are (see references 2 and 3 in the References section). But these technologies will not actually affect America's energy consumption until they come into widespread use, and predicting how long that change will take is a challenge.

Vehicle technologies have changed in the past. For example, fuel-injection systems replaced carburetors, and engine cylinders began having four valves instead of two—relatively minor changes that took about 15 years to occur. The expansion of diesels from 15% to roughly 50% of the new cars sold in Europe has taken about 20 years.

"But for a new technology like the hybrid, there's no prior example case study that says it'll take 15 years or 20 years," said Professor Heywood. "We haven't made this large a change in the last eighty-odd years. You have to go back to the 1920s for there to be competition between significantly different types of propulsion systems."

So how can one estimate the time needed for a technology to go from a not-ready-for-market concept to a large enough fraction of the on-the-road fleet to make a difference? As a framework for tackling the problem, Professor Heywood and Mr. Bandivadekar divided the market-penetration process into three phases.

First, the technology must be developed to the point where it is market competitive. Financial incentives from government may help; but in the end the cost, performance, and convenience must be close enough to standard technology that people will want to buy the new vehicle in significant numbers.

Next, the new technology must grow from a modest fraction to a significant fraction of new vehicle production. To achieve that expansion, a manufacturer must use the new technology in numerous vehicle classes, say, compact cars and SUVs and pickup trucks. Each application will require new components (bigger batteries and motors, for example), so the company will need to build new production facilities. Even more time-consuming is the task of developing good designs for the different sizes and versions of the new technology.

Finally, the new technology must become a significant fraction of the on-the-road fleet and—most important—of total miles driven in the United States. The length of time required depends both on how many of the new vehicles are being manufactured (the previous phase) and on the typical lifetime of vehicles that are already in circulation (a determinant of the potential market for new purchases).

Before assessing specific technologies, the researchers had to define what "a significant fraction" meant in phases two and three. Professor Heywood stressed the importance of this definition. "We're trying to estimate 'time to impact,'" he said. "We're not concerned with getting a few new vehicles out there but rather with getting enough on the road to have an impact that in some ways you could discern or measure."

Guided by previous research experience, they estimated that a new vehicle technology would have a measurable impact on energy use when that technology is responsible for about 35% of the total US miles driven. To permit that level of market penetration, in phase 2 the new technology must be in 35% of the new vehicles produced.

The table on page 1 shows the researchers' assessment of four illustrative vehicle technologies: an improved gasoline spark-ignition engine, a diesel engine with improved fuel efficiency and very low emissions, a gasoline spark-ignition-engine hybrid, and a hydrogen fuel cell hybrid (with hydrogen stored onboard the vehicle).

The researchers estimated that the time needed for the first phase is roughly the same for the first three vehicle types. Each is about one "development cycle"—roughly 5 years—away from becoming market competitive. The hydrogen fuel cell is almost completely new technology, so the time required for the first phase is considerably longer.

The estimates in the second phase show more variation. Moving from improved gasoline to cleaned-up diesel to gasoline hybrid to fuel cell hybrid, the times become longer because the technologies become increasingly different from those in use today. As a result, expanding production to additional model types becomes more difficult.

The third-phase estimates show less variation from technology to technology but also increase as the technology becomes less familiar and production buildup is slower. In all cases, the lifetime of vehicles already on the road was assumed to be 15 years, the current average.

Finally, the researchers added up the times required for each technology, then subtracted a bit to account for overlap between the phases. The totals tell a surprising story. The improved gasoline engine—a technology that would seem relatively easy to develop and implement—will take some 20 years to have impact. The diesel requires about 30 years, the hybrid about 35 years, and the hydrogen fuel cell 50 to 60 years.

"I think the value of our approach is that it helps us avoid the trap of being overly optimistic as to how quickly through changes in technology—even near-term technology—we can impact overall US vehicle fleet fuel consumption," said Professor Heywood. "The idea that hydrogen will save us in the near term from our energy appetite is just nuts. You have to go through these stages; and while you can say we'll get through each stage much faster, there's no evidence that we've ever done that before."

The researchers have presented their analysis to audiences at MIT, in the automotive industry, and elsewhere; and the response has been supportive. People commend the researchers' new three-phase framework for thinking about the market-penetration process. Industry personnel stress the value of stepping back from near-term production challenges and taking this broad, strategic view. And there have been few quibbles with the numbers. Indeed, the researchers' initial estimate for the hydrogen fuel cell to become market competitive was 10 to 15 years. But "just about everybody in the business said they'll never do it in 10 years," so the lower number was dropped.

"The point is not that the numbers are tightly accurate," Professor Heywood said. "The point is that these time scales are all long, and some are very long. It adds urgency to the fact that we should start trying to prompt these changes right away."

John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. Anup P. Bandivadekar is a PhD candidate in MIT's Engineering Systems Division. Malcolm A. Weiss is a visiting engineer in the Laboratory for Energy and the Environment. This research was supported by the Alliance for Global Sustainability. Publications are forthcoming. Background information can be found in the following references.

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BIOGRAPHY FOR JOHN B. HEYWOOD

Professor Heywood did his undergraduate work in Mechanical Engineering at Cambridge University and his graduate work at MIT. He then worked for the British Central Electricity Generating Board on magnetohydrodynamic power generation. Since 1968 he has been on the faculty in Mechanical Engineering Department at MIT, where is he now Director of the Sloan Automotive Laboratory and Sun Jae Professor of Mechanical Engineering. His current research is focused on the operating, combustion and emissions characteristics of internal combustion engines and their fuels requirements. He is involved in studies of automotive technology and the impact of regulation. He has also worked on issues relating to engine design in MIT's Leaders for Manufacturing Program; he was Engineering Co-Director of the Program from 1991–1993. He is currently involved in studies of future road transportation technology and fuels. He has published some 180 papers in the technical literature and has won several awards for his research publications. He holds a Sc.D. degree from Cambridge University for his published research contributions. He is a author of a major text and professional reference "Internal Combustion Engine Fundamentals," and co-author with Professor Sher of "The Two-Stroke Cycle Engine: Its Development, Operation, and Design." From 1992–1997 he led MIT's Mechanical Engineering Department's efforts to develop and introduce a new undergraduate curriculum. In 1982 he was elected a Fellow of the Society of Automotive Engineers. He was honored by the 1996 U.S. Department of Transportation National Award for the Advancement of Motor Vehicle Research and Development. He is a consultant to the U.S. Government and a number of industrial organizations. He was elected to membership in the National Academy of Engineering in 1998. In 1999, Chalmers University of Technology awarded him the degree of Doctor of Technology honoris causa. He was elected a Fellow of the American Academy of Arts and Sciences in 2001. He is now directing MIT's Mechanical Engineering Department's Center for 21s' Century Energy which is developing a broader set of energy research initiatives. In January 2003, Professor Heywood was appointed Co-Director of the Ford-MIT Alliance. In 2004, City University, London, awarded him the degree of Doctor of Science, honoris causa.

DISCUSSION

Chairwoman BIGGERT. Thank you very much, Dr. Heywood. And thank you to all of the panelists.

We will now move to Member questions.

And I will yield myself five minutes.

I had the opportunity to drive a hydrogen car about a month ago, and we are going to have to change all our terminology. You don't have a gearshift. You just push a button for drive. You can't step on the gas. I don't know how we are going to get used to saying "stepping on the hydrogen" or something. It just doesn't seem to fit as well. But it was quite an experience. And then opening the hood and being able to put your hand on the engine and it is not hot, it is cool. It is—it must be energy efficient. But I understand that they are talking about it being within the next decade that this might be coming out.

But my question really goes to the development of the fuel and how that is going to be. And I think it was Dr. Bodde that mentioned that the type of hydrogen that would be used. I understood from that that it was either—the car that I was driving was liquid hydrogen, which was stored under the back seat. And then they—but they haven't decided whether compressed hydrogen or liquid would be something that would be used. I—this was a GM car. Sorry. But I know you are all working together. But—and then it can be filled right from the—again, it couldn't be called a gas pump. We would have to change to the hydrogen pump or whatever. But are we really that close? It seemed that they hadn't—at least this—and I am—and from all of your testimony, I see that there hasn't been a decision yet, but it seemed to me between liquid and compressed or whatever we might find. It is kind of like beta versus VHS. You know, which is going to be the way to go, because will this be made, you know, on an industry-wide basis with the research from—on the FreedomCAR? How are we—who is making those decisions, and how is this all integrated with the Department of Energy and the basic research?

So whoever would like to answer that. Mr. Faulkner.

Mr. FAULKNER. Well, I could start, and some of my colleagues can fill in.

I think the timeline that we are working on with our industry partners is 2015 for a commercialization decision. The Department of Energy, the government, doesn't make these vehicles, doesn't make the fuels. We work on research and development to help them, our private sector partners, make these decisions. So looking at that time scale, roughly 2015, start to make the entry point in the market about 2020. There are some cars on the road. You have driven them, I have driven them. But they are not cost-effective yet. There are technology issues we have to sort through, but that is the time scale we are on, and every year, we are progressing closer to that.

Chairwoman BIGGERT. Any other comments?

Dr. CRABTREE. Yes.

Chairwoman BIGGERT. Dr. Crabtree.

Dr. CRABTREE. You mentioned two alternatives: liquid or compressed gas. I think both of those have deficiencies that, in the long-term, really won't give us the driving range that we need. What we need to do is find a way to store hydrogen as part of a solid material as a hydrogen compound. And that is the thing that, really, we can't do yet. If you look at what we could do in the next five years, we could do either liquid storage or gas storage, but we really don't know how to go solid-state storage, and that is the one—that is the area that we need to do if we are going to have a long-time, long-term impact.

So this really is a basic research issue.

Chairwoman BIGGERT. Okay.

Dr. Bodde.

Dr. BODDE. Let me say that I concur with that completely.

We know perfectly well how to compress hydrogen now. The issue, though, is what is going to become of an automobile that is given the casual maintenance that our cars do and that is fueled by a compressed gas at 10,000 p.s.i. for the lightest element on the Earth? Now as we all sit here in this hearing room, if your car is doing what my car is doing, it is out in the parking lot dripping atmospheric pressure fluids onto the paving. Imagine what would happen if it were a very high compressed tank of hydrogen.

So I think for demonstration fleets, that will work fine. In order to pioneer the opening of the technology, it will work just fine. But for the long-term effective hydrogen economy, I agree with Dr. Crabtree. I think we have to have some form of solid-state storage or some form of that near atmospheric pressure storage.

Chairwoman BIGGERT. Dr. Heywood.

Dr. HEYWOOD. Let me broaden that and say that this is one of many areas where we are learning that what we have today is fantastic. Gasoline and diesel fuel have an extraordinarily high energy density, lots of energy per unit volume, or mass, and they are liquids. And we are struggling mightily, and we will need new ideas and research to explore those ideas before we can make gaseous fuels, like hydrogen, manageable in anywhere near the same way.

Chairwoman BIGGERT. Thank you. Thank you.

Mr. Chernoby.

Mr. CHERNOBY. Just in closing, I would agree with the comments of all of my colleagues here.

At DaimlerChrysler, we do believe that compressed hydrogen is probably the near-term alternative for limited fleet use, but in the long-term, we absolutely must provide the customer with a range. We absolutely must provide them with the space, as Dr. Heywood said earlier, that they enjoy in their moving "living room," and that is going to require something different than compressed hydrogen, and we do not think that liquid, at this point, from what we see, is the answer. There has to be basic research to find something else that is going to find something that is going to satisfy all of those needs.

Chairwoman BIGGERT. So it really will be a conglomerate that will make this—everyone will probably be on the same track because of the necessity when we find the right type of fuel?

Dr. CRABTREE. It is interesting, if you look at what is—what the commercial options are now that—the demonstration fleets, some are liquid, some are gas. Each one has their own proponents. Not too many are solid-state. That is the one, I think, that has to come.

Chairwoman BIGGERT. Thank you.

Going back and forth, Mr. Carnahan, would you be ready, or should we have one more question from the other side of the aisle?

[No response.]

Chairwoman BIGGERT. Thank you. Chairman Inglis, you are recognized for five minutes.

Chairman INGLIS. Thank you, Madame Chairman.

You know, when I was a kid, Alcoa Aluminum used to advertise on "Meet the Press" with a very effective jingle that said, "Alcoa can't wait. We can't wait for tomorrow." And I wonder whether the role that we have is to be saying to the academics, "We can't wait." And I wonder if the role of Mr. Chernoby and people in the private sector is to say, "We have got to do it, because we want to make some money at it." But I wonder if our role is really to say, like President Kennedy did in 1961, we have got to get to the Moon before the end of the decade.

So maybe you could comment on what is the role of the people up here, the government folks. What should we be saying? It seems to me that the statistics that you have cited are alarming. The—two things are alarming. One is our use of fuel, as Dr. Heywood talked about, and the other is the length of time that we are hearing. So these seem to be on a collision course. We have got this enormous use, and we have got this time that is working against us. And so one of my items here was talking about commitment, which is a question for us in the government. What kind of commitments should we make to really moving this along? And anybody want to comment on what should be the role of government in this process to light the fire on all of the researchers and to really insist, like Alcoa, "We can't wait until tomorrow"?

Dr. HEYWOOD. And I am glad you said, "We can't wait until tomorrow," because that is absolutely the case. And in some areas, we are getting a move on. We have got a sizable hydrogen program. In other areas, we are not, particularly, in my view, in government efforts to regulate through fiscal and regulations like CAFE, to force movement. I think the government's responsibility is to both push and pull these technologies into the marketplace.

Research is another way of sort of smoothing, lubricating, seeding that process. And I think that is a very important thing for you to think about as well. But I urge you to hang on to this. We can't wait. We have got to assess how this problem is developing and getting worse and sort out what we, government and others, can do collectively to get a move on in resolving these problems.

Chairman INGLIS. Yes, sir.

Dr. Crabtree.

Dr. CRABTREE. So you mentioned getting to the moon, which is often applied to hydrogen and sometimes to the larger energy problem as well. I think there is one difference from the Apollo program. There, President Kennedy could say, "Let us do it," and he had the NASA do it. It was very well coordinated. In the case of energy, cars, and hydrogen, it has to be sort of the economy. It is a complex system. It is a lot of people interacting and making independent decisions, so you don't get that direction from the top.

So I think what the government can do is incentivize that activity. And there are really two aspects to it. One is what we can do now, sort of incremental hydrogen economy, and we have heard some of the—my colleagues have talked about that. One is what we would like to be able to do, the mature one that we need, let us say, 20 or 30 years from now that would really have an energy impact. The first one is sort of a commercial demonstration stage now. So you need one kind of incentive for that.

The second one is really basic research. You need a completely different kind of incentive for that. You have to work on both levels, and soon these two, sort of—these two prongs will come together and we will get the result that we want.

Chairman INGLIS. Here is my idea. Somebody comment on this, maybe Mr. Chernoby or Dr. Bodde might want to talk about this, is that gas at $3 a gallon lights a fire in the consuming public. When it gets to that level and you go to fill up your SUV and it is $42, I think you say, "This can't be." I mean, "I can't continue to spend $42 per fill-up." Right? I mean, does that light the—DaimlerChrysler, does that get you going? Does that get you excited?

Mr. CHERNOBY. Well, a couple of things.

You talked about commitment of the researchers. I can just share that the researchers we deal with, I can assure you, there is huge commitment, huge tenacity and focus on trying to get these problems solved, so I am not worried, really, about the motivation of the researchers. But similar to what Dr. Heywood said earlier and what you just mentioned, I think the role of government is two critical areas.

Number one, it is obviously to help all of us in a pre-competitive environment with basic research, because we have got to overcome these challenges. But then you talked about the marketplace. That is the key here. That is—for me, that is the big difference between this challenge and the Apollo program. Without the marketplace in poll, there is no penetration, and without product penetration, there is no motivation to build an infrastructure.

So I would say, short-term, it is not just about seeing the research, but it is about sitting down with all of us, the energy industry, the auto industry, and other constituents, and we have got to talk about how can we get that motivation in the marketplace. I don't personally—and this is not speaking for the company, personally, I don't believe $3 is going to do it. I mean, you are—like Dr. Heywood said, I mean, you look at the costs and the challenges we have to overcome on some of these technologies today, there has got to be a pretty big incentive or a reason for a customer to value and move to that. That is why we think there is a lot of transition, like Dr. Heywood said, that we are going to go through before we ultimately get to the hydrogen economy. But working closely with all of us on what is the business model going to be and how can the government play a role in that business model to make it viable for not only an automotive company but an energy company as well to make this a reality. But without the marketplace, it is not going anywhere.

Dr. BODDE. My observation on federal policies, if you allow me.

If you look at the history of federal policy and energy, going back to the first Arab oil embargo of October of 1973, the chief problem, as I see it, has been consistency. We have gone from one thing to another thing. When oil prices were high in the 1970s, there was Project Independence. When oil prices fell in the 1980s, it was all, "Well, what the heck. Let the market reign here." I think the chief ingredient of any effective federal policy is going to be consistency. Durability over the long-term. That allows entrepreneurs, innovators, investors to plan on the economic regime that is going to prevail over the time scale that it takes for them to bring technologies into the marketplace.

And so item one, I would say, is consistency.

Item two is attention to the demand side. All of this talk about research, about CAFE standards, and so forth, all deals with the supply side, that is the supply of vehicles, the supply of fuels. There has to be a demand side pull from consumers as well.

Now it is interesting to observe, as Dr. Heywood has, the response to the more fuel-efficient vehicles that haven't proven to be the more fuel-economic vehicles. Fuel-efficiency, that is in the sense of moving metal down the road, has improved consistently over the last 20 years. Fuel economy has been flat. The reason is the increase efficiency was taken as greater weight, as greater acceleration, as greater vehicle performance, and this is what the marketplace is demanding.

My guess, also, is that at $3 a gallon, that might not change very much, and I think serious consideration has to be given to other demand-side policies that start to create a consumer interest in translating greater efficiency into greater economy.

Mr. FAULKNER. Sir, your red light has been on for a while, but you raise a really fascinating and philosophical question. Could I respond for a minute?

Chairman INGLIS. If the Chair will allow it.

Mr. FAULKNER. Is that allowed?

You noted the alarming rise in the use of oil. That is true. That has been going on for some time. Many are aware of that, and the length of time we are talking about, 2015, 2020, full breakout in the market 2030, 2040, 2050, and then you noted, we can't wait. But I think—it may be unpopular, but I think, in a sense, it is our duty to say we have to wait, not that that is complacent but that fundamental science doesn't occur overnight. Some of these things everyone has talked about, breakthroughs that are needed, and if you are set on the right pace research and development. You talk about commercialization of these technologies in the private sector. It is going to take a while to affect those changes.

And I would note that the President sees the urgency of that, that is why he set the vision. That is what he talked about this fundamental issue we have to address. And for the government, the federal role, the Department of Energy, we have to manage it. There are several different programs. It is a difficult task to integrate the Office of Science's fundamental research in our office and other departments.

And Congress's role is to hold our feet to the fire. Ask us for metrics. Ask us to come in and justify what we are spending. And I think, as the President has said, and the Secretary, pass an energy bill.

Chairwoman BIGGERT. Thank you.

The gentleman from Missouri, Mr. Carnahan, is recognized for five minutes.

Mr. CARNAHAN. Thank you, Madame Chairman.

Welcome to all of you, and this is a very timely and important discussion that we are having here today. And I was fascinated just recently reading the—if you haven't seen it, look at the August issue of National Geographic on things that are coming after petroleum, basically, and they highlight a lot of these new technologies.

But I want to particularly ask Mr. Chernoby, or anybody else on the panel, about the FreedomCAR research and where you see that going from here, and really give me a better idea of where that is today.

Mr. CHERNOBY. I would summarize a few key points.

We have talked a lot about hydrogen and fuel cells and hydrogen storage today. If you look at the FreedomCAR research portfolio, we manage a portfolio that is even broader than that. Similar to what Dr. Heywood said earlier, it is critical as well, as we research things for the long-term, what can we be doing to implement things we learn in the short-term? There is quite a bit of research going on still in lightweight advanced materials, very important, and as soon as something gets on the shelf that engineers can grab and use and the supply base can figure out how to process, we will implement it, if it provides the right value to the customer: lighter weight vehicles, more fuel efficiency. We don't have to wait for a hydrogen economy. There is basic battery research going on, another critical enabler.

We have several examples like that that we manage in this precompetitive environment at FreedomCAR. So we absolutely believe that—DaimlerChrysler, and I think my compatriots and Ford and GM would agree, this is absolutely the best way to make sure we compile some of the brightest minds, not only in industry, but in academia and the other research environments around the world. And it is that combination of minds that is actually going to help us get these breakthroughs to market, not just in the long-term for the hydrogen, but feeding in all of the other things we are doing in our portfolio to provide benefit in the near-term as well.

Mr. FAULKNER. Sir, if I could add, the Secretary——

Mr. CARNAHAN. Yes, please.

Mr. FAULKNER.The Secretary of Energy, Sam Bodman, was out in Michigan recently where he did two events in one day. He cut the ribbon, groundbreaking of the new solar factory, but he also was with Mr. Chernoby and his colleagues to talk about renewing two agreements with the U.S. Car Group. One of them was on batteries and one of them was on materials.

And I think that kind of success that we have in partnering together with the auto industry, if there wasn't success, they wouldn't be wanting to sign up and renew these agreements. And there are—am I correct that the batteries that we have pioneered in that consortium are now on every hybrid in America?

Mr. CHERNOBY. Yeah, absolutely. Some of the very basic and preliminary work on what we call nickel metal hydride batteries was done through that consortium, and that is what you will find in basically every hybrid vehicle on the road today.

Mr. CARNAHAN. We have also talked about several incentives here today, and I have worked with some here in the Congress about instituting a tax credit that would go partially to consumers and partially to manufacturers to help in this transitional time period to these alternative fuel vehicles.

What kind of impact do you see that having? Some have argued because the demand is growing and the technology is coming online that those kinds of incentives aren't necessary. And I would be interested in your comments about that.

Mr. CHERNOBY. Well, I would add, similar to what Dr. Heywood said earlier, let the data speak for itself.

If you look at the penetration of these—some of these technologies, it has not been in astronomically large numbers. I mean, they occupy a very, very small percentage of the annual vehicle sales in, not only the United States, but around the world. So any incentive that is going to help the customer find the right value equation, and that is why I urge you to think about not only incentives—don't pick a single technology. Think about the broad range of technologies. One may be more attractive to one customer versus another. And that is what we have got to focus on, providing the ability for those technologies to penetrate across as broad of a range of the market as we can. We, at DaimlerChrysler, feel we very much ought to focus on today's clean and advanced diesel to augment the hybrid discussion, because there are a lot of customers who drive in a highway-driving environment.

So absolutely, we believe that we have to do something, as Dr. Bodde said, on the demand side and continue to do so, not only in the long-term hydrogen economy, but in the short-term as well.

Dr. BODDE. That said, however, perhaps we should not be too pessimistic about reading the current data. It is characteristic of any technology, if there is a long gestation period in which not much seems to be happening in the marketplace in which market share growth and market penetration doesn't happen, then a tipping point is reached and the technology takes off.

I mean, you look at Internet use, Internet subscribers. The Internet has been around for a long time, and it is only in the last five years that we get this vertical—near-vertical acceleration.

My guess is that the same thing is going to happen with the hybrid vehicles, perhaps hybrid diesel vehicles. The same thing is going to happen with the hydrogen fuel cell vehicles.

What we need to be about is to look at the conditions needed for that marketplace takeoff to occur and to work specifically to put those conditions in place so that the market itself will then take it over.

Mr. FAULKNER. Just another comment.

I think it is important not to get too far ahead of the technology in incentives. The President has proposed tax incentives for hybrids, but I think the fuel cell vehicles are still a ways down the road, and you can consider those as that technology improves. Timing is very important.

Dr. CRABTREE. Briefly, that—we heard a lot about incentivizing and getting the technology out there for the consumer and for the manufacturer, but I think it is important to incentivize the research as well. The things we can do now and put out now or that consumers can decide about now and make now are really not the ones that we want to do 20 years from now to have a big impact on energy.

So we shouldn't leave that basic research component out of the equation.

Mr. CARNAHAN. Thank you.

Chairwoman BIGGERT. Timing is everything.

Mr. CARNAHAN. Thank you, Madame Chair.

Chairwoman BIGGERT. And your time has expired.

And the gentleman from Maryland, Mr. Bartlett, is recognized for five minutes.

Mr. BARTLETT. Thank you very much.

I have many questions, but time will permit, perhaps, only three quick ones.

I understand that if we were to wave a magic wand and every American car could have a fuel cell in it with platinum as a catalyst that one generation—and it doesn't last all that long, I understand, but one generation would use all of the platinum in all of the world. Is that true?

Secondly, right now today, 85 percent of all of the energy we use in this country comes from fossil fuels. Are you all familiar with Hubbard's Peak? Do you know what is meant by Hubbard's Peak? Okay. We now may be at Hubbard's Peak in terms of oil. If that is true, gas is not far behind.

And I would caution, don't be sanguine about this enormous supply of coal. At current use rates, it will last 250 years. If you increased its use exponentially only two percent a year, and we will have to do more than that if we run down Hubbard's Peak with gas and oil, it lasts 85 years. When you recognize that you probably are not going to run your car by putting the trunk full of coal, you are going to have to convert it to a gas or a liquid, now you have shrunk it to 50 years. That is all that is out there at two percent growth rate and converting it to some form we are going to use.

Only 15 percent of our energy today comes from renewables. I include in that the eight percent that comes from nuclear and only seven percent from true renewables. Since hydrogen is not an energy source, you will always use more energy producing the hydrogen than you get out of it. Where are we going to get all of this energy as we run down Hubbard's Peak? Are we going to have a really nuclear nation, because the effective growth in energy from the renewables is really pretty darn limited?

And the third question deals with: all of you seem to agree that if hydrogen—if we are going to move to a hydrogen economy, you have got to have solid-state storage. Is there something in the science that inherently makes hydrogen storage a higher density than electron storage? What you are really talking about now is just another battery, aren't you, which is what hydrogen solid-state storage is going to be? Another battery? In the science, is there something inherently so superior about hydrogen storage that it is going to be a better battery than storing electrons?

Is it true about platinum that one generation of American cars lasting, what, 200 hours for each solar—for each fuel cell, we have used all of the platinum in all of the world?

Dr. CRABTREE. Well, may I comment on that?

I really don't—I have heard that statement as well, and I haven't tried to verify it.

Mr. BARTLETT. Could you, for the record, all of you, give us some input on that? It is really nice to know that, because if that is the path we are running down, it is not going to be a very fruitful one.

INSERT FOR THE RECORD BY DOUGLAS L. FAULKNER

A study by TIAX, LLC determined that there are sufficient platinum resources in the ground to meet long-term projected platinum demand if the amount of platinum in fuel cell systems is reduced to the Department of Energy's (DOE) target level. The DOE-sponsored study shows that total world platinum demand (including jewelry, fuel cell and industrial applications) by 2050 would be 20,000 metric tons against a total projected resource of 76,000 metric tons. This study assumes that fuel cell vehicles attain 80 percent market penetration by 2050 (from U.S., Western Europe, China, India and Japan). The study shows that the limiting factor in keeping up with increased platinum demand is the ability of the industry to respond and install additional production infrastructure. Since in the out-years, recycling would provide almost 60 percent of the supply, the industry will have to be careful not to overbuild production capacity in a more accelerated market demand scenario.

- Platinum availability is a strategic issue for the commercialization of hydrogen fuel cell vehicles. Platinum is expensive and is currently critical to achieving the required levels of fuel cell power density and efficiency.

  As such, the Department has been focused on reducing and substituting for (with non-precious metal catalysts) the amount of platinum in fuel cell stacks (while maintaining performance and durability) so that hydrogen fuel cells can be cost competitive with gasoline internal combustion engines.

- Significant progress has been made and is still being made by national laboratories, universities and industry to reduce the amount of platinum needed in a fuel cell stack by replacing platinum catalysts with platinum alloy catalysts or non-platinum catalysts, enhancing the specific activity of platinum containing catalysts, and depositing these catalysts on electrodes using innovative processes. The Office of Science has recently initiated new basic research projects on the design of catalysts at the nanoscale that focus on continued reduction in the amount of platinum catalyst required in fuel cell stacks.
- Typically, it takes three to five years to increase platinum production capacity in response to an increase in demand. Fuel cell vehicle production may create a brief platinum supply deficit, leading to short-term price increases.
- The TIAX study shows that platinum prices over the last one hundred years fluctuated based on major world events (e.g., world war, etc.); however, the mean price (adjusted for inflation) remained stable at $300 per troy ounce. However, over the last couple of years platinum has been higher at $900 per troy ounce.

Mr. BARTLETT. Secondly, where are you going to get all of this energy, if we are at Hubbard's Peak, and we probably are, with oil at $60 a barrel and going nowhere but up, I think? Where are you going to get this energy?

We have got to have a big culture change until we are using less energy. We are like a young couple that just had a big inheritance from their grandparents, and they have affected a lifestyle where 85 percent of the money they are spending comes from their grandparents' inheritance, only 15 percent from their income. And their grandparents' inheritance is not going to last until they die. Now they have got to somehow transition themselves from this lavish lifestyle, living largely on the inheritance from their grandparents. How are we going to do that, and where are you going to get the energy from from this hydrogen economy?

You know, what we are really doing is nibbling at the margins. We have got to face the fundamental problem that we are at Hubbard's Peak and going to start down the other side shortly. Where are you going to get the energy to come from? What are you telling people?

Dr. HEYWOOD. May I respond to that one, please?

That is one reason I have talked about these two paths forward, because to make the drastic changes that—in culture lifestyle economies that you are really suggesting, which I think we will have to consider, within this century most likely, have to make. That is going to take time.

But in the nearer-term, there are things we can do that are better than nibbling at the edges. Yes, they have that characteristic, but they will do more. We can—you know, we could half our transportation energy consumption with the sort of technologies that are almost ready today, but we need to realize that that is what we will have to do in some way to survive in the long-term. And I think that discussion needs to be held much more publicly, and we have all got to contribute to this and understand the dilemma that we are facing.

Mr. BARTLETT. Thank you very much.

Before my time runs out, is there something scientifically, inherently so much better about a hydrogen battery than there is an electron battery that we should be pouring these billions of research into that?

Dr. HEYWOOD. The recharge time is one big difference. You could recharge a hydrogen tank relatively quickly compared to recharge an energy storage battery.

Mr. BARTLETT. I sleep all night. My battery can charge while I sleep.

Is there something inherently better about density?

Dr. CRABTREE. May I comment on that?

I think the energy density that you can store in hydrogen, as a chemical fuel, is higher than you can get from electricity as an electrical fuel——

Mr. BARTLETT. But we are still working on that and don't, in fact, know, correct?

Dr. CRABTREE. If you look at some interesting charts in this report, you will see that hydrogen has the ability to replace your battery in your laptop and give you three times or four times the run time for the same weight and the same volume.

Mr. BARTLETT. Good. We ought to be moving——

Dr. CRABTREE. As a matter of fact, it is better.

Mr. BARTLETT. We ought to be moving quickly then.

Thank you.

Dr. BODDE. One final comment, if I may, sir.

You asked the old what source of energy. Eventually, you get to nuclear and renewables that eventually—this 85 percent inheritance is gone, no matter what scenario you are in, an environmentally limited one or other, and you are into nuclear for whatever supply you have.

Mr. BARTLETT. Thank you for helping to get that message out.

Chairwoman BIGGERT. The gentleman from Alabama, Mr. Sodrel, is recognized for five minutes.

Mr. SODREL. Indiana.

Chairwoman BIGGERT. Indiana.

Mr. SODREL. Yeah, Indiana.

Chairwoman BIGGERT. Excuse me. There is a little difference.

Mr. SODREL. But—well, now we do say "you all" in southern Indiana, and I understand how you could make a mistake.

Going to the question that Mr. Bartlett framed about how we produce hydrogen, I understand the Icelanders that—embarked on a robust program trying to create hydrogen using geothermal energy. Are any of you familiar with what is going on there? It is kind of a joint industry effort, is it not, where they are—they have a lot of volcanoes and a lot of heat. And I understand they are trying to convert their entire country to hydrogen fuel. Given that their country only has 300,000 population, it would be a little bit like us converting a city to hydrogen fuel, but do you know how that is coming along?

No?

Mr. FAULKNER. We can get you details for the record, though, sir, if you wish.

Mr. SODREL. Yeah, I would appreciate it.

INSERT FOR THE RECORD BY DOUGLAS L. FAULKNER

Iceland's goal is to become the first nation in the world to achieve the vision of a hydrogen economy. The move to a hydrogen economy has significant government support, and surveys conducted by Icelandic New Energy indicate significant public support as well. With a population of less than 300,000 (the majority of which resides in the capital of Reykjavik), transforming the Icelandic transportation sector to hydrogen will require far fewer hydrogen fueling stations than what will be required in the United States. Advances include:

- Iceland has an abundance of relatively inexpensive renewable energy that is used for heating and provides 100 percent of the Nation's electricity (80 percent from hydropower and 20 percent from geothermal).
- Currently, there is one hydrogen fueling station, located along a major highway in Reykjavik, which serves as a national demonstration project. Hydrogen is produced on site via renewable electrolysis. The station is a publicly accessible retail fueling station that also offers gasoline and diesel and includes a convenience store. It supports the operation of three hydrogen fuel cell buses that run regular routes around Reykjavik; there are no other hydrogen vehicles at this time.
- The next phase of the country's hydrogen demonstration will involve the conversion of the entire Reykjavik bus fleet to hydrogen. Future phases will include promoting the integration of fuel cell powered vehicles for passenger use and examining the possibility of replacing the fishing fleet with hydrogen based vessels.
- Iceland collaborates with the United States through the International Partnership for the Hydrogen Economy (IPHE), which was established in November 2003 to facilitate global collaboration on hydrogen and fuel cell research, development, and demonstration (RD&D). With a membership including 16 countries and the European Commission, the IPHE provides a forum for leveraging scarce RD&D funds, harmonizing codes and standards, and educating stakeholders and the general public on the benefits of and challenges to the hydrogen economy.

Mr. SODREL. The second question relates to the FreedomCAR initiative.

We have a lot of foreign manufacturers of automobiles. I know Toyota has an enormous plant in Georgetown, Kentucky. It is kind of in my neighborhood. Honda, and other foreign automobile manufacturers have made significant investments in fuel cell. How do you feel about greater involvement of foreign car makers that have domestic plants in this FreedomCAR initiative? Would it help shorten the time frame here or should we ask them to participate?

Dr. BODDE. Well, in my opinion, the world auto industry is truly a global auto industry, and frankly, it makes little sense, in my opinion, to distinguish between what is domestic and what is foreign. I mean, if you look at the research alliances that are now created, you see them between General Motors and Toyota. You see them between Ford and other foreign companies. And so these things all kind of fit together anyway as an international research picture. And so I think almost whether you do or don't include them in the U.S. program, that technology is going to get to them one way or another, because it is a worldwide technology institution.

Mr. CHERNOBY. Well, we have had some discussion in the U.S. Car/FreedomCAR effort about including some of our compatriots around the world. At this time, we haven't made any final decisions on whether we want to do that or not, but we absolutely, in the pre-competitive environment, like Dr. Bodde had said, look at what we are doing around the world. One of the challenges that we do have, though, is there isn't necessarily consensus in some of the world governments on how we ought to approach this effort, and the codes and standards, and the effect, eventually, on not only the infrastructure of the vehicles that go along with it.

So worldwide harmonization is clearly one of the barriers that we always work on in the auto industry and both jointly with government. And it is likely to be one here unless we figure out a way to get it under control.

Mr. SODREL. Thank you. I don't have any further questions.

Chairwoman BIGGERT. I thank the gentleman from Indiana.

The gentleman from Minnesota, Mr. Gutknecht.

Mr. GUTKNECHT. Ohio.

No, I am from Minnesota.

Chairwoman BIGGERT. It is nice that you care to admit it.

Mr. GUTKNECHT. Listen. First of all, let me offer this disclaimer. I am not a scientist. I don't play one. And we are honored to have you scientists here to talk to us.

Those of you who did not hear Roscoe Bartlett's special order last night, I hope you will all at least get a chance, and I hope Roscoe will put together a "Dear Colleague" to share with the rest of us some of the interesting information he has shared in his special order last night on the House Floor. It was last night, wasn't it, Roscoe?

Mr. BARTLETT. Yes.

Mr. GUTKNECHT. Okay. And what he really said, and I will just extend his remarks a bit here, was he said that energy is so cheap today, and he had some—in fact, I would yield to the gentleman a minute, if he wants, to share some of the examples of just how cheap energy really is.

Mr. BARTLETT. Oh, thank you very much.

A barrel of oil is about $60 today. And you can buy the refined product of that for about $100 at the pump, 42 gallons of gas, $2 and something a gallon, right? That will buy you the work equivalent of 12 people working all year for you. That is the work output you are buying from $100 worth of gasoline. If you go out this weekend and work really hard all day, I will get more mechanical work done with an electric motor with less than 25 cents worth of electricity. That is what you are worth, in terms of mechanical work: less than 25 cents a day.

This—these fossil fuels are so darn cheap. We are just as assuredly addicted to them as a cocaine addict is to his drug. It has become a drug for us.

Mr. GUTKNECHT. Well, reclaiming my time, and I—those were just some of the remarks he made last night, and I thought it was fascinating. And it really sort of underscores the importance of this meeting, but it also—I think we need to look at this whole energy thing in that context, that fossil fuel energy is incredibly cheap, even at $60 a barrel. Somebody figured it out, we still pay four times more for a gallon of water in a convenience store than we pay for that gallon of gasoline, even at $60 a barrel. And I am not defending the oil companies or the oil barons that have us "over the barrel," no pun intended.

I want to come back to—and I was particularly interested in some of the comments by Dr. Heywood, because I think that, in some respects, you nailed it, that—I am a believer in doing all we can to advance the science relative to hydrogen power and some of these other things, but I have come to the conclusion, at least, again, as a layman, that hydrogen is, in some respects, a very, very good battery, but I think we have to—we don't want to oversell it long-term, in terms of its value as an energy source. And I am interested in some of the other technology.

And maybe, Dr. Faulkner, you could comment on this, because I know there are some people—there are people who have come in to see me, and again, I am not a scientist. I don't play one here in the Congress, but I am just a curious guy. One of the technologies that people have talked to me about are super magnets. Are any of you doing any work with super magnets? And do you know what I am talking about?

All right. We will have them come and talk to you, because I found it fascinating that we now have—well, I will go on to a different subject.

INSERT FOR THE RECORD BY DOUGLAS L. FAULKNER

The term "Super magnets" is a broad description for several families of rare Earth magnets. I am not aware of any DOE work in the area of super magnets. Superconducting magnets, on the other hand, are electromagnets, which use an electric current to generate a magnetic field, and the electricity runs through superconducting materials, such that very large magnetic fields can be generated without electrical resistance creating large amounts of waste heat. The Department's Office of Science uses superconducting magnets in some of its particle accelerators.

Mr. GUTKNECHT. And that subject is really about renewable fuels, because on the other Committee that I serve on, the House Agriculture Committee, I chair a Subcommittee, and we have responsibility for some of the renewable fuel programs. And there again, there are some amazing things happening, sometimes without any oversight responsibility or funding from the Federal Government in terms of producing this fuel even cheaper.

Just out of curiosity, how many of you know right now how much it costs at a—one of our more advanced ethanol plants to produce a gallon of ethanol? What would the cost be? What would you guess?

Dr. Faulkner.

Mr. FAULKNER. Well, about $2.10.

Mr. GUTKNECHT. Next?

Dr. BODDE. I would have to look that one up for you, but I go with his number in the absence of anything else.

Mr. GUTKNECHT. All right.

Mr. CHERNOBY. I would have been more in the $3 realm.

Mr. GUTKNECHT. Okay.

Dr. HEYWOOD. I would add that those costs depend on where you draw your boundary and what costs that add up to that figure are included. There is a lot of variability in studies of producing ethanol and the reality, and it depends how the numbers are worked out.

Mr. GUTKNECHT. Well, let us do simple arithmetic. You have to buy the corn, right? It is about $2.20 a bushel right now. And you have to amortize the cost of the plant, right? The biggest cost in producing ethanol right now is in energy. I mean, you have to cook the corn. But according to my most efficient plants in my District, right now, at $2.20 a bushel of corn, and we have to assume the cost of producing that corn, and believe it or not, maybe even a little profit for the guy who grows it is in that $2.20, the answer is, and not only from my ethanol plants, but also according to the

Chief Economist at USDA, the answer is 95 cents a gallon. Does that surprise you? It surprises most Americans. And I say that, because right now, in both the pure cost basis and in terms of BTUs, ethanol is cheaper than gasoline.

I yield back my time.

Chairwoman BIGGERT. Thank you.

The gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much.

I am from California. I am very proud of being from California.

I would just like to get down to some fundamentals, and first of all, let me suggest that Roscoe Bartlett adds a great deal to every hearing that I go to, and I am happy to have him with us and making his contributions.

Let us—I would like to ask—go back to the cost of hydrogen. From what I take it, after the exchange between you folks and Roscoe, is that there actually isn't an energy savings reasons to go to hydrogen as a fuel, because it actually would use more energy to create it than what you get out of it once it is actually manufactured, is that correct? So we are actually—the hydrogen fuel angle is that it will—it is a cleaner burning fuel for the air, is that why we want to go in that direction?

Mr. BARTLETT. If the gentleman would yield for a quick moment.

Mr. ROHRABACHER. Yes.

Mr. BARTLETT. It is true that it takes more energy to produce hydrogen than what you get out of it. When you use hydrogen, you can conveniently use it in a fuel cell that gets at least twice the efficiency of the reciprocating engine. So at the end of the day, you may use less energy, in spite of the energy loss. We are not going to suspend the second——

Mr. ROHRABACHER. Right.

Mr. BARTLETT.—law of thermodynamics. In spite of that loss, we may end up using less energy with hydrogen.

Mr. ROHRABACHER. So would it depend on, as Roscoe is suggesting, that we—that the development of fuel cell type engines rather than the current type of engines that we have in automobiles?

Dr. BODDE. Well, both are certainly true. You do need a fuel cell, of course, to offset the inefficiencies in producing the hydrogen. But on the other hand, anything that you manufacture is subject to the second law. And so there is always an increase in entropy or a degrading of the energy source, no matter—from any human activity.

Mr. ROHRABACHER. Well, I have—actually, I have been told—we just had a briefing the other day on biodiesel that suggested that that is not the case with biodiesel, with canola oil, that actually you get more BTUs out of—there are more BTUs left over by the process by a three to one margin than it takes to actually produce the biodiesel.

Dr. BODDE. As Dr. Heywood said, it depends where you draw the boundaries around the system.

Mr. ROHRABACHER. But none of you have heard that that is—you think that is an inaccurate statement if it is—when the boundaries are drawn the same around hydrogen as around biodiesel?

Dr. BODDE. I don't know the specifics of that particular one, sir, but I would be suspicious of anything that appears to create energy out of nothing. That energy always comes from some place.

Mr. ROHRABACHER. Yeah, well, we know that solar—as my colleague is suggesting, that the plants are actually taking in solar energy, and that is part of the process that nature has provided us, and that is the explanation of where extra energy could come from. And do any of you have anything else to say about the—comparing a biodiesel approach to a hydrogen approach in terms of the cost of energy in creating your final product?

Dr. HEYWOOD. Let me comment on that.

One advantage of hydrogen, and I think it is real, is that it has no carbon. So it is analogous to a gasoline or diesel fuel. You can put it in the tank of a vehicle. And when it is used to drive the vehicle, there is no carbon dioxide, no greenhouse gases, emitted, so that is one of its important advantages.

Mr. ROHRABACHER. Right. I think that is an advantage with the biodiesel as well. Is—does biodiesel create greenhouse gases? I——

Dr. HEYWOOD. Well, that——

Mr. FAULKNER. It might be a net zero, but——

Dr. HEYWOOD. That depends on the details.

Mr. ROHRABACHER. Right, because the plants absorb a certain amount of the——

Dr. HEYWOOD. And I would add that this may well not be an either or, because we talked primarily about passenger vehicles, but the freight part of our transportation system is very significant in terms of its energy consumption. And the big piece is the long-haul trucks, which use diesel engines. They are very efficient engines, and there is nothing on the horizon that looks like it could challenge them, in terms of efficiency.

So sources of fuel for diesel engines in—of the long-term future, is something we should be looking at and——

Mr. ROHRABACHER. Right.

Dr. HEYWOOD.—exploring and developing, and biodiesel is one option.

Mr. ROHRABACHER. Well, it is—if you have to reconfigure the engine of every car that is manufactured in order to take hydrogen in a way that is efficient, meaning you have to end up with a fuel cell engine rather than the engines that we have, it is enormous costs in terms of transition. So we would want to make sure the end result was taking care of the fundamental problem, which is running out of energy.

Let me ask you about the hydrogen engine.

Now someone told me that a byproduct of a hydrogen engine or a fuel cell is water, and—pure water, but would this not be a problem in areas like in half of the United States where it freezes in the wintertime? Would this not be a—some kind of a problem to have water coming out of the engine?

Mr. CHERNOBY. Well, actually—I will comment.

That has been one of the challenges that we have been working on, not just water coming out of the engine, but water within the fuel cell itself. What you will find, during the process of converting the hydrogen to electricity in the fuel cell, there is quite a bit of heat that is generated to warm the water up. And the challenge we have been working on, I think, we—not only DaimlerChrysler, but other OEMs as well, have found ways to overcome is how do we manage that water within the fuel cell during that initial start-up stage when that heat is in there.

So clearly, you are absolutely right. The challenge of that water being there in a cold environment is something that has to be managed.

Mr. ROHRABACHER. We have not—that particular hurdle has not been jumped over yet.

Mr. CHERNOBY. We have made exceptional progress in the last 12 months. I won't say we are done.

Mr. ROHRABACHER. Okay. Because I can't imagine—I can—coming from California, as I do, we wouldn't mind having, I guess, more water on our roads, but if it froze, if we lived in Minnesota, as my friend here does, I would imagine that a significant part of the year, the last thing you want to have is water spread on the road and having to drive your car or have to rely on the road for transportation.

So this is a significant—it seems to me that that would be a significant problem.

Thank you very much, Madame Chairman.

Chairwoman BIGGERT. Thank you.

The gentleman yields back.

The gentleman from Texas, Mr. McCaul.

Mr. MCCAUL. Thank you, Madame Chairman.

I am a member of the hydrogen fuel cell caucus, and we were introduced to a hydrogen fuel cell car, and I was able to drive it. And it was a great experience, but I asked them how much it cost to build them—and we obviously have the technology today to do it, but I asked how much did it cost to build this, and the answer was $1 million for the car.

That is obviously the issue here, bringing the cost down.

The energy companies in my district, when I talk to them about this issue, and I am very interested in it, they tell me that the timeline is 20 to 30 years out in the future. I don't want to accept that answer, and I wanted to get your response to that.

And in addition, I wanted to ask the question or possibly get a comment on the energy bill that we hope is going to come out of conference committee. There will be approximately $2 billion appropriated for alternative energy, including hydrogen. And where would you think—where would you direct that money if you were king for a day and could call the shots on that?

And then finally, the role of the universities, I have a university in my District, and in my view, I think the universities have a role to play with respect to developing these alternative energies.

I will just open it up to the panel.

Dr. HEYWOOD. Let me comment on the time scales.

It is important that we say—or sort out time scale to what. And we have got fuel cell cars out already. There will be larger fleets 10 or 15 years from now. The DOE commercialization decision is pitched for 2015, 10 years from now. Our judgment was that fuel cells—we will know whether they are marketable within about 15 years. That is not all that different.

But then there is this time scale to build up production. And we have never gone through a large-scale change in a propulsion system, except for the diesel transition in Europe. Diesels took over from 10 percent of the market in Europe in 1980 to 50 percent now. So it took 25 years. Diesels, a well-established technology, to go from small scale to 50 percent of the market. How long will it take fuel cells? That is where we get to 20, 30, 40 years before there are enough fuel cells to have an impact on our energy consumption.

Mr. MCCAUL. So the energy companies are—they are accurate when they say that?

Dr. HEYWOOD. They are right.

Mr. MCCAUL. Okay.

Dr. CRABTREE. May I comment?

The last two parts of your question about where should the funding go and what—and the role of universities.

I believe that there is an enormous amount of basic research that needs to be done, and the best place—one of the best places to do that is universities. Universities and national labs working together can actually accomplish that goal.

When you have $2 billion to spend, you—it actually isn't a lot if only a fraction of it goes to hydrogen. You have to be careful with how you spend it, and I think there needs to be a balance. So there should be a balance between helping industry do the research, as many of the companies do, and universities and national labs. I think these are the three places it should go——

Mr. MCCAUL. Good.

Dr. CRABTREE.—with very carefully targeted goals.

Dr. BODDE. Let me offer a comment, also, sir, if I may, on the role of the universities.

I think it is important to recognize that universities are fundamentally “people factories.” That is, their basic product is people. And turning out people who are not only capable in the technology, but capable innovators is probably a very primary thing and probably one that may have been underappreciated in the university for a number of years.

Beyond that, of course, is the basic research, the blue sky research. But I think there is an emerging role for universities, also, as innovation centers, as centers not only for the creation of new technology ideas, but the capturing of those—of the economic value in those ideas, because as we look at competitive worldwide industries, we are beginning to see increasing pressures on the central R&D functions in virtually every company. And if that is to happen, if that translating function is to happen, then it has got to go someplace, and I believe the universities can emerge and play some role, not the only role, of course, but an increasing role in that.

Mr. FAULKNER. A couple of comments, sir.

Universities are a key partner for my office across the board, and they are for this hydrogen initiative. I mentioned in my oral testimony that we have three Centers of Excellence we have initiated. They include 20 universities just in that alone.

On the cost, I think one thing to mention is, yes, there aren't that many cars on the road, so just like anything else, the prices are high. The more you make, the more the costs come down.

One thing we have started to look at, and I mentioned this in my oral testimony, I think this is an exciting field, is manufacturing R&D. I think we need to look more at this and other renewable areas, too, but to look at how to take things in the laboratory out into the plant floor or the factory floor and move it on out into commercialization. And we are going to be looking more and more at that in the years ahead. This is a spin-off of the President's manufacturing initiative. And we are looking at things like high-volume manufacturing, standardizing components, developing an infrastructure, developing a supplier base. And this is going to be a critical factor in helping to bring those costs down as you manufacture the hydrogen initiative.

Mr. MCCAUL. If I could ask one more question, Madame Chair.

Twenty to thirty years to have market saturation, but when do we think the first hydrogen cars will actually be out on the market?

Mr. CHERNOBY. Well, again, it gets back to your time question. I don't find it so easy to actually put a specific date on the invention of technology and research. If we had that kind of crystal ball, I think we would be in a lot better shape. But we look forward to vehicles, and then when you say ready, it depends upon, again, at what value for the customer and what price point. But during the—this next decade is when we would expect, at DaimlerChrysler, we ought to have that commercial vehicle viable for the marketplace, from a technical perspective.

But it is only as good as having available the infrastructure. I thought the ethanol discussion was very interesting. We have built millions of vehicles capable of running on ethanol, and they are out there in the marketplace today. But yet it shows you that unless you have got market pull and market incentive, it doesn't all come together to benefit either the environment or energy security.

Mr. MCCAUL. Thank you, Madame Chair.

Chairwoman BIGGERT. Thank you.

I think we have time for a few more questions, if everybody is very brief asking the question and answering the question.

So Chairman Inglis, would you like to go ahead for five minutes? Thank you.

Chairman INGLIS. I thank you.

Mr. Chernoby, I understand that you have some dealings with the—with codes and standards tech team. And one of the significant roles of the Federal Government or government somewhere may be the setting of codes and standards, especially for the storage of hydrogen. Do you want to comment on any suggestions that you have for us at the federal level or what should be our approach? It is a little bit early, I know, to—maybe to project those, but suggestions from you about how to approach codes and standards.

Mr. CHERNOBY. I would give you three key suggestions.

Number one, don't try to move to locking down a code or a standard too early while technology is still in the evolutionary stage. When technology starts to settle down, then, in a pre-competitive environment, we can all work together, both industry and government, to set the right standards.

So number one, don't move too quickly.

Number two, as you already do in a very proactive mode, work with us. We will all work together to try to find the right balance to make sure that every standard we issue is going to be viable in the marketplace and provide everything it has got to do, whether it be safety for the consumer right on down to the various environmental benefits we might need.

And then finally, we have got to work together to keep an eye on the global codes and standards. And I know the government is already participating in some harmonization community—or collective efforts around the world. We have got to do our best, as we try and develop these codes and standards, that they are very similar so that we can gain volumes of scale, bring the costs down, and make the vehicles viable in the marketplace.

Chairman INGLIS. With these test vehicles that have been mentioned that we are driving around, have there been any local fire chiefs in various cities that have said, "Not in our city," or anything like that, I mean, such that we are already seeing some discrepancies in the standards?

Mr. CHERNOBY. I wouldn't say in those terms, but there have been local fire chiefs that have raised their hand and said, "Come talk to me. We would like to have some input. We would like to work with you." And that is virtually in almost every state where we are participating today. So we absolutely welcome and—that type of conversation effort, so we are collectively working together to find the rest—the best answer.

Chairman INGLIS. Anybody else want to comment on that? The codes and standards?

Thank you, Madame Chair.

Chairwoman BIGGERT. Thank you.

We will—I think we will skip over, if you don't mind, Dr. Bartlett, to Mr. Schwarz from Michigan, who just arrived for his first round.

Mr. SCHWARZ. Thank you, but I have no questions.

Chairwoman BIGGERT. Oh, well, then we won't.

Mr. Bartlett is recognized.

Mr. BARTLETT. Thank you very much.

Let me take just a moment to define, for those who are listening or those who may be reading this testimony, what we mean by "Hubbard's Peak." This resulted from the work of a geologist working for the Shell Oil Company back in the 1940s and 1950s who noticed the exploitation and exhaustion of oil fields that tended to follow a bell curve, increasing production to a peak and then falling off as you pull the last oil out of the field. He—in estimating the fields yet to be found and adding those to the fields he knew were in existence for the United States, he predicted, in 1956, that the United States would peak in oil production in about 1970. His prediction turned out to be exactly right. Every year since 1970, we have not only found less oil, we have pumped less oil.

Using his analysis techniques, he predicted that the world would peak at about 2000. That slipped a little because of the Arab oil embargo, oil price spike hikes, and a worldwide recession. And there are many insiders who believe that we are now at Hubbard's Peak.

And so Hubbard's Peak represents the peak oil production in the world, and it is only downhill after that. A plateau for a while, and then downhill after that.

I would just like to caution and get your comment on it, that we shouldn't be too optimistic about the energy we are going to get from agriculture. Tonight, 20 percent of the world will go to bed hungry. Until we learned to do no-till cropping, we were losing the battle with maintaining our topsoil. It was ending up in our bays, and from the whole central part of our country, to the Mississippi delta. If—to get a lot of energy from agriculture, we are either going to have to eat the corn that we would have fed to the pig, we are going to have to live lower on the food scale, because you can't feed the corn to the pig and then eat the pig, because there is an awful—that is a very poor energy transfer, by the way, when you are doing that.

Also, if we are going to take a lot of the biomass off, I have some real concern about our ability to maintain topsoil. As I said, until we learned to do no-till farming, we were losing that battle. We are just now barely able to hold the quality of our topsoil with no-till farming. If we are raping the soil of a lot of this organic material, the tills will deteriorate, the soil will have no acceptable tills, and we are—you know, it is going to become a mud pit when it is wet and a brick when it is dry. That is how you make brick. You take soil that has no humus in it and put it in an oven and bake it.

Do you share some concerns about the potential for getting energy from agriculture in the long haul?

Dr. HEYWOOD. Let me respond.

Yes, I do. There is a question what—how big a contribution we think it might be able to make.

There are several questions. One is how big a contribution, and the other is exactly what you have just talked about, what are the long-term environmental impacts of monocultures grown on a large scale to produce fuel.

And I have a Ph.D. student who is working on a project that is focused exactly on that, because there is very—there is not a lot of prior work that looks at these longer-term impacts. And what we have found so far is that people's predictions on these impacts vary a lot. So there really is a need to dig into that question and understand it better.

But even if biofuels contribute five percent or 10 percent to our liquid transportation fuel system, that is—it is not easy to find five and 10 percent. So that might be an important five and 10 percent.

Mr. FAULKNER. I believe, sir, a quick answer for me is I am more sanguine than you might be on that subject. I would note that the Department of Energy and Agriculture just recently published a report that we internally call "The Billion Ton Study." That is over a billion tons of forest material and agricultural material, that is not just the corn kernel. There is starch. It is also waste material, like corn stalks and sugar cane gas, are available—or could be available in the future to produce biofuels, products, and power, and I think that is a study I would like to get to you, if that is okay.

INSERT FOR THE RECORD BY DOUGLAS L. FAULKNER

In April 2005, the U.S. Departments of Energy and Agriculture published the following report assessing the potential of the land resources in the United States for producing sustainable biomass: *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply.* This study indicates that a billion tons of biomass supply consisting of renewable resources from both agricultural and forestry supplies could be utilized in an environmentally and economically sustainable manner. According to the report, these resources are capable of supplying more than 30 percent of the Nation's present petroleum consumption and include agricultural residues such as corn stalks and sugarcane bagasse. Presently, the Department is supporting the Department of Agriculture in its efforts to determine how much of the residue can be removed without reducing soil fertility and depressing grain yields in subsequent years after residue removal.

[The report appears in Appendix 2: Additional Material for the Record.]

Mr. BARTLETT. Mr. Secretary, I am not sure we—it is appropriate to call these things "waste material." Anything that goes back to the soil to maintain the health of the soil, putting organic material back into the soil, that is really not a "waste material." For one year, you may see it as "waste material," but if you keep doing that for a long time, I have some concern about what is going to happen to our topsoil and our ability to grow these crops.

Dr. CRABTREE. May I make one comment on your question about where the energy will come from after Hubbard's Peak?

It is just one statistic, you might be interested, one fact. The sun gives, in one hour, more energy to the Earth than we use in one year, so there is an enormous resource in solar energy, if we knew how to tap it, that would, indeed, supply our needs.

Mr. BARTLETT. Thank you. I am a big solar enthusiast. I have a place in West Virginia off the grid, and we produce all of our electricity, so I will tell you that you have to be pretty sparing in your use of electricity. And we have a number of panels. You are going to have to have a very different lifestyle when you can't use your grandparents' inheritance anymore, you have to live on your 15 percent income.

Dr. BODDE. With that said, sir, I think we are just beginning to see the effects of energy conservation, or efficient energy use, I guess I should say, and as energy prices rise, as engineers begin to look at the services that energy provides, as opposed to the energy itself, I think there is huge potential for that to relieve some of this problem already. Will it relieve the whole thing? No, of course not. But as Dr. Heywood said, five or 10 percent is not bad.

Mr. BARTLETT. Just one comment, Madame Chairman. Thank you for the time.

We better do that, sir, or we are going to have no energy to invest in the alternatives that we must transition to. Today, we are using all of our energy, just barely able, at $60 a barrel, to produce enough to keep our economies going. We have no energy to invest, essentially none to invest. We have to make big investments of time and energy if we are going to transition. And we will transition, by the way. We will either do it on our course or at nature's course. But we will transition from fossil fuels to renewables. The question is, how bumpy will that ride be?

Chairwoman BIGGERT. Thank you.

The gentlelady from Texas, Ms. Jackson Lee.

Ms. JACKSON LEE. Thank you very much, Madame Chairperson. This is a very important hearing.

While you gentlemen are sitting there, conferees are meeting on the massive energy policy bill, and I would venture to say that although the Science Committee and the previous speaker and others worked their heart out, the predominance of the bill obviously deal with fossil fuel.

But the Science Committee did have its voice, and I am pleased to note that there were a number of options and alternatives and excellent additions to the legislation per this committee.

I am also pleased to note, as I understand it, Mr. Faulkner, that we have added $33 million in fiscal year 2006 regarding the hydrogen program. I hope that is accurate, and you might comment in my questions.

Let me just say that I come from Texas, so I come from oil country. And in fact, one of my amendments in the bill spoke to determining the extent of deposits off the Gulf of Mexico so that we could plan long range in a more organized manner what we had at our access, if we will, particularly in light of the fact that the greater exploration is probably more off the Louisiana and Texas coasts than it might be off of Texas—off of California and Florida.

So there are some concerns about energy resources, particularly oil and gas, even though there are those of us who live in that environment and certainly support that environment in a safe and healthy way, we are also open-minded to recognize that the United States has to have options.

And so I pose these questions with the backdrop of the development that is going on off the shores of Louisiana and Mexico and also international oil development and the new findings on LNG. There are options that I think that we should be involved in.

I will pose two questions, keeping that in mind, and a sub-question.

One, it may have been asked, but I am interested in the proposed sources for hydrogen, particularly the options include nuclear and natural gas, clean coal, wind, and renewables. And I would be interested from all of you as to what shows the most promise.

Then we have done some work in the Science Committee on fuel cells. And in fact, we had some amendments along those lines in the energy bill. Fuel cells and fuel production are experiencing competitive pressures significant enough to affect pricing, is my question, is the market in fuel cells, if that pressure is affecting pricing? And if it is not, when will we see a truly competitive fuel cell market? And what drives down prices and advances technology?

Mr. Chernoby, in your remarks, I would be interested in whether you have hybrid cars already, using hydrogen or other alternatives.

And then for all of you to answer the question of the great need to educate more scientists and engineers, which is an issue that I have worked on on this committee. I am frightened by the prospect that we may not have a farm team of physicists and chemists, engineers, and I have worked to help finance the historically black colleges and Hispanic-serving colleges and community colleges. But I welcome your comments on what we could do on expanding that area.

And I yield to the gentlemen.

I ask, also, that my remarks may be submitted into the record.

Chairwoman BIGGERT. Without objection.

Ms. JACKSON LEE. Mr. Faulkner, would you start, please? And is that $33 million accurate? Do you know? Or have we given you more?

Mr. FAULKNER. Yes, ma'am. The President announced an initiative for $1.2 billion over five years. We are on track for that initiative. I was looking at the chart in front of me. Fiscal year 2005 appropriations for the whole initiative, which includes my office, the Nuclear Office, Fossil Office, Science, and also the Department of Transportation, appropriations for fiscal year 2005, was, roughly, $225 million. Our presidential request for that same group is roughly $260 million.

You mentioned——

Ms. JACKSON LEE. And you are getting more money for hydrogen? That is what I was asking. You don't have that——

Mr. FAULKNER. Well, this is the hydrogen fuel initiative. It is fuel cells, hydrogen production——

Ms. JACKSON LEE. Thank you.

Mr. FAULKNER. You asked several other questions. I will provide answers for a couple of those, and my colleagues will probably fill in others.

You asked what shows the most promise for sources of hydrogen. I think, right now, it is too early to say. We are pursuing several different pathways. We are still early in this initiative, and I would hate to cut off promising research and development by picking a winner or a loser this early in the game.

You talked about scientists and engineers, and I would just note that we have an initiative that I personally am very fond of in our office with the National Association for State Universities and Land Grant Colleges that we have been working on with them for the last couple of years. It's not directly related to the hydrogen initiative, but we think there is a lot of excitement here, and we share your interest in building these—growing more scientists—the scientists and engineers in America. And if you would like, we could give you more information on that, and that does include historically black colleges you mentioned.

Ms. JACKSON LEE. I would. Thank you.

INSERT FOR THE RECORD BY DOUGLAS L. FAULKNER

Since 2004, the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) and the National Association of State Universities and Land Grant Colleges (NASULGC) have been building a partnership to improve communication between the two scientific communities, advance the development and use of energy efficiency and renewable technologies, and educate the young scientists and engineers that America needs for securing our energy future.

For EERE, the 217 NASULGC institutions of higher education, which include 18 historically black institutions and 33 American Indian land-grant colleges, provide an opportunity for focusing research, extension/outreach, and curriculum development activities on energy efficiency and renewable energy issues. EERE can use NASULGC's Cooperative Extension and Outreach networks to improve the dissemination of results coming from university researchers and DOE research laboratories, and to spread the use and adoption of energy-saving and renewable energy technologies and products for residential, commercial, and other sectors.

For NASULGC affiliated institutions, the outcome is to develop relevant curriculum, research, and outreach programs with EERE's latest technologies that will assist their students and the citizens of their state. NASULGC can work with EERE to help its member institutions increase their responsiveness to practical issues and provide opportunities for faculty and students to gain access to research and cutting edge knowledge.

EERE and NASULGC are working together to assist young people's understanding and appreciation for math and science through a hands-on learning program with 4–H kids. Young participants apply physics, mathematics, and other disciplines to lighting and other energy technologies. Energy efficiency and renewable education programs are also being delivered to youth and adults.

Dr. BODDE. One comment, if I may, on the colleges and colleges as "people factories," in particular.

I think that is very important to the economic growth and the scientific growth of this country.

One of the things, though, that I think that research universities have to do is learn to become more effective partners with technical colleges to allow an effective transition and effective unified program between them. That is one of the things that we are trying to put in place at the ICAR now is a partnership with a—the local technical university so that we provide to the upstate coalition in—or the upstate auto cluster, I should say, a completely unified educational program that ranges from the technical level to the graduate research level.

Dr. HEYWOOD. Could I comment on that question about education?

From our perspective, I think government graduate fellowships focused on specific areas do several very useful things. They pull young people into those areas, and they become—that becomes their area of expertise. And also, fellowship students are extremely useful, from a faculty member's perspective, because they are, in a sense, free labor to start on a new topic. And so they really have an effect of allowing faculty members to branch out into new research areas, and that is exactly the sort of—pulling young people into this—these areas that are going to be critical to us for the next many, many decades, and also providing opportunities for starting up new and, hopefully, interesting and promising research activities.

Back to the sources of hydrogen, I would like to add just one comment.

I think it is—Mr. Faulkner is quite right. It is too early to start to make choices, but I think it is worth saying something about many people's feeling that if we have got renewable electricity, then we can make hydrogen with, sort of, no environmental impacts. Well, if we got renewable electricity, that is fantastic stuff, and it will displace coal-generated electricity. And I sometimes feel like, well, why would you take a really good wine and convert it into a not so good wine. Electricity is a fantastic wine. Hydrogen isn't quite as good.

So I think that is a very good question. There are questions like that that we need to dig into, but it is too early to say. But we are going to have to be imaginative, because if we don't produce the hydrogen without releasing greenhouse gases, we have really—we have not moved forward very much at all.

Dr. CRABTREE. Yeah, may I comment on that, too?

I would like to reinforce what Dr. Heywood said that it is very important to produce the hydrogen without carbon. And the one way in which you can do that is to split water. There are many ways to split water. You mentioned nuclear and electrolysis, but there are other ways, too, notably solar energy. It would be wonderful to take a beaker of water, put it into a container that is highly technological, set it in the sun, and simply produce hydrogen with no other energy input. And in fact, that can be done in the laboratory now with about 18 percent efficiency. Of course, it is much too expensive to do commercially, but I think that is the challenge.

So if we can do that, we have solved lots of problems: we don't have any dependence on foreign energy sources, because the sun falls on everyone's head; we don't produce any greenhouse gases; we don't produce any pollutants; and the supply is, effectively, inexhaustible.

So I think this is the route we should go. It is a question of which renewable energy sources we use.

Dr. BODDE. One further comment on universities.

The American university has become truly an international, multi-national enterprise. There are students coming to us preferentially from all over the world. We have attracted into our universities some extraordinary talent, the greatest talent that exists in many countries. I think we need to find ways to retain that talent within this country, not only when they are graduate students, but afterwards. And I think we should look again at our security policies and ask if we are not straining out a whole lot of folks that we really wish that we would have around here?

Mr. CHERNOBY. And just to close your question on the fuel cell vehicles.

Yes, at DaimlerChrysler, we have approximately 100 different fuel cell vehicles on the road around the world, many of those here in the United States in the DOE demonstration project, gaining valuable data to help us understand what are the new problems we face when we move from the lab to the environment.

And I would add, on education, we don't—we, at DaimlerChrysler, also very—think it is very important to attract young people to the technical arenas. We participate very strongly in efforts at the elementary school level, the middle school level, and through things like the first robotics competition at the high school level. It is absolutely critical to attract them to the technical fields in the first place before they get to the collegiate type of environment.

Ms. JACKSON LEE. Thank you.

Chairwoman BIGGERT. The gentlelady's time has expired.

Ms. JACKSON LEE. Thank you very much.

Chairwoman BIGGERT. Just a quick couple of questions to—before we close.

Dr. Bodde, the first recommendation of the National Academy's report was for DOE to develop an increased ability to analyze the impact of new technologies, such as hydrogen, on the entire energy system so that the Department can wisely set priorities for energy R&D. How would you rate the Department's current systems analysis effort? And should it be changed, in your opinion, to improve it?

Dr. BODDE. Well, it is certainly too early to judge, but I think the response from the Department of Energy was quite immediate and quite effective. The office was established, housed at the National

Renewable Energy Laboratory, and has begun to—a wide-scale set of works.

But I think this modeling of the entire energy system is very important, because, in the end, it has got to function as an integrated system where we have got to understand how it can function as an integrated system. Further, we have to understand how that system is evolving. So it is one thing to create models for the system, but it is another thing, also, to monitor progress as it goes along to monitor where bets are being placed, say, in the private sector. Where is private venture capital going in these things?

And I guess if I could offer one suggestion for a direction that this systems integration or modeling effort would go, it is to add to those capacities an ability to look at where the private sector is going right now, the bets that private investors are placing in new technologies.

Chairwoman BIGGERT. Thank you.

And then, Dr. Crabtree, the DOE is currently funding learning demonstrations with the auto makers and energy companies. Is the information that DOE is getting from the auto makers worth the price of the demonstrations, given the technical challenges that remain?

Dr. CRABTREE. Well, that is a very difficult question to answer. Let me say something generally, which may not be quite the specific answer you are looking for.

I think it is very important to have demonstration projects, because there you learn what the problems are, and you learn how to innovate. And if you look at the history of energy, and let us say, internal combustion engines, that is how the progress was made. So we can't discount that as a very important way to go forward.

I would balance that with the feeling that we need to put basic research on the table as well. It is really both of those efforts that are going to make the hydrogen economy vibrant, competitive, innovative, and lasting for 100 years, as the fossil fuel economy has done.

Chairwoman BIGGERT. Would you say that the money would be better spent on basic research, or does there need to be a balance?

Dr. CRABTREE. I think there needs to be a balance. There absolutely needs to be a balance.

Chairwoman BIGGERT. Thank you.

And I have one more here, if I can find it.

Mr. Chernoby, what role do the entrepreneurs or start-up companies and venture capitalist investors have to play in helping DaimlerChrysler accelerate the commercial introduction of the advanced hydrogen fuel cell vehicles?

Mr. CHERNOBY. Absolutely, they are going to play a critical role, especially in those areas where we develop a new technological innovation that may not be of significant interest to a big company at this point in time to invest. The entrepreneur may be our avenue to actually get that into the commercialization, as Dr. Bodde mentioned earlier.

So we absolutely see that linkage as one that may be a very critical path in order to get this to a reality.

Dr. BODDE. Just a footnote on that, Madame Chairman.

Chairwoman BIGGERT. Sure.

Dr. BODDE. When the laser was first invented at Bell Labs, the inventors of it had a very hard time getting it patented.

And why did they have a hard time getting it patented? Well, it turns out that, for the telephone, it was then understood there was absolutely no use for this innovation. And so it was only by great persuasion that Bell Labs actually managed to capture the patents for this enormously useful, broadly applicable innovation.

Chairwoman BIGGERT. Thank you.

And with that note, we will—before we bring the hearing to a close, I want to thank our panelists for testifying before the Subcommittee today. I think it was—you are just experts in your fields, and it was very, very helpful to all of us.

And if there is no objection, the record will remain open for additional statements from the Members and for answers to any follow-up questions the Subcommittee may ask of the panelists. So without objection, so ordered.

The hearing is now adjourned.

[Whereupon, at 12:05 p.m., the Subcommittee was adjourned.]

Appendix 1:

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Douglas L. Faulkner, Acting Assistant Secretary, Energy Efficiency and Renewable Energy, Department of Energy

Questions submitted by Chairman Judy Biggert and Chairman Bob Inglis

Q1. Dr. Bodde recommended that the Department of Energy (DOE) keep track of the efforts of auto suppliers and smaller private ventures that support the automotive industry. Has DOE taken any steps in this direction, and what else can be done?

A1. We agree that it is important to stay abreast of commercial and technical developments of auto suppliers and smaller private ventures. A strong supplier base capable of providing parts for advanced vehicles is important to maintain the U.S. auto industry's competitiveness especially given auto manufacturers' increased reliance in recent years on their first and second tier suppliers.

We monitor developments at supplier companies and smaller private ventures by regularly attending technical conferences, sponsoring technology assessments, tracking the technical literature, visiting R&D facilities, and meeting with researchers. Most importantly, we provide a substantial portion of our transportation-related R&D funding to such companies. In FY05, the Department of Energy's, Hydrogen, Fuel Cell and Infrastructure Program spent approximately $72 million, or 32 percent of its budget and the FreedomCAR and Vehicle Technologies Program spent approximately $35 million, or 40 percent of its light duty vehicles budget to fund research at such companies. In addition, many suppliers work directly with our national laboratories which provides further insights into the types of technology challenges arising and how they are being addressed.

Q2. How is DOE working to ensure that the technologies developed under the FreedomCAR program that can be used in conventional vehicles are moved into the marketplace, and that the efficiency gains from the technologies are used to improve fuel economy?

A2. New vehicle technologies normally take about 15 years to reach maximum market penetration. Ultimately, companies must make independent decisions on which combination of technologies makes sense for each to commercialize based upon the establishment of viable business cases. Even if performance and cost targets are met, other market factors (e.g., availability and price of gasoline, investment capital conditions/risk, etc.) will influence industry's decision to commercialize a particular technology.

DOE works closely with industry through the FreedomCAR and Fuel Partnership and our cost-shared R&D projects to help strengthen the business case for the adoption of technologies on which we work. Partnerships help facilitate technology transfer and information dissemination by creating a common understanding of technical capabilities and barriers and by providing a forum in which to exchange ideas. In addition, as technical progress is made, performance targets are met and validated, and cost is reduced, the technologies become more attractive for industry to adopt and commercialize.

Q3. What steps might the industry take to assure customers that hydrogen-powered vehicles meet the same or higher standards of safety compared to current vehicles?

A3. Ultimately, customer assurance of safety will be accomplished by establishing a safety record and experience base that demonstrates safe use of hydrogen by the public. Since that experience base does not yet exist, it is critical that early hydrogen demonstrations operate with safety at the highest priority level. To accomplish this, both DOE and industry are working together through the following activities to ensure safety:

- *Establishing codes and standards.* All major domestic and international codes and standards organizations are working with industry and other stakeholders to establish the initial safety standards and codes which will guide the roll-out of hydrogen technology. A number of key codes and standards have been completed and are in the process of being adopted. As the technology evolves over the next decade, these codes and standards will be revised. In addition, the Department of Transportation is performing their regulatory role of establishing vehicle standards, crash worthiness and pipeline safety.

- *Ensuring safety of demonstration vehicles and fueling.* To ensure safety during hydrogen demonstrations, layers of safety systems are being employed. For example: 1) Vehicles are equipped with a number of hydrogen leak detectors that trip below the concentration level of hydrogen that would support combustion, 2) Accident sensors (similar to those used to deploy air bags) are employed to prevent fuel flow following an accident, and 3) Service stations are equipped with sensors and monitors, and refueling operations are conducted by trained personnel.
- *Ensuring safety of DOE projects.* DOE has implemented a series of measures to ensure safe operation of our R&D program: A primary measure is the DOE Hydrogen Safety Panel, an independent group which counsels DOE on safety matters, performs reviews of project safety plans and conducts site audits of facility conducting R&D.
- *Training.* DOE is working with government, industry and fire professionals to develop and conduct training for first responders.
- *Reporting incidents and lessons learned.* DOE is in the process of establishing an international hydrogen incident database so that information from hydrogen incidents or "near-misses" from around the world can be shared throughout the hydrogen community, helping to prevent future safety problems.

Q4. Professor Heywood argues that because of the high risk of failure of the hydrogen research initiative, DOE should increase funding for alternative vehicle technologies, such as electric vehicles and biomass fuels. What do you think the chances are that technical barriers will cause the hydrogen initiative to fail? Is DOE providing enough funding to alternatives?

A4. We believe the Administration's requests have provided enough funding for R&D in vehicles and biomass. We agree that their merits are significant. We also believe the chance of achieving technical success in the development of hydrogen technologies is very good, due to extensive program planning, management and review.

Question submitted by Representative Roscoe G. Bartlett

Q1. In your opinion, is a limited world platinum supply likely to be a barrier to the widespread adoption of fuel cells?

A1. No. A study by TIAX, LLC determined that there are sufficient platinum resources in the ground to meet long-term projected platinum demand if the amount of platinum in fuel cell systems is reduced to the Department's target level. The DOE-sponsored study, shows that world platinum demand (including jewelry, fuel cell and industrial applications) by 2050 would be 20,000 metric tons against a total projected resource of 76,000 metric tons. This study assumes that fuel cell vehicles attain 80 percent market penetration by 2050 (from U.S., Western Europe, China, India and Japan). The study shows that the limiting factor in keeping up with increased platinum demand is the ability of the industry to respond and install additional production infrastructure. Since in the out-years, recycling would provide almost 60 percent of the supply, the industry will have to be careful not to overbuild production capacity in a more accelerated market demand scenario.

- Platinum availability is a strategic issue for the commercialization of hydrogen fuel cell vehicles. Platinum is expensive and is currently critical to achieving the required levels of fuel cell power density and efficiency. As such, the Department has been focused on reducing and substituting for (with non-precious metal catalysts) the amount of platinum in fuel cell stacks (while maintaining performance and durability) so that hydrogen fuel cells can be cost competitive with gasoline internal combustion engines.
- Significant progress has been made and is still being made by national laboratories, universities and industry to reduce the amount of platinum needed in a fuel cell stack by replacing platinum catalysts with platinum alloy catalysts or non-platinum catalysts, enhancing the specific activity of platinum containing catalysts, and depositing these catalysts on electrodes using innovative processes. The Office of Science has recently initiated new basic research projects on the design of catalysts at the nanoscale that focus on continued reduction in the amount of platinum catalyst required in fuel cell stacks.

- Typically, it takes three to five years to increase platinum production capacity in response to an increase in demand. Fuel cell vehicle production may create a brief platinum supply deficit, leading to short-term price increases.
- The TIAX study shows that platinum prices over the last one hundred years fluctuated based on major world events (e.g., world war, etc.), however, the mean price (adjusted for inflation) remained stable at $300 per troy ounce. However, over the last couple of years platinum has been higher at $900 per troy ounce.

Question submitted by Representative Michael E. Sodrel

Q1. Please provide details of Iceland's effort to convert entirely to a hydrogen economy. Is DOE working with Iceland on this effort? Have they made any advances, including in geothermal energy, that will help to advance a hydrogen economy in the U.S.?

A1. Iceland's goal is to become the first nation in the world to achieve the vision of a hydrogen economy. The move to a hydrogen economy has significant government support, and surveys conducted by Icelandic New Energy indicate significant public support as well. With a population of less than 300,000 (the majority of which resides in the capital of Reykjavik), transforming the Icelandic transportation sector to hydrogen will require far fewer hydrogen fueling stations than what will be required in the United States. Advances include:

- Iceland has an abundance of relatively inexpensive renewable energy that is used for heating and provides 100 percent of the Nation's electricity (80 percent from hydropower and 20 percent from geothermal).
- Currently, there is one hydrogen fueling station, located along a major highway in Reykjavik, which serves as a national demonstration project. Hydrogen is produced on site via renewable electrolysis. The station is a publicly accessible retail fueling station that also offers gasoline and diesel and includes a convenience store. It supports the operation of three hydrogen fuel cell buses that run regular routes around Reykjavik; there are no other hydrogen vehicles at this time.
- The next phase of the country's hydrogen demonstration will involve the conversion of the entire Reykjavik bus fleet to hydrogen. Future phases will include promoting the integration of fuel cell powered vehicles for passenger use and examining the possibility of replacing the fishing fleet with hydrogen based vessels.
- Iceland collaborates with the United States through the International Partnership for the Hydrogen Economy (IPHE), which was established in November 2003 to facilitate global collaboration on hydrogen and fuel cell research, development, and demonstration (RD&D). With a membership including 16 countries and the European Commission, the IPHE provides a forum for leveraging scarce RD&D funds, harmonizing codes and standards, and educating stakeholders and the general public on the benefits of and challenges to the hydrogen economy.

Question submitted by Representative Michael M. Honda

Q1. Given the level of innovation in advanced vehicle technologies as demonstrated by foreign-owned automobile manufacturers such as Toyota, Nissan and Honda, would it benefit the U.S. to expand more of the cooperative research, development and demonstration programs (including FreedomCAR) to include foreign-owned companies with domestic R&D and manufacturing facilities?

A1. The Department's public/private partnership to develop hydrogen and hybrid-electric vehicle technologies—the FreedomCAR and Fuel Partnership is not a partnership with individual auto companies, but is between DOE and the U.S. Council for Automotive Research (USCAR). Under the USCAR umbrella, car companies are able to engage in cooperative, pre-competitive research, and to coordinate the industry's interaction with government research organizations. Auto companies that are conducting substantial automotive research and development activities within the U.S. are able to apply for membership in USCAR.

Even though many foreign companies have substantial production facilities within the United States, they do not have staff in North America with the appropriate R&D expertise or experience to qualify for participation in the development of technology goals and milestones for these programs.

Foreign car companies, however, have been and continue to be able to contribute their ideas to the programs by meeting with DOE program managers and by participating in DOE workshops, stakeholder meetings, program reviews, and solicitations. They also are able to provide input through public comments on pre-solicitation and go/no-go decision notices. We also frequently visit their R&D facilities and monitor technological developments outside of the United States.

ANSWERS TO POST-HEARING QUESTIONS

Responses by David L. Bodde, Director, Innovation and Public Policy, International Center for Automotive Research, Clemson University

Questions submitted by Chairman Judy Biggert and Chairman Bob Inglis

Q1. What steps might the industry take to assure customers that hydrogen-powered vehicles meet the same or higher standards of safety compared to current vehicles?

A1. Years of experience with hydrogen production and use clearly demonstrate that a high degree of safety can be achieved. But all this experience has been gained in applications that are professionally managed and maintained. When hydrogen is introduced into the consumer economy, an entirely different set of issues arise, not only for consumers but also for first-responders to emergencies.

Safety will be especially important during the transition period, as any hydrogen-related accidents will draw intense public scrutiny. This applies to every part of the hydrogen supply chain—production, logistics, dispensing, and on-vehicle use. Thus, all parts of an emerging hydrogen industry, not just the vehicle makers, must move aggressively to define and resolve potential safety issues. The Department of Energy should take the lead here—for example, by raising the importance of safety in its FreedomCAR program. This could be done by creating a “safety team” in addition to the team developing codes and standards. Further, safety should be considered a system-wide issue and integrated into all the technical teams.

Some specific issues pose special concerns. In my view, high pressure hydrogen storage on-board vehicles poses the greatest single safety challenge, especially as these vehicles age. Plainly, much design effort should be devoted to fail-safe systems, and manufacturers must build these vehicles for quality and durability. For the longer-term, low-pressure, solid-state storage systems might offer relief, but for now these remain research goals and far from marketplace reality.

Finally, all companies participating in the emerging hydrogen economy must share safety-related information widely. This serves their self interest, as an accident anywhere is likely to impugn hydrogen activities everywhere.

Q2. What have you learned from your experience on the National Academies’ review panel on FreedomCAR? What recommendations do you feel most important?

A2. The FreedomCAR and Fuel Partnership takes on an extraordinary challenge: to precipitate revolutionary change in a global vehicle and fuels infrastructure that has served well for over 100 years and that continues to perform well from a consumer perspective. The challenge is in part technological, but in equal measure it is social and economic—yet the chief policy instrument used by the Federal Government has been technology development. The technologists, however, cannot do it all, and private businesses must respond to the marketplace. Therefore, success will require strong and consistent leadership from elected officials in order to supplement technology as a pathway to change.

In my view, the most important recommendation from the National Academies’ review were:

- Hydrogen storage and fuel cell performance. Extraordinarily ambitious goals have been set for the FreedomCAR and Fuel Partnership, especially in the crucial areas of on-vehicle hydrogen storage and fuel cell performance. Increased attention and support will be required, especially for membrane research, new catalyst systems, electrode design, and all aspects of energy storage.
- Risk hedging. As a hedge against delay in meeting these goals, the program should emphasize:
  - Advanced combustion engines and emissions controls;
  - Battery storage of energy, a “no regrets” strategy that will also serve the hybrid electric vehicles, plug-hybrids, and eventually the hydrogen fuel cell vehicle; and,
  - Management of electric energy systems, also serving all forms of electric drive vehicles.
- Congressionally directed funding. The panel noted that diversion of resources from critical technology areas increases the risk that the program will not meet its goals in a timely manner.

Q3. Professor Heywood argues that because of the high risk of failure of the hydrogen research initiative, the Department of Energy (DOE) should increase funding for alternative vehicle technologies, such as electric motors and biomass fuels. What do you think the chances are that technical barriers will cause the hydrogen initiative to fail? Is DOE providing enough funding to alternatives?

A3. My own concern is not so much that the hydrogen initiative will fail by encountering some fundamental physical barrier. Rather, I fear that technical barriers and parsimonious funding will delay deployment of a hydrogen economy well beyond the goals set by the DOE.

In the meantime, this nation—and, indeed, the world—will continue to rely in the internal combustion engine. Therefore, simple prudence would suggest we hedge our bets (as above) both with improvements to the ICE and with alternative fuels that could backstop a delayed hydrogen economy.

Question submitted by Representative W. Todd Akin

Q1. In your testimony, you stated that, "coal offers the lowest cost pathway to a hydrogen based energy economy." However, within DOE, the carbon sequestration program is managed separately from the hydrogen and vehicles programs. What can we do as a Congress to encourage greater cooperation between these programs, and how does the current structure of DOE hinder efforts to use coal for hydrogen fuel cells?

A1. This separation has concerned at least two National Academies' committees as well. The concern is to bring the several parts of this very complex set of programs to fruition at the appropriate time. The systems analysis function was established to provide the analytical means to accomplish this. However, implementation, as you note, is in question.

Question submitted by Representative Roscoe G. Bartlett

Q1. In your opinion, is the limited world platinum supply likely to be a barrier to the widespread adoption of fuel cells?

A1. Yes, we plainly must develop alternative design approaches that avoid the use of expensive materials like platinum. Otherwise, fuel cells will become too costly for wide scale deployment. Membrane and catalyst research will be important here—see response A2 to Chairman Biggert and Chairman Inglis, above.

Question submitted by Representative Michael M. Honda

Q1. Given the level of innovation in advanced vehicle technologies as demonstrated by foreign-owned automobile manufacturers such as Toyota, Nissan, and Honda, would it benefit the U.S. to expand more of the cooperative research, development, and demonstration programs (including FreedomCAR) to include foreign-owned companies with domestic R&D and manufacturing facilities?

A1. Yes, I think there could be some value in that, though the information sharing must be reciprocal. But more importantly, I believe the FreedomCAR and Fuel Partnership should make greater efforts to engage the entrepreneurial sector of the U.S. economy. If we look at past technological revolutions, we observe that the industry incumbents rarely led the change. The telegraph companies did not bring us the telephone, the telephone companies did not bring us the Internet, and the electron tube makers did not bring us solid state electronics. Thus, much evidence suggests that encouraging entrepreneurship in road transportation might provide a powerful pathway to a hydrogen economy.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Mark Chernoby, Vice President, Advanced Vehicle Engineering, DaimlerChrysler Corporation

Questions submitted by Chairman Judy Biggert and Chairman Bob Inglis

Q1. What steps might the industry take to assure customers that hydrogen-powered vehicles meet the same or higher standards of safety compared to current vehicles?

A1. Hydrogen-powered vehicles will be required to meet the same safety standards as current vehicles. What government and industry can do together to prepare the public for hydrogen vehicles is safety education. For example, first responders to a hydrogen vehicle accident need to know proper procedures for ensuring safety of the vehicle occupants just as they have been trained for current vehicles. A good first step towards this end is the Department of Energy's Hydrogen Vehicle Validation program. Government and industry are working together to develop public education programs that include hydrogen safety.

Q2. Professor Heywood argues that because of the high risk of failure of the hydrogen research initiative, DOE should increase funding for alternative vehicle technologies, such as electric vehicles and biomass fuels. What do you think the chances are that technical barriers will cause the hydrogen initiative to fail? Is DOE providing enough funding to alternatives?

A2. As a partner of the FreedomCAR program we are satisfied with the diversity of the Department of Energy's alternative vehicle research programs. DaimlerChrysler also believes as Professor Heywood in a broad research portfolio approach to the future. Hydrogen storage is one of the high risk challenges for public acceptance of a hydrogen vehicle. The challenge is high but it is a risk we must take as we pursue all alternatives to the current vehicle propulsion technologies.

Question submitted by Representative Roscoe G. Bartlett

Q1. In your opinion, is a limited world platinum supply likely to be a barrier to the widespread adoption of fuel cells?

A1. The current platinum loading of fuel cell electrodes is cost prohibitive for most commercial applications. In order to gain consumer acceptance platinum in a fuel cell must be reduced to a fraction of the current level. Therefore, the supply of platinum will be of less concern when fuel cells are ready for the mass market.

ANSWERS TO POST-HEARING QUESTIONS

Responses by George W. Crabtree, Director, Materials Science Division, Argonne National Laboratory

Questions submitted by Chairman Judy Biggert and Chairman Bob Inglis

Q1. What steps might the industry take to assure customers that hydrogen-powered vehicles meet the same or higher standards of safety compared to current vehicles?

A1. The public acceptance of hydrogen depends not only on its practical and commercial appeal, but also on its record of safety in widespread use. The special flammability, buoyancy, and permeability of hydrogen present challenges to its safe use that are different, but not necessarily more difficult, than for other energy carriers. One important step to insuring hydrogen safety is research to understand the combustibility of hydrogen in open spaces where it is naturally diluted and in closed spaces where it may concentrate by accumulation. Additional areas of research needed for hydrogen safety are the effect of mixing with volatile hydrocarbons like gasoline or alchohol, on hydrogen ignition, the embrittlement of materials by exposure to hydrogen that may cause leaks, and the development of sensing techniques selective for hydrogen.

A second key element is development of effective safety standards and practices that are widely known and routinely used, like those for self-service gasoline stations or plug-in electrical appliances. Despite the danger of open exposure to gasoline and household electricity, the injury rate from these hazards has been minimized by thorough education to a few simple codes and standards. Similar codes and standards need to be developed and widely disseminated for hydrogen.

Q2. In your testimony, you explain the challenge of hydrogen storage as follows: that we are searching for a material that allows, at the same time, both close and loose packing and weak and strong bonding of hydrogen molecules. Is there any known precedent or parallel phenomenon that gives us some confidence that such a material exists or can be created?

A2. The challenge of simultaneously satisfying the twin criteria of high storage capacity and fast charge/release rates is formidable. However advances in nanoscience over the last five years open promising new horizons for satisfying the seemingly conflicting requirements of strong bonding and close packing for high capacity and weak bonding and loose packing for fast charge/release. A storage medium composed of tiny nanoparticles, for example, can provide short diffusion lengths for hydrogen within the nanoparticle leading to high charge/release rates, combined with dense packing of hydrogen as a chemical compound with the host medium. Two promising new materials have been developed in the last year: ammonium borane (NH_3BH_3) and $MgC_{12}(NH_3)_6$, each of which can be artificially nanostructured to enhance its release rate while maintaining its high hydrogen storage capacity.

The search for new nanostructured storage materials is enormously streamlined by theoretical modeling of their storage behavior using modern density functional theory implemented on computer clusters containing hundreds of nodes. Such advanced modeling enables accurate simulation of the storage capacity and release rate of hundreds of candidate materials without the expensive and time consuming step of fabricating them in the laboratory. This efficient "virtual screening" dramatically increases the number of materials that can be searched, with only the most promising candidates tested for physical performance in the laboratory. The formulation of density functional theory and powerful computer clusters enabling this efficient screening were not available even a few years ago.

Q3. Professor Heywood argues that because of the high risk of failure of the hydrogen research initiative, the Department of Energy (DOE) should increase funding for alternative vehicle technologies, such as electric vehicles and biomass fuels. What do you think the chances are that technical barriers will cause the hydrogen initiative to fail? Is DOE providing enough funding to alternatives?

A3. The demand for energy is projected to double by 2050 and triple by 2100. This means that by 2050 we must create an energy supply chain and infrastructure that duplicates today's capacity. This challenge is beyond the reach of a single energy source or energy carrier. To meet the challenge, we must develop a mix of energy options and rely on each to shoulder a portion of the load. Like hydrogen, the alternatives suggested by Professor Heywood are worthy of serious consideration, but they are not without their risks. Electric vehicles substitute electricity for fossil fuels at the point of use, but the electricity they require must be generated, typically from burning fossil fuels like coal and natural gas. Thus the pollution, greenhouse gas emission, and fossil fuel consumption at the point of use is simply shifted to the point of electricity production. This option has approximately neutral impact on the national energy challenges of adequate supply, secure access, local pollution and climate change.

Biomass fuels, while carbon neutral, are not plentiful enough to displace all the gasoline used for transportation in the Nation. Even the most optimistic estimates for biomass fuels claim only to be able to replace the foreign oil used for transportation, and this would occur only after a long development period graced by significant breakthroughs in genetic engineering that are presently beyond the reach of science. Because significant breakthroughs are required, it is impossible to rank the risk of failure of biomass fuels as greater or less than that of hydrogen.

Many energy options must be developed simultaneously, and each will require breakthroughs that we do not know how to achieve at present. Hydrogen solves all four national energy challenges: it is abundant, widely accessible, and free of pollution and greenhouse gas emission if produced by splitting water renewably. Other energy options like electric cars and fuel from biomass address only some of the challenges, and may require equally expensive and difficult breakthroughs. Without the advantage of a crystal ball, it is prudent to invest in several of the most promising energy options. Hydrogen is among the most promising options, for its ability to address, and perhaps solve, all four energy challenges. Alternatives should also be funded, though electric cars themselves have little direct impact on the energy challenges. Biomass addresses climate change much less effectively than hydrogen (it is carbon-neutral, while hydrogen is carbon-free) and is only abundant enough, even with massive planting of energy crops, to supply a fraction of our transportation fuel needs.

Question submitted by Representative Roscoe G. Bartlett

Q1. In your opinion, is a limited world platinum supply likely to be a barrier to the widespread adoption of fuel cells?

A1. There is consensus that if all the family cars and light trucks in the Nation were converted to hydrogen fuel cell propulsion, there is not enough platinum in the world to supply the catalysts needed for their operation. This is a clear barrier to the immediate replacement of internal combustion engines with fuel cells using present technology. However, many other factors, such as the lack of viable on board hydrogen storage media, the short lifetime of fuel cell energy converters under normal automotive use, the poor starting performance of fuel cells in cold weather, and the high expense of fuel cells compared to internal combustion engines, prevent significant penetration of fuel cell cars in the marketplace in the near future. Under these conditions, the scarcity of platinum for catalysts is not the major factor limiting widespread use of fuel cell automobiles.

The replacement of platinum by less expensive and more active catalysts is a vibrant field of research with promise of significant progress before the other factors limiting fuel cell penetration are resolved. We know that plentiful, less expensive catalysts exist, because we see them every day in the biological world. Green plants use abundant, inexpensive manganese as their catalyst for the water splitting step in photosynthesis. The molecular configurations and reaction pathways for the catalysis of water splitting in plants, however, remains tantalizingly just beyond our scientific reach. Using powerful computer analysis and the world's most intense x-ray sources located at DOE national laboratories, scientists are now on the verge of solving the structures of the natural catalytic reactors that plants use in photosynthesis. When these catalytic mechanisms are fully revealed in a few years, we will be able to reproduce them, perhaps in improved form, for use in the artificial environment of fuel cells. This breakthrough, which is now within sight, will open new horizons for catalysis not only in fuel cells, but also in a host of other energy conversion applications. It's achievement will require significant advances in several scientific frontiers: high resolution structure determination, advanced density functional modeling of the structure and dynamics of the catalytic process, and nanoscale fabrication of artificial catalytic assemblies. Investments in these high risk-high payoff scientific advances will yield ample dividends in fundamental knowledge and control of the natural catalytic mechanism of green plants.

ANSWERS TO POST-HEARING QUESTIONS

Responses by John B. Heywood, Director, Sloan Automotive Laboratory, Massachusetts Institute of Technology

Questions submitted by Chairman Judy Biggert and Chairman Bob Inglis

Q1. What steps might the industry take to assure customers that hydrogen-powered vehicles meet the same or higher standards of safety compared to current vehicles?

A1. Safety is a major concern in the FreedomCAR and Fuels Program. The FreedomCAR and Fuels Program has a group within its management structure which involves representatives from industry that is focused on safety. An understanding of the key safety issues and appropriate responses to those issues are being developed. Existing vehicle and fuel safety regulations will apply to hydrogen-fueled vehicles, and the need for new requirements and standards is being explored. Dealing with hydrogen-related safety issues will be a significant challenge, but in my judgment is unlikely to be a show-stopper. Those involved in the program are well aware that major safety incidents would adversely affect the broader public's response to an evolving hydrogen-fueled vehicle program.

Q2. You make several recommendations for areas to receive increased funding, ranging from improved combustion engines to electric batteries. Unfortunately, we are living in difficult budget times, and any increase must be accompanied by a decrease, or an increase in revenues. Are there areas of research that you feel the Federal Government should not be funding at current levels?

A2. We are living in difficult budget times because of the tax reductions the President and Congress have implemented over the past five years. Few of us have yet realized just how serious our transportation energy predicament is, or that petroleum availability shortages could affect our transportation system within the next decade or so. Failure of the supply of gasoline, diesel, and aviation fuel to grow to meet the anticipated growth in demand for these fuels (both in the U.S. an elsewhere) would be expected to create major economic and social impacts. It would take significant time before we would be able to respond effectively.

We need to recognize that substantial government R&D support for several potentially promising engine, fuel, and vehicle technology opportunities will be required to move these technologies forward towards potential deployment. We need a broader and more balanced U.S. transportation energy technology R&D program; our current government efforts are too focused on hydrogen which, while promising, may not in the end prove to be implementable. Our longer-term choices in the transportation energy area (hydrogen and fuel cells, electricity and battery powered vehicles, much lighter and smaller vehicles, biomass-based fuels, liquid fuels from oil sands, heavy oil, coal) are all extremely challenging ones to attempt to implement.

Are there areas where the federal R&D budget could be cut to provide resources for a broader set of such initiatives? I do not have sufficient knowledge of our government's R&D activities in an overview sense to attempt an answer to that question. One factor that makes that an especially difficult question, in my judgment, is that our government lacks a coherent industrial and technology development policy. One consequence of that lack is that we risk losing our global leadership position in transportation energy technologies and the business opportunities that go with that leadership role.

Question submitted by Representative Roscoe G. Bartlett

Q1. In your opinion, is a limited world platinum supply likely to be a barrier to the widespread adoption of fuel cells?

A1. Platinum production capacity would have to expand substantially if current technology fuel cells (which have a high platinum requirement) were produced in large numbers. However, they will not be produced in large numbers because current technology fuel cells are too expensive to be commercially viable, and their technology with its substantial platinum requirement will have to change significantly before fuel cells can become commercially viable. What is already happening that will stress the platinum supply system is the growth in light-duty vehicles worldwide (from 750 million today to an anticipated two billion in 2050), and the expanding demand for automotive catalysts and their requirement for noble metals like platinum that goes along with that worldwide vehicle growth. Thus, it is clear that much improved automotive fuel cell technology, with much lower platinum loadings, will need to be developed if fuel cells are to become a practical and marketable technology.

September 9, 2005

Dr. Arden L. Bement, Jr.
Director
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230

Dear Dr. Bement:

The Subcommittees on Energy and Research of the U.S. House of Representatives' Science Committee held a joint hearing entitled *Fueling the Future: On the Road to the Hydrogen Economy* on Wednesday, July 20, 2005 at 10:00 a.m. in Room 2318 of the Rayburn House Office Building.

Please address the National Science Foundation's (NSF's) participation in the President's hydrogen initiatives for the record of the July 20, 2005 hearing. Specifically, your response should address the following questions:

- What progress has been made toward addressing the principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel since the Administration announced its hydrogen initiatives, FreedomCAR and the President's Hydrogen Fuel Initiative? What are the remaining potential technical "showstoppers?"

- What are the research areas where breakthroughs are needed to advance a hydrogen economy? How is NSF-funded research addressing those basic research questions?

- What hydrogen research is NSF currently funding? How much of this research, if any, is collaborative with private industry? How much, if any, is coordinated with the basic research effort at the Department of Energy (DOE)?

- How does the NSF coordinate with the Office of Science and Technology Policy, DOE and the other agencies involved with the Hydrogen Interagency Task Force? How is information exchanged between the agencies and to what extent is it beneficial to NSF? How does NSF ensure that its research results are available to other agencies? Is the Task Force successful in helping agencies understand what hydrogen issues other agencies are working on, and to what degree?

Please email or fax your responses by October 21, 2005. If you have any questions please contact Mele Williams of the House Science Committee at 202-225-7858. Thanks again for your participation in the hearing.

Sincerely,

JUDY BIGGERT
Chairman
Subcommittee on Energy

BOB INGLIS
Chairman
Subcommittee on Research

Enclosures: Transcript & Member Questions
cc: The Honorable Michael M. Honda, Ranking Minority Member, Committee on Science, U.S. House of Representatives; and the Honorable Darlene Hooley, Ranking Minority Member, Committee on Science, U.S. House of Representatives

ANSWERS TO POST-HEARING QUESTIONS

Responses by Arden L. Bement, Jr., Director, National Science Foundation

Q1a. What progress has been made toward addressing the principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel since the Administration announced its hydrogen initiatives, FreedomCAR and the President's Hydrogen Fuel Initiative?

A1a. The National Academies' report, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (http//www.nap.edu/books/0309091632/html/), published in 2004, identifies the following principal technical barriers to a successful transition to the use of hydrogen as a primary transportation fuel: 1) Development and introduction of cost-effective, durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems; 2) development of the infrastructure to provide hydrogen for the light-duty-vehicle user; 3) sharp reduction in the costs of hydrogen production from renewable energy sources over a time frame of decades; and 4) capture and storage ("sequestering") of the carbon dioxide by-product of hydrogen production from coal.

The National Science Foundation, as part of the interagency Hydrogen R&D Task Force, established and co-chaired by OSTP and DOE, participates in monthly meetings at the White House Conference Center in order to ensure coordination among the agencies and to address relevant research related to potential technical barriers. NSF-supported principal investigators (PIs) have contributed to important developments addressing hydrogen production and storage and fuel cell-related basic research. For production of hydrogen, a progression can be expected of using natural gas, then coal, biomass, and ultimately water as feedstocks. One NSF PI is studying improved production of hydrogen from methane (a principal component of natural gas) and the oxygen in air using high pressures and reactor conditions that favor so-called "cool flames." Such systems hold promise for substantially improving the ratio of hydrogen to water produced in the reaction and have the advantage that catalysts are not needed *(http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0215756).*

New reforming catalysts that produce hydrogen from hydrocarbons and steam and that have increased activity and improved stability toward key catalyst poisons are being identified through NSF awards. In addition, new catalytic routes to hydrogen from renewable resources like plant byproducts have been developed for use in water *(http://www.nsf.gov/od/lpa/news/03/pr0369.htm)* and could to used in fuel cell applications. Some progress has been made in developing a new generation of non-platinum-based fuel cell catalysts.

Advances in research related to formation of hydrogen from water are exemplified by *Science* magazine's having listed water as a Breakthrough of the Year for 2004. NSF PIs are determining structural and dynamic properties of nanoscale clusters of small numbers of water molecules and how they interact with the protons and electrons that are intimately involved in charge transfer leading to hydrogen production. Their studies are also addressing the nature of bonds between water molecules and surfaces, information that will help us understand reactions at fuel cell electrodes. Progress in catalyzed photo-induced electron transfer that is relevant to production of hydrogen from renewable solar energy has been reported from work conducted by NSF PIs and provides insight into the multiple electron transfer events that characterize this process.

Materials for storing hydrogen are under active development by NSF PIs. "Molecular containers" that are porous on the nanoscale are being synthesized and their hydrogen-storage properties characterized, as are various solid-state materials ranging from metal alloys to carbon nanotubes. These developments have been recently summarized *http://pubs.acs.org/isubscribe/journals/cen/83/i34/html/8334altenergy.html.* NSF PIs have also identified materials like palladium nanowires that can detect hydrogen at extremely low concentrations. Such sensor materials could serve as leak detectors for hydrogen and contribute to its safe use in storage and transportation systems.

Fuel cell developments attributable to NSF support are exemplified by progress in low-temperature versions of these devices. In particular, improved performance has been seen with the introduction of fully fluorinated membranes and better electrode structures that increase catalyst utilization.

High temperature Solid oxide fuel cells (SOFCs) have the potential to operate at high efficiency without noble metal catalysts. Currently available oxide membranes, which are critical for ionic transport in higher-temperature fuel cells, are inefficient and fail to operate at the lower temperatures needed for use in transportation. Several NSF projects are focused on studying lover-temperature oxide-ion membranes to minimize corrosion and differential thermal expansion, while maintaining selectivity and permeability.

Also noteworthy has been the success of NSF PIs in exploiting the exquisite machinery of microbes, which can utilize hydrogen without the elaborate storage and pressure systems of conventional approaches. A single-chambered microbial fuel cell *(http://www.nsf.gov/news/news_summ.jsp?cntn_id=100337)* has been shown recently to offer highly mobile and efficient energy production.

Q1b. What are the remaining potential technical "showstoppers?"

A1b. The aforementioned National Academies' report articulates several "showstoppers." For example, at this time, capabilities of hydrogen storage materials are still inadequate. If catalysts for fuel cells are to he economically competitive, they would either need to be about an order of magnitude more active and have high resistance to poisoning by carbon monoxide if they contain expensive platinum; or alternative, efficient non-platinum-based catalysts would need to be found. There are also challenges associated with developing manufacturing techniques that would enable catalyst coatings to be deposited uniformly on surfaces of arbitrary shape.

Q2a. What are the research areas where breakthroughs are needed to advance a hydrogen economy?

A2a. Catalysis impacts many of the technical areas for which breakthroughs are needed to drive a hydrogen economy. Ranging from fuel cell electrodes to photo-induced production of hydrogen, better catalysts will be critical for making progress. In turn, catalyst improvement requires better understanding of a variety of technical issues. Membrane performance, for instance, demands excellent ionic conductivity along with physical and chemical durability. Such a combination of properties poses a challenge due to the lack of fundamental knowledge of synthesis-structure-function relationships in the polymers that are commonly employed as membranes. Another example involves the use of platinum supported on carbon for electro-catalysis in low-temperature acid fuel cells. Reduction of loadings of platinum or other precious metal in electrodes has been identified as essential in order to reduce system costs, but there are also problems with catalyst dissolution and corrosion of the material that supports the catalyst.

Novel materials are needed for safe and reliable hydrogen production and storage, as well as for developing infrastructure to distribute hydrogen. Failure mechanisms due to materials degradation, such as hydrogen-induced embrittlement in pipelines, need to be understood and controlled. As noted above, better membrane materials for fuel cells and superior hydrogen storage materials are needed.

Most hydrogen is currently synthesized from natural gas. Other potential sources of hydrogen include coal and biomass through gasification processes. Basic research is needed to identify optimal hydrogen production strategies from these feedstocks and, for biomass, to ensure effective gas cleanup. Carbon management must be addressed when using fossil fuels as a feedstock.

Splitting water through electrolysis and photolysis needs to be aggressively pursued. Fundamental questions about water's properties at the molecular level still exist and must be resolved if we are to design systems that can more efficiently split water by photochemical or electrochemical means.

There are also basic questions about biological systems that use hydrogen that hold promise for significant increases in energy efficiency if they could be used to form the basis for hydrogen-fueled systems. Central to our understanding of biological systems is the enzyme hydrogenase, the catalyst for reversible hydrogen oxidation. Hydrogenases are components of chemically driven energy production in microbes in the absence of oxygen. Understanding them using physical, genomic and biochemical methods could yield important information for design of systems that mimic the efficiency of chemical and light energy transduction found in biological systems. Guided by advances in theory, modeling and simulation, the synthesis of "model" systems that possess characteristics of hydrogenases represents a promising complementary approach to this objective.

Q2b. How is NSF-funded research addressing those basic research questions?

A2b. The principal investments of NSF-funded research related to fuel cell and hydrogen themes are in the following areas: 1) mechanisms of hydrogen production and utilization in microbes and cellular membranes (Biological Sciences and Geosciences directorates); 2) catalysis, hydrogen production, purification and storage of hydrogen, fuel cell membrane characteristics, and fuel cell design (Engineering and Mathematical and Physical Sciences directorates); 3) experimental and theoretical studies of electrode reactions, water clusters, photo-induced electron transfer reactions, and model hydrogenase systems (Mathematical and Physical Sciences directorate); and 4) materials, including preparation, processing, characterization and properties for potential fuel cell applications and for sequestration of greenhouse gases (Mathematical and Physical Sciences). Some representative projects illustrating how NSF PIs are addressing the research challenges outlined in section 2a were given in section 1a.

It should be noted that many of NSF's investments are made in response to unsolicited proposals. These may involve individual investigators or multi-investigator teams. The level of investment in hydrogen- and fuel cell-related research, approximately $20 M annually, reflects the strong interest in the U.S. academic scientific and engineering research community in the basic research issues associated with these technologies.

It is also noteworthy that there has been considerable synergy with developments arising from investments in nanotechnology. In addition to the examples of palladium nanowire hydrogen sensors and nanoporous solids that can store hydrogen, membranes prepared from multiple nanostructured layers appear to have promising characteristics with respect to fuel cell usage. Bacteria, which might be regarded as "nano-machines," have recently been found to use hydrogen in extreme environments such as hot springs, *(http://www.eurekalert.org/pub_releases/2005-01/uoca-ymf012405.php.* Learning how these organisms live on hydrogen and how they convert it to other forms of energy may have the potential for transformative discoveries upon which to build a hydrogen economy.

Q3a. What hydrogen research is NSF currently funding?

A3a. Areas of concentration are reflected in the interagency Hydrogen R&D Task Force topic areas. NSF is represented on 14 teams focusing on catalysis; materials for hydrogen storage; materials research; materials performance, measurement, and analysis; biological and biomimetic hydrogen production; physical and chemical interactions of materials and hydrogen; multi-functional materials and structures; photo-electrochemical hydrogen production; characterization and new synthesis tools; hydrogen internal combustion engines; hydrogen turbines; SBIR/STTR; and workforce/education. Currently, NSF funds approximately 130 awards per year in the areas listed above.

Q3b. How much of this research, if any, is collaborative with private industry?

A3b. The principal mechanisms that NSF uses to promote interactions with industry are the SBIR/STTR and Grant Opportunities for Academic Liaison with Industry (GOALI) programs, although the latter is only a small fraction of the agency's portfolio. Some individual investigator awards also have industrial collaborations. NSF estimates a current investment of about $4 M in SBIR/STTR awards in hydrogen-related technology. NSF and DOE established a Memorandum of Understanding that offers NSF SBIR/STTR grantees with technology of interest to DOE additional resources through DOE's "Commercialization Assistance Program."

Q3c. How much, if any, is coordinated with the basic research effort at the Department of Energy (DOE)?

A3c. There is considerable coordination with DOE in areas of mutual interest. For example, the two agencies co-chaired a session at the National Hydrogen Association (NHA) Annual National Hydrogen Conference this past April that focused on funding opportunities across agencies for the SBIR/STTR community. For essentially all of the topic areas being coordinated by the interagency Hydrogen R&D Task Force in which NSF participates (section 3a), DOE is also represented. Staff members of these two agencies are collaborating in developing short white papers describing the specific technical challenges associated with each topic area, along with representatives from other agencies as appropriate. Informal relationships have included extending invitations to workshops and contractors' meetings, and sharing information on program announcements, proposals, and awards. The information that is shared helps to ensure appropriate partitioning of investments between the targeted, often short-time-frame perspective of DOE and the high-risk, often longer-term perspective of NSF.

Q4a. How does the NSF coordinate with the Office of Science and Technology Policy, DOE and the other agencies involved with the Hydrogen Interagency Task Force?

A4a. The interagency Hydrogen R&D Task Force holds monthly meetings at the White House Conference Center. This provides an excellent opportunity to meet with representatives from OSTP, DOE and the other agencies involved with the Task Force. NSF currently has two representatives who regularly attend the meetings.

Q4b. How is this information exchanged between the agencies and to what extent is it beneficial to NSF?

A4b. We have found that the topic areas have been effective in connecting staff members across agencies that support research in areas of common interest. Additionally, the Task Force established a website, *http://www.hydrogen.gov,* that provides information from all of the participating agencies that is of value both to the agencies and the external community.

Q4c. How does NSF ensure that its research results are available to other agencies?

A4c. Beyond the informal contacts of technical staff facilitated by the Task Force, the NSF has a searchable award database and collects annual and final reports from its PIs. All of this information is available to technical staff at other agencies. NSF convenes workshops on topics related to the hydrogen initiative. The Task Force meetings and contacts provide a mechanism for inviting representatives from other agencies to participate in the workshops and learn about the latest results of NSF's PIs and their thoughts on promising future research and education directions.

Q4d. Is the Task Force successful in helping agencies understand what hydrogen issues other agencies are working on, and to what degree?

A4d. Our experience has been that the Task Force has been quite successful thus far in lowering barriers to interagency collaboration and providing broader perspectives for investments related to the hydrogen initiative. Most meetings include updates from agency representatives on the various topical areas, meetings, and workshops. In addition, there have been presentations on the International Partnership for the Hydrogen Economy and on specific programs of participating agencies that have provided useful information on the scope of the federal investment.

Appendix 2:

ADDITIONAL MATERIAL FOR THE RECORD

STATEMENT BY MICHELIN NORTH AMERICA

Mr. Chairman and Members of the Committee, thank you for the opportunity to present this testimony today on behalf of Michelin North America.

Since 1889, Michelin has been contributing to progress in the area of mobility, through its expertise in the field of tires and suspension systems and the company's willingness to invest in innovation. In a number of instances, Michelin has been the force behind technological breakthroughs, such as the radial tire, the "Green tire" and the X One single wide-based tire.

Michelin is the world leader in the tire industry. We manufacture and sell tires for every type of vehicle, including airplanes, automobiles, bicycles, earthmovers, farm equipment, heavy-duty trucks, motorcycles, and the Space Shuttle. The company also publishes travel guides, maps and atlases covering North America, Europe, Asia and Africa. In 2004 Michelin produced nearly 195 million tires and printed 19 million maps and guides. Our net sales totaled approximately $19 billion. Our tire activities and support services account for 98 percent of our net sales. Suspension systems, mobility assistance services, travel publications and Michelin Lifestyle products account for the remaining two percent of our total business.

Michelin sells its products in over 170 countries, operates 74 production manufacturing facilities in 19 countries and employs nearly 127,000 people around the world. Michelin operates three technology centers on three continents, one of which is located in Greenville, South Carolina. Greenville is the headquarters of Michelin North America which employs over 23,000 people and operates 21 manufacturing facilities in 17 locations.

Michelin is in the business of sustainable mobility. What does that mean? How goods and services move has been a fundamental factor in the development of society, as a tool of discovery and a means of communication and interaction between people.

Roads have played a key role in the phenomena of urbanization, globalization of exchanges and, more generally, economic growth. Road mobility provides access to the world and makes for a more fluid job market, by increasing travel opportunities to and from our homes and places of work. Roads provide those located in areas away from economic centers with a way of bringing products to the marketplace.

Furthermore, mobility is freedom, perhaps one of the most basic freedoms in any country. To encourage mobility, to support the growth of infrastructure and ease of travel is to encourage freedom itself. With freedom comes responsibility—to travel safely, to conserve limited resources and to respect the environment.

Alongside these advantages, advances in modern modes of transport have often involved significant social and environmental impacts. Transport worldwide, and road transport in particular, is currently developing in a context of population growth, urban development and an increasing awareness of the impact of human activity on the environment. In light of these factors, a transition towards a new attitude to mobility is clearly needed. Sustainable mobility takes into account the necessity of providing satisfactory responses to travel requirements. It must also move toward a reduction in the impact of mobility on the environment, become accessible to more people in as safe a manner as possible and be compatible with the economic objectives and constraints of public authorities, private companies and non-governmental organizations.

Michelin views this concept of sustainable mobility as being in concert with our five core values: respect for customers, respect for facts, respect for people, respect for shareholders and respect for the environment. These values, and how we concretely translate these values to executable actions, are articulated in Michelin's Performance and Responsibility Charter and subsequent Performance and Responsibility reports.

Why is the notion of sustainable mobility important? Between 1950 and 2003, the number of vehicles on the roads throughout the world went from 50 million to more than 830 million, including nearly 700 million cars. According to the projections of the World Business Council for Sustainable Development (WBCSD), the number of passenger vehicles on the roads throughout the world will reach 1.3 billion in 2030. The distances traveled by people will increase by nearly 50 percent between 2000 and 2030. Over the same period of time, truck freight is forecast to increase by 75 percent.

As stated earlier, this increase in road traffic has an impact on the environment. Transport represents 26 percent of carbon dioxide emission (17 percent for road transport, nine percent for other modes of transport) according to the International Energy Agency. In industrialized countries, transport consumes about 65 percent of oil resources.

In 2000, as a way of responding to the consequences of increased mobility, Michelin joined with 11 other corporate members of the WBCSD—BP, DaimlerChrysler, Ford, General Motors, Honda, Nissan, Norsk Hydro, Renault, Shell, Toyota and Volkswagen—to establish the Sustainable Mobility Project. The goal of this group was to carry out an assessment of mobility throughout the world, analyze the challenges facing the sector and identify the directions to take in order to address these challenges.

Even before participating in the Sustainable Mobility Project, Michelin recognized the necessity of addressing the impacts of rapidly increasing road transport. In 1998, for the celebration of the hundredth anniversary of Bibendum—Michelin's corporate icon known around the world as the "Michelin Man"—Michelin organized a rally of advanced technology vehicles. Challenge Bibendum has won worldwide recognition as the premier clean and safe vehicle event in the world, where industry, policy-makers and experts can review the latest technologies and share their visions. The event provides the opportunity to evaluate different technical options that exist to tackle the energy, environmental and safety issues associated with freight and individual mobility worldwide. This event has taken place in Europe, in North America and, last year for the first time, in Asia.

Challenge Bibendum is a mechanism that assists in resolving questions associated with emissions, oil consumption, urban congestion and road safety. It is a unique event for several reasons:

- Challenge Bibendum is open to all energy sources and all powertrain options. No other event is solution-neutral in both concept and competition.
- Vehicles are evaluated in real driving conditions, using precisely defined criteria relating to performance, safety and the environment.
- Advanced technology vehicles are tested using today's on-road vehicles as a point of reference.
- A "ride and drive" enables all participants to test and experience for themselves the various technologies.
- An educational information center and a symposium, all organized in partnership with the event's participants, complete the technological competition.
- Challenge Bibendum is an open forum where all parties concerned from the public and private sectors can freely exchange opinions.

Challenge Bibendum provides an international platform for road vehicle manufacturers to demonstrate state-of-the-art technologies and for participants to witness, assess and document the progress which these advanced, real-world technologies continue to make, as well as showcase the opportunities they represent.

This event, unlike any other in the world, serves as a testing ground and the only one that showcases concept cars featuring technologies, often for the first time, alongside production vehicles that have already made very significant progress. Furthermore, Challenge Bibendum serves as an exchange forum for industry leaders, university researchers, public policy-makers and the media.

Representatives from numerous organizations from around the world, such as the U.S. Department of Energy, the U.S. Environmental Protection Agency, the World Bank, the European Commission, Japan's Ministry of Land, Infrastructure and Transport and the WBCSD attended the 2004 event in Shanghai, China. In all, 2,000 people, representing more than 200 organizations from 45 countries, gathered at the 2004 Challenge Bibendum.

What conclusions could one draw from the 2004 Challenge Bibendum and the follow-on Bibendum Forum and Rally held in Japan just last month? First, there is no single technology, device, or component that resolves the question of how to achieve sustainable mobility within the parameters we have constructed. The fact that Challenge Bibendum is an event that displays multiple technologies underscores the fact that many of those technologies will help us attain the goal of sustainable mobility. A more holistic view needs to be taken as we move forward. Likewise, when environmental impact issues are examined, it is appropriate to view the consequences of transport from a "well to wheel" perspective. The environmental impact to gather, refine or otherwise provide the energy to the vehicle from its source must be taken into consideration.

From the standpoint of technology, the 2004 Challenge Bibendum revealed the following:

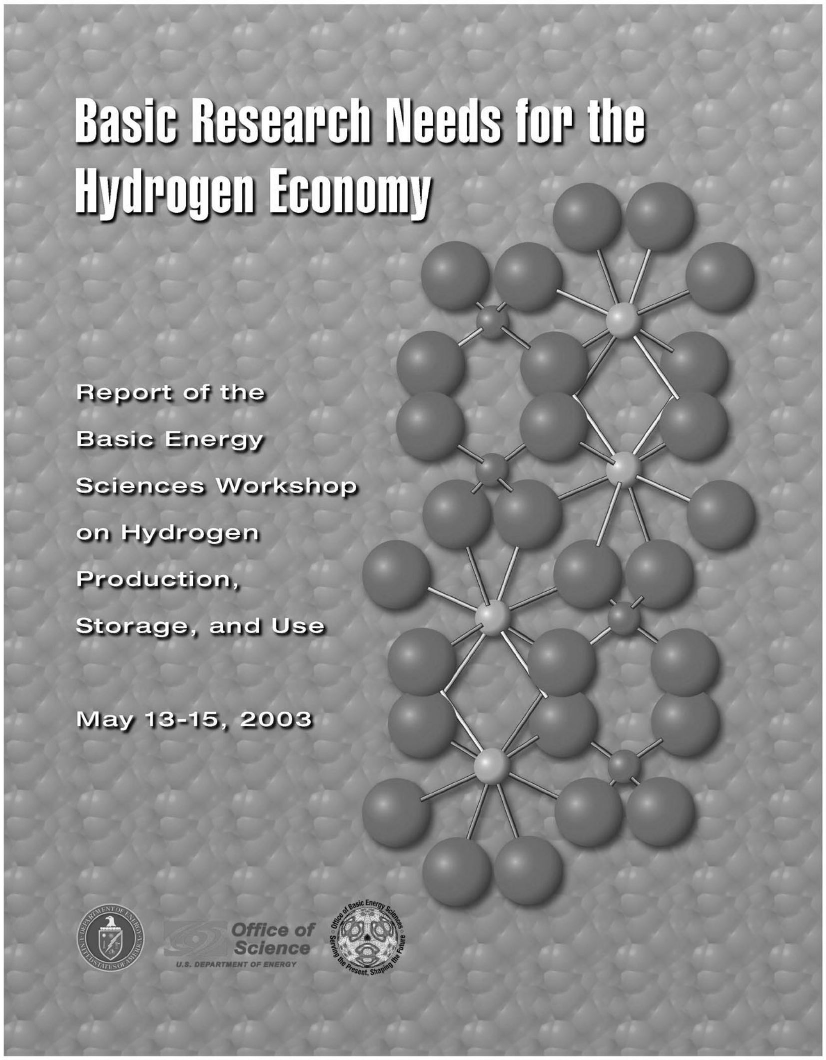
- The future will include a variety of technologies and non-petroleum fuels.
- Advanced internal combustion engines, both diesel and gasoline, continue to make outstanding progress in terms of cleaner combustion, more power density, less noise and less energy consumption.

- Urban pollution can be tackled through sulfur free fuels, particulate filters, next-generation combustion engines and exhaust gas treatments, as well as the progressive development of electric traction.
- Hybridization brings both great driving performance and environmental efficiency, especially for higher power and larger size vehicles; it opens a wide array of technical solutions.
- Biofuels offer a very significant potential to help reduce CO_2 emissions.
- New generation batteries offer much greater promise for electric traction of two-wheelers, cars, taxis, buses, by providing higher power and energy densities—a range of more than 200 miles is now a reality.
- Fuel cell vehicle driving performances are improving rapidly; with a current range of up to 250 miles.
- Active safety systems such as Electronic Stability Programs (ESP) have proven their efficiency, more systems are becoming widely available, and passive safety is also improving greatly.

Some conclusions regarding policy were drawn, as well:

- In order to achieve improvements in air quality, energy supply and safety, it is urgent to act now.
- Benefits will only be achieved when these advanced technologies achieve significant market share.
- Progress will be faster by quickly disseminating and implementing the advanced technologies already available while working on future technologies. This has to happen in all countries, especially in emerging countries to enable them to develop their transportation systems.
- Different solutions will be developed in different parts of the world depending on energy resources, transportation requirements and existing infrastructures.
- Safer and cleaner vehicles go hand-in-hand.
- Cleaner fuels are on the critical path for many emerging countries in order to enable the introduction of advanced technologies.
- Joint action between industries and governments is critical to achieve progress towards sustainable mobility.
- Moving towards greater global regulatory harmonization is required to speed up the adoption of cleaner, safer and more sustainable technologies.

Michelin looks forward to hosting the next Challenge Bibendum (June 2006) in order to measure additional progress. Until then, Michelin remains committed to improving mobility and reducing as much as possible the impact of its activities and products on the environment.



Basic Research Needs for the Hydrogen Economy

Report of the
Basic Energy
Sciences Workshop
on Hydrogen
Production,
Storage, and Use

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Office of Basic Energy Sciences
Serving the Present, Shaping the Future

Cover Image:

The cover shows the crystal structure of the alanate $NaAlH_4$, a new class of hydrogen storage materials. Al atoms are red, Na atoms are green, and H atoms are blue. In this class of materials, hydrogen "encapsulates" Al to form a hydrogen-rich anion, AlH_4^-, whose structure resembles that of methane, CH_4. The alanate structure differs from that of the metal hydrides like MgH_2, where hydrogen is encapsulated by metal ions, and the hydrogen density is correspondingly lower. In the cover image, the diameter of the hydrogen atoms is enlarged to reflect the very high scattering cross section of neutrons for hydrogen and deuterium. This high sensitivity makes neutron scattering a natural tool for probing the interaction of hydrogen with materials. In the report, see the sidebar, Using Neutrons to "See" Hydrogen, on page 38).

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Basic Research Needs for the Hydrogen Economy

Report on the Basic Energy Sciences Workshop
on
Hydrogen Production, Storage, and Use

Chair: Mildred Dresselhaus, Massachusetts Institute of Technology
Associate Chairs: George Crabtree, Argonne National Laboratory
Michelle Buchanan, Oak Ridge National Laboratory

Panel Chairs: Production Tom Mallouk, Pennsylvania State University
Laurie Mets, The University of Chicago

Storage Kathy Taylor, General Motors (retired)
Puru Jena, Virginia Commonwealth University

Fuel Cells Frank DiSalvo, Cornell University
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PREFACE

Global energy consumption is expected to increase dramatically in the next decades, driven by rising standards of living and a growing population worldwide. The increased need for more energy will require enormous growth in energy generation capacity, more secure and diversified energy sources, and a successful strategy to tame greenhouse gas emissions. Among the various alternative energy strategies, building an energy infrastructure that uses hydrogen — the third most abundant element on the earth's surface — as the primary carrier that connects a host of energy sources to diverse end uses may enable a secure and clean energy future for the Nation.

The Basic Energy Sciences (BES) Workshop on Hydrogen Production, Storage, and Use, held May 13–15, 2003, was stimulated in part by an earlier study commissioned by the Basic Energy Sciences Advisory Committee (BESAC) to assess the basic research needs to assure a secure energy future. The charge to that study was to identify the fundamental scientific challenges of the 21st century that "… Basic Energy Sciences must consider in addressing the [DOE] missions in energy efficiency, renewable energy sources, improved use of fossil fuels, safe and publicly acceptable nuclear energy, future energy sources, science-based stockpile stewardship, and reduced environmental impact of energy production and use." The study identified 10 basic research directions in response to this charge, one of which was "Basic Research toward the Hydrogen Economy."[1]

In his State of the Union address in January 2003, President Bush unveiled the Administration's Hydrogen Fuel Initiative. The goals of this Initiative are to lessen America's dependence on imported oil and reduce greenhouse gas emissions. The President stated:

> With a new national commitment our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen and [be] pollution free.

Inspired, in part, by the President's announcement, and as a follow-on to the BESAC-sponsored energy security study published in February 2003,[1] BES established the present study on Basic Research Needs for the Hydrogen Economy. The study was planned and executed in the period from March to July 2003.

Prof. Mildred Dresselhaus of the Massachusetts Institute of Technology chaired the workshop, and Drs. George Crabtree (Argonne National Laboratory) and Michelle Buchanan (Oak Ridge National Laboratory) served as the Associate Chairs. The Associate Director of DOE's Office of Science, Basic Energy Sciences, Dr. Patricia M. Dehmer, challenged the workshop chair and associate chairs to:

> Identify fundamental research needs and opportunities in hydrogen production, storage, and use, with a focus on new, emerging and scientifically challenging

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[1] "Basic Research Needs to Assure a Secure Energy Future," A Report from the Basic Energy Sciences Advisory Committee (Feb. 2003); available at http://www.sc.doe.gov/bes/besac/Basic_Research_Needs_To_Assure_A_Secure_Energy_Future_FEB2003.pdf.

> areas that have the potential to have significant impact in science and technologies. Highlighted areas will include improved and new materials and processes for hydrogen generation and storage, and for future generations of fuel cells for effective energy conversion.

Three panels were assembled to examine the charge in depth. Their topics and chairs were:

Basic Research Challenges for Hydrogen Production

Co-Chairs: Tom Mallouk (Pennsylvania State University)
Laurie Mets (The University of Chicago)

Basic Research Challenges for Hydrogen Storage

Co-Chairs: Kathy Taylor (General Motors, retired)
Puru Jena (Virginia Commonwealth University)

Basic Research Challenges for Fuel Cells and Novel Fuel Cell Materials

Co-Chairs: Frank DiSalvo (Cornell University)
Tom Zawodzinski (Case Western Reserve University)

Each panel was composed of about 15 panelists and 5 speakers with a broad spectrum of expertise from universities, DOE national laboratories, and industry. The panelists and speakers also included foreign experts, primarily from Japan and Europe. The names of the panel members and speakers, as well as the agenda for the workshop, are provided in the appendix.

Four questions were posed to the panels:

- Where are we now?
- What do we already know?
- Where do we want to be?
- What do we need to do to get there?

To initiate answers to these four questions, program officers in the DOE Office of Energy Efficiency and Renewable Energy (EERE) briefed each of the panels before the Workshop and provided a multitude of reading materials. Mark Paster briefed participants on hydrogen production and delivery, JoAnn Milliken on hydrogen storage, and Nancy Garland on fuel cell activities under the FreedomCAR and Fuel Initiative. Harriet Kung served as the BES contact throughout the study.

To set the stage for the Workshop, overview presentations were given. The panels carried out their in-depth work from the evening of the first day through the morning of the third day. The afternoon of the third day was devoted to oral reports of the findings of each panel, followed by closing remarks.

Millie Dresselhaus launched the Workshop with an overview presentation on its goals, approaches, and framework. Pat Dehmer then gave a brief overview of BES, the background for the Workshop, and her expectations. To broaden the perspective, a plenary session of five speakers reviewed the present status of knowledge and the targets, requirements, and challenges of various aspects of a hydrogen economy. Steven Chalk (DOE/EERE) addressed the Workshop on the Administration's FreedomCAR and Fuel Initiative by laying out the President's vision, as well as the plans and strategy of EERE in response to the Administration's Initiative. Specifically, a number of basic research areas in hydrogen production, storage, and fuel cells were outlined for possible collaborations between EERE and BES. The potentially most vexing problem, that of hydrogen storage, was reviewed in general by George Thomas (Sandia National Laboratories, retired). He highlighted the many scientific and technical challenges of hydrogen storage to enable hydrogen to be used as an energy carrier. Scott Jorgensen (General Motors) gave the transportation industry's perspective. He addressed hydrogen storage issues in vehicular applications with special reference to the FreedomCAR targets and goals. Jae Edmonds (Pacific Northwest National Laboratory) briefed the workshop participants on Hydrogen and Climate Change, while Jay Keller (Sandia) presented the Science of Hydrogen Safety.

Following the plenary talks, the panel chairs reviewed the current status, summarized the technology goals, and identified key fundamental scientific challenges for their panels, in the context of the background provided by the pre-workshop briefings and plenary presentations. A summary of the cross-cutting issues was presented, and Millie Dresselhaus and Pat Dehmer made closing remarks.

This Workshop Report responds to the four research challenges for the hydrogen economy outlined by Secretary of Energy Spencer Abraham in his address to the National Hydrogen Association[2]:

- Dramatically lower the cost of fuel cells for transportation,
- Develop a diversity of sources for hydrogen production at energy costs comparable to gasoline,
- Find viable methods of on-board storage of hydrogen for transportation uses, and
- Develop a safe and effective infrastructure for seamless delivery of hydrogen from production to storage to use.

The reports of the panels on hydrogen production, storage, and use in fuel cells and the high-priority research directions identified by the Workshop address these research challenges.

The focus of the Workshop was to identify knowledge gaps in the scientific and technological bases for hydrogen production, storage and use, and to identify high-priority fundamental research directions that would likely have high impact on enabling a hydrogen economy. In

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[2] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003); available at http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESS RELEASE.

addition, the Workshop focused on identifying cross-cutting issues, whereby progress made in one area would significantly impact other areas, thereby accelerating the overall progress of the hydrogen initiative. The Workshop aimed primarily at defining bold new research directions to address long-term “Grand Challenges,” as well as identifying intermediate-term “show-stoppers.”

This Report is the result of a team effort by the panel chairs and Workshop chairs and is based on the presentations and discussions, as well as input from panel members. The document underwent a review process before release. Our intent is to issue a Report that accurately reflects the current scientific and technological status of a potential hydrogen economy, as well as the many great challenges that must be met for its successful implementation.

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EXECUTIVE SUMMARY

The coupled challenges of a doubling in the world's energy needs by the year 2050 and the increasing demands for "clean" energy sources that do not add more carbon dioxide and other pollutants to the environment have resulted in increased attention worldwide to the possibilities of a "hydrogen economy" as a long-term solution for a secure energy future. These two challenges were the focus of the Basic Energy Sciences Advisory Committee (BESAC) Subpanel Study published in February 2003,[1] in which basic research on moving toward a hydrogen economy was identified as one of the 10 general research areas of greatest urgency for a secure energy future. This Report, together with President Bush's Hydrogen Fuel Initiative, as enunciated in his 2003 State of the Union Address, led to the present more detailed study of the "Basic Research Needs for the Hydrogen Economy."

The enormous gap between our present capabilities for hydrogen production, storage, and use and those required for a competitive hydrogen economy was evident from the BESAC Energy Security Report and many other studies.[2,3] To be economically competitive with the present fossil fuel economy, the cost of fuel cells must be lowered by a factor of 10 or more and the cost of producing hydrogen must be lowered by a factor of 4. Moreover, the performance and reliability of hydrogen technology for transportation and other uses must be improved dramatically. Simple incremental advances in the present state of the art cannot bridge this gap. The only hope of narrowing the gap significantly is a comprehensive, long-range program of innovative, high-risk/high-payoff basic research that is intimately coupled to and coordinated with applied programs. The best scientists from universities and national laboratories and the best engineers and scientists from industry must work in interdisciplinary groups to find breakthrough solutions to the fundamental problems of hydrogen production, storage, and use. The objective of such a program must not be evolutionary advances but revolutionary breakthroughs in understanding and in controlling the chemical and physical interactions of hydrogen with materials.

To identify the research directions necessary to narrow the gap significantly, a Basic Energy Sciences (BES) Workshop on Basic Research Needs for the Hydrogen Economy was held in May 2003. More than 120 scientists and engineers from academia, industry, and the national laboratories attended. Participants also included research leaders from abroad and experts from the Offices of Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy within the U.S. Department of Energy. A plenary session at the start of the workshop captured the present state of hydrogen research and development and the challenges posed in reaching

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[1] "Basic Research Needs to Assure a Secure Energy Future," A Report from the Basic Energy Sciences Advisory Committee (Feb. 2003); available at http://www.sc.doe.gov/bes/besac/Basic_Research_Needs_To_Assure_A_Secure_Energy_Future_FEB2003.pdf.

[2] Programmatic Publications, DOE Energy Efficiency and Renewable Energy, Hydrogen Fuel Cell Infrastructure Technology Program; available at http://www.eere.energy.gov/hydrogenandfuelcells/pubs.html#roadmaps.

[3] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003); available at http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE.

a hydrogen economy. A closing plenary session aired the conclusions reached by the three panels, which covered detailed assessments of the most urgent research needs for hydrogen production, storage, and use in fuel cells.

The detailed findings and research directions identified by the three panels are presented in this Report. They address the four research challenges for the hydrogen economy outlined by Secretary of Energy Spencer Abraham in his address to the National Hydrogen Association[3]: (1) dramatically lower the cost of fuel cells for transportation, (2) develop a diversity of sources for hydrogen production at energy costs comparable to those of gasoline, (3) find viable methods of onboard storage of hydrogen for transportation uses, and (4) develop a safe and effective infrastructure for seamless delivery of hydrogen from production to storage to use.

The essence of this Report is captured in six cross-cutting research directions that were identified as being vital for enabling the dramatic breakthroughs to achieve lower costs, higher performance, and greater reliability that are needed for a competitive hydrogen economy:

- Catalysis
- Nanostructured Materials
- Membranes and Separations
- Characterization and Measurement Techniques
- Theory, Modeling, and Simulation
- Safety and Environmental Issues

In addition to these research directions, the panels identified biological and bio-inspired science and technology as richly promising approaches for achieving the revolutionary technical advances required for a hydrogen economy.

Many of the technical barriers to a commercially viable hydrogen economy span the functional areas of production, storage, and use. Overcoming these barriers requires an integrated approach, in which scientific breakthroughs in one area stimulate ground-breaking progress in the others. Such an integrated research approach, as outlined in this Report, emphasizes cross-cutting research directions and promotes broad interdisciplinary efforts, as well as strong coordination between the basic and applied sciences and cooperation among BES and the Offices of Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy.

The need for new materials with better performance and durability is overarching, encompassing many challenges and having broad consequences on the ability to achieve a hydrogen economy. Recent dramatic advances in the controlled synthesis and self-assembly of nanostructures and composite materials and in the ability to design and tailor materials for particular applications by using modern synthetic approaches (such as combinatorial techniques) and advanced modeling and simulation approaches show promise for achieving the revolutionary progress in materials development that is needed to drive the transition to a hydrogen economy.

Nanoscience introduces a powerful and virtually untapped new dimension to the broad research directions identified in this Report. The reason is that materials exhibit radically new properties that cannot be anticipated from their behavior in the bulk. Semiconductor nanoparticles, nanoporous solids, and organic/inorganic nanoscale composites exhibit unique properties that will enable more efficient light harvesting and product separation in solar hydrogen production. The power of nanoscale science for revolutionary breakthroughs is compellingly demonstrated by the dramatic nanoscale catalytic properties of gold. Normally an unreactive metal, gold at nanometer sizes becomes a potent catalyst comparable in activity to platinum, one of the best catalysts for hydrogen use in fuel cells. The dramatic improvements in catalytic activity that depend on nanoscale size and shape provide a powerful "knob" for the development of new, highly efficient catalysts. This Report identifies catalysis, specifically nanoscale catalysis, as being a high-payoff research direction for achieving the revolutionary breakthroughs that would lower the cost and raise the performance and reliability of technologies needed for hydrogen production, storage, and use in fuel cells.

Moreover, catalysts are central to energy conversion and will play a key role in materials synthesis and processes for the hydrogen economy. Since catalytic performance is a limiting factor for many essential elements of the hydrogen economy (including fuel cell efficiency, storage kinetics, and production capacity), the need for improved catalysts is great. A fundamental understanding of the chemical and physical processes involved in catalysis at the atomic level in any of these areas would drive collateral progress in all three, as would the development of novel and specially designed nanostructural catalytic particles and their support structures.

Biological and bio-inspired energy conversion designs have produced remarkable innovations that integrate light harvesting with charge separation and transport, charge transfer for fuel formation and stability through robust and self-healing processes into model systems. Bio-inspired supramolecular systems, particularly those that are combined with nanoscale catalysts, offer a very promising low-cost alternative to conventional, semiconductor materials for solar hydrogen production. Basic research on the fundamental molecular-level and supramolecular-level processes that underlie biological hydrogen metabolism and oxygen reduction offers an untapped high-risk/high-payoff opportunity for achieving dramatic breakthroughs that would span all phases of hydrogen production, storage, and use.

Research needed for achieving a hydrogen economy could benefit greatly from recent advances in experimental designs and instrumentation. Neutron scattering techniques that are especially sensitive to hydrogen and deuterium have enabled powerful probes of the hydride structure and hydrogen interactions with materials. The rapid development of scanning probe techniques has enabled a host of new atomic-level studies of bonding and the electronic structure of hydrogen on surfaces, of the role of nanoscale catalytic reaction chemistry, and of the often dramatic changes in materials behavior that occur at nanometer-length scales. These developments await detailed applications to the challenges of probing the interactions between hydrogen and nanostructures. Aberration-corrected transmission electron microscopes enable *in situ* atomic-level imaging of hydrogen on surfaces. The brilliance and picosecond pulse width of modern synchrotrons can resolve the time development of the surface and bulk interactions of hydrogen with materials. These sophisticated experimental approaches offer great potential for incisive studies of fundamental hydrogen behavior in materials.

Today there is a need for very high permeability and selectivity in gas separations, for high ionic conductivity with minimal fuel crossover in fuel cell membranes, and for much more durable membranes that are capable of separations at high temperatures under extreme chemical environments. Meeting these three needs calls for an intensive effort in materials synthesis, characterization, and modeling of specially designed nanostructured porous materials, robust inorganic films for high-temperature separations in corrosive environments, electronically conductive gas diffusion membranes, and low-cost, high-conductivity proton conductors.

Theory, simulation, and computation closely coupled with well-designed experiments are critical for bridging the vast gap between the present state of the art and the science and technology needed for a hydrogen economy. Recent dramatic advances in methodology (theory and algorithms) and increases in computational power have opened up new possibilities for theoretical studies of the interactions of hydrogen with materials, from catalyst design to improved kinetics of hydrogen release to controlling the hydrogen embrittlement process. All these capabilities need to be exploited in order to design new materials and associated chemical and physical processes for hydrogen production, storage, and use that have vastly improved performance and reliability, yet cost less.

The safety of a hydrogen economy is considered in this study. Safety issues are especially important because hydrogen has exceptional buoyancy, ability to migrate through very small channels, and combustion properties. Safety is not only a technological issue but is also a psychological and sociological issue. Safety concerns require the mounting of a basic research program on the transport, kinetics, and hydrodynamics of hydrogen gas in enclosed structures and on its combustion properties, as well as the development of efficient and selective sensors for detecting hydrogen leaks. In addition, a public safety education program and a suitable training program for personnel working with hydrogen will be required to ensure a safe and effective hydrogen infrastructure.

This study considers the environmental impact of a hydrogen economy, particularly with regard to assessing the degree to which a hydrogen economy would be truly environmentally friendly. In this connection, research should be carried out to address possible environmental consequences of a large potential increase in the amount of hydrogen released to the environment. High-priority research areas identified in this study focus on assessing the effect of such an increase in hydrogen on present-day geochemical, biological, and atmospheric processes.

The panels assembled to carry out this study started their investigation by focusing on the large gap between present knowledge and technology and that required by a hydrogen economy. However, as the panels carried out their work, optimism increased, as participants noted the many recent advances in chemistry, materials research, and computation that are opening up exciting new research opportunities. These opportunities have the potential to significantly narrow the knowledge/technology gap.

The hydrogen economy offers a grand vision for energy management in the future. Its benefits are legion, including an ample and sustainable supply, flexible interchange with existing energy media, a diversity of end uses to produce electricity through fuel cells or to produce heat through controlled combustion, convenient storage for load leveling, and a potentially large reduction in harmful environmental pollutants. These benefits provide compelling motivation for BES to mount a major, innovative basic research program in support of a broad effort across the applied research, development, engineering, and industrial communities to enable the use of hydrogen as the fuel of the future.

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INTRODUCTION AND OVERVIEW

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INTRODUCTION AND OVERVIEW

The hydrogen economy offers a compelling vision of an energy future for the nation and the world that is at once abundant, clean, flexible, and secure. We can envision the hydrogen economy as a linked network of chemical processes that *produces* hydrogen through fossil fuel reforming, biomass conversion, and electrolytic, biophotololytic, or thermochemical splitting of water; *stores* hydrogen chemically or physically; and *converts* the stored hydrogen to electrical energy and heat at the point of use. This vision of an energy stream, originating in the sun, flowing through hydrogen as a carrier to perform electrical work, and producing water as its only by-product, effectively addresses the major energy challenges of the 21st century. The biological world began developing its own hydrogen economy three billion years ago, using hydrogen, carbon, and oxygen to establish the cycle of photosynthesis and respiration that defines life on earth. The human-engineered hydrogen economy can take similar advantage of hydrogen and its chemical and physical interactions with materials to flexibly link a variety of energy sources to a multitude of energy uses.

While the hydrogen economy represents a visionary strategy for our future energy security, significant scientific and technical challenges must be overcome to achieve its implementation. The hydrogen economy spans three functional areas: production, storage, and use; each area has its special set of grand technical challenges. Recent advances in materials science, chemistry, physics, biology, computation, and nanoscience provide considerable promise for breaking through many of these current barriers. These advances underpin our vision and provide confidence that the hydrogen economy is achievable.

Before the hydrogen economy can become a reality, however, two barriers must be overcome. First, the individual technical steps that make up the hydrogen economy must be connected by an infrastructure that provides seamless transitions from production to storage to use. This infrastructure must link a range of functions and will take a variety of forms that have not yet been analyzed for their technical or commercial viability. The infrastructure needed to implement hydrogen as a primary energy carrier is equivalent to those now in place for the production and use of fossil fuels and for electricity. Hydrogen can exploit parts of these existing energy infrastructures through its production from reforming natural gas and other fossil resources and its reaction with oxygen in fuel cells to produce electricity.

The second barrier to the realization of the hydrogen economy is the demonstration in the marketplace that hydrogen as an energy carrier is economically competitive. Although hydrogen can be used for stationary generation of power, for automotive transportation, and as a battery replacement for personal electronics, it is far from being sufficiently attractive in cost, performance, and reliability to displace existing conventional technology in these areas. For hydrogen to achieve significant penetration in the marketplace, the methods of its production, storage, and use must be improved dramatically beyond their present cost, performance, and reliability levels. These gaps are enormous. For example, automotive proton exchange membrane (PEM) fuel cells can now deliver power at about \$3,000/peak-kilowatt (kW) compared with \$35/peak-kW for internal combustion engines. Equally large is the gap separating the performance and reliability records of fuel cell and conventional cars.

Bridging the gaps that separate the hydrogen- and fossil-fuel–based economies in cost, performance, and reliability goes far beyond incremental advances in the present state of the art. Rather, fundamental breakthroughs are needed in the understanding and control of chemical and physical processes involved in the production, storage, and use of hydrogen. 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. Such breakthroughs 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 *Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use* examined the current state of the art in each of these areas, analyzed issues blocking rapid development of the hydrogen economy, and identified high-priority fundamental research directions to address these challenges. The research challenges cover every sector of the energy community, represented at the Workshop by the U.S. Department of Energy's (DOE's) Offices of Fossil Energy, Nuclear Energy, and Energy Efficiency and Renewable Energy. While each of these sectors faces its own set of challenges, very often a given research direction requires input from several sectors and returns benefit across the board. High-performance catalysts, for example, are sorely needed for reforming of fossil fuels, solar cell photolysis, and fuel cell operations. There is an extraordinary opportunity for strong cooperation among DOE's Basic Energy Sciences, Fossil Energy, Nuclear Energy, and Energy Efficiency and Renewable Energy programs in identifying basic research needs and sharing research benefits across the energy community.

Although the workshop and this Report divide the technical barriers and research needs into the three functional areas of production, storage, and fuel cells (the primary means of hydrogen use), it is clear that nearly every issue cuts across these boundaries. To present the commonality of the technical barriers and research needs across functional areas, this Report discusses cross-cutting research in each of the Panel Reports and also summarizes these research areas in a special separate section of the Report. The degree of overlap in research needs across production, storage, and fuel cells is remarkable. This strong cross-cutting feature enables global organization of research on technologies required for a hydrogen economy by research thrust, such as new materials, catalysts, or membranes, which address technical challenges in more than one functional area.

The high-priority research directions reflect the interdisciplinary needs of the hydrogen economy. Its technical barriers do not respect the traditional boundaries among chemistry, physics, materials, and engineering sciences. Rather, they span disciplines and require integrated response teams conversant with many fields. This matches a growing trend in science — to reach across traditional frontiers to address fundamental problems from several points of view. Basic research on the hydrogen economy will benefit from and reinforce this trend.

Nearly all the proposed research directions recognize an urgent need to exploit the power of modern theory and modeling. Dramatic advances in computational power, parallel processing, and numerical simulation open many previously intractable aspects of the fundamental atomic and molecular processes occurring at the interface of hydrogen with materials to theoretical analysis. Theory and modeling of these interactions have wide impacts on the problems of the hydrogen economy, from catalysis to hydrogen storage, fuel cell operation, and hydrogen-induced embrittlement of metals. Rapid advances can be made by closely coupling forefront computational methods to laboratory experiments, enabling each to guide, interpret, and stimulate the daily progress of the other.

The research needs of the hydrogen economy resonate with compelling development in another major field: nanoscale science and technology. The research needs of the hydrogen economy are quintessentially "nano." Catalysis, hydrogen storage materials, and electrode assemblies for fuel cells all depend on nanoscale processes and architectures to achieve high performance. The advances in nanoscale materials, nanoscale assembly techniques, and nanoscale instrumentation, such as scanning probes and *in situ* aberration-corrected electron microscopy, are perfectly matched for research that will provide the breakthroughs required for a hydrogen economy. The technical barriers to the hydrogen economy all hinge on understanding and controlling the atomic- and molecular-level processes at the interface of hydrogen with materials. These processes are shaped at the nano scale, and nanoscale research has the potential to provide revolutionary breakthroughs that will make the hydrogen economy possible.

Safety and the environment are key issues affecting the viability of the hydrogen economy. Greater exposure of the public to hydrogen in everyday life requires a thorough assessment of the safety hazards for each element of the hydrogen economy and concomitant education and training in preventive and acute safety procedures. While the primary beneficial effects of the hydrogen economy on the environment are clear, we must be mindful of the possible indirect effects of additional anthropogenic hydrogen emissions on the complex dynamics of the environment. Safety and the environment are social as well as technical issues that require careful attention if the hydrogen economy is to be successful. The Workshop recognized the great importance of these two areas and identified basic research directions in safety and the environment, concurrent with fundamental research in the areas of hydrogen production, storage, and use, which are critical to achieving a hydrogen economy.

Implementing the hydrogen economy represents perhaps one of the most fundamental and wide-ranging influences on the social fabric of our times. It will lead to a reorganization of our energy culture that compares to the deployment of the fossil fuel economy in the late 19th and early 20th centuries, and the development of the electric power generation and distribution system in the mid and late 20th century. The benefits of the hydrogen economy to society are many and compelling. To realize these benefits, a strong program of innovative basic research aimed at making revolutionary advances in lowering the cost and raising the performance and reliability of the hydrogen economy is essential.

REPORTS OF THE PANELS ON BASIC RESEARCH NEEDS FOR THE HYDROGEN ECONOMY

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BASIC RESEARCH CHALLENGES FOR HYDROGEN PRODUCTION

CURRENT STATUS

The Need for Hydrogen Production

Current U.S. energy systems are not sustainable. They primarily exploit limited resources and will soon accumulate unacceptable environmental impacts. Carbon dioxide (CO_2) from energy production now contributes 82% (weighted by global warming potential) of greenhouse gas emissions in the U.S. Because the effect of CO_2 release is cumulative, the need to find alternative means of energy production is becoming increasingly compelling. Recent estimates call for the generation of more than 30% of primary power from non-carbogenic sources by 2020 in order to stabilize the global mean temperature increase due to CO_2-induced warming at 2°C (Caldeira et al. 2003). Although hydrogen is not an energy resource itself (because no natural hydrogen reserves exist), it has the potential to serve as an energy carrier at the core of a carbon-neutral system of energy production and use. Cost-effective production of hydrogen in sufficient quantities to meet growing energy demands, however, is a challenge that cannot be resolved without intensive effort in both basic research and engineering. The U.S. requires an enormous amount of energy, making this a daunting challenge. Because of the short timeline for development of large-scale hydrogen production capacity, the need to address the underlying basic science questions is immediate.

The need to develop alternative energy technology is also driven by the limited petroleum reserves in the U.S. At this time, petroleum is the major contributor to energy production. Fossil fuels currently provide 85% of the nation's energy supply, with oil accounting for 39% of that total; natural gas, 24%; and coal, 22%. By 2020, the use of fossil fuels, which totaled approximately 3.3 terawatts (TW) in 2000, is projected to increase by 32%, maintaining roughly the same proportions of oil, natural gas, and coal.[1] Transportation consumes about two-thirds of the nation's oil, and this figure is expected to remain essentially constant through 2020. In 2000, the U.S. imported 52% (net) of its oil supply; by 2020, this percentage is expected to increase to 65%. Oil imports accounted for about one-fourth of the U.S. trade deficit in goods in 2000. Clearly, as long as oil continues to be the most significant component of U.S. energy use (especially for transportation, as illustrated in Figure 1a), it will be a large contributor to trade deficits, to the cumulative effects of CO_2 emissions (Figure 1b), and possibly to geopolitical instability.

Carbon-neutral hydrogen production technologies (including technologies that use and reuse carbon but are not net producers of CO_2) could exploit many resources in sufficient supply to meet the needs of a hydrogen economy. These resources include sun-energized resources (solar, biomass, wind) and nuclear energy. Geothermal and geochemical resources could also play a role. In each case, development is needed. Substantial improvements in efficiency and reductions

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[1] In terms of energy use, 1 gigawatt (GW) of power — the output of most light-water nuclear reactors — corresponds to approximately 1.06 million tons/year (Mtons) of hydrogen. One terawatt-year (TW-yr) of energy is equivalent to 1.06 gigatons (Gtons) of hydrogen. The 3.3 TW use of fossil fuels in 2000 would thus correspond to approximately 3.5 Gtons of hydrogen.

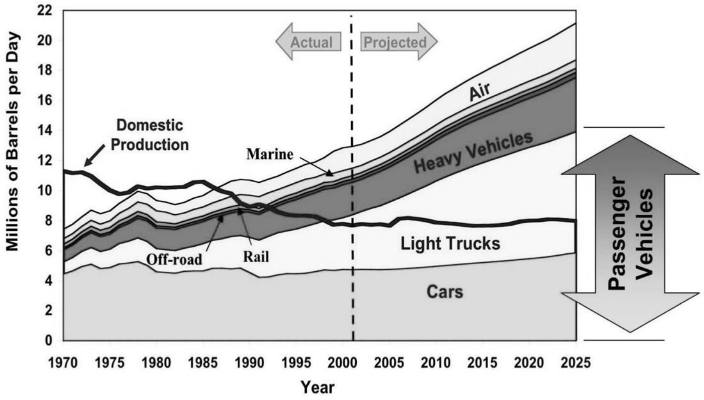


Figure 1a U.S. Consumption and Production of Petroleum Products Trend in Opposite Directions (Transportation needs are a major determinant of consumption [Source: Energy Information Administration 2003].)

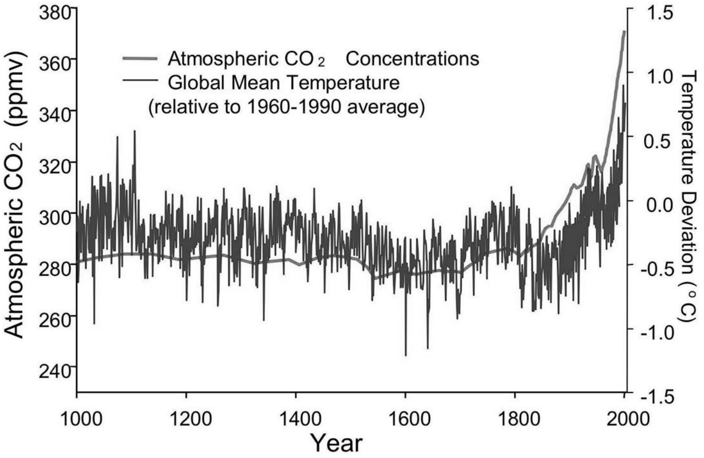


Figure 1b Increased CO_2 Emissions Causing a Rise in Atmospheric CO_2 Associated with a Rise in Global Temperature (Sources: CO_2 data from Ethridge et al. 2001, Keeling and Whorf 2002; temperature data from Jones et al. 1998, Peterson and Vose 1997)

in both capital and operational costs are needed to enable hydrogen production to meet the nation's future energy needs. Each technology faces a different set of technically diverse scientific challenges, although some of these challenges (improved chemical processes, catalysis, materials, and separations) are common to all.

Hydrogen Production from Fossil Fuels

Hydrogen is currently produced on an industrial scale (9 Mtons/yr in the U.S.) through steam reforming of natural gas. At present, most of the hydrogen made from fossil fuels is used in the fertilizer, petroleum, and chemical industries. Natural gas resources will be sufficient for several decades to expand this capacity by the additional 40 Mtons/yr that will be needed to support the FreedomCAR and Fuel Initiative. The total energy used for transportation in the U.S., however, is equivalent to approximately 200 Mtons/yr of hydrogen and is expected to increase to approximately 265 Mtons/yr by 2020 (EIA 2003). Meeting that increase poses a greater challenge.

Other fixed carbon reserves, such as coal or biomass feedstocks, could be used to generate hydrogen via reforming processes. Relative to natural gas, however, these resources generate approximately twice as much CO_2 per amount of hydrogen produced. This factor puts additional pressure on the development and economics of carbon sequestration (storing the CO_2 produced, rather than releasing it into the atmosphere). These feedstocks also contain variable amounts of water, sulfur, nitrogen, and nonvolatile minerals that substantially complicate reforming process engineering. Nevertheless, if an economic and safe method for CO_2 sequestration is developed, economic factors (the general availability and relatively low cost of coal) may enable coal to play a significant mid-term role in hydrogen generation. Reliance on coal as a sole source of energy for generating hydrogen for FreedomCAR transportation needs would require doubling of current domestic coal production and consumption. Two technically effective strategies for hydrogen production from coal or biomass are under development: (1) reforming under partial oxidation and (2) a combined-cycle method that uses $Ca(OH)_2$ to force the reforming reaction by adsorbing CO_2 as it is produced (Lin et al. 2002).

Although the technology is available for generating hydrogen in quantity via reforming of natural gas or possibly other carbon reserves, the hydrogen produced is not of sufficient purity for direct use in the low-temperature (<130°C) fuel cells under development for transportation applications. The last stage in current reforming processes, the water-gas shift reaction, leaves enough carbon monoxide (CO) in the product stream to poison the fuel cell anode. Current methods for removing this residual CO include pressure-swing adsorption, preferential oxidation, or catalytic methanation, all of which add cost and complexity to the fuel processing system. Basic research can supply alternative solutions to this problem, which could come in the form of more active catalysts for the low-temperature water-gas shift reaction, better gas stream separation processes and membranes, or CO-tolerant catalysts at the fuel cell anode [see section on fuel cells].

WATER ELECTROLYSIS: PROTON REDUCTION AND WATER OXIDATION

Electrolysis is a process for breaking water (H_2O) into its constituent elements (hydrogen, H_2, and oxygen, O_2) by supplying electrical energy. The advantage of this process is that it supplies a very clean hydrogen fuel that is free from carbon and sulfur impurities. The disadvantage is that the process is expensive, relative to steam reforming of natural gas, because of the cost of the electrical energy needed to drive the process.

Chemically, the electrolysis of water is simply the reverse of the electricity-generating reaction that occurs in a fuel cell. Physically, an electrolyzer is designed very much like a fuel cell, with two electrodes immersed in a common aqueous electrolyte solution. The reaction can be thought of as occurring in two "half-cells" separated by a gas-impermeable electrolyte membrane (the figure provides a schematic drawing of the electrolysis process).

In the cathode half-cell, hydrogen ions (protons) are reduced to hydrogen:

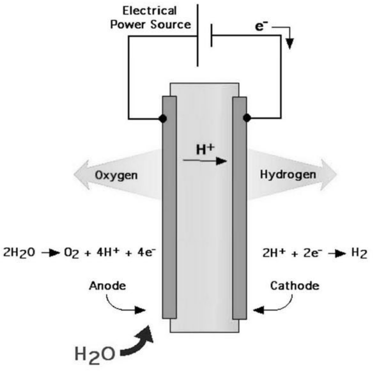
$2\ H^+(aq) + 2e^- = H_2(g).$

On the anode side, water is oxidized to oxygen and protons:

$2\ H_2O(liq) = O_2(g) + 4\ H^+(aq) + 4e.$

By multiplying the first half-reaction by two and adding the two half-reactions together, we obtain the overall reaction:

$2\ H_2O(liq) = O_2(g) + 2\ H_2(g).$



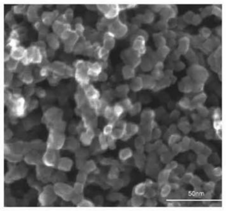
Because water is a very stable molecule relative to oxygen and hydrogen, this reaction requires input of energy. In principle, the reaction can be driven by an applied voltage of 1.23 V, which translates to a free energy input of 237 kJ/mole of hydrogen. In practice, somewhat larger driving voltages (1.55–1.65 V) are used because of slow kinetics in the two half-cells. The energy efficiency of the cell can be calculated simply as the theoretical voltage (1.23 V) divided by the applied voltage; for example, a cell operating at 1.60 V would have an efficiency of $1.23/1.60 \times 100\% = 77\%$. The process of oxidizing water in the oxygen-evolving half-cell is mechanistically and kinetically more complex than the hydrogen-evolving process because it requires four electrons and proceeds through a series of distinct oxidation intermediates. In an uncatalyzed reaction, some of these intermediate electron transfer steps require more energy than others, and some are slower than others. As a consequence, extra voltage is needed to drive the cell, primarily at the oxygen-evolving electrode, and efficiency is reduced. An ideal catalyst for water oxidation would equalize the energy required at each step in addition to equalizing the rates of each electron transfer, thus maximizing efficiency. The water oxidation complex that supports oxygen evolution in photosynthesis is one catalyst that comes close to meeting this ideal and provides a tantalizing model for building catalysts for electrolyzer anodes and fuel cell cathodes.

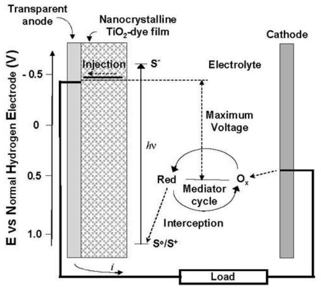
Solar Hydrogen

Solar hydrogen, which is produced by driving water electrolysis with solar cells, by direct photocatalytic water splitting into hydrogen and oxygen, by photobiological water splitting, or by solar thermal processes, represents a highly desirable, clean, and abundant source of hydrogen. Hydrogen made this way is suitable for use, without further purification, in low-temperature fuel cells and even in alkaline fuel cells, which are more efficient but more carbon-intolerant. While solar-to-electric energy conversion is an established technology, current solar cells are either too expensive or too inefficient for widespread application. However, the potential capacity for solar hydrogen is quite large. The estimated power output from 10% efficient solar cells covering 1.7% of the land area of the U.S. (an area comparable to the land devoted to the nation's

DYE-SENSITIZED SOLAR CELLS

A promising new technology in solar energy conversion is the dye-sensitized photoelectrochemical cell, or Grätzel cell (Grätzel 2001). This cell consists of a highly porous, thin layer (~15 µm) of titanium dioxide nanocrystal aggregates (~20 nm in diameter; see scanning electron micrograph), the same material used as the pigment in white paint. The nanocrystals are coated with a dye and a liquid electrolyte that contains reactive iodide ions or other diffusible oxidation/reduction mediator, sandwiched between two conducting glass or plastic plates sealed together (schematic drawing shows the mediator cycle and electron injection). When excited by light (S_0 to S^* transition in the figure), the dye becomes oxidized (S^+ state), injecting electrons into the titanium dioxide. In the figure, oxidation/reduction potentials of the various reactants are depicted relative to the normal hydrogen electrode (left axis). The titanium dioxide layer then transmits electrons to the conducting glass electrode, which is connected to an external circuit. The reduced reduction/oxidation mediator transfers electrons to re-reduce the dye, and the oxidized form diffuses away in the electrolyte. The return path for the electrons is through the other electrode to the oxidized mediator in the solution, which completes the cycle by diffusing back to the film layer.





The energy available from the cell depends on the difference between the oxidation/reduction potential of the mediator and that of the dye/nanocrystal interface. The film surface area is huge — about 2,000 m^2/m^2 of cell surface — because of the small size of the titanium dioxide particles (the surface-to-volume ratio is inversely proportional to the particle size). Thus, the probability of light absorption is high even though the dye thickness is only a single molecular layer. While bare titanium dioxide nanocrystals can absorb photons and eject electrons to an electrode, they absorb only in the ultraviolet region of the spectrum, which is a small fraction of the solar spectrum. This is a useful behavior in such products as sunscreen and self-cleaning window coatings, but it makes the particles less than 1% efficient in converting total solar energy to electrical or chemical form. The adsorption of organic dyes onto the surfaces of the particles extends their absorption into the visible region, increasing solar conversion efficiency. It has recently been found that carbon atoms doped into the titanium dioxide nanocrystals in the place of some of the oxygen atoms can provide a similar effect (Kahn et al. 2002). The power conversion efficiency of the Grätzel cell is currently about 10%, and the cells are stable in sunlight over a period of years.

The Grätzel cell is fabricated from inexpensive materials. If efficiency could be improved and manufacturing costs lowered further, it would be a strong candidate for solar hydrogen production via water electrolysis. Problems with the Grätzel cell that still require innovative solutions include reducing energy losses in the iodide/iodine redox cycle and at the electrode interfaces, extending the spectral response farther into the red, and reducing costs in the production of the transparent conductor-coated glass.

interstate highways) is 3.3 TW, equivalent to the total U.S. fossil fuel use in 2000. To place this capacity in perspective, 3,300 new 1-GW nuclear power plants would need to be built — roughly 1 for every 10 miles of coastline or major waterway — to supply the same 3.3 TW of power. This capacity is more than 30 times greater than that provided by the 103 nuclear plants now in the U.S. Such growth in nuclear power is not feasible today because of the severe constraints in cost, nuclear fuel supply, site availability, safety, public acceptance, and waste disposal. Nevertheless, thermochemical cycles that use the heat from nuclear reactors to produce hydrogen by water splitting are being developed and could, in principle, play a role in the hydrogen economy on a smaller scale (see below).

The most efficient and also the most costly sources of solar electricity for water electrolysis are solid-state photovoltaic (PV) devices. Commercially available photovoltaics include single-crystal silicon and GaAs, amorphous silicon, and polycrystalline thin film materials, such as CdTe and $CuIn_{1-x}Ga_xSe_2$, which have solar-to-electric power conversion efficiencies ranging between 12% and 25% under full sunlight. Tandem photovoltaics, which are two-bandgap devices (for example, GaAs and $GaInP_2$) utilizing a greater fraction of the solar spectrum, are more efficient, but also more expensive, and are envisioned for special use in solar concentrator systems and space applications.

Current water electrolysis systems (see sidebar on water electrolysis) that produce hydrogen gas operate at about 75% energy efficiency (free energy content of hydrogen relative to input electrical energy), giving an integrated efficiency of hydrogen production from solar energy via PV/electrolysis of ~15%. This sets an efficiency standard for other technologies to meet using less costly and more abundant resources for materials. Lower-cost alternatives include photoelectrochemical cells based on polycrystalline and nanocrystalline semiconductors, dye-sensitized titanium dioxide (see sidebar on dye-sensitized solar cells), the Texas Instruments silicon microsphere system, and thin film devices based on organic liquid crystals and/or polymers (Grätzel 2001). The lower efficiency of hydrogen generation in each case arises from energy losses in electrolysis, where the most significant problem is catalysis of the water oxidation reaction. The water oxidation reaction is particularly kinetically demanding because it is a four-electron, four-proton process.

The efficiencies of different kinds of PV devices have followed similar time-efficiency development curves, which began in the 1950s for single crystal silicon; in the 1970s for amorphous silicon, CdTe, and copper-indium-diselenide and related thin film devices (CIS/CGIS); and in the 1990s for dye-sensitized nanoparticle TiO_2, organic, and photocatalytic systems. This trend is illustrated in Figure 2 (Kazmerski 2001). The newest of these systems are the least developed and offer the greatest opportunities for contributions from basic research.

Hydrogen from Biological and Biomimetic Systems

Solar energy capture based on photosynthesis can follow one of two routes: (1) storage of energy by CO_2 fixation (biomass) followed by hydrogen production via reforming or fermentation, or (2) direct water splitting to hydrogen and oxygen (e.g., using blue-green or green algae [biophotolysis]). Biological energy conversion systems use readily available materials for conversion and catalysis, and these systems are also self-maintaining. For these reasons, they might be able to compete on a cost basis with other hydrogen production systems. Biomass is currently a substantial component of global energy consumption. Of the 13 TW of global energy used in 1998, approximately 1.2 TW can be attributed to biomass. This amount, however, represents unsustainably burned, as opposed to renewably farmed, biomass. The solar-to-chemical energy conversion efficiency of current biomass crops (switchgrass and poplar) is in the range of 0.4% of total solar irradiance, and further losses would be incurred in the conversion to hydrogen. It is plausible that genetic research could improve this yield two- to three-fold, but fundamental limitations would prevent it from rising above the range of a few percent, thereby requiring use of large arable land areas to contribute significantly to the hydrogen economy. In

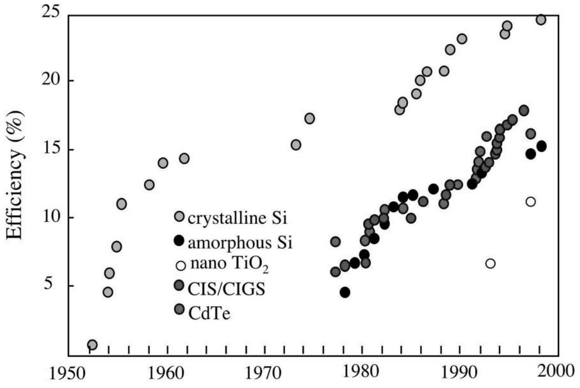


Figure 2 Power Conversion Efficiency Trends over Time for Different Kinds of Photovoltaic and Photoelectrochemical Devices (CIS = cadmium-indium-selenide; CIGS = cadmium-indium-gallium-selenide) (Source: Kazmerski 2001)

contrast, biophotolysis in natural populations of algae currently has peak yields of hydrogen in the range of 5% solar conversion efficiency, although this is only at low light intensities, about 10% of typical solar intensity in the U.S.; lower efficiency is found at higher light levels. Thus, research is needed to make these yields sustainable and to find new organisms or engineer the photosystems of existing organisms that will give similar efficiencies in full sun.

Globally, biological processes produce at a minimum of more than 250 Mtons/yr of hydrogen (see sidebar describing hydrogen in the biosphere).[2] Most of this hydrogen arises from anaerobic fermentation of carbon previously fixed by photosynthesis. Six to 17 Mtons/yr of hydrogen is produced as a by-product of terrestrial biological nitrogen fixation. This biological hydrogen is completely used as an energy carrier that fuels the growth of organisms and the maintenance of essential life processes. Much of it is consumed in CO_2 or organic acid reduction by methanogenic archaebacteria that give off methane as a by-product. On the oceanic continental shelves and in permafrost regions, this methane has accumulated in the form of extensive methane hydrate deposits, the extent of which exceeds all known petroleum, coal, and natural gas deposits. In other locales, methane is released to the environment, and a portion enters the

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[2] Assumes biogenic methane entering the atmosphere (380 Mtons/yr [Etiope and Klusman 2002]) arises 1/3 from methanogens using 4 moles of biogenic hydrogen per mole of methane produced and 2/3 from those utilizing 2 moles H_2 per mole CH_4. Ten percent of this methane arises from rice paddies, and the bulk of the remainder is from plant transpiration of methane from anaerobic sediments in fresh water and coastal wetlands. In open water, which covers much more anaerobic sediment, the methane released never reaches the atmosphere. Sulfate-reducing bacteria consume an amount of biogenic hydrogen similar to that consumed in methane biosynthesis on an annual basis. The total flux of hydrogen in the biosphere has not been directly estimated, but it is likely to exceed this minimum by at least an order of magnitude and possibly by two orders of magnitude.

atmosphere. If methane hydrates could be used, either by reforming them to make hydrogen or using them directly in fuel cells that generate electricity, they could have a large impact on the global energy economy. However, utilization of methane hydrates presents daunting technical challenges because of the depth at which they are found, because of their dispersion as ice-like crystals in ocean sediments, and because of their decomposition (to methane gas and liquid water) at ordinary pressures.

In some specific cases, details of the biological processes linked to hydrogen metabolism and of the enzymes involved as essential catalysts have been investigated and are reasonably well known. However, efforts to understand the variety of organisms and the diversity of biochemical mechanisms that participate in this extensive biological hydrogen energy economy are still at an early stage. The emergence of highly capable tools for genomic analysis of microorganisms and for dissecting the interlocking metabolic functions of microbial communities presents an opportunity for extremely rapid progress in this promising area of research (Reysenbach and Shock 2002). It is possible that exploiting and mimicking components of these natural hydrogen-producing systems, once they are better understood, will enable key improvements in efficiency and reduction in the cost of solar hydrogen production.

Thermal Energy for Hydrogen Production

Production of hydrogen from thermal energy sources is a conventional technology via the multistep route of thermal energy to electricity, and electricity to hydrogen and oxygen by electrolysis of water. The heat can be delivered from a conventional fossil energy source, a nuclear reactor, or a solar concentrator/receiver. The net efficiency (heat energy to hydrogen) is about 26%. Current hydrogen production costs, not including storage and delivery costs or the long-term costs of nuclear waste management, are \$4–\$5/kg (nuclear thermal) and \$15/kg (solar thermal). Experience with solar thermal generators is not as extensive as with nuclear plants; hence, costs for solar thermal systems are expected to drop more quickly as development proceeds.

In principle, hydrogen can also be produced by using thermal energy from solar concentrators or from nuclear reactors to drive thermochemical water-splitting cycles, the overall output of which is water splitting to hydrogen and oxygen without intervening electricity generation. These cycles need temperatures of 500°C or more, well within the range of solar concentrators but higher than can be achieved by today's light-water reactors. These temperatures are also within the range of present-day, gas-cooled reactors and designs for future nuclear power plants (Marcus and Levin 2002). The reactor operating temperature is a key factor because higher temperatures enable faster chemical reactions and higher efficiencies, at the expense of a harsh thermal and chemical materials environment. Because of the technical challenges that they raise, high-temperature reactors will also take longer to reach commercialization. High-temperature solar collector/receivers have been demonstrated and could potentially drive very efficient cycles. For example, the National Renewable Energy Laboratory has demonstrated 51% thermal collection efficiency in a 2,000°C process fluid. The potential advantages of higher operating temperatures, siting in desert locations, and lower capital cost of solar concentrators must be offset against the lower duty cycle (8 h/day) of solar power relative to nuclear reactor power.

HYDROGEN IN THE BIOSPHERE

Hydrogen gas (H_2) generated by high-temperature and radiolytic chemical processes deep in the earth's crust and vented into the oceans has been an important source of energy supporting the growth of living organisms since the origin of life some 4 billion years ago. The emergence of oxygenic photosynthesis ~3 billion years ago enabled cyanobacteria to use solar energy for the splitting of water to hydrogen and oxygen. As a consequence, biological sources of hydrogen became predominant, expanding annual global production of hydrogen by an estimated two to three orders of magnitude to the range of 250–1200 Mtons/yr of H_2 (Hoehler 2001).

In the modern biosphere, hydrogen is a ubiquitous biological energy carrier, primarily between microbes, in a wide variety of habitats — particularly in anaerobic environments like the sediments just below the soil surface. Hydrogen is produced as a product of anaerobic cellulose degradation by bacteria in termite guts and cattle rumen and in fresh water and marine sediments. Hydrogen is generated as a by-product of nitrogen fixation by cyanobacteria in rice paddies and algal mats and by nitrogen-fixing bacteria in nodules growing on the roots of peas, soybeans, and other legumes. Methanogenic archaebacteria use the hydrogen produced by anaerobic fermentation and as a by-product of nitrogen fixation by cyanobacteria to generate methane, which is transpired by the plants into the atmosphere.

Hydrogen and carbon monoxide are products of microbial methane oxidation. A number of eukaryotic algae even generate hydrogen via photosynthesis when they find themselves in anaerobic environments. Other organisms, necessarily closely associated with the producers in microbial consortia, completely consume this biogenic hydrogen within 0.1-5 sec of its production and before it can diffuse more than 0.1 mm away or accumulate to concentrations more than a few parts per million. Because of this tight cycling, very little biogenic hydrogen escapes to the abiotic environment or to the atmosphere.

These consumers are known to use hydrogen energy to support a diverse array of metabolic activities, from methane production to nitrate and sulfate reduction. About 125 Mtons of H_2 is consumed per year in the production of the fraction of biogenic methane that escapes into the atmosphere (much more methane is produced but is consumed by other bacteria before it reaches the atmosphere), and at least another 125 Mtons/yr supports sulfate reduction in the upper reaches of anoxic marine sediments. Members of this biological hydrogen energy economy inhabit all extremes of living environments, from hyperthermic (113°C) deep ocean vents to frozen tundra soils to ancient aquifers and salt deposits deep in the earth. The photochemical water oxidation reaction center that catalyzes oxygen evolution from water — photosystem II — has higher quantum efficiency than any artificial photochemical or photoelectrolytic system yet devised by humankind. One type of the known hydrogenase enzymes that catalyze the reduction of protons from water to produce hydrogen (or the reverse), the iron-only hydrogenases, catalytic rates of more than 25,000 turnovers/second, among the highest of any known enzyme.

The biosphere uses a small fraction of total available solar energy (<0.5% of net primary photosynthetic productivity) to produce hydrogen on a scale and at a rate compatible with human energy needs. Both hydrogen production and consumption use highly selective and efficient catalysts constructed of materials readily available in the environment that operate in aqueous environments and at temperatures compatible with life. An understanding of the catalytic mechanisms and integrated energy processes of these biological systems promises insights that could revolutionize our approaches to developing human energy economies. In the past, culturing and studying these organisms has been challenging, both because of the extremes of their habitats and the complexities of their associations and interdependencies. The experimental tools provided by modern methods of genomic analysis and by *in situ* metabolic analysis on the scale of bacterial cells have finally provided an exciting opportunity for developing the necessary understanding.

Nuclear reactors, such as the helium gas-cooled reactor which has demonstrated ~900°C temperatures, have not yet been commercialized, giving them a long development horizon. Lower-temperature, gas-cooled reactors may offer nearer-term implementation of hydrogen production and a materials-friendly environment at the expense of lower production rates. The advanced high-temperature reactor concept, developed in the Generation IV reactor initiative, is proposed to match hydrogen production requirements via thermal cycles with maximum temperatures of 700–950°C. It is a more advanced reactor that would use a low-pressure molten salt coolant rather than high-pressure helium as a coolant. Further out in time, fusion energy might become an important source of high-temperature heat for driving thermochemical hydrogen production.

A related technology is the electrolysis of water assisted by heat from a nuclear reactor. By performing electrolysis at elevated temperatures using heat from a high-temperature reactor, the overall efficiency of the process can be increased relative to low-temperature electrolysis. In both cases, the energy source is noncarbogenic. A third (carbogenic) way in which nuclear energy can be used to augment hydrogen production is in nuclear-assisted steam reforming of natural gas. Here, nuclear energy replaces fossil fuel combustion as the means of driving the endothermic steam reforming reaction. Thus, less natural gas would be used to produce the same amount of hydrogen.

More than 100 different thermochemical cycles have been proposed for performing the overall water splitting reaction in high-temperature reactors (Brown et al. 2002). At present, the most promising high-temperature cycles appear to be a calcium bromide-iron oxide cycle, the sulfuric acid-hydrogen iodide (sulfur-iodine or S-I) cycle, and the Westinghouse cycle. Also, an important lower-temperature cycle, (copper-chloride [Cu-Cl]), can produce hydrogen using heat from current and near-future reactors. The Cu-Cl cycle, originally proposed in the 1970s, has recently been proven in the laboratory, and several commercially appealing variants are being evaluated. This cycle has an estimated efficiency of ~40% at its envisioned operating temperature of 550°C, not including cogeneration of electricity. A key challenge for the Cu-Cl cycle is effective catalysis of the low-temperature reactions. The calcium bromide cycle has four fixed-bed reactors, each of which performs one step of the cycle at temperatures around 760°C. Overall efficiencies of 45–49% (including cogeneration of electricity from waste heat) are projected. In this process, hydrogen and oxygen are produced at subatmospheric pressures and removed via membranes; hence, there is a major challenge for membrane technology and for compression/storage of hydrogen. In the S-I cycle, which uses all fluid reagents, a higher temperature (825–900°C) is used for the oxygen-evolving reaction, and higher efficiencies (~50% and ideally 60% with cogeneration of electricity) are possible. The individual reactions in the S-I cycle have been demonstrated, although not in a continuous process, nor at the temperatures envisioned for implementation of the technology. This cycle is being actively researched in several laboratories, including the Japan Atomic Energy Research Institute (Japan), Commisariat à l'Energie Atomique (CEA) (France), and Department of Energy laboratories (Sandia National Laboratories, Idaho National Engineering and Environmental Laboratory) and General Atomics in the U.S. Among the key challenges with this approach is the verification of durable high-temperature, chemically inert materials for fabrication of the chemical reactors needed to withstand the thermochemical cycle over economically useful lifetimes (Trester and Staley 1981). The Westinghouse cycle is a variant of the S-I process where a low-temperature, low-voltage electrolysis step (a fraction of that required for water electrolysis) replaces several chemical reactions in the S-I process.

BASIC SCIENCE CHALLENGES, OPPORTUNITIES, AND RESEARCH NEEDS IN HYDROGEN PRODUCTION

Fossil Fuels

Fundamental advances in catalysis, membranes, and gas separation could enable more efficient, lower-cost fossil hydrogen technologies. Processes that combine hydrogen generation and separation in a single reactor (for example, membrane reactors for methane steam reforming) could improve conversion efficiency and thus reduce emissions. Very pure (99.999%) hydrogen is needed for some applications, in particular for current-generation polymer electrolyte membrane fuel cells (PEMFCs); therefore, hydrogen purification technologies need further development. Advances in techniques for the removal of CO in particular, including improved gas separations and improved catalysis for the low-temperature water-gas shift reaction, are needed for both on-site reformers and centralized hydrogen production facilities. These are critical early research targets because they would affect the design of reforming plants built to meet the projected increase in hydrogen demand. Coal is also a potential source of energy for hydrogen production but poses greater challenges for obtaining high-purity hydrogen. Catalysts that resist poisoning by contaminants, which are more abundant in coal, must be developed for the water-gas shift reaction. Materials must be developed that are durable under the more acidic reforming conditions of the partial oxidation reaction that is the first reaction step in current-design, coal-based hydrogen production plants.

Because both natural gas and coal reforming processes generate CO_2 (coal generates approximately twice as much per unit H_2), their value in meeting the fundamental goals of a hydrogen economy depends on developing safe, effective, and economical methods for CO_2 sequestration. Deep ocean injection, injection into depleted oil/gas wells and saline reservoirs, and injection into unmineable coal seams are three potential sequestration technologies (Kim and Edmonds 2000).

Understanding the feasibility and safety of carbon capture and sequestration is key for the long-term use of fossil hydrogen with near-zero CO_2 emissions. This involves basic understanding of the geological processes (geoscience, flows in porous media and interactions, as well as transport of CO_2 in aqueous environments) that may be involved in CO_2 storage and release. Living organisms in deep ocean locales take up CO_2, but basic understanding of the carbon flows in those ecosystems is insufficient to enable prediction of the biological impact of deep ocean sequestration. Innovative concepts continue to be needed for CO_2 sequestration.

Two research needs in fossil-fuel-based production are considered to have high priority. These needs are discussed in the following sections.

Catalyst Development. Improved catalysts are needed to overcome kinetic constraints in all phases of the hydrogen economy, including production, storage, and utilization. A general goal involves developing catalysts that rely less on noble metals, which will become a limiting resource in large-scale hydrogen energy systems. In hydrogen production via reforming of fossil resources, high priorities include catalysts that would support a lower-temperature, water-gas shift reaction, and improved catalysts for desulfurization of feedstocks. Catalysts are needed that are more active, more specific, more stable, and less susceptible to poisoning and fouling. Recent advances in analytical tools and methods (see Figure 3), in the combinatorial synthesis of catalytic materials, and in the theoretical modeling of their active site properties at an atomic level provide an unprecedented opportunity for rapid advances to meet the needs of catalyst development. An integration of experimental and computational approaches is needed to understand and control active site structures, catalytic mechanisms, and catalyst design on the nano scale. This is particularly important for the design and discovery of cost-effective catalysts that can produce hydrogen from fossil resources of sufficient purity for use in PEM fuel cells.

Improved Gas Separations. Efficient, high-volume gas separations are needed for preparing input gas streams, separating process gases, and purifying product streams. To satisfy these needs, semipermeable membranes are an attractive option, but improvements in membrane selectivity and robustness, particularly at elevated temperatures (200–400°C), are essential.

Solar Hydrogen

For solar PV, photoelectrochemical, or photocatalytic hydrogen production to become an economically viable technology, it is necessary to dramatically reduce the cost while maintaining a high level of efficiency. The trade-off between efficiency and cost for PVs is illustrated in Figure 4. Similar considerations apply to hydrogen production by PV-driven electrolysis, although some fixed costs may be reduced by eliminating the need for inverters and power

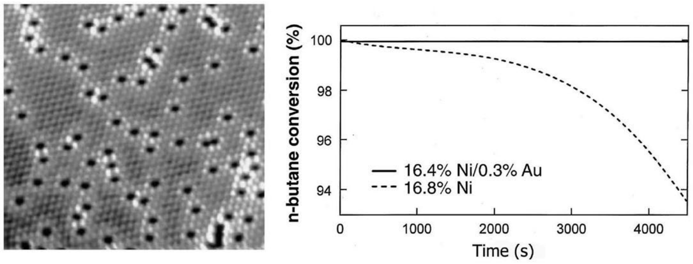

Figure 3 (Left) Scanning Tunneling Microscopy Image of a Ni Surface Alloyed with Au (The Au atoms are shown in black; the neighboring Ni atoms have a distinct electronic structure, which is different from those of Ni atoms farther away. Quantum chemical calculations show these Ni atoms to be less carbon-poisoned.) (Right) Experimental Confirmation that the Addition of Au to a Ni Catalyst Removes the Decrease in Activity with Time because of Graphite Formation (Source: Besenbacher et al. 1998)

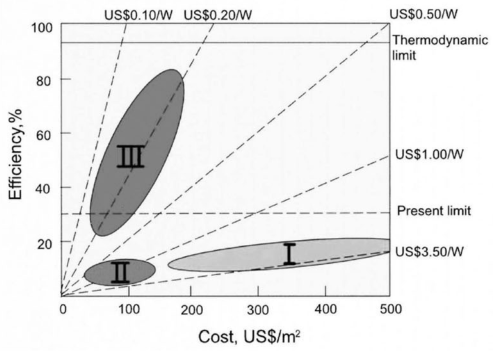

Figure 4 Efficiency Compared with Cost Per Unit Area of PV Devices (The diagonal lines show installed 2001 price of modules per peak-watt. The theoretical limit for Shockley-Queisser devices [present limit] is 32%, a figure that is approached by the best single-crystal silicon solar cells [see Figure 2]. Third-generation devices [shown in red] may exceed this limit by using multiple absorbers, hot carrier effects, or photocurrent doubling via impact ionization. The latter two phenomena are associated with quantum size effects in semiconductors and are being studied in semiconductor nanocrystals [Source: Green 2000]).

transmission lines. The real figure of merit for solar cells is the installed cost per peak-watt (dashed diagonal lines), which depends on conversion efficiency, module cost, and other baseline costs associated with connection to power grids, land use, and maintenance.

Both expensive single-crystal and less expensive polycrystalline devices follow roughly the same cost-efficiency curves in Figure 4. The efficiencies of these devices are limited by several factors. First, light of wavelength longer than the bandgap wavelength is not used, and the excess energy of shorter wavelength light is lost to heat. Second, grain boundary recombination and related losses reduce the quantum yield of light-to-electrical energy conversion. The cost/efficiency trade-off between single-crystal and polycrystalline cells is predominantly a consequence of this second factor. Third, the photovoltage is reduced by resistive losses in PVs and by the overpotentials needed to drive interfacial redox reactions at useful rates in photoelectrochemical cells.

The grand challenge for solar hydrogen is to become economically competitive with energy from fossil fuel sources. In today's market, devices that reside on the $0.20/peak-watt line would be needed. It is likely that this will be achieved only by developing new molecular-level designs and chemical processes for making very inexpensive solar cells or photocatalysts, as well as by understanding and exploiting emerging physical effects that can lead to higher efficiencies. Very low-cost solar cells ($0.20/peak-watt) could, in principle, create a “disruptive technology” (Christensen 1997) that would initially enter the energy market in low-end niche applications and eventually improve to the point of displacing high-volume legacy technologies, such as fossil fuel reforming and fossil generation of electric power. However, it is important to note that low-efficiency PV and photoelectrochemical devices (<10%) do not represent a viable solution to the problem even at very low cost because of the unavoidable baseline costs that other system components (frame, supports, wiring, inverter, land, taxes, etc.) add to the installed price.

There is now a substantial potential to leverage recent scientific advances to achieve these goals. The past 10 years have witnessed dramatic advances in our ability to control the structure of matter (semiconductor nanocrystals, supramolecular assemblies, porous inorganic solids, molecular thin films, micro-phase separated polymers) on the nanometer-length scale, which is the relevant length scale for photoinduced energy transfer, charge and redox product separation, recombination, and hot carrier thermalization. There has also been remarkably rapid progress in the maturing of closely related technologies, which include organic light-emitting diodes (OLEDs) and organic/polymer-based electronics. The physical makeup of devices in these allied technologies suggests that one could develop a reel-to-reel process for manufacturing solar cells that would be similar to the process used to make photographic film as a lamellar composite of many dye, nanoparticle, and polymer layers. Solar cells for producing hydrogen would be made from semiconductor particles, dyes, polymers, catalysts, and other components, once an understanding of the relevant physical phenomena and the necessary chemical assembly processes were in hand. The challenge is thus one of design and assembly of two- and three-dimensional photosystems, in which the optimal spatial arrangement of components achieves efficient light harvesting, charge carrier separation, and catalyzed generation and separation of hydrogen and oxygen.

Several research needs in solar hydrogen are considered to have high priority. These needs are discussed in the following sections.

Light Harvesting. New strategies are needed that will allow the solar spectrum to be used efficiently — in tandem (dual absorber) semiconductor systems or multichromophoric molecular arrays, for example, or in systems that exploit new physical phenomena, such as hot carrier injection, photocurrent doubling through impact ionization, or photon energy up/down conversion.

Charge Transport. Fundamental understanding of the phenomena that relate to energy loss mechanisms is needed. For instance, factors that control the mobility of carriers in polymers and hybrid systems, and the chemical nature and energetics of grain boundaries and surface states must be better understood. Controlling these processes should increase efficiency in PV and photoelectrochemical cells.

Chemical Assembly. Synthetic routes to organic/inorganic/polymer hybrids with controllable structure are needed, along with molecular-level understanding of the principles of their assembly. Because of their potential importance in low-cost solar devices, an important goal in this area is to make defect-free semiconductor nanoparticles with control of size, shape, and interfacial chemistry, and to understand light-induced dynamic processes involving them. Related goals are to control energy and electron transfer in supramolecular and biomimetic photoredox systems and to understand the processes that can lead to higher efficiency in multicomponent photocatalytic assemblies and in self-assembling organic photosystems, such as multilayer polymer films, molecular organic crystals, liquid crystals, and block copolymers. *In situ* characterization of multicomponent chemical systems is also of key importance to the development of efficient solar cells and photocatalysts for hydrogen production because their optimization requires a molecular-level understanding of structure.

Interfacial Chemistry. Increased understanding of electron transfer reactions at the molecule-inorganic (semiconductor and metal) and molecule-solution interfaces is needed to allow these processes to be controlled. Investigations of the processes involved in understanding semiconductor sensitization are needed to develop new sensitizers for improved dye-sensitized cells. New interface-specific investigative tools are required for studying structure and dynamic processes. These studies are important for improving the efficiency of dye-sensitized and organic solar cells because their performance depends critically on the kinetics of interfacial electron transfer reactions.

Catalysis and Photocatalysis. Improved molecular and heterogeneous catalysts, particularly for the oxidation of water to oxygen, are needed. Mechanistic studies of photocatalytic systems for direct water splitting, CO_2 reduction, and cyclic water cleavage with coupled redox catalysts will allow the development of improved photocatalysts.

Polymer and Materials Chemistry. New molecular components for PV cells are needed, including transparent conductors (particularly inexpensive polymeric conductors and p-type materials), electron- and hole-conducting polymers, semiconductors that have appropriate light-absorption characteristics and are stable in water, and corrosion-resistant coatings. Research on light-harvesting polymers, photonic crystals, and nonlinear optical materials is needed to better utilize the solar spectrum. New characterization tools are required for studying chemical, electrochemical, and photochemical processes in solid and polymeric materials. Polymer- and organic-based solar cells have the potential to convert solar energy at very low cost, if their efficiencies can be improved.

Theory and Modeling. With increased computational power and a background understanding of electron transfer in biomimetic and biological systems, theory and modeling can play an increasingly important role in our understanding and predicting the behavior of complex photosystems. The important features of these systems (such as femtosecond dynamics in sensitizer molecules and particles, and the branching of kinetic pathways in complex molecular assemblies and photoelectrochemical cells) are often at the "ragged edge" of experimental observation.

Stability. Fundamental studies are needed to understand and subsequently control parasitic processes that can degrade solar cells (particularly dye-sensitized, organic, polymer, and nanoparticle-based cells), with the goal of achieving a 10- to 15-year useful life.

Hydrogen from Biological and Biomimetic Systems

Sunlight is the primary energy source that fuels the entire biosphere, including biological hydrogen production. Like solar energy, natural biological hydrogen production is substantial on a global scale but suffers from being highly distributed and low in density compared with humankind's more concentrated energy needs, such as transportation. The energy efficiency of hydrogen production in natural populations of microorganisms and ecosystems is low in comparison with production via PV electrolysis. The efficiency limits encountered in biological energy conversion systems are related in large part to the energy needs of the living organisms themselves. Hydrogen is only one of many carriers in the energy economy of living organisms. Hence, only a portion of the solar energy acquired in photosynthesis enters into pathways that produce hydrogen, and often the hydrogen production process is many energy conversion steps removed from the initial photosynthetic reaction. Because the primary efficiency of natural photosynthetic light reactions is high (quantum yields near 1 for absorbed light, energy efficiency ~30% of total solar irradiance), direct coupling of photosynthesis to hydrogen production could, in principle, yield a highly efficient process. Achieving such efficiency, however, poses a number of basic research challenges. Recent advances in the development of tools for detailed genetic engineering of organisms capable of photosynthetic hydrogen production offer unprecedented opportunities.

Research into the fundamental mechanisms of the biological catalysts of light energy conversion, hydrogen activation, water oxidation, and intermediate electron transport, and into the design and operational principles that underlie self-assembly and self-renewal of these catalysts and energy conversion chains, holds considerable promise for developing less expensive and more efficient synthetic solar hydrogen systems. Advances in genomics and proteomics, and in the *de novo* design and biochemical synthesis of protein-based catalytic systems are strong enablers in this research. Our understanding of cofactors involved in biochemical oxidation-reduction processes and our ability to create functional synthetic mimics (Figure 5) also suggests that we are close to developing improved biomimetic catalysts for some of the most important reactions (hydrogen evolution, water oxidation) needed in hydrogen production.

Several research needs in biological hydrogen metabolism are considered to have high priority. These needs are discussed in the following sections.

Direct Production of Hydrogen Using Living Organisms. Fermentative organisms or microbial consortia could play a direct role in hydrogen production from fixed carbon energy reserves, such as biomass or natural gas, and also in removal of CO from hydrogen gas streams. Research is needed to understand the diversity and capacity of natural hydrogen production systems and to understand how to optimize their utilization in hydrogen-production processes. Photosynthetic hydrogen production could play a leading role in direct solar conversion, but research is needed

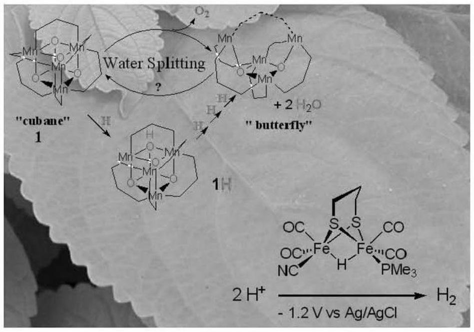

Figure 5 (Upper left) Synthetic Water Oxidation Catalysts Based on the Design of the Natural Photosystem II Manganese Cluster (Source: Maneiro et al. 2003) (Lower right) Synthetic Hydrogen Activation Catalysts Based on the Design of the Natural Reversible Iron-hydrogenase H-Cluster (Source: Gloaguen et al. 2002) (These catalysts are showing promise in mimicking many of the catalytic properties of their natural counterparts. Further advances could enable these biomimetic catalysts to play key roles in electrochemical hydrogen generation and utilization and in photochemical hydrogen production.)

to improve its efficiency, capacity, and reliability. Research is also needed in gas-separation technology for separating the mixed low-pressure H_2/O_2 gas stream that emerges from biophotolysis.

Engineered Systems Employing Biological, Biomimetic, or Bio-inspired Catalysts. The enzyme catalysts that living organisms use in both hydrogen production and consumption consist of readily available materials, such as iron, sulfur, nickel, molybdenum, manganese, and various organic cofactors in their catalytic mechanisms. Biological catalysts operate efficiently at relatively low temperatures (4–110°C) in aqueous environments. Research is needed to identify microbes and component redox enzymes and cofactors for producing/metabolizing H_2 and other fuels (e.g., CO and CH_4), understanding the mechanisms of these catalysts, and understanding how to exploit their designs in artificial systems. Research also is needed to develop and interface biological and biomimetic redox catalysts into nanostructured two- and three-dimensional complexes for hydrogen/oxygen catalysis, sensing, and energy transduction. Research is also needed for understanding the synthesis and assembly of the cofactors that participate in biological catalysis of hydrogen activation and water oxidation.

Systems Engineering Exploiting Biological Principles. The energy conversion systems of living organisms are highly organized nanoscale devices integrated into mesoscale architectures that incorporate self-repair mechanisms into their designs. An understanding of the principles governing the production of these organized systems, as well as their self-repair, may enable adoption of similar principles in the production of artificial systems with similar properties. Hydrogen is used extensively as an energy carrier between organisms that use it to energize a wide variety of different biological activities. Greater understanding of the scaling and organizational principles underlying the efficiency and stability of this diversified natural human engineered hydrogen energy economy may provide key insights that would support planning of a human-engineered hydrogen economy.

Thermal Energy for Hydrogen Production

Thermal hydrogen production places severe demands on reactor design because of the need to deliver heat at high temperatures (500–950°C). The problem of finding materials (both construction materials and membranes for separations) that resist corrosion and failure at high temperatures in extremely aggressive chemical environments is a potential roadblock for this technology. In this context, there are large incentives to reduce the temperature by 100-200°C for the S-I cycle, in which the high-temperature–controlling step is the catalytic decomposition of SO_3 to SO_2 and oxygen. Lower-temperature operation (e.g., at 725°C), however, requires cooling of unreacted sulfuric acid and reaction products, separation of components, and reheating of sulfuric acid, which results in high internal recycle with high costs and lower efficiency. There are multiple thermochemical cycles (S-I, Westinghouse, sulfuric acid-bromine) that use the same high-temperature chemical reaction (Brown et al. 2002); thus, the benefits of improving this high-temperature step accrue to several leading thermochemical cycles. The Cu-Cl cycles (Argonne Low-Temperature Cycles, ALTC-1 and ALTC-2) avoid many of the materials and reactor issues of the higher-temperature cycles by operating at a maximum temperature of 500°C. In this case, the lower operating temperature creates a new set of challenges in terms of catalysis and separations. Work is needed to assess the potential for exploiting the higher available temperatures from solar concentrators to access even more efficient thermochemical cycles. Parallel work would also be needed to identify and solve the materials and separations issues that would arise at these higher reactor temperatures.

Several research needs in thermochemical energy for hydrogen production are considered to have high priority. These needs are discussed in the following sections.

High-temperature Materials. The materials needs are severe because of the requirement to operate in a harsh chemical environment at elevated temperature. For example, in the S-I cycle, ductile and corrosion-resistant materials are needed for H_2SO_4 concentration. Operation at very high temperatures (700–950°C) requires advances in construction materials and very efficient heat transfer.

Separations. Improved separations processes that work at high temperatures are critical to the efficient running of thermal hydrogen cycles. Opportunities for improved separations for the

S-I cycle include separation of SO_2 and O_2 from SO_3 to lower peak process temperatures, separation of H_2O and HI from $H_2O/I_2/HI$ mixtures, and removal of H_2 to shift this equilibrium. Membranes that might be used in these and related improved separation processes must have long-term stability in an aggressive chemical and physical environment. For the lower-temperature Cu-Cl cycles, efficient gas and liquid separations are also needed to shift the equilibria of component reactions and to separate the products (hydrogen and oxygen) from gaseous HCl and water.

Thermodynamic Data and Modeling for Thermal Cycles. Additional thermodynamic data (for sulfuric acid at high concentrations and for $I_2/HI/H_2O/H_2$ reactions) are needed inputs in reactor design. This involves modeling of aqueous fluids under extremely nonideal conditions. The optimum cycles for solar-matched thermal hydrogen production need to be determined.

Catalysis. Improved catalysts for the high-temperature SO_3 decomposition reaction would allow more flexibility in reactor design by enabling the cycle to run at lower maximum temperature. Reactive distillation of HI in the S-I cycle may also require catalysis.

New Thermochemical Cycles. Although much work was performed on thermochemical cycles in the 1970s and hundreds of cycles were identified, advances in nanotechnology and other areas of science may enable the development of improved cycles.

CROSS-CUTTING ISSUES

Several of the basic research needs in hydrogen production mirror those of hydrogen storage and use. These needs are discussed in the following sections.

Catalysis

Research is needed in the area of catalysis in all aspects of hydrogen production. Such research includes integrating molecular and heterogeneous catalysts into solar photoelectrochemical and photocatalytic systems, interfacing biological and biomimetic catalysts with chemical and electrochemical systems, improving catalysts for fuel processing, and developing catalysts for use in thermal hydrogen cycles. The areas of hydrogen production and use are strongly linked through catalysis because fuel cell catalysts that are not easily poisoned by CO would enable the use of reformed hydrogen with less extensive purification. Better fuel processing catalysts would reduce the need for separations processes that remove CO. Similarly, the development of intermediate-temperature fuel cells (200–400°C) that tolerate CO would greatly relax the requirements for fuel processing catalysts. Cost and scale considerations in hydrogen production and use call for the development of all of these next-generation catalysts from abundant raw materials.

Separations

Improved membranes and chemical separation processes are needed in fuel processing, in the separation of hydrogen and oxygen produced by photocatalysis and photosynthesis, and in the high-temperature chemical processes of thermal hydrogen production.

Interfacial Chemistry and Materials

Solar PV/photoelectrochemical and biomimetic hydrogen production involve electron and ion transfer at catalyst/electrolyte interfaces and present materials problems similar to those for PEM fuel cells. Corrosion-resistant materials are needed in thermal hydrogen production. For thermally assisted electrolysis, further development of high-temperature materials is needed, similar to that of solid oxide fuel cells.

Theory and Modeling

Theory has a unique role in many aspects of hydrogen production, storage, and use. In hydrogen production, theory is particularly important in uncovering the mechanisms of heterogeneous, molecular, and biological catalysis, in understanding the complex photoredox processes associated with solar hydrogen production, and in modeling the chemical processes involved in hydrogen-producing thermal chemical cycles.

CONCLUSIONS

The development of safe, sustainable, and cost-effective hydrogen production on the scale of the U.S. energy economy presents urgent and difficult challenges. The near term (5- to 10-year) goals are to improve the processes that can provide hydrogen from resources of limited capacity or sustainability. These include fossil fuels, with sequestration of CO_2, and biomass. The long-term goal (>10 years) is to develop the means to produce hydrogen cost-effectively from high-capacity, noncarbogenic resources, namely, solar and possibly nuclear energy. Meeting these goals will require a sustained effort to address a diverse set of basic scientific challenges.

In hydrogen production from fossil resources, breakthroughs in catalysis and separations, as well as an understanding of the processes involved in carbon sequestration and release, are needed. Catalysis research can leverage recent advances in nanoscale and molecular synthesis, in characterization tools that allow active sites to be probed directly, in modeling of complex chemical systems, and in high-throughput synthesis and screening methods.

The longer-term goal of developing very efficient, low-cost solar cells (solar “paint”) and photocatalysts for hydrogen production requires an understanding of light-induced dynamical processes in molecules, polymers, and semiconductor nanoparticles. There is a need to understand the rules of chemical assembly on the length scale (0.5–10 nm) of charge separation and recombination. There is also a pressing need for research on new semiconductors, polymers, supramolecular assemblies, and catalysts that will enable the synthesis of two- and three-dimensional integrated chemical systems for efficient light harvesting, charge separation, and fuel formation. These systems may integrate biological or bio-inspired catalysts. Understanding the pathways by which hydrogen is made and processed in living organisms may enable breakthroughs in this area, for example by providing nonprecious metal catalysts for water oxidation-reduction reactions and allowing fuel processing reactions to run at lower temperatures.

Thermochemical cycles (using heat from high-temperature solar and possibly nuclear sources) can in principle be used to generate hydrogen from water economically and in large quantity. The most significant challenges in this area are to (1) develop materials that are cost-effective and compatible with extreme chemical and thermal environments (e.g., aqueous sulfuric acid at 700–950°C) and (2) develop efficient separations processes and catalysts that can function in the same environment.

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BASIC RESEARCH CHALLENGES FOR HYDROGEN STORAGE

CURRENT STATUS

Effective storage and delivery of hydrogen — produced from diverse sources and intended for diverse uses — are key elements of the hydrogen economy. Flexible use of hydrogen as a carrier of energy requires a means to store excess product for later use, to transport stored hydrogen from the point of production to the point of use, and to charge and discharge hydrogen conveniently from the storage container according to need. In addition to interfacing production with use, hydrogen storage provides a load-leveling mechanism for the cyclic renewable energy production from wind and solar sources.

Two kinds of storage functions with very different requirements are needed for the hydrogen economy. Hydrogen storage systems used for such stationary applications as residential heating and air-conditioning, neighborhood electrical generation, and many industrial applications can occupy a large area, employ multistep chemical charging/recharging cycles that operate at high temperature and pressure, and compensate for slow kinetics with extra capacity. Hydrogen storage for transportation, in contrast, must operate within minimum volume and weight specifications, supply enough hydrogen to enable a 480-km (300-mi) driving range, charge/recharge near room temperature, and provide hydrogen at rates fast enough for fuel cell locomotion of cars, trucks, and buses. The hydrogen storage requirements for transportation applications are thus far more stringent and difficult to achieve than those for stationary applications. Finding onboard hydrogen storage solutions for transportation applications is one of the major challenges in achieving the hydrogen economy.

Because two-thirds of U.S. oil consumption is used to meet transportation energy needs, this sector presents not only the most difficult challenges, but it also provides the most intense driver for the hydrogen economy. Developing effective hydrogen storage for transportation is a central challenge for basic research and a key factor in enabling the success of the hydrogen economy. The operating requirements for effective hydrogen storage for transportation include the following:

- Appropriate thermodynamics (favorable enthalpies of hydrogen absorption and desorption),
- Fast kinetics (quick uptake and release),
- High storage capacity (specific capacity to be determined by usage),
- Effective heat transfer,
- High gravimetric and volumetric densities (light in weight and conservative in space),
- Long cycle lifetime for hydrogen absorption/desorption,

- High mechanical strength and durability, and
- Safety under normal use and acceptable risk under abnormal conditions.

Specific performance targets for the coming decade for a successful transition to hydrogen-fueled transportation, as specified by the Department of Energy's Office of Energy Efficiency and Renewable Energy, are presented in Table 1.

Table 1 FreedomCAR Hydrogen Storage System Targets

Targeted Factor	2005	2010	2015
Specific energy (MJ/kg)	5.4	7.2	10.8
Hydrogen (wt%)	4.5	6.0	9.0
Energy density (MJ/L)	4.3	5.4	9.72
System cost ($/kg/system)	9	6	3
Operating temperature (°C)	-20/50	-20/50	-20/50
Cycle life-time (absorption/desorption cycles)	500	1,000	1,500
Flow rate (g/s)	3	4	5
Delivery pressure (bar)	2.5	2.5	2.5
Transient response (s)	0.5	0.5	0.5
Refueling rate (kg H_2/min)	0.5	1.5	2.0

[a] Source: Milliken (2003).

A storage capacity of approximately 5–10 kg of useable hydrogen is needed, depending on the vehicle, to provide a 480-km range for a fuel cell/electric vehicle. A refueling time of less than 5 min is targeted for 2015. Current technology for hydrogen storage involves tanks in which hydrogen is stored as a compressed gas or as a cryogenic liquid. With compressed gas and liquid storage, the hydrogen is easily accessible for use. These storage methods, however, fall far short of the FreedomCAR targets because of the volume of the tanks that would be required using present technology. Solid-state storage, in which the hydrogen is absorbed in a solid material, holds considerable promise for meeting the FreedomCAR targets, but no completely satisfactory material has been identified yet.

Hydrogen storage is a crucial step for providing a ready supply of hydrogen fuel to an end use, such as a car. Without effective hydrogen storage systems, a hydrogen economy will be difficult to achieve. Hydrogen storage is considered by many to be the most technically challenging aspect of achieving a hydrogen-based economy. Current hydrogen storage materials or systems are still far short of achieving target goals set for either 2010 or 2015. For example, we need a factor of ~2 improvement in both hydrogen storage capacity and energy density, and perhaps an even higher improvement factor for hydrogen release, to achieve targets goals within the next decade. Incremental improvements in current technologies will not be sufficient to meet the prescribed requirements for hydrogen storage. Basic research is essential for identifying novel materials and processes that can provide the revolutionary breakthroughs needed to make the hydrogen economy a reality.

Below we describe current methods of hydrogen storage, along with fundamental research issues that are needed to achieve the required hydrogen storage goals. Although this discussion focuses primarily on hydrogen storage for onboard vehicle use, hydrogen storage materials and systems developed for vehicle applications could find more general energy storage uses. One common requirement for all hydrogen storage technologies described below is the need to develop materials suitable for use in containers that house hydrogen storage media. Also, safety is a potential concern for widespread hydrogen use because of the very wide flammability range of hydrogen. Specific information on hydrogen safety and the research directions associated with the science of hydrogen safety is presented in High-priority Research Directions.

Gaseous and Liquid Hydrogen Storage

Storage of hydrogen as a gas in tanks is the most mature storage technology at present. Composite gas storage tanks are already available at 5,000 psi. Recently 10,000-psi tanks have been demonstrated and certified. These high-pressure tanks use new lightweight tank materials, such as carbon-fiber–reinforced composites. The major drawback of gaseous storage for transportation applications is the small amount of hydrogen that can be stored in a reasonable volume. Even at 10,000 psi pressures, the energy content is significantly less than that for the same volume of gasoline — 4.4 MJ/L (10,000 psi) for hydrogen compared with 31.6 MJ/L for gasoline. The energy used in compressing the gas, which depends on both the initial and final pressures, is another consideration, as is the large pressure drop during use.

Principal research needs for improved compressed gas storage include the development of novel materials that are strong, reliable, and low in cost. For example, fiber-reinforced composites for storage containers require new fiber synthesis techniques that reliably produce high-quality fibers and new binders that are strong and impermeable to hydrogen. A better understanding of the mechanisms responsible for the failure of storage container materials is also needed. Because many of the system parts exposed to hydrogen will be metallic, researchers need a better understanding of the atomic-level processes responsible for hydrogen embrittlement in candidate materials in order to develop strategies to prevent failure resulting from long exposure to hydrogen. The development of embrittlement-resistant materials will require well-coordinated basic and applied research to allow their practical application to pressurized gas storage. In addition, smart sensors that can detect hydrogen leakage and the corresponding safety feedback systems need to be fully developed to ensure safe implementation of gaseous hydrogen storage.

Storage of liquid hydrogen in cryogenic containers offers a significant advantage: more hydrogen can be stored in a given volume as a liquid than can be stored in gaseous form. For liquid hydrogen, researchers predict 8.4 MJ/L compared with 4.4 MJ/L for compressed gas (at 10,000 psi). The density of liquid hydrogen is 70.8 kg/m^3 at standard temperature and pressure. Note that these values are still less than half of those required to meet FreedomCAR goals. The automobile manufacturer BMW has been working on the development of a hydrogen-fueled fuel cell vehicle with onboard liquid hydrogen storage (Porvetto 2003). A major drawback of liquid storage is the large quantity of energy required for liquefaction — presently about one-third of the energy value of the hydrogen stored. Loss of hydrogen through evaporation is also an issue, especially with small tanks. High-pressure cryogenic tanks are also being explored to alleviate the requirement for very low temperature storage.

Basic research needs related to liquid hydrogen storage include the discovery of new lightweight, low-volume, and low-cost materials that have very low heat transfer. These materials must demonstrate strength, integrity (no leakage), and durability. There is also a need for novel, strong materials, developed through experiments and computer simulations, that minimize heat transfer and are amenable to mass production. Researchers need to identify "failsafe" methods to safely handle boil-off of hydrogen and address other safety issues associated with liquid hydrogen. New approaches are also needed that reduce the cost of liquefaction and make it more energy efficient. Finally, close coordination between basic and applied research is needed to expedite development and application of new technologies for handling cryogenic liquids.

Solid-state Storage

Solid-state storage refers to the storage of hydrogen in metal hydrides, in chemical storage materials, and in nanostructured materials. This method of hydrogen storage offers perhaps the best opportunities for meeting the requirements for onboard storage. In these materials, hydrogen can be stored both reversibly and irreversibly. Reversible storage means that hydrogen is released by raising the temperature of, for example, a metal hydride at a suitable pressure; hydrogen is subsequently replaced (stored) through the control of temperature and hydrogen pressure. Although temperature and pressure are the two typically controlled thermodynamic parameters, other types of energy (e.g., mechanical and acoustical) can be employed to control both the release and uptake of hydrogen. Ideally, storage and release of hydrogen should take place at temperatures between 0°C and 100°C and pressures of 1–10 bar and on time scales suitable for transportation applications. Some materials contain strongly chemically bound hydrogen that is not readily retrievable. Only hydrogen that can be made easily accessible will meet the hydrogen storage requirements for transportation applications.

Hydrogen is irreversibly stored in some materials, including chemical hydrides, and is released by chemical reaction with another substance, such as water. The heat released upon hydrolysis is energy that can be captured and used. The resulting hydrolysis product cannot be used again to store hydrogen without chemical reprocessing, as described in the accompanying sidebar on the supply chain of a borohyride hydrogen storage system. Hydrogen storage using recyclable hydrocarbon carriers, such as methylcyclohexane, has also been demonstrated. However, these liquid carriers store low ratios of usable hydrogen for their weight. In addition, these carriers require a long release time, because the catalyst used for dehydrogenation must first be brought up to operating temperature.

Researchers believe that metal hydrides may represent ideal storage systems. Although a database (http://hydpark.ca.sandia.gov) lists more than 2,000 elements, compounds, and alloys that form hydrides, none of these materials has yet been demonstrated to meet all of the FreedomCAR targets listed in Table 1. Conventional metal hydrides, which are well

USING SODIUM BOROHYDRIDE FOR ONBOARD HYDROGEN STORAGE

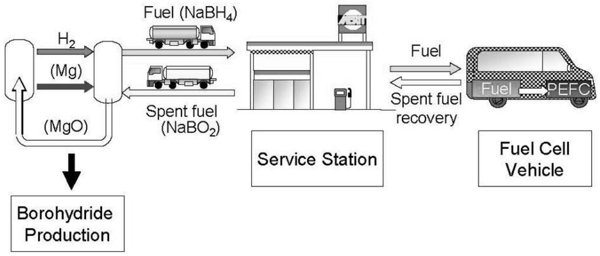
Sodium borohydride ($NaBH_4$) is a rich source of hydrogen being developed by Millennium Cell under the trade name "Hydrogen On Demand." The chemical reaction in which hydrogen is formed is as follows:

$$NaBH_4 + 2\,H_2O \xrightarrow{\text{catalyst}} 4\,H_2 + NaBO_2$$

Sodium borohydride is derived from borax, a nontoxic compound used in laundry detergents. The hydrogen storage density of $NaBH_4$ is high. A 30 wt% $NaBH_4$ fuel (30 wt% $NaBH_4$, 3 wt% NaOH, and 67 wt% H_2O) has a theoretical hydrogen content of 6.6 wt% — equal to about 66 g H_2/L, compared with 70 g H_2/L for liquid hydrogen and 23 g H_2/L for compressed hydrogen (at 5,000 psi).

The supply chain for onboard hydrogen storage and use of $NaBH_4$ is shown in the diagram. The $NaBH_4$ fuel is delivered to a service station following production. The fuel is processed onboard a vehicle by means of a catalyzed reaction with water to generate the hydrogen needed to power a fuel cell. The spent fuel (containing $NaBO_2$) is recovered from the vehicle and shipped from the service station to a central reprocessing facility, where it is reprocessed back to $NaBH_4$. Schemes for spent fuel regeneration have been demonstrated and are believed to be feasible.

Hydrogen storage materials can be divided into those that are recharged with hydrogen onboard a vehicle and those that must be removed from the vehicle for recharging or reprocessing. Total hydrogen fuel costs — including costs for hydrogen production, transportation of hydrogen or storage materials, and reprocessing — will be among the many factors that will determine the method selected for delivering hydrogen to the fuel cell onboard a vehicle.



characterized and have well-established values for interstitial hydrogen storage, include intermetallics of the types AB, AB_2, AB_5, A_2B, and body-centered cubic metals. These materials typically store between 1.4 and 3.6 wt% hydrogen. Examples of these intermetallic compounds are TiFe, $ZrMn_2$, $LaNi_5$, and Mg_2Ni. Their hydrogen storage properties are listed in Table 2; it should be noted that the hydrogen storage capabilities in general are a factor of 3 lower than FreedomCAR requirements.

Note that Table 2 provides the amounts of hydrogen that are stored, but not the amounts that are released. Furthermore, the values presented in Table 2 do not take into account the energy required to bring about the release of the hydrogen from the material. The reversible hydrogen capacity is typically 50–90% of the maximum hydrogen capacity for these intermetallics. In addition to limits in hydrogen availability, other issues need to be considered as new hydrogen storage materials are developed and characterized, such as the ease of activation, sensitivity to gas impurities, rate of hydrogen absorption/desorption, heat transfer, cyclic stability, and

Table 2 Hydrogen Storage Properties of Intermetallic Compounds

		Maximum Hydrogen Capacity		
Type	Intermetallic	H/M[a]	wt%	Temperature (K) for 1 atm $P_{desorption}$
A_2B	Mg_2Ni	1.33	3.6	528
AB	TiFe	0.975	1.86	265
AB	ZrNi	1.4	1.85	565
AB_2	$ZrMn_2$	1.2	1.77	440
AB_5	$LaNi_5$	1.08	1.49	285
AB_2	$TiV_{0.62}Mn_{1.5}$	1.14	2.15	267

[a] H/M is the hydrogen-to-metal atomic ratio in the compound.

Source: Sandrock (1999).

physical properties (e.g., volume change and decrepitation). From an engineering perspective, the design and optimization of practical storage beds may well require at least a factor of 2 increase in the percent hydrogen mass and volume that would be necessary for use in thermal management. Thus, the materials listed in Table 2 (and related materials) presently appear to have limited potential for meeting the targets listed in Table 1.

Needed breakthroughs in hydrogen storage technology will require revolutionary new materials to meet the hydrogen storage requirements, and not simple, incremental improvements in current technologies. These breakthroughs require investments in fundamental research to develop and examine new materials and obtain an atomic- and molecular-level understanding of the physical and chemical processes involved in hydrogen storage and release. For example, researchers have only recently learned of the improved hydrogen storage potential of many novel lightweight metal hydrides. Understanding fundamental issues about the interactions of hydrogen with these and other novel materials is critical to identifying effective materials for hydrogen storage.

BASIC SCIENCE CHALLENGES, OPPORTUNITIES, AND RESEARCH NEEDS IN SOLID-STATE HYDROGEN STORAGE

Development of new solid-state materials for hydrogen storage presents many scientific and technical challenges. Fundamental research is needed to understand the interaction of hydrogen in solid-state materials in order to realize the potential of these materials for hydrogen storage. The knowledge gained from this research will allow the tailored design and synthesis of new materials that will meet the requirements for efficient hydrogen storage.

The research effort will require a multidisciplinary approach involving physics, chemistry, materials science, and engineering. Also needed is a strong integration among experiment and theory, modeling, and simulation that will not only help researchers understand the experimental data, but also allow them to identify key parameters that will facilitate major advances in hydrogen storage technology and guide subsequent experiments. This multidisciplinary, integrated research effort will lead to the discovery of new hydrogen storage materials.

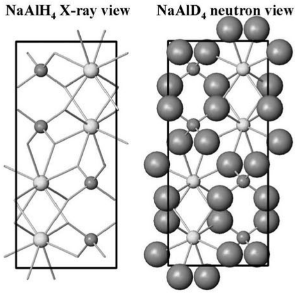
The fundamental questions that need to be asked for any potential solid-state hydrogen storage material include the following. Does hydrogen physisorb or chemisorb? Does it bind molecularly or dissociatively? Where does the hydrogen reside? What is the nature of its hydrogen diffusion? What are the activation barriers for hydrogen desorption? What adverse effect does hydrogen have on the structural and mechanical stability of the host material? What is the nature of bonding of hydrogen with host atoms — ionic, covalent, or metallic? What roles do surface morphology and defects play in hydrogen absorption and desorption? In what ways is it beneficial to store hydrogen in novel materials, such as nanostructures and porous materials? How do catalysts help in reducing the operating temperature and pressure for hydrogen uptake and release?

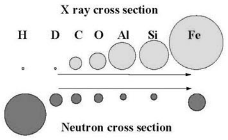
As we gain insight into these fundamental questions, new materials can be designed and synthetic approaches can be devised to produce tailored materials more efficiently. Reliable information about the structural, thermodynamic, physical, and chemical properties of these materials is needed. New capabilities for studying materials and chemical and physical processes at the nano scale will help us develop an understanding of how the unique surfaces and interfaces in nanostructured materials might impact the energetics, kinetics, and thermodynamics of hydrogen storage. Also, these capabilities will provide insight on how shape, curvature, and pore size affect the surface chemistry and binding that are so important for hydrogen storage.

These studies will require state-of-the-art analytical and characterization techniques, including a new generation of neutron and x-ray scattering techniques (see sidebar on neutron and x-ray scattering) and imaging tools. Researchers will also need to develop a comprehensive theoretical understanding of the interactions of hydrogen with storage materials (e.g., the nature of bonding and the role of structure and nanophase boundaries). For example, multiscale computational approaches may be applied to model absorption and desorption in hydrogen storage materials. Computational approaches should also be used — together with experimental data — to help identify mechanisms for degradation of hydrogen storage materials, which limit the lifespans of these materials, particularly with repeated hydrogen storage and release cycles. Finally, experiments on model hydrogen storage systems should be benchmarked against calculations at all length scales. Taken together, this knowledge will allow the design of novel materials for optimum hydrogen storage and release and provide a means to control and maintain the structural properties of candidate hydrogen storage materials and improve their durability. Below, these and other fundamental research needs are outlined for two key areas that hold promise for meeting the goals of hydrogen storage: metal and complex hydrides and nanostructured materials.

Metal Hydrides and Complex Hydride Materials

Over the past four decades, materials for solid-state hydrogen storage have been nearly exclusively metals and metallic alloys, in which the metal matrix is expanded and filled with absorbed hydrogen atoms that are usually located in tetrahedral or octahedral interstitial sites.





USING NEUTRONS TO "SEE" HYDROGEN

To characterize the materials and processes involved in hydrogen production, storage, and use, researchers need atomic- and molecular-level information on structure, hydrogen diffusion, and interatomic interactions, as well as the nanoscale and macroscopic morphologies that govern their useful properties. Neutron scattering provides unique capabilities for giving this basic information. Their sensitivity to light (low-Z) atoms — such as hydrogen, lithium, and oxygen — make neutrons a valuable probe for investigations related to catalysis, membranes, proton conductors, hydrogen storage materials, and other materials and processes related to hydrogen production, storage, and use. This capability is illustrated in the figure at the right, which compares the neutron and x-ray scattering cross sections of a number of elements.

The figure at the left further illustrates how neutrons can identify the presence of hydrogen atoms in the structures of alanates used for hydrogen storage. Structural characterization using x-rays cannot reveal the site of hydrogen incorporation, which is critical to a fundamental understanding of the mechanisms of hydrogen storage. Neutrons also have a unique ability to distinguish hydrogen from deuterium, allowing isotope substitution to be used to provide additional insight into the structure of materials and into the interactions occurring between hydrogen and these materials. Another advantage of neutron-based techniques is that materials and chemical processes can be studied under realistic conditions, rather than under the high-vacuum or other controlled conditions required by other methods.

Neutron sources can provide continuous beams of neutrons (from reactor-based sources located at the National Institute of Standards and Oak Ridge National Laboratory) or pulsed beams (from spallation sources at Argonne National Laboratory and Los Alamos National Laboratory). A new generation of pulsed sources, such as the Spallation Neutron Source (SNS) currently under construction at Oak Ridge, will have advantages that are of particular interest to hydrogen studies. The intense flux of the SNS will allow samples to be studied using single-pulse, broadband techniques, which will permit neutron diffraction to determine hydrogen positions accurately and dynamically. Inelastic spectrometers allow researchers to examine diffusion processes on an atomistic level and relate them to structure. Understanding this relationship is a vital step to developing better, more affordable materials, such as membranes for selective purification of hydrogen. Similar techniques can be applied to determining diffusion paths in promising proton and ion conductors. Single-pulse determinations will allow *in situ* measurements to be made in real time during charging/discharging cycles in hydrogen storage materials and as a function of external parameters, such as pressure and temperature.

Increasing the efficiency and affordability of fuel cells requires a better understanding of the molecular-level processes involved in oxidation and reduction at electrodes, catalytic processes, and ion and proton transport, as well as the development of polymer-electrolyte-membranes and solid oxide electrolytes. The performance of these components involves several size (nm to μm) and time scales readily accessible with neutron scattering techniques. Examples of other areas that can be examined by neutrons include *in situ* studies of new catalyst materials, hydrogen-induced embrittlement in materials, uptake and release of hydrogen in metal and complex hydrides, and studies of materials used in new photovoltaic cells and coatings for solar energy devices.

Atomic hydrogen stored in these interstitial sites recombines at particle surfaces to form molecular hydrogen upon release. A major emphasis of materials-related research has been to *encapsulate hydrogen*. Capacities exceeding two hydrogen atoms per metal atom have been demonstrated by using this approach. Most metal matrices investigated to date, however, consist of relatively heavy elements, and gravimetric storage capacities usually do not exceed 2 wt% hydrogen when transition metals are major components.

Figure 6 is a van't Hoff diagram showing the dissociation pressures and temperatures of a number of hydrides (Bogdanovic and Sandrock 2002). Light elements, such as Mg, have shown promising levels of stored hydrogen (3–7 wt% hydrogen), but they release hydrogen at high temperature (e.g., 552 K at one atmosphere) (Sandrock 1999). Although improvements in the kinetics of magnesium-based alloys have been achieved by nanostructuring and adding catalysts (Oelerich et al. 2001; Barkhordarian et al. 2003), the thermodynamics remain virtually unchanged (i.e., rather modest shifts in plateau pressures/van't Hoff lines). In comparison, $NaAlH_4$, a low-temperature (LT) hydride, and Na_3AlH_6, a medium-temperature (MT) hydride, offer promise for lowering the hydrogen release temperature while attaining high storage capacity (above 5 wt%) by using both phases to provide hydrogen. Hydride formation in nearly all metal systems generally involves about a 15–25% volume change that must be accommodated in storage vessel designs. Another issue that needs to be addressed is the thermal management of the heats of absorption and desorption to (1) enhance the kinetics during filling and discharge of the hydrogen storage systems and (2) avoid degradation effects during long-life operation.

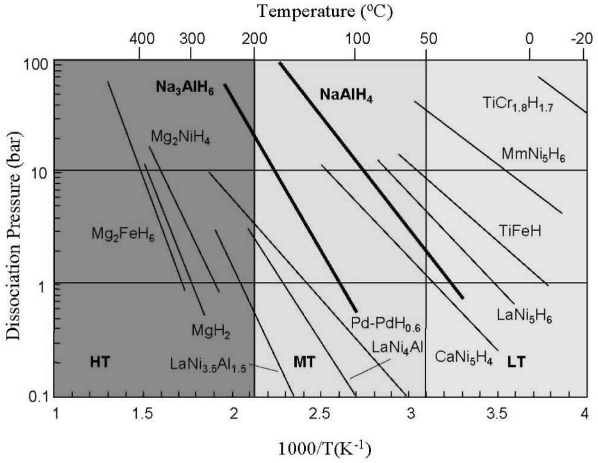


Figure 6 van't Hoff Diagram Showing Dissociation Pressures and Temperatures of Various Hydrides

A different concept in solid-state storage of hydrogen is to *encapsulate by hydrogen,* thus opening the possibility of approaching the hydrogen content of methane. In some ways, CH_4 would seem to be the ultimate hydrogen storage compound, in which four hydrogen atoms surround a single carbon atom. However, because CH_4 is gaseous, it offers little practical benefit over storage of hydrogen itself. Further, the hydrogen-carbon bonds of methane are too strong for easy hydrogen recovery. Novel solids — such as alanates (aluminohydrides), borohydrides, and imides — in which the metal atom is surrounded by four to six hydrogen atoms forming a complex negatively charged anion, mimic the structure of methane and may provide a much-needed breakthrough in the solid-state storage of hydrogen. As shown in Table 3, their theoretical total hydrogen capacities are high (from ~7 to 18 wt%).

Solid storage materials with a high volumetric density of hydrogen (up to 100 g H_2/L) would exceed the density of a cryogenic liquid at 20 K (~70 g H_2/L). The sidebar on light hydrides compares the mass density and volume density of hydrogen for a number of hydrides. Use of these materials is critically dependent on whether (and how) the stored hydrogen can be conveniently released at a temperature that is within acceptable bounds and how the materials can be recharged with hydrogen. Mixing hydrides to make complex, multicomponent hydrides could potentially allow the synthesis of storage materials with specifically tailored properties. For example, the ionic bonding of hydrogen-rich $[MeH_n]^{p-}$ anions with various light-element cations provides a means for precise chemical substitutions in the cation sublattice, thus bridging the gap between hydrogen-poor intermetallic hydrides and hydrogen-rich LiH, BeH_2, and MgH_2 compounds. Thus, these complex hydrides have perhaps the greatest potential to provide both a high wt% hydrogen and desirable release/absorption kinetics. Reaching the potential of hydrogen storage in these complex hydrides will require fundamental research in a number of areas, as outlined in the following sections.

Table 3 Hydrogen Storage Capacities of Hydrides

Hydride	Hydrogen (wt%)[a]
$NaAlH_4$	7.5
$LiAlH_4$	10.6
$Mg(AlH_4)_2$	9.3
$NaBH_4$	10.7
$LiBH_4$	18.5
$Mg(BH_4)_2$	14.9

[a] Note that these are theoretical total hydrogen contents and not reversible hydrogen capacities.

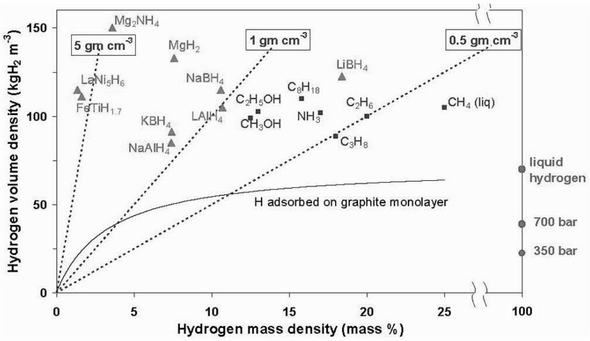
Source: Sandrock (1999).

Stoichiometric Complex Hydrides. A fundamental understanding of the physical, chemical, and mechanical properties of complex hydrides is needed, including desorption pressure, release kinetics, and chemical stability after multiple charging/discharging cycles.

Multicomponent Complex Hydrides. Basic knowledge of the structures of multicomponent complex hydrides is needed, as well as knowledge of their hydrogen storage behavior, the nature and homogeneity ranges of complex hydrides, hydrogenation-dehydrogenation kinetics and mechanisms, electronic structure, thermodynamics, and the kinetics of direct synthesis from the elements.

COMPARING MATERIALS' HYDROGEN DENSITIES

Candidate materials for hydrogen storage will need to have high hydrogen packing density, as well as low weight. This sidebar compares these two properties — the mass density and volume density of hydrogen — for a number of different hydrogen-containing materials. The hydrogen density in the material is simply proportional to the material density through the mass fraction. Three straight-line plots are shown in the following chart for 5, 1, and 0.5 gm cm^{-3}.



The best materials for hydrogen storage applications should be in the upper-right quadrant of the chart. Intermetallic hydrides, such as LaNi$_5$H$_6$, have high volumetric densities, but generally are heavy — with specific gravities in the range of 5–10 gm cm^{-3}. They tend to populate the left-hand portion of the chart. Lighter compounds, with specific gravities of ~1 gm cm^{-3}, need to have high hydrogen-to-metal ratios to achieve high volumetric density. Some examples with high hydrogen content are shown in the chart. Note that the hydrogen densities in solids tend to be comparable to the densities of hydrogen in hydrocarbon fuels, alcohols, and ammonia. Furthermore, they exceed the packing density of hydrogen in its liquid state at ~1 bar pressure.

Also shown is a plot for hydrogen adsorbed on a single plane (monolayer) of graphite. The density calculation also accounts for the carbon. Density values for liquid hydrogen and for compressed gas at 350 bar (5,000 psi) and 700 bar (10,000 psi) are plotted at 100% mass fraction for comparison.

The chart is based on one published by Schlapbach and Zuttel (2001).

Synthesis and Processing. The majority of complex hydrides have been prepared via lengthy solvent-based synthesis; only a few (e.g., LiAlH$_4$ and NaBH$_4$) have been prepared without solvents. Novel materials and processing approaches need to be developed for these and other lightweight hydrides, and these materials need to be evaluated in terms of their potential for enhanced hydrogen storage performance.

Dopants. One of the most important, but least understood, findings is the critical role of dopants in achieving reasonable kinetics and reversibility of complex hydrides. For example, the addition of Ti-based compounds (such as TiCl$_3$ or Ti[OBu]$_4$ to NaAlH$_4$) was found to lower the first decomposition temperature of the hydride, so that 3.7 wt% is released at 353 K, but at the expense of lowering the hydrogen content from 5.5 wt% in the hydride without a catalyst (Bogdanovic and Schwickardi 1997; Bogdanovic and Sandrock 2002). Also TiCl$_4$-catalyzed

$LiAlH_4$ releases ~5 wt% hydrogen at ambient temperatures during mechanochemical processing and ~2.5 wt% hydrogen at temperatures below 423 K during heating. However, the reversibility of hydrogen in this material is yet to be demonstrated (Balema et al. 2000).

Nitrides and Imides. A recent report on hydrogen storage in lithium nitride of 11.4 wt% (~6 wt% cycleable) under pressure has sparked interest in the potential for nitrides and imides as hydrogen storage media (Chen et al. 2002). While the temperature required to release the hydrogen was high in this initial study, alkali metal nitrides and related compounds deserve additional study.

Nano-scale Hydrides. Studies regarding the benefits of nanoscale versions of hydride materials relative to their bulk counterparts should be undertaken over the wide range of potentially interesting hydride materials for hydrogen storage. Theoretical guidance for designing potentially interesting nanoscale hydride materials should be used.

Nanostructured Materials

Currently, there is considerable excitement about a new class of materials with unique properties that stem from their reduced length scale ($1 < d < 100$ nm). Examples of these types of materials include both carbon-based materials — such as nanotubes, nanohorns, fullerenes — and non-carbon-based nanomaterials made of other atoms (including nanoscale versions of the hydride materials discussed above). Researchers have demonstrated that at the nano scale, materials can have distinctly different properties than those observed in their bulk-material analogs. New synthesis techniques have opened the door to designing materials with specific architectures to yield desired properties. The small size of nanostructured materials strongly influences the thermodynamics and kinetics of hydrogen adsorption and dissociation by increasing the diffusion rate, as well as by decreasing the required diffusion length. The diffusion rate can also be influenced in general by changes in the phonon modes, which directly influence the transport rate. In addition, materials at the nano scale offer the possibility of controlling material parameters more independently than in their bulk counterparts. The advantages that can be realized because of nanoscale size could thus potentially minimize some of the current limitations of bulk complex hydrides, for example, and make some of these materials attractive for hydrogen storage.

Nanoscale hydrogen storage materials can be divided into two general categories. The first is "atomic" hydrogen storage materials ("dissociative" materials), which require the reversible dissociation of molecular hydrogen into hydrogen atoms and the bonding of these atoms with the lattice of the storage medium. Dissociative materials would include such storage materials as the complex hydrides discussed previously. The second category is "molecular" hydrogen storage materials ("nondissociative" materials), which, by virtue of their high surface area and microporosity, store hydrogen in the molecular state via weak molecular-surface interactions (e.g., van der Waals forces or physisorption). These materials include nanotubes, nanohorns, and non-carbon–based structures that have been tailored to have various sizes, surface areas, surface modifications, and other properties to control the physical characteristics of the materials. For example, calculations have shown advantages of curved surfaces in nanomaterials that exhibit an increase in their adsorption potential (Simonyan and Johnson 2002), and the storage of hydrogen on various carbon materials has been shown to correlate with the surface area of the material (Nijkamp et al. 2001). The hydrogen adsorbed on carbon nanotubes at 77 K is due to physisorption and is limited to 2 wt% (Zuttel and Orimo 2002).

Figure 7 shows the structures and micrographs of various carbon allotropes, including a double-wall nanotube, nanohorns, a nanotube bundle, and a cup-stacked carbon nanofiber (or multiwall nanotube) showing exposed edge planes (Eklund 2003; Endo et al. 2003). A simulation of the structure of adsorbed hydrogen in an optimized array of nanotubes at 298 K and 200 bar of hydrogen pressure is shown in Figure 8, which indicates that hydrogen atoms can adsorb both inside and on the surface of nanotubes (Johnson 2002). In addition, Figure 9 illustrates a recently reported example of hydrogen adsorption on a metal-organic nanostructure (Rosi et al. 2003). These nanostructured materials have a significant fraction of their atoms on the surface or in the adjacent subsurface of the structure. The possibility of tailoring the hydrogen storage and release properties of high-surface-area carbon materials by appropriate functionalization needs further exploration.

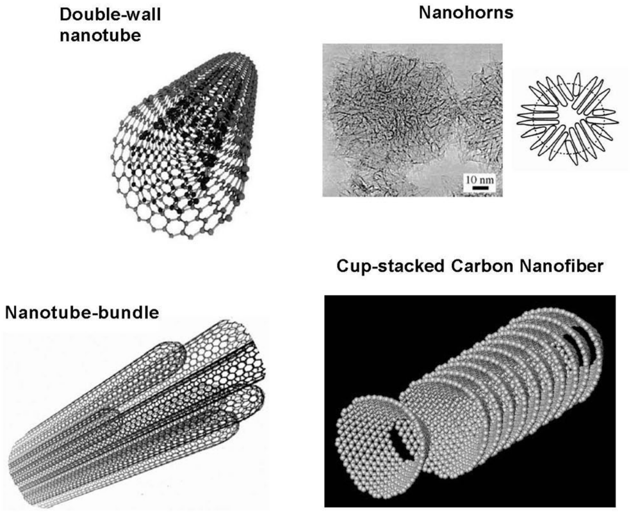


Figure 7 Structures and Micrographs of Selected Carbon Allotropes and Nanostructures (Sources: Nanohorns [upper right], Eklund 2003; nanofiber [lower right], Endo et al. 2003)

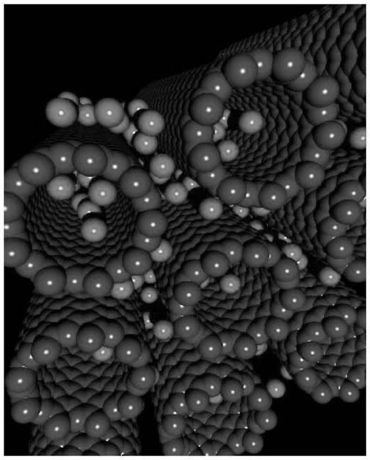


Figure 8 Simulation of the Structure of Adsorbed Hydrogen in an Array of Nanotubes at 298 K and 200 bar of Hydrogen Pressure (Source: Johnson 2002)

To learn how to design new nanomaterials for practical hydrogen storage, researchers need to gain considerable fundamental knowledge about these materials, incorporating both experimental and theoretical approaches, as discussed in the following sections.

Nondissociative Materials. For nondissociative materials, in which hydrogen is bound in molecular form, a means for increasing the hydrogen-surface interactions needs to be developed to facilitate storage at the target operational temperatures. For example, the strength of the molecular binding could be enhanced by adding suitable dopants. This will require understanding the mechanisms responsible for these interactions and the development of processes to design tailored materials that incorporate specific dopants. Theoretical guidance would be valuable in designing tailored materials.

Carbon Nanostructures. Studies of the reversible storage of hydrogen in carbon nanotubes have produced conflicting results, pointing to the need for (1) a new understanding of their synthesis and processing, (2) careful characterization of nanostructured materials, and (3) well-controlled and accurate hydrogen storage/release measurements and measurement techniques.

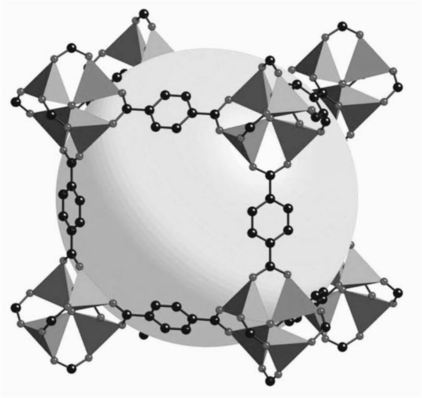


Figure 9 Schematic of a Single Crystal X-ray Structure for the Metal-organic Framework of Composition Zn_4O(1,4-benzene dicarboxylate)$_3$ Showing a Single Cube Fragment of a Cubic Three-dimensional Extended Porous Structure (This metal-organic compound adsorbed up to 4.5 wt% hydrogen at 78 K and 1 wt% at ambient temperature and 20 bar. Variants of this structure show promise for even better performances regarding hydrogen storage [Rosi et al. 2003].)

Novel Storage Concepts. Novel concepts for storage of hydrogen in nanostructured materials, such as nanoporous inorganic-organic compounds and polymers, need to be investigated. Methods for efficient synthesis of these materials are needed, as well as new tools for their nanoscale structural, chemical, and physical characterization.

High-surface Area Materials. Materials with large intrinsic specific surface area hold promise for hydrogen storage, and new materials with carefully designed architectures may meet the hydrogen storage needs for specific applications. These materials can involve physisorption or chemisorption of hydrogen on surfaces, as occurs with clathrates or zeolites. While these materials are unlikely to meet the required hydrogen density for on-vehicle storage on a gravimetric basis, they may prove suitable for stationary applications.

Nanophase Materials. Nanophase materials (e.g., nanoparticles and nanoporous media) offer promise for new classes of materials for hydrogen storage that can be effective for storing either atomic or molecular hydrogen. For example, nanoscale hydrogen storage materials might provide short diffusion distances, new phases with better capacity, reduced heats of adsorption/desorption, and faster kinetics, as well as new surface states capable of catalyzing hydrogen dissociation.

Undissociated Materials. For undissociated molecular hydrogen storage, concepts for new materials with specific surface chemical functionalities need to be evaluated, leading to the formation of intermediate-strength bonds between the surface and molecular hydrogen to permit efficient storage/release characteristics. These materials may also be designed with specific architectures, such as tunable pore size distributions, to enhance performance.

Characterization Techniques. Great care is required to characterize the structure, surface, and hydrogen storage/release properties of high-surface-area nanomaterials. Clearly, researchers need to identify the structure and surface properties of high-performance nanomaterials to facilitate modeling and provide an understanding of the structure-property relationships. Characterization of nanoscale materials presents a considerable challenge primarily because, at the nano scale, existing analytical tools lack the required detection sensitivity. Thus, new characterization tools that have increased detection sensitivity, while retaining high detection selectivity, need to be developed.

Theory and Computation

A fundamental understanding of the hydrogen interaction in materials requires a synergistic approach involving both theory and experiment. Theory and computation can be used not only to understand experimental results, but also to guide them. The large advances in methodology (theory and algorithms) and increases in computational power in recent years have opened up new possibilities for theoretical studies of hydrogen storage. Broadly speaking, four classes of theoretical approaches are available for studying these systems: (1) the quantum mechanical approach, which yields information about electronic structure and chemical bonds; (2) the empirical and semi-empirical approaches, which yield atomistic information about hydrogen trapping at vacancies and impurities; (3) the mesoscale approach, which yields information about average trapping at distributions of defects; and (4) the continuum methods, which yield information about transport through a real material.

Coupled with molecular dynamics, these approaches can predict the thermodynamic properties and time evolution resulting from thermally activated processes such as diffusion and chemical reactions. Direct simulations of time evolution can cover time scales of picoseconds (10^{-12} s) when using quantum mechanical methods to evaluate atomic forces, but up to nanoseconds (10^{-9} s) when empirical and semi-empirical potential energy functions are used. Mesoscale approaches, such as kinetic Monte Carlo, can cover much longer time scales (up to seconds), and continuum methods can cover time scales from seconds to hours. The behavior of hydrogen spans all these length and time scales and thus poses serious challenges for theory and computation. As yet, there is no general approach for integrating simulations on different length and time scales. Modeling is mainly carried out separately at each length and time scale with limited integration. Researchers need to find ways to integrate these methods in order to address the problems involving hydrogen production, storage, and use. The real challenge is to couple these approaches so that predictions of real materials behavior can be made with a solid physical and chemical basis.

Theory and computation can play two important roles in the development of hydrogen storage materials. First, each approach allows researchers to understand the physics and chemistry of the hydrogen interactions at the appropriate size scale. Researchers can use information generated at any of these levels to help choose new hydrogen storage materials. The second, and perhaps more powerful, application of theory and computation lies in the boot-strapping of information between theoretical levels. For example, the energetics data obtained from quantum mechanical calculations are used directly in the development of the semi-empirical potentials. The trapping energetics and kinetics obtained by using these potentials are used in a mesoscale calculation to determine effective properties as a function of microstructure. These results are then used directly in continuum calculations to predict the recycling properties of an engineering material. In principle, the entire process of material selection, processing, and — ultimately — material performance in service, can be accurately simulated.

To ensure that the modeling is accurate, it is critical that predictions at each size scale be compared with appropriate experimental information. Perhaps the largest contribution that theory and computation can make in the development of new hydrogen storage materials is to reduce the number of choices (and thus reduce the required development time) that researchers must investigate. Only through a multiscale approach, such as the one described above, can we expect predictions accurate enough to be useful in materials development. Examples of research areas for theory and computation are outlined in the sections that follow.

Hydrogen Interactions with Surface and Bulk Microstructures. Computational tools are needed to understand the interaction of hydrogen with surfaces and determine how hydrogen diffuses and interacts with step edges. The sites that hydrogen atoms occupy in the bulk, the energy barriers for its diffusion, its effect on the electronic structure of the host, its interaction with lattice defects (such as vacancies, voids, impurities, grain boundaries, and dislocations), and the effect of temperature and pressure on hydrogen interaction — all of these are important for a comprehensive understanding of hydrogen storage in materials.

Hydrogen Bonding. Theory can help elucidate how the ionic and covalent bonding between hydrogen and metal atoms in light complex metal hydrides can be changed by alloying. Similarly, an understanding of the role of catalysts/dopants in altering the nature of hydrogen bonding in these hydrides can be provided by theory and modeling.

Role of Nanoscale. Computational modeling can provide insight into the relationship of size and shape to the nature of hydrogen bonding and binding energies in nanostructured materials, and can thus help with the design of nanostructured versions of hydrides that may provide more efficient hydrogen storage capabilities.

Surface Interactions. In porous materials, such as clathrates, researchers need to understand how the hydrogen interacts with the surface of the materials.

Multiscale Hydrogen Interactions. A multiscale approach is needed to understand the electronic structure, dynamics, and energetics of hydrogen in materials.

Functionalized Nanocarbons. Theoretical modeling of functionalized nanocarbon materials is needed to guide the development of carbon-based nanostructures that demonstrate more desirable hydrogen storage properties than their pristine, nonfunctionalized counterparts.

CROSS-CUTTING ISSUES

Several of the basic research needs required to attain the goals for efficient hydrogen storage are similar to those needed in hydrogen production and use.

Catalysis

Catalysts can play a critical role in improving the kinetics and thermodynamics of hydrogen storage systems, allowing improved uptake and release of stored hydrogen with reduced need for thermal activation. The role of dopants in improving hydrogen release from metal and complex hydrides needs to be understood at the molecular level to facilitate development of improved storage materials.

Nanostructured Materials

A major advantage of nanostructured materials for hydrogen storage is that specific architectures can be designed into these materials to enhance the weight percentage of stored hydrogen and to control the kinetics involved in the adsorption/release of hydrogen. Incorporation of tailored nanostructures may allow dissociative hydrogen storage materials, such as the metal and complex hydrides currently used in bulk for hydrogen storage, to demonstrate substantial improvements in storage/release. Carbon nanostructures (including nanotubes and nanohorns) and the analogous non-carbon–based nanostructures show particular promise for effective nondissociative hydrogen storage. In both types of hydrogen storage, fundamental studies of the atomic and molecular processes involved in hydrogen adsorption and release are needed to enable the design of improved storage materials.

Theory, Modeling, and Simulation

As described above, close association of theory, modeling, and simulation with experiments is critical to understanding the chemical and physical processes involved in hydrogen storage and the subsequent design of improved storage materials.

Analytical and Characterization Tools

Major improvements in current analytical techniques are needed to meet the high sensitivity requirements associated with nanostructured materials, while maintaining high specificity in characterization. Ideally, researchers would like to be able to study hydrogen adsorption and release processes on individual nanotubes; such studies would include determination of the amount of hydrogen adsorbed, identification of the site of adsorption, and characterization of the physical/chemical parameters involved in hydrogen adsorption at a particular site. Many of the specialized experimental techniques available at synchrotron and neutron user facilities will be valuable for studying hydrogen storage materials. In particular, neutron scattering will provide unique capabilities for understanding the interactions of hydrogen with a storage material. These tools will also benefit from developments that will enhance the sensitivity of measurement tools to permit the detailed characterization of nanomaterials.

Safety

As with all technologies needed to achieve a hydrogen-based economy, safety issues need to be considered for technologies and materials that will be deployed for hydrogen storage devices. In particular, improvements are needed in the containers used to store gaseous and liquid hydrogen in the short term, and in solid-state hydrogen storage materials in the long term. Hydrogen presents particular challenges for the materials used for storage containers, including factors that affect container lifetime and leakage. Fundamental research will be needed to understand materials degradation and failure processes to allow design of improved materials for hydrogen storage.

CONCLUSIONS

Hydrogen storage is a key technology required for attaining a hydrogen-based economy. It represents the most challenging technical hurdle to reaching this goal. The storage capabilities of current technologies, such as gas and liquid hydrogen storage in containers or use of simple hydrides, are far from the requirements for viable onboard automotive storage. Simple, incremental improvements in these technologies will not allow researchers to meet the rigorous storage requirements. The breakthroughs needed to reach FreedomCAR targets will be attained only by fundamental research that will reveal the underlying principles in controlling hydrogen uptake and release. Understanding these chemical and physical processes will allow new, higher-efficiency, recyclable hydrogen storage materials to be designed.

Nanoscience has the potential to provide revolutionary new capabilities that will have a profound impact on hydrogen storage. Improvements in today's metal and complex hydrides can be achieved by careful design of two- and three-dimensional nanoarchitectures that include dopants and tailored voids to improve the weight percentages of stored hydrogen and provide control of the kinetics and thermodynamics of hydrogen storage/release. Carbon and non-carbon nanostructures have shown particular promise for the storage of molecular hydrogen. New insights into the mechanisms of hydrogen uptake and release in these materials are needed to design new functionalization strategies and architectures for improved hydrogen storage.

Fundamental studies of nanomaterials used in hydrogen storage will require the availability of new highly sensitive and selective analytical tools to match the scale requirements of these nanomaterials. Finally, discovery of new hydrogen storage materials will require close coupling between experimental and computational research activities to elucidate the physical and chemical processes involved in hydrogen storage and release, while modeling and prediction of these processes are needed so that improved materials can be designed efficiently.

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BASIC RESEARCH CHALLENGES FOR FUEL CELLS AND NOVEL FUEL CELL MATERIALS

CURRENT STATUS

Fuel Cells in the Hydrogen Economy

Fuel cells provide the final step in a hydrogen economy in which chemical energy carried by hydrogen fuel is transformed into electrical energy. Fuel cells are especially well suited for this task because they operate with high efficiency, they do not produce pollution, and they provide electrical power that can be tailored to a wide variety of applications — from large stationary power plants to transportation vehicles to consumer devices like cell phones and personal computers. Fuel cells link hydrogen and electricity, two highly compatible energy carriers that embody the ideals of a sustainable energy economy: they are clean, abundant, and adapt flexibly to many sources of fuel production and to many uses. The same electrochemistry that drives the conversion of hydrogen to electricity in fuel cells also drives the production of hydrogen by electrolysis of water. These two technologies — electrolysis and fuel cells — bracket the vision of the hydrogen economy as a clean and sustainable means of energy production and use. Advances in materials, electrolytes, catalysts, and nanoscale design that benefit one of these processes automatically benefit the other.

The basic fuel cell types span a remarkable range of operating temperatures, construction materials, and performance specifications. Table 4 lists the basic types of fuel cells; the electrolyte, conducting ion, and operating temperature are indicated along with some notable features. A thorough and highly readable explanation of fuel cells in the hydrogen economy can be found in Larminie and Dicks (2003).

Fuel cells directly convert the chemical energy stored in molecular hydrogen to electrical energy. Because this electrochemical conversion does not rely on the heat of combustion, some fuel cells can have a higher limiting efficiency than the Carnot cycle that governs conventional "heat engine" power plants. Although fuel cells offer many advantages for a diverse set of applications, so far they have been introduced only on a limited scale and at high cost. The promise of high efficiency and low pollutant emissions continues to drive research and development (Vielstich et al. 2003). While several fuel cell technologies have been developed and demonstrated for use in the commercial and consumer market, significant challenges, some longstanding, must be overcome if fuel cells are to be used on a large scale.

Fuel cells currently under development consist of a variety of materials, designs, and technologies that are primarily determined by the operating temperature, from ambient to as high as 1,000°C (see the sidebar for a simple description of a fuel cell.) Nevertheless, there are serious and difficult obstacles to widespread implementation of fuel cell technology. Most of the challenges arise from the need for inexpensive, more-durable materials that also have better operating characteristics, especially in the case of the electrocatalysts, membranes (ionic conductors), and reformer catalysts. Reformers offer the potential for operating fuel cells by using a range of primary fuels. Some current and proposed fuel cell power systems that are

Table 4 Fuel Cell Types and Their Operating Features

Fuel Cell Type	Electrolyte	Conducting Ion	Temperature (°C)	Features
Polymer	$CF(CF_2)_nOCF_2SO_3^{2-}$	H^+ (hydrated)	60–80	High power density, Pt catalyst, must be kept wet, poisoned by CO
Alkaline	KOH	OH^-	90	High power density, cannot tolerate CO_2
Phosphoric acid	H_3PO_4	H^+	200	Medium power density, Pt catalyst, sensitive to CO
Molten carbonate	Li_2CO_3 / K_2CO_3	CO_3^{2-}	650	Low power density, Ni catalyst, needs CO_2 recycle
Solid oxide	$Zr_{0.92}Y_{0.08}O_{1.96}$	O^{2-}	700–1,000	Medium-to-high power density, accepts CO as fuel
Direct methanol	$CF(CF_2)_nOCF_2SO_3^{=}$	H^+ (H_2O, CH_3OH)	60–120	Medium power density, low efficiency, high Pt content

[a] Source: Kumar (2003).

capable of using fuels other than hydrogen may serve as transitional technologies along the path to a full hydrogen economy. These hydrocarbon-based fuel cells may be important in increasing the efficiency of fuel use and in decreasing emissions or noise, a highly valued aspect in some military, as well as in some commercial/consumer, applications. Indeed, some of the fundamental problems in fuel cell technology are independent of the fuel source, as we discuss later.

A major use for fuel cells in a hydrogen economy is in portable and mobile applications in which compact and efficient power sources are needed. Powering transportation vehicles with fuel cells is especially attractive, because it has the potential to significantly reduce automotive pollution and the production of greenhouse gases, reduce the demand for imported oil, and conserve fossil fuel reserves. Transportation applications now drive a significant fraction of research and development (R&D) on fuel cells in industrial and government sectors (U.S. Department of Energy [DOE] 2002). DOE has established target performance specifications for demonstration and implementation of transportation fuel cell technologies. These goals point out the difficult technical challenges to the development of automotive fuel cells that are sufficiently inexpensive, effective, and durable to displace current internal combustion engines. Overcoming these challenges to produce commercially viable automotive fuel cell technologies requires innovative fundamental research on the catalysts, the electrochemistry, the membrane materials, and the nanoscale behavior governing the performance and cost of fuel cells.

WHAT IS A FUEL CELL?

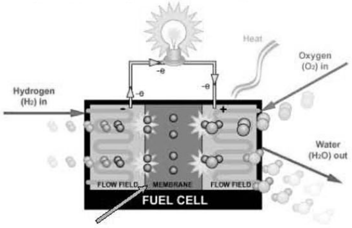
The fuel cell was invented by Sir William Grove in 1839. It was not until the 1950s, however, that the National Aeronautics and Space Administration (NASA) constructed the first practical fuel cells to produce power for space vehicles.

Fuel cells directly convert the energy released in certain chemical reactions, primarily combustion (oxidation) of hydrogen or a carbonaceous fuel, to electrical energy. Typically, combustion reactions are of interest because they release a large amount of energy per unit mass of fuel and because some of these fuels are available at relatively low cost. The reaction of hydrogen (the fuel) with oxygen (the oxidizer) to produce water is such a suitable reaction. Other fuels used in fuel cells include methane, methanol, and even gasoline. More chemically complex fuels, like gasoline, typically require pre-processing into a hydrogen-rich gas stream before introduction to the fuel cell.

The fundamental building block of a fuel cell is an electrochemical cell (see figure) consisting of two electrodes separated by an ionically conducting medium (or membrane). The ionically conducting medium can be an acid, base, or salt (in liquid, they are in polymeric or molten forms) or a solid ceramic that conducts ions; the choice of electrolyte is dependent on the nature of the fuel, the temperature of operation, and the specific application of the technology. Fuel enters the cell on the left side and oxygen enters on the right side. Any reaction products (water and perhaps carbon dioxide [CO_2] — depending on the fuel and type of cell) must also exit the cell. As fuel is oxidized, electrons are released to travel through the external load to the cathode, where oxygen consumes the electrons. The following other essential parts of a real fuel cell are omitted from the diagram: all the container and support materials that keep the fuel and oxygen flowing (but separate) and direct the reaction products out of the cell, the interconnections between a series of cells, etc.

The electrodes serve several functions. First, they must be electronically conducting. Second, they usually contain the electrocatalytic materials that facilitate the reaction of fuel at one electrode (the anode) and of oxygen at the other electrode (the cathode). Some catalytic materials are much better than others at facilitating the reactions and may themselves also be electronic conductors. Grove used solid pieces of platinum metal for both electrodes; platinum was both the conductor and the electrocatalyst. In most contemporary low-temperature fuel cells, platinum electrocatalysts are still used, but in highly dispersed form as nanoparticles.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{electrical power} + \text{heat}$$



Membrane conducts protons from anode to cathode
proton exchange membrane (PEM)

The electrocatalyst is highly dispersed in order to attain large electrochemical reaction rates that result in high electrical power output. Furthermore, for the fuel cell to function properly, the electrocatalyst particles have to be easily reached by the fuel (or by oxygen on the other side of the cell), and they also must be contacted by the ionically conducting medium and by the electronically conducting medium. Consequently, current low-temperature fuel cell electrodes consist of porous composites of ionic/electronic conductors with embedded nanosize particles of the electrocatalyst in order to obtain as high an electrical power from as small an amount of precious metal as possible. The electrode contains open pores for the fuel (and any waste products) to enter or exit the electrode. Producing electrodes that offer optimal performance is challenging.

More than 150 years after Grove's discovery, fuel cells that operate near room temperature still contain the precious metal platinum. One goal of an ambitious fuel cell R&D program is to replace the expensive platinum with much cheaper materials. No one thinks this objective will be easy to attain — after all, nothing better has been found in 150 years!

Many web sites are dedicated to fuel cells and to Sir William Grove; a few of the many interesting ones are listed below:

http://fuelcells.si.edu/basics.htm (at the Smithsonian Institution)
http://science.howstuffworks.com/fuel-cell.htm
http://education.lanl.gov/resources/fuelcells/
http://chem.ch.huji.ac.il/~eugeniik/history/grove.htm
http://www.voltaicpower.com/Biographies/GroveBio.htm
http://www.eere.energy.gov/hydrogenandfuelcells/

In this Report, we discuss primarily the challenges and problems associated with low-temperature fuel cells (operating from 40 to 150°C or 200°C) and, to a lesser extent, with high-temperature (650–1,000°C) fuel cells. While there are many possible technologies, any one of which could be the optimal fuel cell for a specific (or even most) applications, much of the recent R&D effort has focused on these two technologies. They also serve as models for discussion of the many significant challenges to the large-scale implementation of fuel cell technologies. Low-temperature fuel cells, in particular, are the focus of current automotive fuel cell R&D activities that, when implemented, would be a major component of the hydrogen economy.

Low-temperature Fuel Cells

The use of fuel cells in the transportation sector could potentially provide substantial benefits and is perhaps the largest potential market for fuel cells. However, present technology cannot come close to the cost targets that will allow substitution of a fuel-cell–based "engine" for an internal combustion engine. All current designs of fuel cells for this application are low-temperature (about 80°C) technologies based on polymeric membranes as proton-conducting electrolytes. The need for low-temperature fuel cells in this sector is driven by system considerations — in particular, overall weight and volume, fuel conversion efficiency, fast start-up times, and long out-of-use periods. Current estimates of polymer proton exchange membrane (PEM) fuel cell system costs, when extrapolated to mass production, exceed $100/peak-kW. To compete economically with the internal combustion engine, however, the cost must approach $35/kW. Present-day costs for low-volume production are roughly $3,000/kW for hydrogen-based fuel cell systems. The need to reduce the costs by nearly two orders of magnitude underscores the long pathway to the goal of automotive application of fuel cells (potential stationary applications can be viable at much higher costs in terms of dollars per kilowatt-hour).

The primary difficulties in achieving the automotive cost targets lie in the materials used in the fuel cell stack. Polymer electrolyte membranes, precious metal catalysts (typically platinum or platinum alloys), gas diffusion layers, and bipolar plates account for 70% of the cost of the system. Any two of these are projected to cost more than the target for the *full system* unless researchers can achieve significant advances in power density and materials optimization and durability.

Additional significant challenges for PEM fuel cells (PEMFCs) involve functionality and durability issues. New membranes that exhibit adequate durability and proton conduction properties at temperatures exceeding 100°C (while also maintaining these properties at low ambient temperatures) are needed because they enable the system to achieve more effective heat rejection — a must for automotive systems — as well as higher impurity tolerance in the fuel and improved overall system efficiency. Efficiency can be increased through improved thermal integration of the stack and the balance of the plant, as well as through the production of higher-quality waste heat for possible use in combined cycles. Operation in this temperature range provides a new set of challenges that are only now being addressed.

Durability of PEMFCs in transportation applications is a key issue that has been amplified in importance as fuel cell engineering has matured. Roughly 5,000 h of operating life are required, based on a simple calculation of a 250,000-km vehicle lifetime at an average speed of 50 km/h.

Performance degradation rates of the polymer membrane under the cycling conditions of automotive fuel cells can be substantial, especially as materials are pushed into higher operating temperature regimes. At present, the degradation mechanisms are only partly understood. Multiple chemical and mechanical processes undoubtedly contribute to this degradation. For stationary fuel cell applications, an even more demanding lifetime — a minimum of 40,000 h or approximately 5 yr — of continuous operation is desired.

High-temperature Fuel Cells

Solid oxide fuel cells (SOFCs) are the technology currently under most active development for applications requiring high operational temperatures (near 800°C). The solid oxide is used as the ionically conducting membrane, transporting oxygen ions from the cathode to the anode of the fuel cell. The much higher temperature of operation in SOFCs offers some advantages over most current PEM cells. A wide range of fuels, from hydrogen to hydrocarbons (especially natural gas), can be used and may enable a transition from a hydrocarbon to a hydrogen economy. In addition, in certain modes of operation, SOFCs have demonstrated the longest lifetime of any fuel cell system. For example, a 100-kW system fabricated by Siemens-Westinghouse has successfully produced power for more than 20,000 h without any measurable degradation in performance (George et al. 2002). Unlike PEMFCs for automotive applications, SOFCs in stationary applications can run for a long time without being turned off, a factor favoring long life. The waste heat production from SOFCs is at a temperature suitable for cogeneration, resulting in systems with excellent efficiencies — projected to be up to 85%. Phosphoric acid fuel cell systems operating at 200°C have demonstrated combined heat and power efficiencies in excess of 80% (Maston 1998). Until major issues such as unacceptably poor power densities and cost are addressed, however, the SOFCs that have been developed to date cannot be broadly commercialized. Many of the key barriers are materials-related. For example, materials corrosion, inability to thermally cycle, and integrity of seals are still major issues (see subsequent discussion). Targets of less than $400/kW have been set but, as in the case of PEMFCs, there are presently no obvious pathways for reaching such cost targets.

If these challenges can be overcome, SOFCs may benefit the transportation, as well as the stationary power, sector. For transportation, auxiliary power units can be used to maintain power for refrigeration and human comfort with the engine power off, providing benefits in terms of lower emissions. While SOFCs, in contrast to PEMFCs, can easily be operated with natural gas (or even gasoline) in addition to pure hydrogen, their poor durability under extended thermal cycling (heating to operation temperature and then cooling to room temperature) does not yet allow them to be used in configurations in which frequent shutdowns are required. On the other hand, in stationary applications, where shutdowns do not occur very often, extremely high efficiency can be attained for combined-cycle and cogeneration systems.

Many of the engineering challenges in design of the electrode assembly, the fuel-oxidizer-water-waste flows, etc., have been met in both the low- and high-temperature fuel cells to at least a first approximation. Major challenges that remain (i.e., cost, durability, efficiency, insensitivity to impurities) can be addressed only by developing new and better materials in conjunction with continued (and in some cases, accelerated) advancement in both our fundamental understanding of fuel cell processes and engineering to incorporate new approaches. The proportions of this challenge are immense, and the need to address fundamental scientific questions associated with fuel cells is immediate.

These challenges represent a significant opportunity for a broad range of R&D in chemistry, nanoscience, and materials sciences. The primary needs are addressed more specifically in the following pages.

BASIC SCIENCE CHALLENGES, OPPORTUNITIES, AND RESEARCH NEEDS IN HYDROGEN FUEL CELLS

The heart of the fuel cell is formed from two electrocatalytic electrodes separated by an ionically conducting membrane — the so-called membrane electrode assembly (MEA). Although the specific challenges are different for different fuel cell technologies, the underlying key materials issues are similar: cost, performance, and durability.

Cathodes

In all fuel cell technologies, independent of the fuel and operating temperature, oxygen is reduced at the cathode. In all cases, independent of the particular material used as the cathode electrocatalyst, the overpotential for the reduction of oxygen at operating currents is too high. This overpotential is caused by the slow electrochemical kinetics of oxygen reduction, and it represents an additional driving force needed to obtain significant currents in the cell. The result is a decrease in cell voltage, with a corresponding loss in efficiency. The problem is especially severe in near-ambient-temperature fuel cells, in which the only cathode catalysts that are currently acceptable and used are Pt or Pt-based alloys. The high overpotential results in a loss of 300 to 400 mV out of a Nernst voltage of 1.23 V per cell. Furthermore, the activation overpotential for oxygen reduction at Pt is high even at very low currents, as illustrated in Figure 10. Thus, cheaper materials with lower overpotential are sorely needed.

Platinum is generally used in the cathode as carbon-supported nanoparticles. Mass-specific power densities range from 5–10 g_{Pt}/kW (i.e., \$125–\$250/kW) for direct methanol fuel cells (DMFCs) to 0.5–1 g_{Pt}/kW (i.e., \$12.5–\$25/kW) for the others. The lower mass-specific power densities observed for DMFCs arise mainly from poor anode kinetics and even poorer cathode performance caused by methanol crossover, requiring much higher noble metal loadings compared with hydrogen-fueled PEMFCs. While noble metal cost is less critical for applications in which small power sources (in the 1-W range) are needed, Pt cost and Pt supply constraints for large-scale automotive applications require mass-specific power densities in the range from 0.1 to 0.2 g_{Pt}/kW (see Figure 11) (Gasteiger and Mathias 2002). Dramatic improvements in overall performance, efficiency, and cost can be achieved by reducing the overpotential. The high overpotential for oxygen reduction, however, is a long-standing problem and, so far, research on the fundamental processes of oxygen reduction and catalysis has not yielded a breakthrough. Clearly, new insights from theory and modeling, new creative ideas, and (most likely) new materials are needed.

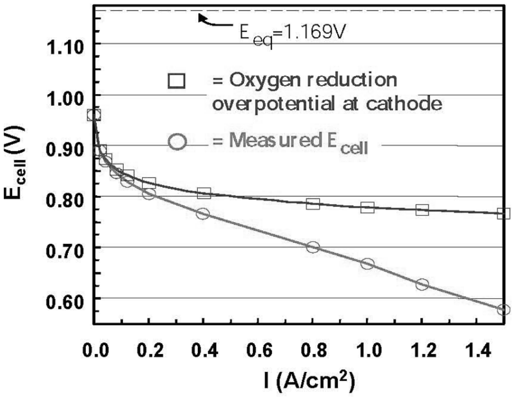


Figure 10 (Lower curve) Cell Voltage (E_{cell}) of a State-of-the-art H_2/Air Membrane Electrode Assembly Operated at 80°C versus the Current Drawn from the Cell (in amp/cm^2) (Gasteiger and Mathias 2002) (The equilibrium [theoretical] cell voltage [1.169 V] is shown by the dashed line at the top of the figure.) (Upper curve) Reduction from the Theoretical Value Caused by the Oxygen Reduction Overpotential at the Cathode Alone (Note that the overpotential is large at all but the very lowest currents. The remaining loss in potential at a given current is caused by internal resistance in the cell and to O_2 gas transport limitations through the air in the porous cathode composite.)

The oxygen reduction overpotential often increases as the hours of operation increase. Depending on the exact operating conditions, voltage degradation rates of 1–100 µV/h are typical. System requirements (heat rejection, performance) generally drive the system temperature to the upper limit of the specific fuel cell system (e.g., greater than 80°C for automotive PEMFCs), where degradation rates are highest. Current automotive PEMFCs operating at >80°C show degradation rates of >50 µV/h; <10 µV/h are required (5,000-h life). Stationary PEMFC systems operate at ≤80°C, with degradation rates from 10 to 20 µV/h, while <1 µV/h is required (40,000-h life). Researchers believe that these degradation phenomena are caused by chemical or structural changes in the catalysts or their supports that are intrinsic or driven by the presence of various impurities; however, fundamental studies of the mechanisms of degradation are sorely needed.

The state of understanding in this area is improving, and several Pt alloys have been shown to provide higher oxygen reduction rates. A promising way of reducing Pt loading, and perhaps increasing reduction activity, may involve a metal nanoparticle surface "decoration" by using a submonolayer-to-monolayer amount of Pt. This approach showed promising results with the

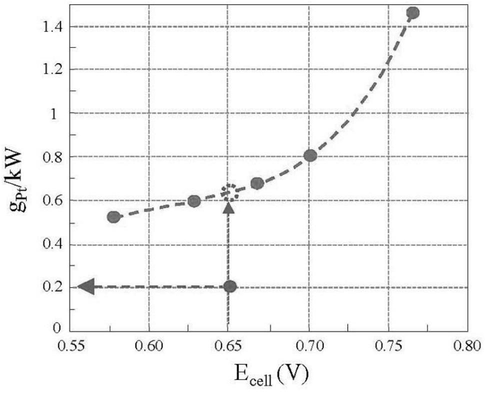


Figure 11 Mass of Pt Used in the Fuel Cell — a Critical Cost Issue (This plot shows the power density per gram of Pt that can be obtained in a state-of-the-art H_2/air membrane electrode assembly operated at 80°C at different operating cell potentials. The present design is to operate at a cell potential of 0.65 V, which must use about 0.65 g of Pt nanoparticles to attain a power output of 1 kW. For cost, weight, and volume reasons, the Pt loading must be decreased to about 0.2 g of Pt/kW output [Gasteiger and Mathias 2002].)

Pt/Ru anode catalyst (Brankovic et al. 2001). However, the long-term stability of these systems in the PEMFC environment and at cathode potentials is still unproven. It is therefore critical to understand the fundamental principles underlying both the performance and corrosion stability of Pt alloys at all particle sizes and coverages and, of course, of any new materials that are proposed or invented.

Finally, the currently used carbon supports for Pt (either fully or partially graphitized materials) corrode under certain system-imposed operating conditions (e.g., idle operation, start/stop) and thus limit fuel cell system durability. More durable support materials are needed. Recent advances in nanostructured carbons, such as cup-stacked carbon nanofibers, have been introduced for use in fuel cell and lithium (Li) battery applications in Japan (Endo et al. 2002). Such materials might be useful for fuel cell cathodes.

Some biological enzymes apparently reduce O_2 at a high rate and low overpotential (Katz et al. 2003). These enzymes are unlikely to be directly useful in fuel cells for many reasons, including their instability at fuel cell operating temperatures. We know the stoichiometry and structure of the inorganic core of the enzyme. The challenge lies in mimicking this property in more robust materials by understanding the operation of the enzyme — whether properties of the organic part, such as flexibility and stereochemical blocking, also play an important role. These enzymes hint that there may be a solution to the long-standing challenge of the efficient electrochemical reduction of oxygen — a solution suitable for fuel cell applications. Clearly, considerable research is required to determine whether bio-inspired materials that are significantly cheaper and more efficient than Pt can be used as cathode electrocatalysts in low-temperature fuel cells.

A conducting perovskite, such as strontium-doped lanthanum manganate (LSM) (e.g., $La_{0.84}Sr_{0.16}MnO_3$), is normally employed as the cathode electrocatalyst in SOFCs. At typical operating conditions (800°C and 0.5 A/cm^2), the overpotential is 100–300 mV. There is a major push to reduce fuel cell operating temperatures to replace some of the ceramic components with metals, which have lower manufacturing costs. The metal components that would be used in a reduced-temperature fuel cell would serve as interconnects between individual fuel cells in a fuel cell stack. As the temperature is reduced, there will be a need for a higher-conductivity electrolyte other than zirconia. Current materials under development include $(La,Sr)(Ga,Mg)O_3$ (LSGM) and doped ceria as oxide ion conductors and various oxide proton conductors (Doshi et al. 1999). The real challenge to reduced-temperature operation is the cathode material. $(La,Sr)MnO_3$ is only moderately effective at high temperatures and has unacceptable performance at lower temperatures. Alternatives that have been considered are $(La,Sr)(Co,Fe)O_3$ (LSCF) and $(Sr,Sm)CoO_3$ (SSC). While these materials exhibit potentially higher performance than LSM cathodes, they are difficult to process due to chemical reactivity and thermal mismatch with the electrolyte.

Anodes

In most fuel cells, the main issue is "poisoning" or fouling by impurities in the hydrogen feed stream such as sulfur, hydrocarbons, and carbon monoxide (CO) (CO is only a problem in low-temperature cells). The overpotential for the oxidation of high-purity H_2 is quite small. In fact, for Pt electrodes used in H_2-operated PEMFCs, the anode overpotential is on the order of 10–50 mV, while the cathode overpotential ranges from 300 to 500 mV (Gasteiger et al. 2003). Impurities that react with the anode, however, can substantially increase the overpotential. The same situation occurs in high-temperature SOFCs when hydrogen is the fuel and Ni is used as the anode electrocatalyst. A higher tolerance of impurities would allow the use of less-pure H_2, reducing the cost of hydrogen production. Lower-temperature fuel cells also use precious metals as the anode electrocatalyst; a higher impurity tolerance would reduce the amount of precious metal needed. CO tolerance of available catalysts is marginally acceptable at present but could be improved. Sulfur tolerance is quite low (in the 10-parts-per-billion [ppb] range). The best tolerance to CO has been achieved by combining catalysts with passable tolerance (especially Pt/Ru alloys) with air injection to remove CO from electrode surfaces (Tada 2003). However, the air injection can lead to durability problems.

Anode catalysts that can use fuels other than hydrogen may also be important for several reasons. They may be useful in the transition from hydrocarbon fuels to hydrogen fuel. Pt/Ru alloys have been used for some time as the catalyst in near-ambient–temperature methanol fuel cells. Although the use of Pt/Ru alloys in such cells is not without problems, its performance is considerably better than that of pure Pt. Recently, reports of other materials, such as ordered intermetallic PtBi, which are potentially useful catalysts for the oxidation of formic acid, methanol, etc. (Casado-Rivers et al. 2003), suggest that these materials will be tolerant of at least hydrocarbon and CO impurities. Studies of the sulfur tolerance of these new materials have yet to be undertaken. To make real headway, such catalysts should be significantly more tolerant of impurities than Pt/Ru. Researchers have not yet identified catalysts that operate near ambient temperature and can completely oxidize fuels that contain more than one carbon atom, but such catalysts would be very desirable for using ethanol or other fuels that are not as poisonous as methanol. Finally, if such catalysts can be found, they are likely to be very useful for catalyzing a variety of industrial organic processes, particularly oxidation reactions. So the discovery of novel anode catalysts may impact many other technologies, not all of them directly related to fuel cells.

The situation is similar in SOFCs, in which the poor ability of Ni to catalyze hydrocarbon electroreduction at reduced pressure (carbon deposition is catalyzed instead) and the susceptibility of Ni to oxidation are important problems. High-priority electrode research needs are discussed in the following sections.

Low-temperature Cathode Catalysts. In PEMFCs, improvement of cathode catalysts would not only increase efficiency, but would also lower the mass (and cost) of precious metals and result in system improvements (e.g., less heat rejection). If this challenge can be met, higher-temperature membranes (120°C or so) may not be required for automotive applications. This is, however, a monumental challenge; electrochemists have been working on it for half a century.

In the short term, researchers need to develop materials processes for low-temperature electrodes that reduce the precious metal content in order to reduce cost. These processes could include depositing precious metals only on the *surface* of nanoparticles or using alloys or intermetallic compounds that contain less expensive elements but maintain (or even enhance) the catalytic activity of Pt. Precious metal that is not at the surface of the electrocatalytic nanoparticles is inactive. Reducing Pt content might be achieved via Pt-skin catalysts, Pt-decoration of other nanoparticles, and/or improved support materials; however, the long-term structural and chemical stability of such surface coatings is not known. Another alternative to platinum cathode catalysts is Pt alloys (Thompsett 2003), but their long-term durability has not yet been demonstrated. If the catalyst is supported on a second material, there is also a need to develop catalyst supports that are more resistant to corrosion at high voltages (i.e., idle fuel cell conditions) and transient operation (i.e., start/stop) to improve system durability.

In the long term, the discovery of oxygen reduction catalysts containing much less (or no) precious metal is highly desirable. The breakthroughs may come from materials that are bio-inspired — mimicking those that are as efficient as some enzymes — and from exploiting combinatorial synthesis and analysis methods to rapidly and efficiently search large phase spaces to identify materials with potentially improved catalytic activity. These complex materials may be produced as nanoparticles, which could facilitate high reaction rates and high-power output. Indeed, if the catalysts are active only as nanoparticles (as is the case for gold cathodes in alkaline cells), we can design synthesis strategies to prepare such particles as part of a combinatorial synthesis approach. Theory and modeling of oxygen reduction processes at different catalytic surfaces could guide the synthesis of new cathode materials or otherwise help in the search. Finally, theory could support the effort by helping researchers to understand experimental results for known catalysts.

High-temperature Cathode Catalysts. The main impediment to longer life of SOFCs is the high operating temperature. Lowering the operating temperature by several hundred degrees could significantly improve their lifetime, as well as lower the cost. Two factors currently prevent lower-temperature operation: the poor activity of present cathode materials at lower temperatures and the low oxygen ion conductivity of known, durable solid oxide membranes. Clearly, inventing and developing new materials to address these needs is critical. As with low-temperature cells, combinatorial synthesis and analysis methods may be able to more rapidly and efficiently identify new materials candidates. Also, as with low-temperature cells, modeling and theory could play an important role.

Anodes. The need here is for considerably improved impurity tolerance, especially to sulfur, hydrocarbons, and CO (the last in low-temperature fuel cells only). Improved impurity tolerance would allow the use of less pure hydrogen and perhaps hydrocarbon-based fuels, a potentially useful transition technology. Ordered intermetallic compounds are one potential class of materials that have recently been shown to be tolerant of CO and hydrocarbons, even at room temperature. In fact, such materials may be suitable ambient-temperature electrocatalysts for simple fuels such as methanol (Casado-Rivers et al. 2003). Whether such materials would be similarly effective as anode catalysts in high-temperature fuel cells remains to be demonstrated. In addition, based on earlier results using Cu, researchers believe that Ni in SOFC anodes may be replaced by other inexpensive materials to eliminate the coking problems, boost catalytic activity, and tolerate (or even use) C_2 to C_{10} hydrocarbons. In both cases, sulfur-tolerant anodes would be very desirable.

Understanding Electrocatalysis at the Atomic Level. Well-defined fundamental experiments (e.g., using single crystals) to understand oxygen reduction mechanisms at the surfaces of known materials (Pt, Pt-alloys, Au) and novel materials are needed. Such experiments should not be limited to acid environments. For example, work in alkaline environments may improve our fundamental understanding of why a gold catalyst is active in alkaline and not in acid electrolytes. Breakthrough catalysts for alkaline fuel cells would make such fuel cells attractive for many diverse applications. It is also important to expand this understanding to include interfaces that mimic the conditions at real electrodes that are only partly hydrated so that gases have access to the same surface.

At the same time, improved methods of modeling experimentally realistic electrode phenomena are sorely needed. For example, modeling and simulation have progressed to the point that studies of the dissociation of oxygen on electrocatalyst metal surfaces in the presence of an electrolyte and as a function of potential could be carried out at a high enough level of accuracy to be useful (see Figure 12). Such calculations may provide insights that can be translated into the development of new materials.

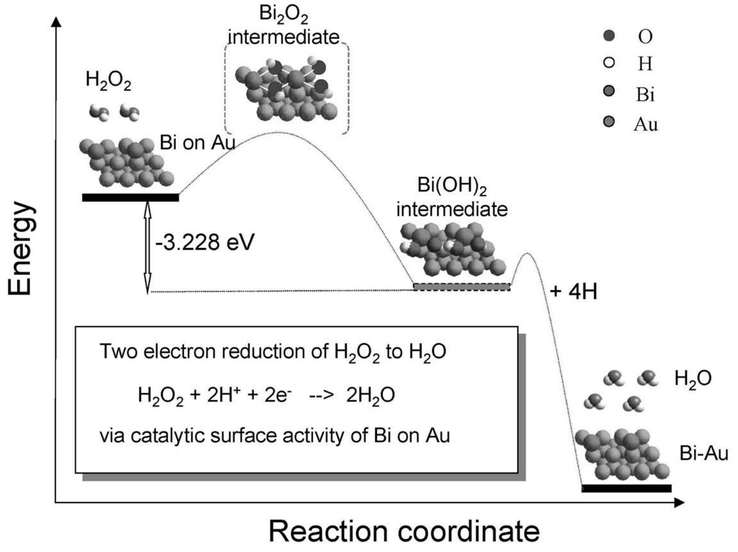


Figure 12 Simulation of the Hydrogen Peroxide Reduction Mechanism by Catalysis on the Bi/Au (111) Surface (The 2 × 2 structure of Bi on Au is a key factor driving the dissociation of the peroxide O-O bond [Sources: Gewirth 2003; Li and Gewirth 2003].)

Membranes

Higher ionic conductivity, better mechanical strength, lower cost, and longer life are all important issues for fuel cell technologies. For near-ambient temperature cells, polymer electrolytes (Nafion is the commercial membrane) must be hydrated to operate. Without complex high-pressure systems, hydration is lost above 80°C; fuel cells ideally should operate at 120°C for heat dissipation reasons (Gasteiger and Mathias 2002; Masten and Bosco 2003). It appears that polymer membranes are easily degraded under high power and on/off cycling. Macroscopic holes can appear even after relatively short-term use. The membranes are also sensitive to ionic impurities produced when the metal components of the fuel cell corrode. Clearly, polymer membranes need considerable improvement.

The polymer membranes presently available for fuel cell applications can be divided into two general classes. Perfluorosulfonic acid (PFSA)-based membranes (e.g., Nafion) have long been the standard. Membranes based on aromatic sulfonic acid moieties have been the primary class of materials investigated as alternatives to PFSAs. The latter class includes a wide range of materials, including sulfonated poly(phosphazenes), sulfonated poly(sulfones), sulfonated poly(ether ketones), and sulfonated poly(trifluorostyrenes), among others. An additional wrinkle to the membrane theme is the inclusion of the proton-conducting phase within a network. Examples include materials prepared by Gore and by Foster-Miller R&D scientists. Advantages of the Foster-Miller approach include (1) the excellent mechanical properties of the membranes, which enable the preparation of very thin (and thus low-resistance) films, and (2) the resistance to swelling of such films, leading to small-dimensional variations with changes in water content. The swelling resistance is highly desirable for fabrication purposes.

Available PFSAs have most of the necessary properties for a good fuel cell membrane. The most significant drawbacks of the PFSA membranes are their relatively high cost, their dependence on water for conduction, and their limited stability at temperatures substantially in excess of 100°C. These last properties are particularly unfortunate because recent work has suggested that substantial improvements in fuel cell performance, either in the presence of CO or when using DMFCs, can be achieved by operating at temperatures above 150°C. Much of the development of aromatic-based membranes has focused on the demonstrated improved thermal stability of the membranes. These membranes, however, are still vulnerable to the loss of conductivity upon loss of water. It is thus at least as difficult to maintain adequate conductivity for these materials. In fact, the conductivity drop is especially severe for aromatic-based membranes because the water lost is associated with membrane swelling, and the acid sites on sulfonated aromatics are less acidic than those of PFSAs.

Water in current proton-transporting membranes is conveyed via two primary mechanisms: electro-osmotic drag of water by protons transported from anode to cathode and diffusion of water along any concentration gradients. In a polymer electrolyte fuel cell, these two mechanisms balance to produce the water distribution in the membranes: electro-osmotic drag and the oxidation reaction tend to create an excess of water in the vicinity of the cathode, while back-diffusion tends to flatten the water concentration profile in the membrane. Generally, researchers want to maximize proton conduction at all water contents and minimize electro-osmotic drag.

To understand water management and the conductance of a fuel cell membrane, researchers need to determine the protonic conductivity, water diffusion coefficient, and electro-osmotic drag coefficient — all as functions of water content in the membrane.

Various approaches to novel polymeric membranes arise from simple (and often simplistic) pictures of the necessary elements of proton conduction in polymer electrolytes. Such pictures need to be replaced with a sophisticated set of guiding principles that are based on carefully designed and executed experimental and theoretical studies. A thorough understanding of proton conduction in electrolyte membranes at the molecular level is still lacking. Such an understanding is likely to aid synthetic chemists in designing new membrane materials.

Another possible approach is to develop low-temperature electrolytes that transport protons in the absence of water. Some research indicates that such a solution may be possible, but many problems, including low conductivity and water solubility, remain (Haile et al. 2001). If solid or polymeric electrolytes that transport other ions such as hydroxide (OH^-) could be found, novel fuel cell technologies could be developed (see subsequent section on Alternative Fuel Cell Technologies).

The electrolyte most commonly employed in SOFCs is yittria-stabilized zirconia (YSZ). As noted above, there has been a move to develop SOFCs that operate at reduced temperatures, primarily for reasons of corrosion resistance and cost and secondarily for reasons of thermal cyclability. Attaining sufficiently low electrolyte resistance at temperatures of ~500°C requires either considerably reducing the YSZ membrane thickness (but so far this is only practical down to thicknesses of about 5–10 µm) or pursuing alternative electrolytes. Materials currently under development include $(La,Sr)(Ga,Mg)O_3$ (LSGM) and doped ceria as oxide ion conductors, as well as various oxide proton conductors, such as $Ba(Zr,Y)O_3$. The doped lanthanum gallates have been demonstrated to have ion conductivities at least ten times better than those of YSZ (Feng and Goodenough 1994), and doped ceria has an even higher conductivity (Steele 1994).

Ceria is generally unsuitable for high-temperature applications because of the electronic conductivity caused by the reduction of Ce^{4+} to Ce^{3+} and associated losses in efficiency. At reduced temperatures (~500 °C), electronic conductivity decreases to negligible levels, enabling high open-circuit potentials and, in principle, good efficiencies can be achieved (Huang et al. 2001). A second challenge associated with the reduction of ceria is the volume expansion under low oxygen partial pressures. The result of such expansion is the generation of significant internal stresses across the electrolyte, exposed to oxidizing conditions on one side and reducing conditions on the other. One strategy for alleviating these stresses is fabrication of very thin electrolyte membranes, which would be desirable in any case to enhance fuel cell performance.

In the case of LSGM, challenges arise from the reaction of this material with the anode electrocatalyst (Ni). The most common solution to this problem has been to incorporate ceria interlayers between the electrolyte and anode (Huang et al. 2001), but this introduces significant fabrication challenges and uncertainties for long-term thermodynamic stability. Moreover, LSGM and related materials undergo structural transformations after prolonged use, and these transformations lead to decreases in the conductivity. A large number of research groups in Japan and Europe are focusing on addressing the challenges facing samaria-doped ceria (SDC) and LSGM-based fuel cells and finding materials with even higher oxygen-ion conductivity. In contrast, not much work in this area is being carried out in the U.S. Because the potential payoff for developing better electrolytes is so great, this area is one that clearly requires serious investigation. High-priority research needs for membranes are discussed in the following sections.

Better, More Durable Membranes. This is a high-payoff area for fuel cell systems. Polymeric membranes that conduct protons (or other ions, such as hydroxide or even oxide) and remain hydrated to 120–150°C are sorely needed to reduce the purity requirements of the hydrogen fuel and enable the use of non-precious–metal catalysts. Of course, such materials also need to have mechanical and structural integrity, as well as improved durability. These goals can likely only be achieved by development of new polymeric, inorganic/ceramic, or hybrid materials. Perhaps nonhydrated proton conductors can be designed to have high conductivity in this temperature regime and even up to 200–300°C. While such high temperatures are less likely in automotive applications, they can easily be tolerated in stationary applications. In SOFCs, stable oxide ion conducting materials with higher conductivities than YSZ — especially at lower temperatures — are badly needed to enhance fuel cell reliability by decreasing corrosion and causing less thermal stress in all the SOFC components. Severe limitations in thermal cycling are related to thermal expansion differences between electrodes and the electrolyte, while interfacial reactions at higher operating temperature limit component lifetimes.

Better Understanding of Electrodes and Electrolytes. Understanding and controlling the structure and morphology of the electrodes and electrolytes and their evolution during operation is crucial to maximizing fuel cell performance. Modeling the electrochemical processes at the electrode-electrolyte interface is essential for optimizing fuel cell electrodes. As theory and modeling become more sophisticated and more widely applied to understanding ion transport, we hope that some guidance for the materials synthesis community may be forthcoming to illuminate the atomistic characteristics that need to be included in new materials.

Membrane-electrode Assemblies

Electrocatalysis in fuel cells requires the efficient interconnection of the array of catalyst particles with transport pathways for electrons, protons, and gases. These three interpenetrating nanoscale percolation networks must be optimized to produce acceptable performance of the electrode. Mass transport limitations within the cathode catalyst layer are a fundamental limiting factor in fuel cells today. If and when better catalysts become available, improving this aspect of membrane-electrode assemblies (MEAs) will become the next important target.

In present-day PEMFCs, for example, the necessary functionality is achieved by the formation of “thin-film composite” electrodes with interpenetrating networks of Pt-coated carbon, ion conductors, and pores. Nonetheless, access to the Pt is not ideal, and mass-transport–related voltage losses occur at high current densities; these losses are often driven by “flooding” of the electrodes and the diffusion medium caused by less-than-optimal management of by-products, especially water. A process or materials system that “self-assembled” these interpenetrating networks into an optimal geometry would be a seminal advance. Hints that such “self-assembled” structures could be prepared are found in the beautiful sequence of ordered phases that have been discovered in multiple component block copolymers (Bates and Fredrickson 1999). Perhaps these can be exploited to produce a more rational design for MEAs. Control of nanostructure in materials systems has advanced substantially in recent years (Garcia et al. 2003), and the preparation of functionalized systems using these concepts could be a highly fruitful path for future research.

One often-overlooked component of the PEM-based MEA is the gas diffusion layer (GDL), which mediates the flow of gases and water between the flow channels into the cell and the catalyst layer. Present-day materials used in this application are based on either carbon cloth or carbon paper macroporous substrates, usually wet-proofed with polytetrafluoroethylene (PTFE, or Teflon™) and sometimes filled with carbon-blacks and/or graphite particles (Mathias et al. 2003). Generally, these diffusion media substrates are coated with a so-called “microporous layer,” which facilitates the removal of water from the electrodes. The GDL (i.e., the diffusion medium substrate and a suitable microporous layer) attempts to control water droplet formation via structure and hydrophobicity controls, thus maintaining water balance in the cell. Understanding the details of mass transport and its relation to structure in these materials is in its infancy, and further improvements will require detailed fundamental understanding and materials characterization, as well as modeling of the two-phase transport phenomena in this component. High-priority research needs for MEAs are discussed in the following section. Also, a brief explanation of neutron imaging of fuel cell operation is provided in the sidebar.

Understanding and Controlling Nano- and Micro-scale Structure. Both materials advances and new concepts are needed in this area. Understanding and controlling by design the three-part percolation network for the electrodes is critical. Each network is structured on the nanoscale (for example, the catalyst particles in low-temperature electrodes are 3–5 nm in size). Experimental and modeling approaches to this problem are needed and must be integrated. Developing new methods for characterizing the "buried" electrochemical interfaces is also necessary, and an understanding of the local environment surrounding catalyst particles could lead to a better definition of the desired features in optimized materials. Finally, studies of the compatibility and bonding behavior of the electrodes to the membrane will be necessary for each promising set of anode-membrane-cathode assemblies.

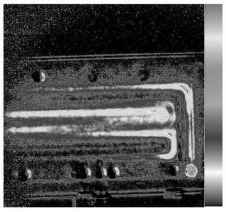
Recent advances in the controlled preparation of organized nanostructures, for example by exploiting the self-organization of di- and tri-block copolymers (Bates and Fredrickson 1999), could provide a pathway to prepare and control the three interpenetrating percolation pathways,

NEUTRON IMAGING OF FUEL CELL OPERATION

The electrochemical conversion of hydrogen and oxygen to water and electricity in a fuel cell occurs at electrode interfaces buried deep within its interior. The reaction takes place over a large surface area with the reactant gases directed to the electrodes through channels in the gas diffusion layer that also collect and drain the water produced. At the heart of fuel cell operation is water; it directly reflects the activity of the basic chemical reaction and can also disable the fuel cell by flooding the gas diffusion channels. Monitoring the ebb and flow of water throughout the fuel cell provides a powerful diagnostic for fuel cell operation.

Because fuel cells are not transparent to visible light, other forms of penetrating radiation must be used to view their internal workings. Neutrons can easily penetrate the metal casing of the fuel cell and still be highly sensitive to hydrogen. This capability makes neutrons a valuable probe for looking at the water distribution and dynamics inside a working fuel cell. Water in quantities less than 1 μg can be detected, corresponding to a spatial resolution of about 100 μm. A neutron image of water inside a fuel cell is shown in the figure.

The neutrons easily penetrate the fuel cell when dry. As the fuel cell runs, water builds up and appears as a darker shadowed region. Digital image analysis allows the representation of the dry cell to be removed from the image, revealing water formation at the cathode and its motion through the gas diffusion media and flow channels. In the image, the gas distribution system of the fuel cell appears as serpentine racetracks, and color enhancement represents the water density increasing from black to red. Images taken every second show the real-time operation of the fuel cell. They can pinpoint regions of high and low chemical activity, as well as identify flooding due to water buildup in the flow channels. This remote observation of water dynamics in the operating fuel cell provides precise space- and time-resolved diagnostics and enables targeted design improvements.



Neutron image of a working fuel cell, showing the distribution of water increasing in density from black to red as indicated in the color bar. The density of water reflects the local activity of the fuel cell reaction and can reveal blocking of the gas diffusion channels by flooding. This image (7.5- × 7.5-cm^2 field of view) shows a fuel cell after 1,000 sec of normal operation. (Courtesy of David Jacobson, National Institute of Standards and Technology Center for Neutron Research) as required. Expanding this research to functionalize the nanostructures to yield conductive and/or electrochemically active materials will be important. The same research emphasis should be placed on understanding, designing, and modeling of GDLs, the effectiveness of which largely controls PEMFC performance at high current densities.

In SOFCs, the MEA is structured on the mesoscale rather than the nanoscale. Here, it is necessary to address the prevention of particle size growth in the electrodes, the changes in morphology, the reaction between components, and the changes in open porosity, among other effects. These are challenging issues because of the high operating temperatures. New methods or new materials that are resistant to such effects are needed.

Bipolar Plates

In practically all applications of fuel cells, individual cells must be stacked (connected in series) to obtain useful voltages. Many designs employ a single conducting plate to connect the cathode of one cell to the anode of the adjacent cell. The plate must then be stable and durable under both oxidizing and reducing conditions and potentials (hence the name "bipolar plate"). However, the durability and stability of the bipolar plate material are serious issues. For example, in the case of metallic bipolar plates (e.g., stainless steel), corrosion products from these plates (e.g., iron and chromium ions) shorten the life of the membrane and the cell electrodes considerably. New materials or corrosion-resistant surface coatings with low contact resistance between the GDL and the plate coating are sorely needed to address this problem.

Bipolar plate materials currently under study for use in low-temperature cells include lightweight metals, graphite, and carbon-thermoset composites. Each of these has limitations in durability or manufacturability. In SOFCs, lower-temperature operation would enable the use of metals or alloys, rather than the currently used conducting oxide materials, as interconnects and bipolar plates. Here, stainless steels might serve as possible interconnect materials, but the chromium has high enough volatility at the higher temperatures to react with the electrode/electrolyte components, causing degradation.

New materials are clearly needed to serve as interconnects, and the possible classes of materials that could be used will be determined by fuel cell operating conditions (such as temperature) and engineering needs (such as weight and volume constraints). High-priority research needs for bipolar plates are discussed in the following section.

New Materials and Novel Interconnect Designs. Even if researchers can make all the desired advances in electrodes and membranes, the success of fuel cells is not assured. In most applications, including automotive applications, the cells must be connected together in series (and possibly in parallel as well). While such connections can be made outside of each cell, a more efficient (especially on a weight basis) connection can be made using a single bipolar plate to connect the cathode of one cell to the anode of another. Because of the different electrochemical environments, however, most materials corrode in such an environment. Corrosion-resistant, electrically conducting materials are needed for this application. Perhaps surface coatings will solve the problem, but there is a lack of research even addressing which materials may be suitable. Reactivity between interconnect materials, gases, and other fuel cell components (containers and seals) has been identified as strongly limiting fuel cell performance and lifetime. Fundamental studies in corrosion science are required. Novel stack designs that mitigate difficulties with seals and interconnects should be investigated. There is a clear need and opportunity for innovative basic research to address cell interconnect issues.

Materials Durability

All materials in every type of fuel cell system degrade, decay, corrode, or otherwise fail under medium- to long-term operating conditions, as mentioned briefly in the sections above. This issue is discussed in greater detail in the following sections.

Low-temperature Cells. For PEMFCs, membrane degradation, electrode structure degradation, plate corrosion, and reformer catalyst lifetime are all issues. The longevity of catalyst-coated membranes, GDLs, and bipolar plates in operating PEMFCs is currently an Achilles' heel for the entire field. Performance degradation is a serious challenge that must be overcome if fuel cells are to realize their widely recognized market potential. Durability problems are typically studied by simply running fuel cells for long periods. Data are then analyzed after the fact to assess the failure modes. Conclusions are based on limited real data concerning the materials used and with less-than-optimal insight into probable failure mechanisms. Although some claims are occasionally made to the contrary, there is no fully validated accelerated life test for fuel cells. Fundamental and applied research into polymer electrolyte fuel cell degradation modes and new diagnostics are required to underpin efforts to improve materials. Degradation mechanisms in cells of all types are poorly understood. There is an urgent need for rational validated accelerated testing, as well as new materials systems that are themselves robust or possess enhanced durability.

High-temperature Cells. In SOFCs, microcracking and material deformation in response to thermal cycling are key factors driving degradation. Another important contribution to degradation is corrosion, which is enhanced by the high operating temperatures in present systems. Recent advances in materials and system design of solid oxide fuel cells offer hope that these degradation issues can be addressed (Kendall 2000). New electrolyte and electrode materials are becoming available, as are new cell designs and new fabrication methods to produce cells with thin electrolytes and engineered interfaces; however, many large challenges remain. Most are associated with durability and the high reactivity of materials at high temperatures. At this time, our understanding of the electrochemical and diffusion reactions that occur at the interfaces between the electrode and the electrolytes is very limited. The development of even better materials and better ways of using them could significantly decrease operating temperatures in SOFCs, allowing the use of cheaper materials and improving durability. Furthermore, the fuel flexibility offered by some electrode designs could allow the use of hydrocarbons or hydrogen as fuels.

Materials properties affect the performance of SOFCs in many crucial ways. Each of the materials aspects of the anode, electrolyte, cathode, seals, and interconnects can serve as a showstopper because of tendencies toward microcracking, thermal expansion mismatch, and corrosion. To produce inexpensive, high-performance SOFCs, further improvements are needed in each of these system components, along with a fundamental understanding and control of the interaction of the various parts.

New materials in both fuel and air electrodes can be as important as the electrolyte in improving performance and lowering operating temperatures. On the cathode side, a number of new materials with potential for improved performance have been discovered (Xia et al. 2002). On the anode side, there have also been exciting developments using alternative materials. For example, conductive ceramics (Tao and Irvine 2003) have been shown to allow reasonable cell performance and provide redox stability, an important factor in applications in which the anode may need to be cycled from low to high temperatures. SOFC anode formulations that do not contain Ni, such as Cu/CeO_2, lanthanum-chromium-manganese oxides and lanthanum-strontium-titanates, exhibit much greater sulfur tolerance (>1,000 ppm) than Ni anodes. Further work needs to be performed to optimize non-nickel anode materials and to evaluate their long-term suitability in solid oxide fuel cells. Similarly, it has been demonstrated that replacing Ni with Cu enables the use of alternative fuels (Park et al. 2000).

Finally, the structure of the interfaces between the various cell components, which can be controlled by synthesis procedures, can have a huge impact on performance. For example, the traditional anode (Ni-YSZ cermet), cathode (lanthanum-strontium-manganate [LSM]), and electrolyte (YSZ) materials can be designed to achieve higher cell performance at 650°C (Kim et al. 1999) than is normally achieved at 950°C (Pross et al. 2003). While a fraction of this enhancement can be explained by the use of a slightly thinner electrolyte (10 µm compared with 40 µm), the major factor in enhancing the low-temperature performance comes from engineering the electrode-electrolyte interface (Virkar et al. 2000). At the present time, this “tailoring” of the structure is largely performed by trial and error. A basic understanding of the needed interfacial structures could simplify the design and manufacturability of such interfaces, especially as new materials are introduced.

In all fuel cells, durability is a system issue. Often, interactions occur between components, either at contacting interfaces or by corrosion products from one component interacting unfavorably with another component. For example, providing a new membrane that operates well at high temperature will often demand modifications to other materials in the fuel cell system. Such membranes must not only be stable in both oxidizing and reducing atmospheres, but they also must be nonreactive with the electrode materials. The poor long-term stability of interfacial connections between components, including issues of electrical connectivity and adhesion, often lead to operational difficulties.

Alternative Fuel Cell Technologies

While the preceding discussion has focused primarily on PEMFCs (and, to a lesser extent, on SOFCs), it is possible that other fuel cell technologies could be enabled by discoveries of novel materials. For example, intermediate-temperature electrolytes (200–500°C) would allow the use of low- or non-precious metal catalysts and fuels containing substantial amounts of CO (thereby eliminating the need for low-temperature water-gas shift and preferential oxidizer [PROX] cleanup of reformed hydrogen). The candidate material would likely be an inorganic proton and/or oxide-ion conductor or even a hybrid or composite membrane structure and would need to provide mechanical durability, high ionic conductivity, and robustness in the fuel cell environment.

Oxygen reduction under basic conditions occurs at smaller overpotentials than under acidic conditions. In fact, alkaline cells are used by the National Aeronautics and Space Administration (NASA) in its space program, where very high-purity hydrogen and oxygen are available onboard. These cells are known to be very efficient and robust. Currently, alkaline cathodes cannot use air as the oxygen source, because the CO_2 in the air reacts with the electrolyte. If there were an efficient and inexpensive way to remove CO_2 from the air, and if carbon-free hydrogen produced by water electrolysis were available, alkaline fuel cells might become practical in transportation applications.

Membrane-free fuel cells have been demonstrated in very low power, short-term use in biological environments (Mano et al. 2003). One question is whether membrane-free concepts can be developed for use in higher-power, long-life systems. Such a system would need electrodes that are very specific and discriminating in their catalytic function. For example, the anode must oxidize only the fuel, even in the proximity of oxygen, and the cathode must only reduce oxygen and not the fuel. In such systems, the formation of stacks of individual fuel cells is a much smaller engineering challenge. Of course, such mixed fuel/oxidizer systems could present substantial safety challenges. The point is not so much that this particular idea is a good one (or not) but that it may encourage the research community to think in entirely new directions.

A broad, long-range research program aimed at finding novel materials for fuel cells would encourage “out of the box” approaches to novel fuel cell concepts.

Fuel Processing

If more efficient means of hydrogen storage are not found for transportation applications — means that allow 6 wt% hydrogen storage or greater (counting the weight of the storage system, containers, etc.) — hydrogen will need to be efficiently extracted from a hydrocarbon source. Potentially, the hydrogen source might even be a recyclable carbon-containing molecular carrier. In that case, an efficient catalyst to remove the hydrogen from the carrier would be needed. Currently, hydrogen is produced by the reaction of hydrocarbons (like methane) with steam; the process also produces CO_2 and CO. For all current PEMFC applications, the CO concentration has to be less than 100 ppm to avoid anode poisoning.

Proposed automotive fuel processing involves several steps, primarily steam reforming and water-gas shift. The first is typically carried out at high temperatures (650°C and above) over an Ni catalyst, and the second is typically carried out at lower temperatures (200–500°C) over Cu- and Fe-based catalysts. Steam reforming cannot be carried out at much lower temperatures because of unfavorable changes in equilibrium, but the Ni catalyst could be improved. The Ni catalyst has problems with “coking” — the formation of carbon deposits on the surface, blocking its active sites. The output gas from the steam reformer contains 3–10% CO. The water-gas shift reactor is currently needed to reduce the CO level to perhaps 2,000 ppm, and then a PROX device reduces the CO content to about 100 ppm. This shift reactor/PROX unit is large — accounting for more than one-third of the mass of the hydrogen-producing plant in current automotive systems — all because of the slow reaction kinetics over the Cu catalyst. Much-improved catalysts and operation at lower temperatures could greatly reduce the size of this component and could enhance prospects for onboard fuel processing. This entire scheme is only sensible if the overall fuel processor/fuel cell system is more efficient than competing power sources, like internal combustion. Otherwise, even higher CO_2 production would result, without any gain in efficiency.

Known catalysts that are efficient in reforming operate at temperatures of 600°C or above. This is a serious drawback because both the energy required for heat-up and the heat-up time for the reformer are substantial (on the order of 10 min). Furthermore, the reformer and water shift reactors add engineering complexity. If impurity-tolerant (no sensitivity to sulfur at the 200-ppm level or to CO at 3–10%) anodes are found, reformer technology would be much more attractive. The 200-ppm requirement for sulfur comes from the current average sulfur content in gasoline. This requirement is scheduled to be reduced to 30–50 ppm in 2005. Other sources, such as methane, can contain much less sulfur. Such anodes would ideally not only be "tolerant," but would actually oxidize the CO to CO_2 and any sulfur to SO_2. Such anodes would reduce the purity requirements for the fuel, independent of its source.

We should emphasize, however, that if the challenges in hydrogen production, and especially storage, can be overcome, fuel processors will not be needed for hydrogen-based fuel cells. High-priority research needs in reformer catalysts are discussed in the following section.

Improved Catalysts. New catalysts need to be explored that will enable water-gas shift chemistry at lower temperatures or with higher kinetics. These catalysts would not only potentially be useful for providing hydrogen from hydrocarbons to vehicular fuel cells, but they also would be a welcome improvement to current hydrogen production processes and other chemical transformations. Catalysts that avoid coking in the steam reformer would likewise be useful to current hydrogen production technologies.

CROSS-CUTTING ISSUES

Several of the basic research needs in fuel cell work mirror those of hydrogen storage and production. These cross-cutting issues are discussed in the following sections.

Catalysis

Clearly, electrocatalysis is a central aspect of fuel cell research. As in the production and storage areas, heterogeneous catalysis and biomimetics are core disciplines for potential advancement. It should be stressed that fuel cell electrocatalysis is a rather unique subfield of heterogeneous catalysis, in that a large variable electric field is generally present at the interface.

Membranes

Membranes that permit the flow of one species (molecules or ions) while blocking the flow of other species are crucial, especially for production of fuel cell technologies. They may also play an important role in storage technologies, depending on which technologies progress to implementation.

Interfacial Chemistry and Materials

Understanding, controlling, and improving materials and material interfaces throughout the multilayer system characteristic of a fuel cell are central to achieving the qualitative improvements in performance and cost required for a successful hydrogen economy. Advances in adhesion, interfacial science, and characterization are equally central to breakthrough progress in fuel cell technologies.

Theory and Modeling

Theory and modeling of electrochemical reactions, catalysis, ionic conduction in membranes, and surface interactions of hydrogen could provide a strong driving force in understanding, controlling, and enhancing the fundamental phenomena that govern the operation of fuel cells and related chemical sciences.

CONCLUSIONS

The development of efficient and cost-effective fuel cell technology solutions for automotive and stationary applications presents a grand challenge that will take a substantial and sustained effort in chemical and materials research, combining both near- and long-term strategies. The major needs are all based on improved or new materials. Meeting this challenge will take a major effort by many scientists and engineers, experimentalists as well as theorists, in an interdisciplinary and collaborative effort. A basic, exploratory research program of significant size is needed to produce these enabling discoveries.

Near-term goals include lowering costs and improving the durability of materials and components sufficiently to enter selected markets. Long-term thrusts include large-scale introduction of fuel cells in vehicles and in a broader hydrogen economy — the desired end-game. Breakthrough advances are needed in electrocatalysis, membranes, and interconnect materials to realize the full potential of these devices for improved efficiency and cleaner power generation. Perhaps even novel fuel cell technologies, based on as-yet undiscovered electrode/electrolyte materials, will need to be discovered to take full advantage of the promise of affordable, high-efficiency power sources based on fuel cells.

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HIGH-PRIORITY RESEARCH DIRECTIONS

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LOW-COST AND EFFICIENT SOLAR ENERGY PRODUCTION OF HYDROGEN

SCIENTIFIC CHALLENGES

Solar energy is the only renewable energy source that has sufficient capacity to meet fully the global energy needs of the next century without potentially destructive environmental consequences. In most respects, similar considerations apply to the economic viability of solar hydrogen and solar electricity: while many kinds of solar cells exist and some are made from abundant elements (such as silicon), their present cost/efficiency ratio is too high for widespread use. The present efficiencies of solar cells range between about 3% and 25%. At the high end of this range are single-crystal silicon photovoltaic (PV) cells, which approach the theoretical energy conversion limit of 32% for single-bandgap devices in sunlight.[1] Single-crystal solar cells are expensive and have been optimized over many years (and hence are unlikely to improve substantially in the future). The low-end cells (organic, dye-sensitized, and semiconductor nanocrystalline cells) are made from inexpensive materials and have not yet been extensively optimized. These technologies are most likely to (1) benefit from advances in basic science and (2) meet the cost constraints of widespread use.

Two basic strategies are available for creating a cost-competitive solar technology for hydrogen production:

- Development of emerging physical phenomena and novel synthetic techniques to achieve ultra-high conversion efficiency (>40%) at moderate cost per unit area, and/or
- Development of novel materials and chemical processes leading to ultra-low-cost per unit area with moderate efficiency (at least 10% efficient solar to stored hydrogen energy).

Both of these practical goals are rooted in basic scientific questions connected to materials synthesis, chemical self-assembly, dynamic photo-redox processes, and catalysis.

RESEARCH DIRECTIONS

This research has three goals: (1) understand the basic science that would lead to a disruptive high-efficiency solar technology, (2) learn to exploit new physical phenomena in quantum-size semiconductor particles and new synthetic techniques for the organization of matter on the nanometer-length scale in order to exceed present limits, and (3) develop analytical tools and theoretical methods for understanding relevant photoprocesses and catalytic chemical reactions. Promising research directions are discussed in the following sections.

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[1] The Shockley-Quiesser limit of solar-to-electric energy conversion efficiency for a single-bandgap device is 32%. The theoretical limit for multigap cells matched to the solar spectrum is approximately 65%. For a review of multigap semconductor/electrolyte cells, see Licht (2001).

Organic-based PV Systems

Organic photovoltaics coupled to electrolyzers, and organic photoelectrochemical cells that produce hydrogen directly, are strong candidates for very low cost solar cells if their efficiencies can be increased to more than 10%. Because the solar-to-electric efficiencies of these cells are typically less than 3%, major advances in basic understanding and new design concepts are needed. Some of the problems of organic solar cells are generic to other kinds of low-cost solar cells. A number of these are discussed below.

Light Harvesting. New strategies are needed to efficiently use the entire solar spectrum. These strategies could involve research on molecular photon antennas, junctions containing multiple absorbers, and physical techniques for up- and down-conversion of light to the appropriate wavelengths.

Photoprocesses in Organic Solids and Thin Films. Research is needed to understand the effects of structure on energy transfer and energy loss, exciton dissociation, and charge carrier recombination.

Self-assembly. Organic and hybrid organic-inorganic systems that spontaneously develop ordered nanostructures are of interest in the design of thin-film organic solar cells. These systems include, for example, di- and tri-block copolymers containing light-absorbing and electron- or hole-conducting segments, liquid crystals, and layer-by-layer assembled thin films.

Chemical Components. New low-cost alternatives are needed for transparent conductors and precious metal catalysts. Research is also needed to make better electron- and hole-conducting polymers. New design concepts are needed to achieve more efficient charge separation in liquid crystal and organic thin-film devices.

Characterization Tools for Understanding Dynamic Processes at Interfaces. Light-induced charge separation often occurs at interfaces in solar cells, and it involves dynamic processes that span many time scales. These time scales encompass hot carrier thermalization (femtoseconds), electron transfer and electron-hole recombination (femtoseconds to seconds), and catalytic water oxidation-reduction (milliseconds to minutes). Better tools are needed to study these processes, which determine the efficiency of photoconversion, particularly on short time scales. High sensitivity is needed to obtain information from specific interfaces or from individual molecules in complex assemblies.

Novel Frameworks for Assembly of Multicomponent Solar Cells and Photocatalysts

Photocatalytic water splitting represents a potential low-cost alternative to photovoltaics, because it generates hydrogen directly from water without the need for wiring, electrolyzers, and other system components. At present, visible-light water splitting has been demonstrated only with a few materials and is very inefficient. Integrated chemical systems, in which light-absorbing and photo-redox components are properly juxtaposed on the nanoscale, have the potential to increase this efficiency. Researchers need to learn to control light-induced charge separation, charge recombination, and coupling to hydrogen- and oxygen-evolving catalysts in these systems. The four-electron oxidation of water to oxygen is a major challenge for these systems because of slow kinetics for all known molecular, colloidal, and solid-state catalysts; research is needed to develop better catalysts. Research is also needed on artificial photosynthetic systems, which are supramolecular photo-redox assemblies organized by microporous solids, membranes, and other nanophase media. Chemical assembly principles that lead to better photocatalysts probably would be useful for increasing the efficiency of organic and semiconductor nanoparticle-based PV cells.

Solar Cells Based on Inorganic Semiconductors and Nanoparticles

Inorganic nanoparticle-based solar cells hold the potential to exceed the Shockley-Quiesser limit of conversion efficiency by exploiting novel physical effects, including hot carrier injection and impact ionization. Recent ultrafast spectroscopic studies show that dye-sensitized nano-TiO_2 cells — one of the most interesting new concepts in solar PV design — function by hot carrier injection from the dye to the semiconductor. Research is needed to understand and exploit these effects in new solar cell designs. Recent advances in semiconductor nanocrystal synthesis suggest that it may be possible to design multicomponent crystals that contain more than one absorber (e.g., as core-shell structures, stripes in nanowires, or branches in dendritic crystals). The challenge is to learn to assemble and wire these nanocrystals into solar cells in useful ways. Much of what has been learned about making very expensive but efficient photovoltaics by using molecular beam epitaxy to define quantum well and multi-bandgap structures might be translated to inexpensive solar cells in nanocrystals.

Theory

Theory and modeling are needed to develop a predictive framework for the dynamic behavior of molecules, complex photo-redox systems, interfaces, and photoelectrochemical cells. As new physical effects are discovered and exploited, particularly those involving semiconductor nanoparticles and supramolecular assemblies, challenges emerge for theory to accurately model the behavior of complex systems over a range of time scales.

POTENTIAL IMPACTS

The payoff from successful research in solar energy would be the production of very pure hydrogen that is cost-competitive with fossil fuels as an energy source. Inexpensive, high-purity hydrogen would greatly accelerate the implementation of fuel cell technology by eliminating some of the costly purification systems currently used. It would also enable the widespread use of proven technologies (such as alkaline fuel cells) that are not useful with carbon-containing fuels. Solar energy is readily available in sufficient supply to enable solar hydrogen to be the dominant global energy source if the cost/efficiency ratio of PV cells can be decreased by a factor of 10 or more.

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NANOSCALE CATALYST DESIGN

SCIENTIFIC CHALLENGES

Catalysis in many forms is vital to the success of hydrogen energy technology. It is essential for the development of more efficient, cost-effective ways of producing hydrogen from reforming fossil fuels, and it is key to the development of photoelectrochemical and photochemical approaches. It is also the cornerstone of fuel cell technology and is important in the activation of hydrogen for storage in solid form. Catalysts with higher activity are needed for reducing kinetic barriers and increasing the thermodynamic efficiency of many different reactions in hydrogen production, chemical storage, and fuel cells. More highly specific catalysts are needed for reducing energy and material losses to parasitic and corrosive side reactions. Many of the currently available catalysts are subject to poisoning, fouling, or corrosion in the presence of reactants or their contaminants. These problems have led to a heavy reliance on platinum and other noble metal catalysts, but the supply of these materials is too limited and the cost too high to support the scale-up of current catalyst-dependent processes needed to meet the demands of a hydrogen energy economy. The replacement of platinum with less expensive and more generally available non-noble metal catalysts emerges as a critical challenge that cannot be met without intensive research into catalytic mechanisms, structures, and fabrication.

Although catalyst development has been based largely on trial-and-error methods, new approaches are critically needed to provide a substantial jump in the ability to design, characterize, and test new catalysts. Several lines of basic research are converging to provide an unprecedented opportunity for developing a robust catalysis science that could lead to revolutionary advances to meet these challenges. These areas of research include advances in nanoscience and nanofabrication, theory and modeling of catalytic properties, nano- to atomic-scale characterization methodologies, and high-throughput combinatorial synthesis. Research strategies are needed that would bring several or all of these advances together for working on problems in catalysis.

Recent developments in nanotechnology have opened new opportunities for the controlled synthesis of nanomaterials with tailored structures. These new materials have several properties important to catalysis, including high surface areas and a large, controllable concentration and organization of the kinds of crystal defect sites that are involved in forming catalytic "active sites." The concepts, technologies, and synthetic capabilities arising from nanoscience provide an entirely new avenue for the controlled production of novel categories of catalysts. These nanocatalysts have potential to provide great improvements in catalytic activity and specificity. In addition, improved capabilities for experimental and theoretical studies of surfaces and nanostructured materials are needed to elucidate atomic and molecular processes involved in catalysis.

Theoretical methods based on electronic structure calculations and on molecular dynamics and Monte Carlo-type simulations have developed to the point that entire reaction pathways can be identified; the basic trends in reactivity from one system to the next are understood for simple reactions. There are also new developments in the treatment of the thermodynamics of surfaces and kinetics of catalytic reactions based on combinations of electronic structure calculations and statistical and kinetic methods. Methods to better understand adsorption and diffusion in molecular sieves and other porous solids are also being developed.

A number of new experimental methods have been developed that allow a detailed analysis of correlated geometric and electronic structure of surfaces. Scanning probe methods now provide unprecedented insights into the structure and composition of surfaces and nanoparticles. In particular, they allow the first detailed analysis of defects and of their effects on surface chemistry. This capability is extremely important because defects are often the active sites for catalytic processes. New *in situ* experimental methods for characterizing real, nanostructured catalysts during turnover have been developed. Recently, it has become possible to use electron microscopy under high-pressure conditions to obtain the first direct images of the structure and dynamics of catalysts in a reactive environment. *In situ* methods have also been extended to spectroscopic techniques that require synchrotron radiation or neutrons. Spectroscopic methods based on synchrotron radiation now provide a very detailed picture of the bonding at surfaces; several new methods allow characterization of surfaces under high pressures of gases or in liquids. Neutron-scattering methods, such as inelastic neutron-scattering spectroscopy, also provide structural and bonding information at high temperatures and pressures. These methods are particularly important for understanding electrocatalysis.

New high-throughput combinatorial synthesis methods are emerging that can be exploited in combination with theory and advanced measurement capabilities to accelerate the development of designed catalysts, including nanocatalysts. The importance of this capability is underscored by the recent development of a novel nonplatinum catalyst for hydrogen production via reforming of reduced carbon (Huber et al. 2003). The ability to rapidly generate and characterize a wide range of compositions provides practical access to extensive experimental feedback into models of catalytic processes. This interplay between theory and experiment forms a recursive process that will accelerate the development of models with the predictive power needed for supporting development of optimized catalysts for specific steps in hydrogen energy processing. An essential issue in this connection is the development of informatics methods that allow rational use of large amounts of data. Better tools are needed for both analyzing and visualizing this multiparameter space.

All of these recent experimental and theoretical developments provide a new basis for uncovering the detailed atomistic processes underlying catalysis and for identifying the active catalytic sites. Once it is understood how alterations in the structure and composition of a catalyst can change the chemical properties and stability of the active site, it will be necessary to control the synthesis of the material with atomic-scale precision. Development of such synthetic methods will be an important part of testing models and advancing the understanding of the critical properties of catalysts and of their supporting structures. In addition, cost-effective fabrication methods will be vital for the practical application of these new designer catalysts.

A combined experimental-theoretical approach is needed to provide a new platform for the design of more selective, robust, and impurity-tolerant catalysts for hydrogen technology. This new platform will enable design and control of physical and chemical properties of the catalyst particles, as well as the properties of their supporting structures at the nano and atomic scales.

RESEARCH DIRECTIONS

The basic research effort in catalysis should provide new methods for catalyst design, synthesis, and characterization. Some fundamental issues, however, need clarification, including:

- Understanding catalytic activity from one system to the next,
- Understanding selectivity and trends in selectivity,
- Understanding deactivation mechanisms,
- Defining and understanding the chemical and structural state of the active site during catalysis,
- Understanding metal-support interactions,
- Understanding size effects in catalysts,
- Understanding metal-metal interactions in bi- and multimetallic catalysis, and
- Finding ways to design novel micro- and mesoporous solids.

Goals for catalysis research as a basis for hydrogen technology should include:

- More efficient, carbon-resistant reforming catalysts;
- More active, low-temperature–shift catalysts;
- Better electrolysis catalysts;
- Better photocatalysts;
- More efficient removal of contaminants, including sulfur and carbon monoxide (CO);
- More CO-resistant anode materials for proton exchange member (PEM) fuel cells;
- Better cathode materials with lower overpotentials for PEM fuel cells;
- Development of hydrogen activation catalysts that depend less on noble metals; and
- Multifunctional catalysts.

POTENTIAL IMPACTS

Developments in catalysis hold important keys to the economic viability of hydrogen energy systems. More active, specific, and durable catalysts would mean that a given amount of hydrogen could be produced or used in a given period of time with smaller, longer-lived production and utilization plants. Hence, the scale-up of hydrogen systems would require less capital investment. Improved catalysts would increase the thermodynamic efficiency of hydrogen production, storage, and use and also improve the economic efficiency with which the primary energy source — fossil, solar, or nuclear — serves our energy needs.

At this time, platinum is the preferred catalyst for many of the processes of interest for hydrogen technology. Unfortunately, this element is very limited in supply. Unless catalysts are found that consist of more readily available and less expensive materials, the strategic goal for the hydrogen economy of relieving dependence on imported resources for our national energy needs will be defeated by the development of a strategic dependence on platinum. A rational strategy for developing such catalysts depends on improved basic nano- and atomic-scale understanding of catalytic mechanisms and on improved methods for formulating catalysts and their supports with properties that are controlled on the nano- and atomic scales. This research direction would fill critical gaps in gaining the necessary understanding.

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BIOLOGICAL, BIOMIMETIC, AND BIO-INSPIRED MATERIALS AND PROCESSES

SCIENTIFIC CHALLENGES

Hydrogen production on a scale necessary for supporting energy needs for humankind faces kinetic constraints that must be solved either by thermal activation or catalysis. Living organisms use hydrogen as an energy carrier on this scale, solving the kinetic constraints with enzyme catalysis adapted to the organisms' thermal environment, which ranges in specific cases from 0°C to more than 100°C. These biological catalysts support integrated energy conversion processes that parallel those needed for most aspects of current or contemplated industrial processes, including ambient catalysis of the water-gas shift reaction, the full equivalent of natural gas reforming (Thauer 1998), and the complete anode reaction of a methane fuel cell optimized for low temperatures (0–20°C) (Nauhaus et al. 2002). Many green algae are capable of utilizing solar energy to energize the photolysis of water into hydrogen and oxygen, a process known as biophotolysis. The supporting enzyme catalysts for all of these activities are synthesized from materials readily available to the organisms from their environments. In spite of the apparent promise of adapting biological materials and principles to produce efficient and cost-effective engineered hydrogen energy systems, the current understanding of many aspects of the biological processes is too limited to support immediate application. Not enough is known about the molecular mechanisms and diversity of the enzyme catalysts, how they are assembled with their cofactors, how they are assembled into integrated systems, how potentially wasteful or destructive side reactions are controlled, how components and systems are maintained in the face of damaging side reactions, or how energy flows are regulated. Because of the central role of kinetic constraints in governing the practical utility of hydrogen energy systems in general, basic research into the fundamental principles underlying biological hydrogen metabolism could lead to crucial breakthroughs toward development of human-engineered hydrogen energy systems.

RESEARCH DIRECTIONS

Research is needed for understanding the mechanisms that underlie the biogenesis, maintenance, and integrated activity of the enzymes and cofactors that support biological hydrogen metabolism. It is an important goal to test this understanding through the development of biomimetic or bio-inspired synthetic catalysts and systems, because these extensions of biological systems may lie along the route toward practical applications in human-engineered hydrogen energy systems. Some promising research directions are discussed in the following sections.

Biomimetic Catalysts for Hydrogen Processing

The future of practical systems for solar energy conversion and storage depends critically on understanding the fundamental principles that determine how molecular systems carry out photochemical charge separation, transport, and storage. Although natural photosynthesis serves as a useful model for designing these systems, we need to go beyond that model to (1) synthesize photoconversion molecules and assemblies that build on these principles and (2) develop general methods to assemble mesoscale photofunctional engineered architectures.

Biomimetic photosynthesis catalyzed by synthetic complexes and assemblies offers a clean way of producing high-purity hydrogen (or other fuels) from solar energy and water. Research in artificial biomimetic photosynthesis is at an early stage and has not yet reached the point that production of integrated, practical systems is feasible. Progress has been promising in demonstrating synthetic catalysts of light-harvesting and photochemical conversion, controlled intermolecular electron transfer, water oxidation, and proton reduction to generate hydrogen. Each of these areas needs additional research; methods must be developed for assembling these biomimetic components into functional assemblies.

Production of hydrogen or other fuels using biomimetic photosynthesis requires a source of reducing equivalents. In oxygenic photosynthetic organisms, water is the source of the reducing equivalents needed for carbon fixation. Because water is readily available, oxygenic photosynthetic organisms predominate in the biosphere. It is highly beneficial to use water as the source of reducing equivalents for biomimetic photosynthesis. Splitting of water into protons and oxygen is energetically demanding and chemically difficult. The manganese-containing, water-splitting catalytic site in natural photosystem II (PSII) complexes performs this reaction at close to thermodynamically limited efficiency (<0.2 V overvoltage), at a high turnover rate ($\sim 10^3\ s^{-1}$), and under mild external but low effective internal pH conditions. In spite of promising recent progress in developing mimetic complexes based on the water oxidation complex of PSII, research is still needed to develop efficient artificial water-oxidation catalysts. A catalyst must be developed that can operate at the very high potential needed for the water-oxidation reaction; can perform a four-electron reaction so as to maximize the energetic efficiency; and can avoid production of corrosive intermediates, such as hydroxyl radicals, and mediate proton-coupled redox reactions.

The biomimetic chemistry involved in the reduction of protons to hydrogen is at an early stage of development. Efficient enzymes called hydrogenases catalyze reactions in which protons are reduced to molecular hydrogen using electrons from different substrates. Three known types of hydrogenases are known: iron (Fe)-centered, Fe-nickel-centered, and metal-free. Functional biomimetic Fe-hydrogenases have recently been demonstrated. They require strong reducing conditions and have low catalytic turnover but hold great promise for the future. The natural reaction centers of hydrogenase enzymes are poisoned by oxygen; methods must be developed for engineering oxygen-insensitive synthetic catalysts or sequestering the catalytic sites from oxygen while allowing access to protons and electrons and release of the hydrogen product.

Research is needed for:

- Understanding the structure and mechanism of the natural biocatalysts for water splitting and all aspects of hydrogen processing,
- Understanding the origin of oxygen-inactivation of hydrogenases and creating oxygen tolerance,
- Translating this understanding into efficient biomimetic catalysts,

- Integrating light absorption capability with catalytic hydrogen and oxygen production, and
- Developing a modular approach based on biomimetic photovoltaics for the direct anodic catalytic oxidation of water and cathodic reduction of protons to hydrogen.

Exploitation of Biodiversity for Novel Biocatalysts and Determination of Mechanisms of Assembly

It is becoming increasingly clear that the diversity of organisms that exploit hydrogen as an energy carrier is immense. Exploration of this potentially rich source of key catalysts for hydrogen production and use is at a very early stage. Moreover, while metals play intrinsic fundamental roles in catalysis and electron transfer (as well as in enzyme structure), very little is known at the molecular level regarding how different types of metal-containing enzymes and proteins are assembled inside a cell, how their assembly is regulated, how assembly mechanisms vary in different organisms, or how metalloprotein assembly might be mimicked in the test tube. Understanding the mechanisms involved would have a major impact on biomimetic technologies. High-throughput technologies specifically directed toward identifying photosynthetic and hydrogen-metabolizing organisms must be developed. Many of the microorganisms that are key players in hydrogen metabolism participate closely with others in complex consortia and are not independently culturable. Methods for discovering and studying these organisms *in situ* must be developed.

Current knowledge of the metabolism of hydrogen and biological solar energy conversion is based almost entirely on traditional biochemical and genetic approaches. Information is available for only a few model photosynthetic and hydrogen-metabolizing organisms. Similarly, our knowledge of metal metabolism has been gleaned from a few selected enzymes, and bioinformatic approaches to define potentially important catalysts on genome-wide scales are currently limited by the incompleteness of the comparative data.

Research is needed for:

- Developing and applying high-throughput methods for screening novel hydrogen metabolizing and water-splitting components in new organisms from diverse environments;
- Developing biochemical, analytical, and computational tools to define the metallo- and redox-proteome;
- Identifying the factors and pathways involved in the expression, synthesis, function, and regulation of the metal cofactors, redox enzymes, and proteins involved in hydrogen metabolism and photolytic water splitting;
- Developing molecular and genomic tools for the construction and evolution of novel hybrid organisms capable of using light to split water and to generate

hydrogen or other energy-containing compounds readily convertible to hydrogen; and

- Developing methods to interface redox enzymes and proteins into complex two- and three-dimensional architectures for catalysis, sensing, and energy transduction.

Coupling between Electrode Materials and Light-driven Catalytic Water Oxidation and Hydrogen Production Components

Investigations into natural light-activated and electron transfer proteins reveal empirical engineering guidelines based on fundamental principles of energy and electron transfer theory that can be applied to the abiotic reproduction of natural activity and function using synthesis and self-assembly. A wide range of donor-acceptor molecules have been produced over the past 20 years that mimic the multistep charge separation scheme of natural photosynthesis reasonably well. In some cases, these artificial reaction centers have been coupled to artificial antenna arrays to increase the cross section for absorption of solar energy. Far less work has been performed on how the charge separation created by these systems can be coupled to electrodes or practical chemical systems for energy storage. Very little work has focused on the interfacial chemistry necessary to produce workable solid-state devices analogous to common silicon-based solar cells or photochemical cells.

Attachment chemistries for electrode-protein-lipid constructions are a well-developed art. But application to redox chemistry has been successful with only the simplest systems and with only modest success with larger protein complexes. On the other hand, many chemical methods are available to attach small molecules to diverse surfaces such as metal oxides and gold. The availability of these methods makes it possible to chemically attach more complex biomimetic assemblies to surfaces; however, investigation of the electronic nature of these spacers and how they promote coupling of charges between the surface and assembly is in its infancy. Also, many molecular recognition strategies result in the self-assembly of complex molecules on surfaces. Once again, biomimetic systems with sufficient complexity to carry out photocatalytic production of hydrogen and water splitting have not been explored.

Research is needed for:

- Developing strategies for the assembly of synthetic photochemical and catalytic units that have fast electronic communication with the surface, controllable orientation, and long-term stability or self-repair; and

- Developing methods for the direct characterization of structure and mechanism of catalyst function on surfaces.

Biomimetic Nanostructures to Separate the Catalytic Functions of Water Oxidation and Hydrogen Production

The presence of oxygen at the catalytic site for hydrogen production inactivates the currently known catalysts. Moreover, it is likely that hydrogen will also react with the catalytic site for water oxidation. Biomimetic nanostructures are required to spatially separate and provide locally controllable environments for the catalytic centers for the production of hydrogen and oxygen. Ways to achieve this include building nanostructured surfaces that isolate key catalytic components, preparing biomimetic diffusion barriers that serve to encapsulate the individual photochemical and catalytic systems, synthesizing oxygen and hydrogen molecular traps and channels for controlling accessibility, and developing multilayered functional structures that achieve three-dimensional spatial separation.

Natural structures have evolved to spatially separate and compartmentalize reducing and oxidizing species on a 4- to 10-nm length scale. In photosynthetic systems, this includes the use of the membranes to separate charge and remove the oxygen product. Enzyme active sites are designed for high specificity and are often protected by the surrounding protein to prevent side reactions. The nature of the electronic coupling of the sites linked by chains of redox cofactors is reasonably well understood.

There is a good working knowledge of the construction of chemically integrated redox cofactor chains as well as self-assembled model proteins. However, further integration of photochemical systems, electron transfer chains, and compartmentalized catalytic systems has yet to be accomplished. There is also the advantage afforded by extensions to hybrid constructions involving inorganic and organic frameworks.

Research is needed for:

- Designing, preparing, and characterizing integrated nanoscale constructs to isolate and compartmentalize photochemical water oxidation and hydrogen formation;
- Establishing connections between components that permit electron and proton flow between these components;
- Developing methods to extend nanoscale functional catalytic units into the 100 nm – 1 μm mesoscale; and
- Developing strategies to efficiently harvest hydrogen and to separate out oxidative by-products.

POTENTIAL IMPACTS

Biological hydrogen metabolism and production processes and catalysts promise inexpensive materials for overcoming kinetic constraints in hydrogen energy systems. Their potential practical utility is essentially unexplored in spite of their clear importance in global energy flows in the biosphere. It is plausible that biological, biomimetic, or bio-inspired components and systems could make critical contributions to all aspects of human-engineered hydrogen energy systems. The scale of the necessary research is challenging, but steady investment could yield important practical results in the long run.

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COMPLEX HYDRIDE MATERIALS FOR HYDROGEN STORAGE

SCIENTIFIC CHALLENGES

Transportation applications require compact, lightweight, responsive, and affordable hydrogen storage onboard the vehicle. A 480-km (300-mi) driving range requires 5–10 kg of usable hydrogen, depending on the size of the vehicle. Basic research is needed to identify new storage materials and to address a host of associated performance and system issues. Such issues include operating pressure and temperature; the life cycle of the storage material; the requirements for hydrogen purity imposed by the fuel cell; the reversibility of the storage; the refueling conditions (rate and time); the hydrogen release rate, time, and delivery pressure; the stability of the system and hydrogen loss through permeation; and overall safety, toxicity, and system-efficiency issues. No material available today comes close to meeting all the needs for onboard storage of hydrogen for fueling a fuel cell/electric vehicle.

Hydrogen can be stored onboard vehicles in its pure form as compressed gas or cryogenic liquid in tanks or in the solid state as a chemical compound. The commercial sector is developing storage for the gaseous and liquid forms of hydrogen, but development is far from meeting the transportation storage targets set by the Department of Energy for 2015. Indeed, some of the requirements for onboard hydrogen storage seem unattainable with simple gaseous and liquid confinement methods. Storage of hydrogen in chemical compounds offers a much wider range of possibilities to meet the transportation requirements, but no single material investigated to date exhibits all the necessary properties. Several compounds of hydrogen with light metals have been identified that contain a high content of hydrogen on a mass basis, namely, sodium, lithium, boron, and aluminum. The performance of these metals for practical systems is severely limited by the high temperatures required to desorb hydrogen and their limited reversibility for storage. For example, $LiBH_4$ contains 18 mass% of hydrogen, but the resulting material cannot be recharged with hydrogen onboard the vehicle. For sodium alanate, the use of $TiCl_3$ as a dopant improves the release kinetics, but at the expense of a dramatic reduction in storage capacity (from 7.5 to 3.7 wt% of hydrogen at $80^{o}C$). Physical methods applied to enhancing hydrogen storage that have shown promise include ball milling and other processes that decrease particle size and increase surface area.

Finding effective hydrogen storage materials is one of the most difficult challenges facing hydrogen-powered transportation. The solution requires breakthroughs in materials performance that come from innovative basic research that looks beyond the storage materials currently known. The exacting demands on storage capacity, charge and discharge conditions, recycling lifetime, and cost span the traditional disciplines of chemistry, physics, and materials science. The fundamental factors that control bond strength, desorption kinetics, degradation due to cycling, and the role of nanosize and nanostructure in bonding and kinetics must be understood. For example, small amounts of heavier elements could be effective in tuning the lattice spacing or altering the chemical and physical properties of hydrogen storage compounds. The strong bonds typically formed by light elements with hydrogen need to be weakened with suitable dopants to improve their kinetics of absorption and desorption. An appropriate bond strength lies between covalent bonds and physisorption. The role of dopants in regulating the reversibility of storage materials at reasonable temperatures and pressures needs to be understood.

Nanostructuring is a potentially promising approach for controlling bond strength, kinetics, and desorption temperatures and pressures. Sophisticated theory and modeling of chemical bonding and kinetics can reveal key factors that control materials performance and guide the search for new materials and for modification of their performance. The search for viable hydrogen storage materials requires high-risk/high-payoff basic research that incorporates exploration of new materials, sophisticated experiments probing their behavior using cutting-edge facilities and instrumentation, and advanced theory and modeling of chemical and physical bonding and kinetics as a function of composition and particle size.

RESEARCH DIRECTIONS

Research in hydrogen storage materials needs to focus on (1) understanding the fundamental factors governing bond strength, kinetics, absorption and desorption behavior, and degradation with cycling; (2) applying these principles to modify the performance of known hydrogen storage materials; and (3) identifying new materials and new classes of materials whose properties can be tailored to meet the transportation and other demands of the hydrogen economy. Of the 2,000 storage materials known, most have not been explored in doped or nano form (Hydride Information Center 2003). Promising research directions are discussed in the following sections.

Fundamental Research

Fundamental research is needed that focuses on understanding the structural, thermodynamic, physical, and chemical properties of light-metal hydrides, such as $NaAlH_4$, $LiBH_4$, $NaBH_4$, $LiAlH_4$, LiH, BeH_2, and Li_3N. Experimental techniques for the development of solvent-free synthetic approaches should be explored. It is necessary to understand lifetime degradation issues, the fundamental atomic processes in absorption and desorption of hydrogen, the role of surfaces and surface catalysts in hydrogen storage, the role of hydrogen-promoted mass transport on phase transformations, and thermo-physical properties of the potential metal hydride hydrogen storage materials.

Nanophase Structures

Many of the intermetallic compound-based hydrides form nanophase grain structures and particle sizes on charging and discharging hydrogen. While this capability can be desirable in minimizing the hydrogen diffusion path and enhancing the rate of charging and discharging, it may also have disadvantages in increasing the susceptibility to corrosion and reducing stability. Control of particle and grain size can enhance other desirable properties. Methods for controlling the particle size and grain size by thermal management during the charging and discharging cycles need to be explored. Theory and modeling of nanophase-grain and particle-size effects may point to fruitful research directions that exploit this degree of freedom for enhancing storage performance.

Transition Metal Dopants

A fundamental understanding of the role of transition metal dopants and processing on the ability to store and release hydrogen in light-metal hydrides at desired temperatures and pressures is needed to control their kinetics on storage and release and their related thermophysical properties.

Surface Barriers

Surface barriers to hydrogen transport can often be decreased by alloying and by the formation of surface phases. Disproportionation of the alloys is an issue during charging and discharging of hydrogen, particularly as high hydrogen concentrations greatly increase the diffusivity of the substitutional alloy elements. Fundamental understanding and effective control of these phenomena need to be developed.

Complementary Theory and Experiment

Close collaboration between theory and experiment aimed at understanding experimental data on structural, thermodynamic, physical, and chemical properties of metal-hydrogen systems should pave the way for the design and synthesis of new hydrogen storage materials. It should be possible to influence the absorption energy by manipulating the electronic and physical structures of the absorbent. Adjusting the lattice parameters and strains, grain structure, Fermi level, polarization, and charge distribution of the absorbents should allow tuning of the absorption potential and hence the thermodynamics of absorption. Experimental data should be generated with an emphasis on state-of-the-art characterization tools and establishment of standards for comparison of data from various laboratories.

Novel Materials

Researchers need to look vigorously for new materials and new classes of materials that deliver dramatically better hydrogen storage performance. Innovative basic science, high-risk/high-payoff research, and breakthrough materials discoveries are needed if the demanding storage requirements for hydrogen-powered transportation are to be achieved.

Comprehensive Database

The catalog of 2,000 potential hydrogen storage compounds represents a potentially fruitful knowledge base for guiding the search for new materials (Hydride Information Center 2003). Although this catalog covers many compounds, its level of information varies widely among materials. A systematic effort to bring a consistent set of data on the hydrogen charge and discharge behavior of the listed materials would be very helpful. Such a comprehensive database would be a valuable resource in stimulating and testing creative new approaches for finding materials with dramatically enhanced storage performance.

POTENTIAL IMPACTS

Developing effective hydrogen storage materials is a necessary prerequisite for viable fuel cell transportation and a versatile hydrogen economy. Currently known storage materials do not have the capacity, charge/discharge rate, or life cycle to allow fuel cell transportation to be a competitive alternative to the internal combustion engine. Beyond transportation, inexpensive and effective hydrogen storage is needed for load-leveling renewable, nuclear, and other energy production cycles that do not match demand cycles, and for interchangeably linking the point of hydrogen production with the point of use. Storage is a key component for nearly every aspect of the hydrogen economy. It is vital not only for transportation but also as an integral part of the production cycle and in nontransportation uses ranging from neighborhood power generation to consumer electronics.

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NANOSTRUCTURED AND OTHER NOVEL HYDROGEN STORAGE MATERIALS

SCIENTIFIC CHALLENGES

Extensive research over the last two decades with more than 2,000 hydrogen storage materials has not produced a viable candidate for onboard storage of hydrogen for automotive transportation. The simultaneous requirements for high storage capacity, fast and full charge and discharge cycles, and long life cycle have not benefited from traditional materials discovery and development techniques. The rapidly developing science of nanoscale materials enables dramatic changes in atomic structure, bond strength, and reaction kinetics, as the length scale for particle size and internal structure decreases. Nanoscale materials science is an innovative and promising approach for creating new functionality from traditional materials. It is the natural direction to search for breakthroughs in hydrogen storage materials that will enable the hydrogen economy. Large surface-to-volume ratios, unique size-specific chemistry and short bulk diffusion lengths favor enhanced hydrogen storage performance. Encouraging possibilities include nanostructures of bulk hydrides that have shown promise (e.g., light-metal hydrides), materials with nanopores such as carbon nanotubes, nanohorns, and fullerene derivatives, organic-inorganic composites, aerogels, and metal-organic frameworks.

The development of a suitable hydrogen storage system for a fuel-cell–powered vehicle is a major challenge. From a research perspective, the focus must be on three basic requirements: high storage capacity, a facile way to remove (desorb) the hydrogen from the material, and a way to quickly and economically recharge (adsorb and/or absorb) the material with hydrogen. The finite size of nanoscale materials positively influences the thermodynamics and kinetics of hydrogen adsorption. This fact is one reason that these materials promise to exhibit fast sorption and desorption of hydrogen. Nanosize adds a degree of freedom for tailoring material properties. The length scale and the curvature of these materials influence the thermodynamics of storage materials. The nanostructured materials that have received the most attention in the literature for hydrogen storage are carbon-based materials. A systematic investigation is needed that explores the hydrogen storage characteristics for nanoporous light elements and a wide range of nanoporous structures. While materials such as carbon nanotubes, carbon nanohorns, and porous carbon have shown promise, the experimental results have been controversial. Target adsorbents need extremely high surface areas to approach the hydrogen storage target; if hydrogen adsorbs on high-surface–area carbon as a single monolayer, however, the maximum storage is only 4.1 wt%. Multilayer adsorption is therefore necessary, and researchers do not yet know how to perform this process. Overall, fundamental principles learned to date provide encouragement that the unique properties of nanosize materials relative to their bulk counterparts will enhance hydrogen storage performance.

Researchers need to focus on understanding the unique surface and interfaces of nanocomposites and how they affect the energetics, kinetics, and thermodynamics of hydrogen storage. Advantages and disadvantages of storing hydrogen atomically and molecularly need to be explored. New methods need to be developed for synthesizing nanostructured materials of known and uniform dimensions for use in experimentation. The role of catalysts in hydrogen storage, uptake, and release in nanomaterials is an important area that can have potential impact.

Good characterization of materials and control of synthesis processes needs to be key requirements. Significant research on materials characterization at the nano scale is needed, using scanning probe microscopy, transmission electron microscopy, and electron diffraction. Developing the experimental techniques to probe nanoscale behavior in the presence of hydrogen is a leading scientific challenge.

RESEARCH DIRECTIONS

The goal of this research is to use fundamentally different physical and chemical properties that are available at the nano scale in the design of new hydrogen storage materials. By changing the structure of a given chemical compound at the nano-level, materials with different properties are obtained, and properties determined by material structure can be controlled. Promising areas of research are discussed in the following sections.

Size and Curvature of Nanomaterials

A systematic investigation of the effect of size and curvature of nanomaterials on the thermodynamics of hydrogen storage is needed. In addition, the influence of finite size on the electronic and atomic structure of materials with promise in their bulk form needs to be explored to see how they can be improved in their nanoforms for enhanced hydrogen storage. One example is to understand the influence of pore size and curvature on the hydrogen interaction that determines the range of the plateau pressure (the pressure at which the hydrogen is released at a given temperature). A complementary approach would be to understand the influence of particle size on the same parameters.

New Classes of Hybrid Hydrogen Storage

By combining different materials with suitable catalytic and thermodynamic properties, new classes of hybrid hydrogen storage materials would emerge. For example, a core material could be selected with respect to its thermodynamic properties, and the mantle could be chosen for its catalytic activity. The combination of functional materials in a layered fashion could open up completely new routes for optimizing the overall performance of such an absorption material. Thin films could be studied as a model system prior to three-dimensional layering in a particle form.

Chemical and Mechanical Stability of Dissociative Storage Materials

The chemical and mechanical stability of dissociative storage materials is of great importance because hydrogen storage materials must withstand repeated absorption and desorption cycles. Work is needed to develop suitable nanoparticles that are chemically stable (resistant to poisoning and oxidation), resistant to segregation, and stable in terms of structure (resistant to sintering and decrepitation). Heat transport in nano-based materials, especially across grain boundaries, needs to be explored as part of this work.

High Surface Area Nanoporous Materials for Hydrogen Adsorption

High surface area nanoporous materials, where hydrogen can be adsorbed on internal surfaces in an ordered or disordered structure, needs to be explored. There are many examples of such materials, such as metal-organic frameworks, aerogels, and intercalation compounds whose potential for storing hydrogen is only now being appreciated. An integrated theoretical and experimental approach to this problem would be especially fruitful, because many possible stable structures could be searched effectively through modeling and simulation techniques.

Storage of Hydrogen at Various Temperatures and Pressures

In view of the mixed results reported so far with carbon-based materials, researchers need to determine if more than 1% storage is possible at normal temperatures and pressures using pure, well-characterized nanocarbon materials. Alternatively, the possible temperature and pressure conditions for multilayer adsorption and the kinds of carbon structures in which this might occur need to be explored. Carbon systems, when functionalized, might have additional potential for hydrogen storage and release. Hybrid materials might be synthesized that combine the surface properties of nanoporous carbon with the bulk properties of other storage materials.

POTENTIAL IMPACTS

The rational design of hydrogen storage materials that exploit the unique structures and size-specific chemistry of nanomaterials could lead to the successful development of hydrogen storage systems.

THEORY, MODELING, AND SIMULATION OF MATERIALS AND MOLECULAR PROCESSES

SCIENTIFIC CHALLENGES

A comprehensive theoretical plan is needed to complement experimental efforts in fundamental scientific research in the design and synthesis of new materials for hydrogen production, storage, and use. The challenges for theory and modeling lie in three related areas: (1) understanding of fundamental chemical and physical processes, (2) understanding of catalytic reaction mechanisms, and (3) design of new materials. Such a plan needs to focus on basic research that helps to create a fundamental knowledge base in these critical research and development areas. Successful efforts in these areas would significantly enhance our ability to meet the key technical challenges of the hydrogen economy.

Understanding of Fundamental Chemical and Physical Processes

Many complex chemical and physical processes are critical to the development of hydrogen production, storage, and use. The challenge for theory is to develop synergistic approaches with experiments to attain a fundamental understanding of these processes. For hydrogen storage, it is desirable to develop an accurate theoretical understanding of how hydrogen (either atomic or molecular hydrogen, depending on the material) reacts with the surface, interface, grain boundaries, and bulk defects of a particular material (Mergalli and Parrinello 2001; Zuttel and Primo 2002). In fuel cell research, fundamental insight into the ionic transport properties of polymer electrolytes (Paddison and Zawodzinski 1998) used in membranes and electron conductivity mechanisms in electrode materials is essential for developing improved electrode and electrolyte materials. Understanding electron transfer processes at interfaces is needed for enhancing the photocatalysis and electrocatalysis processes involved in fuel cells and hydrogen production.

Understanding of Catalytic Reaction Mechanisms

In the catalysis area, the challenge for theory is to develop a fundamental understanding of the controlling factors of catalytic reaction mechanisms from quantum chemical, kinetics, atomistic, and continuum modeling. While few examples exist where theory has led to the actual development of a new catalyst, substantial gains have been made in understanding catalytic reactions. With improved methodologies, theory should be able to contribute significantly to the development of new catalysts and the improvement of existing catalysts. Computations of the controlling factors can help find catalysts with higher activity, higher specificity, higher stability, and less susceptibility to impurities that cause poisoning and fouling. Included are catalysts for hydrogen production (e.g., photovoltaic cells, reforming catalysts) (Erickson and Goswami 2001), fuel cells (electrocatalysts) (Anderson and Albu 2000), and hydrogen storage catalysts (for efficient uptake and release of stored hydrogen with reduced need for thermal activation).

Design of New Materials

The synthesis and design of new materials for hydrogen production, storage, and use would utilize the knowledge base from the fundamental theoretical and experimental studies of chemical and physical processes and catalytic mechanisms. The challenge is to use this knowledge to predict trends (i.e., changes in functionality of a catalyst, storage, or fuel cell material as the composition and structure are varied). This approach can speed up the search for better materials and ultimately make it possible to design new materials with better performance from first principles.

Computational Challenges

Recent advances in theoretical and computational methods and tools have enhanced the ability to use these methods and tools to study fundamental processes, catalytic reaction mechanisms (Kroes et al. 2002), and materials. Four classes of computational methods are available. These methods span the length scales from 0.1 to 10 nanometers (nm) (quantum mechanics), 1 to 1,000 nm (statistical mechanics), 0.1 to 100 μm (mesoscale), and 1 mm to 10 m (continuum mechanics). Traditionally, modeling has been carried out separately for each length scale; only recently have efforts been directed toward integration across length scales. Time scales for quantum mechanical methods are on the order of 1 femtosecond (fs) (10–15 s), whereas continuum methods range from seconds to hours. The challenges for theory in hydrogen research span all these length and time scales, thus posing a serious challenge for theory and computation.

RESEARCH DIRECTIONS

Theoretical understanding and effective modeling of the interaction of hydrogen with materials in all phases of the hydrogen economy research programs are needed. In production, molecular-scale theory and models of the chemistry and catalysts are needed for extracting hydrogen from fossil fuels, water, and biomass. In storage, molecular-scale theory and models are needed for the chemisorption and physisorption of hydrogen on surfaces, its chemical binding with light-metal and complex hydrides in bulk and nanoscale form, its physical and chemical interaction with carbon nanotubes, and the molecular phenomena governing the rate of hydrogen absorption and desorption. In fuel cells, theory and models are also needed for specific electrocatalysts for the oxidation of hydrogen and reduction of oxygen at the electrodes, the mechanisms of proton and oxygen ion conduction in organic and oxide membranes, and the mechanism of degradation of electrode and membrane materials with cycling and use. Beyond the description of phenomena in particular cases, a more demanding and useful goal is the prediction of trends (i.e., the changes in functionality of a catalyst, storage material, or membrane as the composition is varied). This can speed up the search for better materials and ultimately make it possible to design new materials with better performance in hydrogen production, storage, and use from first principles. Promising research directions are discussed in the following sections.

Integration of Experimental and Computational Approaches

In hydrogen production via reforming of fossil resources, an integration of experimental and computational approaches is needed to understand and control active site structures, catalytic mechanisms, and catalyst design on the nano scale. Integration of approaches is particularly important for the design and discovery of cost-effective catalysts that can produce hydrogen of sufficient purity for use in proton exchange membrane fuel cells.

Complex Photosystem Behavior Associated with Hydrogen Production

Theory and modeling are needed to help understand and predict the behavior of complex photosystems associated with solar hydrogen production. With increased computational power and understanding of electron transfer, theory can provide insight into important features of these systems (such as femtosecond dynamics in sensitizer molecules and particles, and the branching of kinetic pathways in complex molecular assemblies and photoelectrochemical cells) that are often at the "ragged edge" of experimental observation.

Modeling of Aqueous Fluids

Modeling of aqueous fluids under extremely nonideal conditions is needed to provide thermodynamic data (for sulfuric acid at high concentrations and for $I_2/HI/H_2O/H_2$ reactions) for input in reactor design for thermal hydrogen production.

Verification of the Accuracy of Theoretical Models

Experimental data are needed on well-characterized storage systems, including measurement of adsorption isotherms, isosteric heats of adsorption, and diffusion and reaction rates as a function of temperature. Once the accuracy of theoretical models has been verified by comparison with such experiments, theory should be able to provide experimental guidance by predicting how to modify materials to obtain better performance.

Effect of Size and Shape on Nanoparticle-Hydrogen Interaction

At the nanostructure level, a fundamental understanding is needed as to how the size and shape of nanoparticles affect their interaction with hydrogen. Understanding this concept can be accomplished, for example, by synergistic experimental and theoretical studies on atomic clusters (where size and composition are known at the atomic level), mimicking the composition of complex metal and chemical hydrides.

Mimetic Methods for Producing Nanoporous Materials

New mimetic methods, which mimic at the molecular level the method by which the material was made at the macroscopic level, are needed for producing computationally molecular-level instances of catalytic and adsorptive materials that are nanoporous but not regular. Such mimetic materials can be used in studies of adsorption and reaction at the molecular level.

Compositional Changes from Binding and Diffusion of Hydrogen

Computational studies of the nature of binding and diffusion of hydrogen in light-metal and chemical hydride storage materials are needed for understanding and predicting the effect of compositional changes. For example, the bonding between hydrogen and some of the light-metal solids, such as magnesium, appears to be ionic, whereas the metal-metal bonding in the host crystal is metallic. This suggests that the ionic or covalent bonding between hydrogen and the host metal lattice in the lightweight alloys might be changed to metallic bonding by alloying with elements. Similarly, an understanding of how catalysts affect the nature of hydrogen bonding is important.

Hydrogen-interface Interaction

Calculation of the interaction of hydrogen with interfaces, such as boundaries between nanocrystals, is needed to understand why and in what cases the presence of such interfaces can increase the magnitude and rate of absorption and desorption of hydrogen in storage materials.

Design of Improved of Storage Materials

Atomistic simulations of hydrogen adsorption and diffusion into mimetically produced adsorbent materials will provide molecular-level insight into designing improved storage materials.

Theoretical Approaches to Hydrogen Storage

It is important to bring several layers of theoretical approaches to bear on the hydrogen storage problem. First-principle calculations of binding, diffusion, and the effect of defects in small systems need to be performed. Results from these calculations need to be fed into methods that can be used to study larger samples, such as potential energy functions or tight binding approaches. Furthermore, the results of such simulations need to be fed into mesoscopic (such as kinetic Monte Carlo) or continuum models that can be used to study longer time and larger length scales.

Scanning of New Materials for Use in Hydrogen Storage

Fast computational methods are needed for scanning new materials for their potential for use in hydrogen storage. For example, simplified density functional theory, combined with genetic algorithms, can be used to search for stable crystal structures. Techniques from informatics could also prove useful. In some cases, better functionals for density functional theory are needed. Linear scaling of first-principle algorithms for metals would be useful in studies of defects and disordered materials.

Hydrogen-induced Failure Mechanisms

Calculation of hydrogen-induced failure mechanisms — both at the atomic level and on larger-length scales — can help in the understanding of the durability of these materials.

Hydrogen Interaction in Nanostructured and Porous Storage Materials

Computational studies of hydrogen interaction in nanostructured and porous storage materials, such as carbons and metal organic frameworks, are needed. Theory can be used to investigate fundamental questions regarding whether hydrogen binds molecularly or dissociatively, where the hydrogen resides, where the activation barriers for hydrogen desorption reside, and how the material can be modified to increase hydrogen adsorption. Such knowledge will make it possible to design the geometric and electronic structure so as to improve the selective adsorption and release of hydrogen from these materials.

Modeling of Experimentally Realistic Electrode Phenomena

Modeling of experimentally realistic electrode phenomena is needed. Studies of the dissociation of oxygen on electrocatalyst metal surfaces in the presence of an electrolyte and as a function of the electrode potential can provide insights that can be translated into new materials. Also, fundamental experimental and theoretical studies of molecular reactions on model systems (e.g., using single crystals) of both known materials (e.g., platinum, platinum alloys, gold) and novel materials can provide mechanistic insight and help to assess the reliability of theoretical predictions.

Combined Methodologies for Improving Proton-conducting Membranes

A combination of experimental and theoretical methods to probe proton dissociation and transport in pores of polymers is essential to find improved proton-conducting membranes. Theory can provide insight into key active molecular fragments in the polymer electrolyte, most notably the sulfonic acid (or other acid) moiety; water solvation and proton dissociation phenomena at the fixed acid site; and transport processes in short segments of polymer electrolytes "pores" as well as in complete models of macroscopic transport.

Effects of Confinement and Catalytic Activity on Reaction Rates in Nanoporous Materials

Careful theoretical studies are needed to separate the effects of confinement (in nanoporous materials) and catalytic activity on reaction rates in nanoporous catalytic materials, since nanoconfinement alone can impact reaction rates by orders of magnitude. Indeed, it is likely that simulation is the only way in which these effects can be studied independently.

Transport and Chemical Reactions during Adsorption and Desorption of Hydrogen in Storage Materials

Calculations of both transport and chemical reactions during the adsorption and desorption of hydrogen in storage materials are needed. Consistent coupling between calculations on different length scales is required.

Hydrogen Lattice and Hydrogen-Hydrogen Interactions that Limit Storage Capacity

Investigation is needed as to the nature of the hydrogen lattice and the particular hydrogen-hydrogen interactions that limit the hydrogen storage capacity to a much lower amount than would be available if more of the interstitial sites could be occupied by hydrogen.

POTENTIAL IMPACTS

Theory, modeling, and simulation have the capability to substantially impact all areas of hydrogen research. Specifically, it is anticipated that computational tools will be increasingly applied to understanding real catalysts for hydrogen production, that they will be a driving force in the rational design of a high-density hydrogen storage material, and that they will play a key role in the development of new electrocatalysts and proton-conducting membranes for more cost-effective fuel cell systems.

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LOW-COST, HIGHLY ACTIVE, DURABLE CATHODES FOR LOW-TEMPERATURE FUEL CELLS

SCIENTIFIC CHALLENGES

Current composite cathodes in low-temperature fuel cells contain a significant amount of platinum (Pt) in the form of very small particles (3 to 5 nm) to catalyze the reduction of oxygen from the air. Even though Pt metal is the best-known catalyst for that application, low-cathode catalyst activity leads to 25–33% efficiency loss (i.e., a loss of about 0.3–0.4 V) over the majority of the operating range of low-temperature fuel cells (10–100% of power [Gasteiger and Mathias in press]).

Enhanced cathode catalysts would not only improve the overall fuel cell system efficiency (well-to-wheel), but it would also significantly reduce the heat rejection load of the system. For example, increasing full-power E_{cell} by 100 mV (from 650 to 750 mV) would reduce the heat-rejection load by 30%. Next to cost, heat rejection is currently a major impediment to automotive fuel cell applications (Masten and Bosco 2003), driving the need for high-temperature membrane research and development.

Cost

Mass-specific power densities for the Pt catalyst range from approximately 0.5–1 g_{Pt}/kW (i.e., \$12.5–25/kW) for PEMFCs using hydrogen as the fuel. In low-temperature fuel cells that use other fuels, such as methanol, the Pt loading is much higher (ca. 5-10 g_{Pt}/kW; that is, about. \$125–\$250/kW) due to problems caused by methanol leaking through the membrane from the anode to the cathode. While noble metal cost is less critical for applications in low-power applications (1-W power range), Pt cost and supply constraints for large-scale automotive applications require mass-specific power densities in the range from 0.1 to 0.2 g_{Pt}/kW or less.

Durability

Cathode performance typically degrades with time; that is, the overpotential for oxygen reduction increases with use. Voltage degradation rates range from 1 to 100 µV/h, depending on the operating conditions. System requirements (heat-rejection, performance) generally drive the system temperature to the upper limit of the specific fuel cell system (e.g., more than 80°C for automotive proton exchange membrane fuel cells [PEMFCs]), where degradation rates are largest. Current automotive PEMFCs at >80°C show degradation rates of >50 µV/h, while much less than 10 µV/h is needed (for 5,000-h life). Stationary PEMFC systems operate at less than 80°C, with degradation rates between 10 and 20 µV/h, while an even more demanding 1 µV/h or greater is required (for 40,000-h life). Because the system operating temperature is generally driven by heat-rejection requirements (Masten and Bosco 2003), more active cathode catalysts (i.e., higher cell voltage and thus improved conversion efficiency) would lead to durability improvements.

Furthermore, the Pt nanoparticles are supported on larger conducting carbon particles. Currently used carbon supports (either fully or partially graphitized carbon-black) also corrode (or oxidize) under certain system-imposed operating conditions (e.g., idle operation, start/stop) and thus limit fuel cell system durability. More durable support materials are desirable. Recent work in Japan suggests that carbon nanotubes show considerable improvement in this regard (Endo et al. 2003). The use of Pt alloys in place of pure Pt improves efficiency and reduces cost (Thompsett 2003), but the stability of Pt alloys in the PEMFC environment is still unproven.

Much of the current development work is hampered by poor electrochemical testing and analysis methods, so that poor catalysts are being pursued for decades, while novel catalysts may be missed. Education in catalyst test methods is badly needed, and test methods need to be developed and communicated so that they can be used by a wider community (e.g., standard electrochemical testing methods in liquid electrolytes rather than full-blown membrane electrode assembly [MEA] testing; also, simplified MEA preparation and testing methods).

Furthermore, determining the activity of cathode catalysts requires some rather detailed knowledge of electrochemistry. Clearly, broad collaborations and joint interdisciplinary research are sorely needed and would enable the “out of the box” thinking that is required for the needed revolutionary advances. Enabling and supporting such activity should be a priority.

RESEARCH DIRECTIONS

Improved Activity of Noble-metal–based Catalysts

Development of cathode catalysts with improved activity, that is, higher voltage at a given mass-specific current density ($A/mg_{catalyst}$, or A/mg_{Pt}), is needed. This addresses three critical issues: efficiency, cost, and system improvements (heat rejection). If solved, the need for high-temperature membranes would also be lessened or eliminated, increasing durability and again decreasing cost. Currently known catalysts with mass activities are superior to Pt and Pt alloys (e.g., PtCo, PtCr [Thompsett 2003]), but their long-term stability is not clear. Long-term electrochemical studies clearly are needed.

Even when the Pt particles are as small as 3 to 4 nm, only 25–40% of the Pt is active in electrocatalysis, since only that fraction of the Pt atoms is at the particle surface. Improved dispersions would reduce the cost of Pt. Cost reductions might be achieved via Pt-skin catalysts, Pt decoration of other nanoparticles, and improved support materials.

Platinum-free Catalyst

Ideally, a catalyst that contains no precious metals is desirable on the basis of cost. Such a catalyst, however, must have at least 10% of the activity of the current Pt catalysts; otherwise, the system volume or weight becomes too large, even if the catalyst is free (current Pt catalysts — 50 wt% Pt/carbon — achieve ~1,000 $A/cm^3_{electrode}$ at 0.8 V in H_2/O_2 PEMFCs at 80°C [Wagner et al. 2003]). New catalysts, with higher activity than Pt but containing no precious metal, would clearly be one of the most highly sought high-risk/high-payoff discoveries in catalysis research for the hydrogen economy. The catalyst has to be produced as nanoparticles and integrated into a membrane electrode assembly; that is, it must be compatible with other fuel cell materials and processes. Finally, these materials must have long-term stability in the fuel cell environment and in use. Clearly, this challenge is daunting, since no better material than Pt has been discovered in the more than 150 years since the invention of the fuel cell.

Fundamental Experimental Understanding of the Activity of Known Catalysts

Such research may provide the insight necessary to design, modify, or invent materials with improved oxygen reduction performance. Research should include studies of well-defined single crystals and surfaces and changes that occur when such materials are in the form of nanoparticles. Researchers should understand the oxygen reduction reaction mechanisms on Pt, Pt alloys, gold, decorated nanoparticles, and other known and recently suggested catalysts. Furthermore, these investigations should not be limited to the acid environment, since work in salt and alkaline environments might improve basic understanding and perhaps lead to unforeseen breakthroughs. For example, these studies might elucidate the unexpected activity of gold in the oxygen reduction reaction in alkaline electrolytes (Ross 2003). These experimental studies should be supported, and perhaps guided, by a rigorous computational and theoretical effort.

Novel Catalysts

Studies of the oxygen reduction reaction on new materials should be undertaken. Possible systems should include ordered phases (such as intermetallics), mixed oxide-metal phases (e.g., $PtSnO_x$) (Swider-Lyons and Bouwman 2003), and supported inorganic and perhaps even organic compounds. This latter category should include bio-inspired systems (Katz et al. 2003), transition-metal macrocyclics, and other likely candidates. Exploiting the synergy between catalyst and support could also be promising. An important goal is the development of catalysts selective for the oxygen reduction reaction, resistant to poisoning, and stable in the fuel cell environment. Computational and combinatorial methods might well play a useful, even central role in catalyst discovery.

Durability of Cathode Catalysts

The stability of carbon-based catalyst supports should be examined by establishing the mechanisms of degradation under open-circuit and transient conditions. Novel carbon materials, such as nanotubes or other substances that are thermodynamically or kinetically stable at anode potentials and operating conditions, should be explored. These studies should lead to the selection of new electrochemically stable supports to provide solutions for the support corrosion problem. Novel support materials with enhanced corrosion stability, possibly including Nb-doped TiO_2 (Chen et al. 2002), tungsten-bronzes, stable carbons, and other materials should be examined. Again, combinatorial approaches may prove effective.

Corrosion, sintering (Tada 2003), de-alloying and other mechanisms that deactivate cathode catalysts should be investigated.

Atomistic Modeling of Reaction Pathways

Modeling of experimentally accessible phenomena associated with the goals discussed above should be undertaken. These efforts could begin with realistic models of the oxygen reduction reaction mechanism on Pt surfaces, including effects of the solvent and electric fields, and the effects of the base metal in Pt-X (X = Co, Ni, Fe, Cr, etc.) alloys. One recent effort to understand the reduction of peroxide on modified Au surfaces demonstrates that such calculations are feasible (Gerwith 2003). Such a theoretical program might be able to make predictions of relevant properties of prospective novel catalysts, or even to propose specific catalyst compositions and structures, and to model catalyst corrosion or dissolution under control of the applied potential for elucidation of durability issues.

POTENTIAL IMPACTS

The discovery of novel low-cost and abundant catalysts that could enhance cathode activity, improve durability, and withstand the cathode environment is key to large-scale deployment of low-temperature fuel cells for hydrogen-based transportation. The high-priority research direction leverages cross-cutting developments in areas of nanocatalysis, combinatorial chemistry, and atomistic modeling and provides an interdisciplinary research strategy toward attaining this goal.

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MEMBRANES AND SEPARATION PROCESSES FOR HYDROGEN PRODUCTION AND FUEL CELLS

SCIENTIFIC CHALLENGES

Membranes and separation technologies are key determinants of efficiency and economy in hydrogen production and use. Ideally, membranes for fuel cells and electrolyzers should be highly permeable to protons (or oxide ions) but impermeable to hydrogen and oxygen. Very highly selective permeability is needed for both process and product gas separations in reformers and storage systems. High ionic conductivity over broader temperature ranges is needed in fuel cell electrolyte membranes. Membranes that can perform separations at high temperatures in extreme chemical environments are essential for efficiently producing thermochemical hydrogen and for improving the efficiency of reformers. Knowledge of membranes with these combinations of properties is limited, as is the basic understanding necessary for their design. These needs for improved separation membranes call for an integrated effort in new materials synthesis, characterization, and modeling.

Low-temperature polymer electrolyte membrane fuel cells (PEMFCs) require expensive catalysts and fuel processing systems because of residual carbon monoxide (CO) in the hydrogen that is made by steam reforming. Residual sulfur in the hydrogen derived from fossil fuels causes catalyst poisoning. Developing advanced membranes or other gas separation methods that can efficiently remove impurities from steam-reformed hydrogen could solve these problems.

Ionically conducting membranes are critically important components of low-temperature (less than 200°C) and high-temperature (greater than 600°C) fuel cells. In PEMFCs, there is a need for proton-conducting membranes that retain conductivity at higher temperatures. Perfluorosulfonic acid (PFSA)-based membranes, such as Nafion, lose conductivity as they begin to dehydrate above 100°C. Proton-conducting polymeric, inorganic, or hybrid membranes that could function above 200°C would represent a true breakthrough for fuel cells, because they would enable the use of inexpensive catalysts and lower-purity hydrogen. Similarly, the utility of solid oxide fuel cells (SOFCs) is largely limited by the lack of inorganic oxide-ion-conducting membranes that function at 600°C and below. In both PEMFCs and SOFCs, the electrolyte membrane, catalysts and gas diffusion layers are part of an integrated system that determines reactivity at a three-phase (catalyst, electrolyte, fuel or oxidant) interface. Learning to control and characterize these nanostructured interfaces is important for developing fuel cells that economize on catalysts and function more efficiently.

The least expensive implementations of photochemical and biophotolytic systems for generating hydrogen from water and solar energy produce mixtures of hydrogen and oxygen. Development of energy-efficient methods for separating the hydrogen from these mixtures requires new approaches. Palladium membranes that are widely used for hydrogen purification in a number of applications cannot be used in this case, because they catalyze the recombination of hydrogen with oxygen. Alternatively, membranes that are gas-impermeable and proton-permeable could be developed as hosts for inorganic or biomimetic photochemical reaction centers that generate pure hydrogen on one side of the membrane and oxygen on the other.

Separation technologies could also play a key role in enabling the production of hydrogen from solar thermal or thermonuclear chemical cycles. In the proposed water splitting cycles, efficient separations are needed to isolate hydrogen and oxygen from other compounds and to shift the equilibria of reactions in the cycle. In some cases, these cycles involve separations under extremely corrosive conditions (e.g., separation of water, sulfur dioxide, and oxygen from unreacted sulfuric acid at 750–900°C in the sulfur-iodine cycle), and thus would require membranes or sorbents made from unusually stable materials.

RESEARCH DIRECTIONS

The goals of the research on membranes include (1) enhancing the efficiency of gas separations for the production of ultra-pure hydrogen, including those involved in both process and product gas separations during production and also for point-of-use (in fuel cells) repurification of hydrogen that is not sufficiently pure (e.g., that made by steam reforming); (2) improving gas-impermeability while retaining high proton conductivity of membranes for PEMFCs and of membranes for hosting nanoscale photochemical reaction centers; (3) enabling novel intermediate- and high-temperature fuel cell designs by means of advanced polymeric and inorganic-ion-conducting membranes; and (4) developing robust inorganic membranes to enable thermal water splitting cycles as a viable means of hydrogen production. Promising research directions are discussed in the following sections.

Nanostructured Porous Materials for Gas Separations in Hydrogen Production

The design and construction of porous materials has recently become quite sophisticated, and a promising opportunity exists to create new materials for improved gas separations. Microporous oxides, metal-organic frameworks, and carbons may be particularly useful sorbents for the removal of sulfur-containing compounds and carbon monoxide from hydrogen. Advances in this area will be driven by the synthesis of new porous materials and their physical characterization as sorption media.

Chemical Assembly of the Catalyst-electrolyte-vapor, Three-phase Interface

Both synthetic advances and an increased understanding of structure-property relationships are needed to create more efficiently functioning electrocatalyst-electrolyte percolation networks for membrane electrode assemblies. The characteristic dimensions of catalyst particles and of pores that transport fuel, ions, and oxygen are in the nanometer regime; this suggests that self-assembling systems on this length scale (e.g., di- and tri-block copolymers, mesostructured inorganic solids, thin films assembled layer by layer) should be studied as a means of organizing these networks. New concepts should be pursued with the goals of enhancing catalyst utilization and reducing resistive losses in fuel cells.

Characterization of Electrochemical and Buried Interfaces

Better techniques are needed to study the microstructure and reactivity of the electrocatalyst/electrolyte interface in membrane-electrode assemblies. *In situ* characterization methods are particularly important because the structure of the interface depends on the local potential gradient and changes with time.

Modeling of Sorption and Transport in Porous Materials and Membranes

Theoretical models are needed to understand a number of phenomena associated with sorption and transport. In membranes, these include atomic-level processes (e.g., the coupled motions of polymer chains, water, and protons in polymer electrolytes), transport in pores, and the relationship between macro-scale conductivity and the structure of pore networks.

Electronically Conductive, Selectively Permeable Gas Diffusion Membranes for Purifying Anode (Hydrogen/Carbon Monoxide) Streams in Proton Electron Membrane Fuel Cells

The purity requirements for hydrogen in fuel cells would be relaxed if gas diffusion layers could selectively transport hydrogen and not carbon monoxide to the catalyst surface. This would require electronically conducting membranes (such as microporous carbons or hydrogen-permeable metals), or perhaps novel gas diffusion layer/catalyst architectures, with selectively high hydrogen permeability.

Membranes for Hosting Nanoscale Catalytic or Photochemical Reaction Centers

Membranes are needed as substrates for organizing oriented two-dimensional arrays of nanoscale catalytic centers. Such catalytic centers could enhance the selectivity of membrane permeability, and conversely the proximity to a selectively permeable barrier could enhance the net activity of integrated catalytic devices. For example, nanoscale photochemical reaction centers embedded and co-oriented within a gas-impermeable membrane immersed in water could generate trans-membrane light-driven electron transfer coupled to pure hydrogen production on one side and oxygen production on the other.

Low-cost, High-conductivity Proton Conductors for Use in Low- (<200^{o}C) and Intermediate-temperature (200-400^{o}C) Fuel Cells

Alternatives to PFSA-based membranes are needed for low-temperature (<200^{o}C) and intermediate-temperature (>200°C) PEMFCs, in particular, materials that retain water and proton conductivity at higher temperatures and have lower gas permeability. These could include new polymers and composite materials with higher thermal stability, and preferably lower cost, than Nafion. Access to the intermediate-temperature regime would significantly improve carbon monoxide tolerance, reduce the need for precious metal catalysts, and improve heat rejection in fuel cell stacks.

Lower-temperature (500-600°C) Fast Oxide-ion Conductors for Solid Oxide Fuel Cells

The discovery of lower-temperature oxide-ion conductors would be an important enabler of SOFC technology, because most of the problems of SOFCs (corrosion, differential thermal expansion) are associated with high-temperature operation. Understanding oxide-ion conductivity in these materials is important for the development of improved electrolyte membranes.

High-temperature Separations Processes and Membranes for Use in Corrosive Environments

Thermal water splitting cycles involve the use of corrosive materials, such as sulfuric acid, hydrohalic acids, and water, at high temperatures. Sorbents and membranes that are stable in such environments will be needed if these thermal cycles are to be run efficiently.

POTENTIAL IMPACTS

Improved gas separation in hydrogen production and use would lower the cost of PEM fuel cells by reducing the need for or eliminating some of the most expensive fuel processing components (water-gas shift and preferential oxidation [PROX] units). Selectively permeable membranes with integrated nanoscale catalytic sites could yield efficient, inexpensive solar-to-hydrogen energy conversion devices as well as efficient electrode interfaces for fuel cells. Increasing the operating temperature of hydrogen/air fuel cells, by developing membranes that are good ionic conductors above 200°C, would allow the use of inexpensive, non-noble metal catalysts and relatively low-purity hydrogen. An ability to conduct efficient separations at high temperatures and in corrosive environments is one of the advances needed for realizing the high efficiencies proposed for solar or nuclear thermochemical water splitting cycles.

ANALYTICAL AND MEASUREMENT TECHNOLOGIES

SCIENTIFIC CHALLENGES

Development of improved methods for hydrogen production, storage, and use requires a fundamental understanding of the structure and properties of new materials and the chemical processes that occur at the interfaces with these materials. New capabilities are needed to study these materials and associated processes directly under realistic environmental conditions, rather than in high vacuum. Furthermore, measurements need to be taken with high temporal resolution, allowing changes to be monitored dynamically. New techniques are also needed that enable multiple analytical measurements to be made simultaneously on the same system. For example, in fuel cells, the three percolation networks (proton, electron, and gaseous) need to be monitored simultaneously to assess new membrane designs. While many techniques are capable of characterizing materials composed of elements with high atomic number (Z), far fewer allow the study of lower-Z elements, particularly hydrogen. This lack of capability is particularly true at high spatial resolution. Such capabilities, for example, would allow fundamental understanding of hydrogen interactions at nanophase boundaries. Emerging capabilities in nanoscience present many exciting possibilities to revolutionize our ability to design and probe tailored materials and selective chemical processes. To fully realize this potential, however, researchers require new tools to characterize these nanoscale materials and associated chemical processes. Working at the nano scale presents many challenges for analytical and measurement science. For example, the curvature, length, shape, and pore size of nanotubes need to be reproducibly measured to assess the effects of these parameters on hydrogen-binding characteristics of these materials. More important, these measurement techniques need to be standardized so that results can be compared among laboratories. Studies of materials and processes at the nano scale also require analytical tools and sensors capable of providing specific chemical and physical information at very high resolution. The advantage of studying catalytic processes of nanostructured clusters, for example, would be realized if we could study the chemical processes occurring at individual nanoclusters characterized for size, shape, crystallinity, etc., rather than on large ensembles of heterogeneous nanoclusters.

RESEARCH DIRECTIONS

Multimodality, In Situ Characterization

In general, spectroscopic tools and sensors monitor a single process at a time. Recent studies, however, have shown that catalytic processes involve more than just a simple interaction of the reactant and the catalytic site. Combinations of analytical techniques and sensors with fast time response are needed to monitor these processes simultaneously and to fully elucidate the chemical transformations; changes in nanoscale structure; reaction kinetics; and other processes involved in hydrogen production, storage, and use. In addition, computational methods are needed to integrate information obtained from multiple sensors measuring different properties on different length scales and time scales.

Electrochemical Process Monitoring

New capabilities are needed for measuring ion and electron transfer processes and chemical transformations that occur at the interface with surfaces, such as nanostructured materials, electrodes, and bio-inspired materials that are used in hydrogen production and fuel cells. Of special interest are techniques that would measure proton conduction in low- or zero-water environments.

Neutron-based Techniques for Studying Hydrogen Reactions

Neutron-based techniques have unique capabilities for studying low-Z atoms. Because of the differences in the scattering of neutrons by hydrogen and deuterium, neutrons show particular promise for examining reactions involving hydrogen, such as understanding the role of surfaces and materials structure in hydrogen storage, catalysis, and membranes. In addition, because of their penetrating nature, neutrons can be used to study reactions at surfaces under high-pressure conditions.

Sensors to Support Hydrogen Infrastructure

Economy-wide deployment of hydrogen as an energy source will demand new sensors and detection capabilities to ensure safe production, storage, and use. Inexpensive and sensitive detectors of hydrogen leaks will be needed to monitor storage devices and pipes. Sensors will be needed to monitor degradation of materials, including weld failures and embrittlement of materials.

Dynamic, High-spatial-resolution Environmental Electron Microscopy

Fundamental research in hydrogen production, storage, and use places additional demands on state-of-the-art electron microscopy to monitor atomic-level processes that occur in materials. Observing these processes under realistic environmental conditions will be valuable for understanding atomic-level changes that occur during catalysis, corrosion, and hydrogen charging and discharging cycles for hydrogen storage. Furthermore, new computational tools are needed to increase the speed at which permit images are collected so that changes in the structure can be monitored dynamically.

Chemical Microscopes

Observing reactions at the nano scale requires new tools that can monitor chemical processes with high spatial resolution. While electron microscopes can provide insight into high-Z elements used as catalysts, electrodes, and other materials, few high-spatial resolution tools can monitor chemical reactions at these surfaces. These "chemical microscopes" would also be able to study nonconducting materials, which are difficult to study with electron microscopes.

Micro- and Nanoscale Sensors

Revolutionary advances in sensitivity are being achieved by scaling down analytical devices to the micro and nano scale, as demonstrated with micro-electromechanical system (MEMS) and nano-electromechanical system (NEMS) devices. For example, microfluidic lab-on-a-chip devices, nanocantilevers, and others have already exhibited femtomole and lower detection sensitivities in materials. Further developments in MEMS and NEMS technologies are needed to provide sensors that can monitor an experiment continuously, providing detailed information on atomic-level and molecular-level processes. Furthermore, these devices have low power requirements, making them amenable to long-term and remote monitoring scenarios.

High-throughput Characterization

With the incorporation of large-scale combinatorial synthesis techniques, new characterization methods will be required to rapidly screen synthesized materials with respect to chemical and physical properties, reactivities, and other benchmarking parameters.

High-sensitivity Measurements for Nanoscale Materials

To realize the full potential of nanoscale science, new analytical and characterization tools are required to measure the chemical and physical processes of very small amounts of materials. Achieving this goal will require increasing measurement sensitivity, while maintaining the selectivity of analytical techniques.

POTENTIAL IMPACTS

Reliable sensors, characterization, and measurement techniques are essential for the implementation of all aspects of a hydrogen economy. Fundamental research to elucidate the atomic- and molecular-level processes involved in hydrogen production, storage, and use will require a new generation of analytical tools that provide high spatial and temporal resolution to capture the multiple chemical and physical processes that occur within materials and at their interfaces. Together with computational tools, the results of these experimental measurements can provide understanding and predict the full range of chemical and physical parameters required for the development of materials and processes needed for efficient hydrogen production, storage, and use.

IMPACT OF THE HYDROGEN ECONOMY ON THE ENVIRONMENT

SCIENTIFIC CHALLENGES

The development of a large-scale hydrogen economy is motivated in part by its beneficial effects on the environment, including a reduction of the anthropogenic emission of carbon dioxide and other greenhouse gases and of atmospheric pollutants associated with the present fossil fuel economy. These beneficial effects are easy to foresee; however, our ability to anticipate the potential of harmful environmental effects from increased emissions of hydrogen itself to the atmosphere is more restricted. Although hydrogen is neither a greenhouse gas nor a toxic substance, it influences the dynamics of atmospheric methane, water vapor, and ozone, and it actively interacts with the biosystem of the soil. The transition to a hydrogen economy may lead to a substantial increase in the amount of hydrogen entering the atmosphere — from a current ~75 Mtons/yr (Novelli et al. 1999) to as much as ~120–180 Mtons/yr, based on estimates of the possible rates of leakage from hydrogen generation, storage, and transport sites (Tromp et al. 2003). In the current steady state, it is hypothesized that the bulk of the hydrogen entering the atmosphere is taken up by microbiological hydrogen metabolism in subsurface soils (Novelli et al. 1999). It is unknown whether this biological sink has the capacity to accommodate the expected increased hydrogen flux, or if the net concentration of hydrogen in the atmosphere will increase. Preliminary modeling indicates that an increased atmospheric concentration has the potential to:

- Affect the oxidizing capacity of the atmosphere,
- Impact the stratospheric ozone layer by moistening the stratosphere,
- Alter the pace of climate change by indirectly increasing the lifetime of methane, and
- Change the balance of hydrogen-consuming microbial ecosystems in subsurface soils.

To reliably quantify the potential impacts of large-scale increases of hydrogen releases to the atmosphere, we need to improve our understanding of the global biogeochemical cycles of atmospheric hydrogen. This research would also provide an engineering constraint on the environmentally acceptable amount of ‘leakage’ from a large-scale hydrogen infrastructure — information that is urgently needed by those industries seeking to develop a safe and efficient hydrogen infrastructure.

Hydrogen is a naturally occurring atmospheric trace gas. The National Oceanic and Atmospheric Administration Climate Modeling Diagnostics Laboratory has collected observations of hydrogen as an atmospheric trace gas at sites around the world on a regular basis. The global average tropospheric concentration is ~500 parts per billion. The two main sinks for H_2 are believed to be reaction with OH radicals and deposition at the surface through the activities of terrestrial microbes, with the latter sink predominating. The primary sources of H_2 to the atmosphere are from oxidation of methane, oxidation of nonmethane hydrocarbons, fossil fuel combustion, and biomass burning. Our understanding of the processes governing the sources and sinks of atmospheric H_2 is limited, and the magnitudes of the fluxes are poorly constrained.

RESEARCH DIRECTIONS

The goal is to develop a fundamental understanding of the processes involved in the global biogeochemical cycling of atmospheric H_2. This knowledge will make it possible to perform a comprehensive assessment of the environmental impact of the release of H_2 to the atmosphere from a developing global H_2 economy.

New Modeling and Simulation Tools

Models of the sources and sinks of atmospheric hydrogen need to be developed and incorporated into global three-dimensional coupled chemistry-climate models. Long time series of observations of atmospheric H_2 are available for testing and comparing models.

Biological and Technological Sources and Sinks of H_2

The H_2 inventory is biologically mediated both as a source and as a potentially major sink. At least two routes lead to the release of H_2. One route to H_2 production is through wetlands fermentation of photosynthetically produced biomass (Schlesinger 1997). Mats of photosynthetic cyanobacteria also generate molecular hydrogen as a by-product of nitrogen fixation at concentrations well above atmospheric (Hoehler et al. 2001). A modest fraction of this biogenic H_2 probably escapes utilization by other microbes and enters the atmosphere. Biogenic hydrogen emanating in one way or another from biological solar energy conversion is thought to have had a profound effect on the evolution of the earth's atmosphere (Hoehler et al. 2001). Much of this impact arises from the role of hydrogen as a source or reductant in the synthesis of methane from carbon dioxide by methanogenic archaebacteria in subsurface soils. Our understanding of the spatial and temporal distribution, magnitude, and intensity of the soil sink for atmospheric H_2, as well as of the fates of the reductant once the hydrogen is consumed, needs to be expanded. The possible effect of increased atmospheric H_2 on soil uptake, fertilization, warrants study.

Importance of H_2 in Determining the Oxidative Capacity of the Atmosphere

Atmospheric H_2 is reactive and first affects the lower atmospheric layer, called the troposphere. It reacts with the trace OH radicals to form water. The trace OH radical inventory is critical to the cleansing of the atmosphere. Hence, any additional stress on OH radicals is a problem. Prinn et al. (2001) recently reported a potentially dramatic variation in the atmospheric inventory. Increasing the stress on the OH radical concentration through the deployment of a hydrogen economy that is leaky would have to be viewed as deleterious. Global atmospheric chemistry models can be used to study the impact of H_2 releases on the oxidizing capacity of the atmosphere.

Role of H_2 Releases on the Stratospheric Ozone Layer

H_2 releases significantly impact the chemistry of the troposphere and the stratosphere, particularly with regard to the long-term stability of the stratospheric ozone layer. Stratospheric chemistry models can be used to study the impact of H_2 releases on the long-term stability of the ozone layer.

Likely Source of H_2 to the Atmosphere from a Hydrogen Economy

It is almost certain that international agreements will be developed that limit the emissions of H_2 to the atmosphere at an environmentally sustainable level as we go forward with the development of a hydrogen economy. The OH radical inventory in the troposphere and ozone depletion in the stratosphere provide constraints on how "tight" the hydrogen economy must be. Estimates show that a 1% leak rate from a hydrogen economy would double current anthropogenic H_2 emissions. Leakage rates much greater than 1% are likely if no action is taken to engineer systems in advance to minimize hydrogen leakage. To quantify the potential impacts of large-scale releases of hydrogen to the atmosphere, we need to develop precise systems-based engineering models of the likely H_2 release arising from a developing global hydrogen economy infrastructure.

Comprehensive Impact Assessment

Ultimately, we must perform a series of simulations to quantify the effects of an increasing H_2 release as a consequence of the large-scale development of a hydrogen economy. Such simulations must be able to assess the impact of these releases on the oxidative capacity of the atmosphere, the long-term stability of the ozone layer, the impact on climate, the impact on microbial ecosystems involved in hydrogen uptake, and the role of those biological impacts in causing indirect effects on the atmosphere and climate. This information can be used to provide a reliable estimate of the maximum leak rate that can be tolerated from an environmental standpoint from large-scale H_2 systems that might be deployed in the future.

POTENTIAL IMPACTS

Improvements in our understanding of the global biogeochemical cycles of atmospheric H_2 will provide essential anticipatory guidance in developing hydrogen energy technologies that minimize environmental impacts. Large-scale implementation of hydrogen energy systems does not seem prudent in the absence of these critical assessments.

- Improving our understanding of the global biogeochemical cycles of atmospheric hydrogen would lead to a reliable quantification of the potential environmental impacts of large-scale releases of hydrogen to the atmosphere.

- This research would also provide an engineering constraint on the environmentally acceptable amount of leakage from a large-scale hydrogen infrastructure — information urgently needed by industries seeking to develop a safe and efficient hydrogen infrastructure.

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SAFETY IN THE HYDROGEN ECONOMY

SCIENTIFIC CHALLENGES

The large-scale use of hydrogen as an energy carrier for stationary, automotive, and portable power generation will result in close contact between hydrogen and the public. In a well-designed hydrogen infrastructure, gaseous hydrogen would remain confined in storage devices and delivery lines as it moved from production to use. The everyday presence of large quantities of hydrogen, however, demands that we understand fully its behavior and danger if significant quantities were to leak into the open environment or into enclosed spaces. Hydrogen is significantly different from today's common fuels because of its tendency to embrittle metals and other containment materials, its rapid leaking behavior, its fast diffusion through the atmosphere, its high buoyancy, and its combustion behavior. These differences in properties and behavior require that special research be done in order to understand and control the safety hazards that a hydrogen economy would pose.

Hydrogen can leak through tiny orifices 2.8 times faster than methane and 3.3 times faster than air because of its small molecular size (Larminie and Dicks 2003). It is flammable over a wider range of compositions in air than is methane, propane or gasoline, and its detonation range is similarly broad (Larminie and Dicks 2003; Ogden 2002). Hydrogen's unusually high diffusion and buoyant velocities in air, however, somewhat compensate for the danger posed by its fast leak rate and wide range of combustible compositions. In the open environment, hydrogen quickly disperses up and away from the source of a leak, rather than concentrating in low-lying areas, as do propane and gasoline vapors. If hydrogen does catch fire, it burns with a nearly invisible flame that is hard to detect. Its ignition energy is lower than methane or propane at most compositions, enabling self-ignition of high-pressure leaks.

Because the combustion behavior of hydrogen differs from that of other fuels, it presents another set of hazards and requires diverse safety precautions. In the open air, for example, the high buoyancy and diffusivity of pure hydrogen make it very unlikely to accumulate to its threshold of flammability, which gives hydrogen an intrinsic safety feature. In enclosed spaces, however, combustible compositions can build up, and precautions such as ventilation and careful monitoring are needed.

The basic kinetics and explosion limits of hydrogen/air are well known (Lewis and von Elbe 1987) because very few chemical species are involved. The ignition step in pure hydrogen/air mixtures (i.e., $H_2 + O_2 \rightarrow H + HO_2$), however, is essentially never involved in accidental explosions. Rather, an external heat source (e.g., a spark from static electricity) or an impurity-assisted lower energy dissociation reaction (e.g., the thermal dissociation of a lubricant or organic film) in the presence of hydrogen initiates the production of radicals and triggers a subsequent runaway chain reaction. Beyond kinetics, the hydrodynamics of hydrogen mixtures in oxygen and nitrogen are complex because of the very different masses and the broad range of transport properties (e.g., diffusivities, viscosities, and buoyancies) of the constituent gases. When chemical combustion is added to the picture, modeling and predicting flame and explosion behavior become more complex, because the relatively unknown transport properties of the airborne neutral radicals (e.g., H and OH) are important in modeling the turbulent characteristics of the explosion. Nevertheless, a thorough understanding of the hydrodynamics and combustion of hydrogen in the open atmosphere and in enclosed spaces as a function of mixing ratio, wind speed, and ventilation rate is needed if we are to recognize and control the safety hazards presented by the hydrogen economy.

An obvious precaution against fire is the prevention of leaks in the hydrogen infrastructure through careful construction, sensing, and maintenance. Hydrogen presents special difficulties, however, because of its tendency to embrittle metallic container materials like stainless steel and its welded joints. Embrittlement arises from hydrogen's ability to diffuse through metals readily, perhaps using grain boundaries as easy flow channels, and weakening internal metal-metal bonds by combining locally with host atoms. Because embrittlement occurs slowly and can cause catastrophic failures of hydrogen storage containers, it creates a basic materials science challenge that must be overcome if the hydrogen economy is to be successful.

The safety hazards of hydrogen in everyday life can be significantly mitigated by simple knowledge of its presence. Hydrogen is largely invisible to human senses, such as sight and smell. Sensors that selectively reveal the presence of hydrogen are needed to provide early warning of leaks before the flammability threshold is reached. Beyond human safety, such sensors would be useful for monitoring, optimizing, and controlling the technical operation of the hydrogen economy, such as fuel cell operation, the charge/discharge cycle of hydrogen storage devices, and hydrogen production by the water splitting or hydrocarbon reforming routes.

Education and training in safe hydrogen practices are important factors in reducing the hazards of a hydrogen economy. Hydrogen-powered cars would expose the public to hydrogen during the refueling process and would release hydrogen to enclosed spaces during maintenance and repair operations. Repair technicians, professional drivers, and the driving public should receive instructions in the safe handling of hydrogen and in emergency procedures, should an accidental release of hydrogen occur. The institutional training and safety procedures for handling hydrogen in the fertilizer and petroleum industries provide one set of models for establishing an appropriate culture of safety as part of a hydrogen economy.

RESEARCH DIRECTIONS

The goal of research on safety in the hydrogen economy is to (1) develop predictive models of the hydrodynamic behavior of hydrogen/air mixtures in open environments and in enclosed spaces; (2) develop predictive models of the combustion and detonation of hydrogen in open and enclosed spaces in the presence of other gases and other materials; (3) develop a basic understanding at the atomic level of hydrogen embrittlement of materials; and (4) identify, discover, and develop inexpensive and effective sensors that selectively and sensitively monitor the presence and concentration of hydrogen. Promising research directions are discussed in the following sections.

Improved Understanding of Ignition Sources for H_2/Air Explosions

Experimental and theoretical studies can help to identify low-energy heterogeneous and homogeneous sources of radicals that can initiate chain branching and consequent explosions in H_2/air mixtures. Resonance-weakened bonds in certain organic lubricants, oils, and films or metal-catalyzed chemical transformations at imperfections or ruptures in metallic containers can be a potential source for generating radicals under external conditions of heat, shock, or stress. Ignition of mixtures of hydrogen with gases other than air needs to be studied. The risk of ignition of commonly occurring mixtures of hydrogen with methane, gasoline, benzene, and other volatile liquids is not well understood.

Improved Modeling of the Hydrodynamics of H_2/Air Explosions

Hydrodynamics modeling capabilities suited to handling H_2/air turbulence explosions in confined spaces need to be developed. Such developments would include a more secure experimental and/or theoretical database of the transport properties of airborne neutral radicals such as H and OH under explosive conditions.

Understanding of the Basic Physics of Hydrogen Transport in Metals and Hydrogen-assisted Damage Mechanisms

Corrosion and hydrogen embrittlement of materials are closely connected to details of their microstructure, and, in particular, to the segregation and diffusion processes that occur at internal interfaces and associated defects, such as dislocations. Although it is well known that the segregation of common solute impurities, such as sulfur and phosphorus, to grain boundaries can promote decohesion of these boundaries, the suspected synergistic role of hydrogen in this process is not well understood. The dependence of interfacial segregation on the nature of the grain boundary is also unclear. Filling this gap would help in designing an optimal microstructure that might, for example, minimize the connectivity of fracture-susceptible boundaries. We need to improve our understanding of the mechanisms and activation barriers for intergranular diffusion, in particular because grain boundaries can act as fast diffusion pathways. Diffusion and bonding of hydrogen in the microstructure of bulk materials are key factors that control hydrogen embrittlement and corrosion. An integrated approach uniting experimental studies with sophisticated theory and modeling is required.

Preventing hydrogen embrittlement by coating exposed surfaces with a self-sealing barrier should be explored. Such a barrier can be created by surface segregation of a dissolved element that reacts with hydrogen to form a protective layer. Breaches of the surface layer are automatically sealed by reaction of hydrogen with freshly exposed surface. Research is needed to identify suitable alloys with components that surface-segregate and form barriers upon reaction with hydrogen.

Sensors for Hydrogen

New concepts for hydrogen sensors are needed to detect the presence of dangerous levels of hydrogen in refueling stations, repair garages, passenger cabins in hydrogen-powered cars, and other situations where the public is exposed to hydrogen. These sensors need to be reliable, highly specific, and low cost, and they need to have low power requirements. For example, resistive sensors could be developed from nanowires or ultra-thin films, where a thin layer of hydride forming at the surface significantly alters the bulk resistivity. Adsorption of hydrogen on carbon nanotubes produces a distinctive signature in the transport properties, especially in the thermopower. Highly selective detection of H_2 can also be achieved with various spectroscopic approaches. For instance, the high reactivity of hydrogen enables chemical sensing, where a hydride forming on the surface of a reactive film can be detected spectroscopically or through its optical reflectivity.

POTENTIAL IMPACTS

Safety is a prime requirement for the success of the hydrogen economy. The development of predictive models for the dynamics of free H_2 in air in open and enclosed spaces would allow the assessment of risk and establishment of safety procedures for specific activities of the hydrogen economy, such as hydrogen vehicle refueling, driving in partially enclosed tunnels, indoor parking, and vehicle repair. Models of hydrogen ignition and detonation in the presence of vapors from common volatile liquids would enable new standards for their use in proximity to hydrogen. Fundamental knowledge of hydrogen embrittlement of metals and welded joints would enable the setting of standards for the materials used in building a hydrogen infrastructure. Sensitive, selective sensors for detecting hydrogen would warn against the danger of fire or explosion in sheltered or enclosed areas.

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CROSS-CUTTING RESEARCH DIRECTIONS

CROSS-CUTTING RESEARCH DIRECTIONS

During the workshop, several recurring basic research needs surfaced that were common to hydrogen production, storage, and use. These "cross-cutting issues" included six areas: (1) catalysis; (2) membranes and separation; (3) nanomaterials and nanostructured assemblies; (4) characterization and measurement techniques; (5) theory, modeling, and simulation; and (6) safety and environmental issues. These cross-cutting issues are described separately below; however, they are actually interdependent in many cases. For example, the combination of new characterization tools with theory, modeling, and simulation can be applied to achieving an understanding at the molecular level of chemical and physical processes that occur at the surface of well-defined nanostructured catalysts. Advances in one cross-cutting area can also impact another area; therefore, care must be taken to evaluate the entire process of hydrogen production, storage, and use as a system. For instance, as new catalytic materials are developed that are more tolerant to impurities, the requirements for separation of impurities from feedstocks are reduced, and, conversely, as new methods for separating impurities are developed, the stringent purity requirements for new catalysts are reduced. Finally, safety and the environment were identified as cross-cutting issues because, ultimately, safety and environmental concerns will impact the large-scale utilization of hydrogen as a reliable energy resource. In the following, each of these cross-cutting issues is discussed in more detail.

CATALYSIS

Overview

Catalysis is broadly recognized as a critical issue in hydrogen production, storage, and use. Catalysts are essential for converting solar energy to chemical energy. Reforming catalysts, which are used to convert fixed carbon resources (from natural gas, petroleum, coal, or biomass) into hydrogen, can provide hydrogen resources that can be distributed across a supply grid. Electrocatalysts — which are catalysts having large voltage gradients at the surface and which thereby affect chemical processes — are employed in photovoltaic (PV) cells and are also integrated into fuel cells for onboard hydrogen generation in automobiles. Catalysts also play a critical role in improving the kinetics and thermodynamics in hydrogen storage systems, allowing more efficient uptake and release of stored hydrogen with reduced need for thermal activation. General needs across these many application areas include catalysts with higher activity, higher specificity, higher stability, and less susceptibility to impurities that cause poisoning or fouling. An additional requirement for catalysts is the use of metals that are less costly and more abundant than platinum and other precious metals.

New catalytic materials need to be identified to meet the demanding requirements outlined above — both catalytic materials based on improved conventional and novel materials and those that take inspiration from biological processes. New catalytic materials, such as organometallics or nanostructured materials, that reduce or eliminate the need for noble metals will reduce the cost associated with catalysts. New materials for catalysis may also be inspired by nature. Natural photoconversion systems, such as those used by nature to perform photosynthesis, use non-noble metals that make high-purity hydrogen. Furthermore, these photoconversion systems often incorporate self-repairing mechanisms to enhance the longevity of catalytic systems in the face of corrosion, fouling, or poisoning of the catalytic sites. These self-regulating characteristics are also found in the design of automotive exhaust catalysts, where multiple catalysts are combined into a single system.

Research Issues

To improve catalytic processes involved in hydrogen production, storage, and use, a fundamental understanding of the molecular-level processes involved in catalysis is required. Achieving this knowledge involves detailed characterization of the active site, the interaction of the reactants (such as fuel or water) with the active site, full characterization of the chemical intermediates formed, and the dynamics of the entire catalytic process. This will entail the production of well-defined (at the atomic level) materials that can be characterized under realistic operating conditions. Emerging techniques that allow synthesis at the nanoscale will open up new approaches for producing tailored structures with controlled size, shape, and surface characteristics. These structures can be produced with specific multielement-, organometallic-, and even stable biological and bio-inspired catalytic sites. For example, nanoscale clusters of mixed metals or even metal spheres coated with thin layers of catalytically active metals could improve the efficiency of the catalytic process, while reducing the need for costly noble metals.

By controlling the functionality and morphology of the catalytic materials, it may be possible to improve selectivity and efficiency of a catalyst by design. Designing catalysts with specific mesoporous structures, for example, can increase the selectivity of the catalyst by restricting the interaction of materials with the catalytic surface. A well-designed nanostructured support can also play an important role in tailoring a catalyst’s activity, selectivity, and stability, as well as generating a more homogeneous distribution of active sites. Furthermore, hybrid catalytic structures with both inorganic and organic functionalities could be made to provide a high degree of control over the catalytic process.

Indeed, broad new classes of catalysts need to be synthesized and characterized to discover new processes that will allow the goals of the hydrogen economy to be achieved. An understanding of the fundamental principles that underlie an effective catalytic process, developed through a synergistic combination of theory, modeling and simulation, and experimental evaluation and exploration, would support the directed design and discovery of new catalysts.

New analytical techniques are needed to rapidly characterize novel catalysts and their activities under realistic conditions. For example, high-resolution microscopes and scanning probe techniques are required to characterize the structure of catalytic sites at the atomic level. Improved spectroscopic probes are also needed to elucidate the interaction of reactants and intermediates with the catalytic site. This information can reveal the mechanisms responsible for the generation of hydrogen products and allow the dynamics of the catalytic process to be studied.

Impact

Advances in catalysis will be critical to providing the revolutionary breakthroughs needed for meeting the technical goals outlined for hydrogen production, storage, and use. In fact, kinetic constraints lie at the heart of most of the major problems that must be solved in order to develop a full-scale hydrogen economy. Catalysis is a multidimensional process, and the resulting complexity can present formidable challenges for improving current technologies by merely using a simple empirical approach. The needed breakthroughs for improvements in catalysis will be achieved only with basic research, to study the molecular processes with well-characterized materials, under realistic conditions. Information obtained in these studies will allow the design of catalysts with highly defined selectivity and higher stability, durability, and efficiency. Computational methods combined with experiments will guide the rational design of new catalysts and will help to predict their catalytic activities.

Specially designed catalysts can also minimize the need for purification of feedstocks or products. New nanoscale materials that incorporate novel structures or special catalytic centers containing hybrid organic/inorganic/biological features could also greatly decrease the cost of the catalytic process by reducing the need for using precious metals as catalysts. A well-designed nanostructured support can also play an important role in tailoring a catalyst's activity, selectivity, and stability, as well as in generating a more homogeneous active site distribution.

Addressing these and other fundamental issues can provide the critically needed insight that will help to develop entirely new concepts for catalysis. These new concepts could provide revolutionary enhancements in catalyst performance, at greatly reduced costs. The challenge is immense. Only through basic research is there a chance to make headway.

NANOSTRUCTURED MATERIALS

Overview

Many of the current limitations in hydrogen production, storage, and use are imposed by materials performance. Nanoscience has the potential to provide entirely new classes of materials with capabilities that transcend these limitations and generate the performance breakthroughs required for a viable hydrogen economy. Nanoscale materials often have distinctly different properties than their bulk material counterparts. Emerging nanoscale synthetic capabilities allow the design of materials with structures tailored for specific physical and chemical properties. Nanoscale probes, such as transmission electron microscopy and scanning probe microscopy, allow the atomic-level characterization of nanoscale structure of surfaces and interfaces that is key to the catalytic activity, molecular dissociation, and ionization that underlie the operation of fuel cells and hydrogen storage materials. This knowledge, coupled with theory, modeling, and simulation techniques, allows deeper understanding of these processes and guides experiments and synthesis of materials with improved properties.

New materials are needed across all aspects of hydrogen production, storage, and use. While metal and composite hydrides have demonstrated capabilities for hydrogen storage, new materials are needed that will increase the weight percentage of stored hydrogen and improve the kinetics associated with hydrogen uptake and release. Improvements are needed in fuel cell materials to achieve higher performance, greater flexibility in the use of fuel sources, and lower cost. New dyes and semiconductor materials are needed to enable light absorption across the entire solar spectrum for use in PV cells for electrolytic hydrogen production. Nanomaterials are central in the development of more efficient and tailored catalysts. For example, in a nanostructured material, the atoms at the surface have varying coordination numbers, all of which are lower than in bulk systems. In some systems, surface atoms with the lowest coordination numbers tend to be more reactive; in other systems, specific surface geometry is required. Furthermore, it has been observed that the reactivity of some atomic clusters can be changed by several orders of magnitude by small changes in cluster size.

Research Issues

Although our knowledge of nanostructured materials is just emerging, these materials have already shown potential for providing needed breakthroughs to achieve a hydrogen economy. The large surface/volume ratios of nanostructured materials produce chemical and physical properties that can be dramatically different from their bulk counterparts. Decreased size leads to quantum confinement effects that may enhance reactivity. Fundamental research is needed to identify the size and structure relationships that determine the catalytic activity, altered bonding strength, and kinetics in nanophase materials. For example, considerable promise for hydrogen storage has been demonstrated by a totally new approach that exploits various nanostructures: nanotubes, nanohorns, nanoribbons, nanostructured and nanoporous materials, zeolites, and clathrates. Improvements in understanding the processes that control the adsorption of hydrogen could improve the performance of these materials. This knowledge would allow the geometric structure — shape, surface area, pore size, and curvature — and surface-molecule interactions to be designed to improve the selective absorption and efficient release of hydrogen from these materials. Functionalizing their surfaces to catalyze the release of hydrogen and to improve the selectivity and weight percentages of hydrogen absorption could also enhance the hydrogen storage properties of these materials. Nanomaterials also may be exploited to produce novel properties that are dominated by surface interactions rather than bulk behavior. For example, it may be possible to make lower thermal conductivity materials for tanks for liquid hydrogen storage, using nanostructured constituents with many interfaces.

More traditional hydrogen storage materials, such as metal and complex hydrides, would also benefit from new capabilities provided by nanoscience. Specific nanoscale architectures may be designed into these materials to increase surface area and incorporate dopants to enhance the percentage of stored hydrogen and to improve the kinetics and thermodynamics of hydrogen uptake and release. At present, there is little understanding of the fundamental processes involved in hydrogen storage with bulk metal and complex hydrides. This includes knowledge of the atomic and molecular processes responsible for the interaction of hydrogen with the hydrides, the kinetics of hydrogen uptake and release, and the mechanisms for associated degradation mechanisms responsible for the limited durability of these materials. Fundamental research on nanostructured hydrides may also provide insight into the mechanisms responsible for the recently reported improvements in storage and kinetics of hydrides when dopants are added to these materials. Similarly, improvements in the lifetimes of hydride-based storage materials may be possible if we examine nanostructured materials to elucidate the mechanisms for associated degradation processes and sensitivity to impurities. This knowledge, when combined with computational modeling, is expected to allow the directed design of new, higher-efficiency, recyclable hydride-based materials.

Fuel cell electrodes require inhomogeneous structure on the nano scale, with mutually interpenetrating networks for ionic, electronic, and chemical transport. A fundamental understanding at the atomic level of the dissociation, ionization, and ionic conduction at the electrochemically active interface region is critical to improving fuel cell operation. Once these processes are understood, catalytic nanomaterials could be designed with the appropriate physical and chemical characteristics to improve performance, such as better chemical and thermal stability, increased tolerance to impurities, and lower cathode overpotentials for oxygen reduction. In the last case, bio-inspired catalysts that reduce oxygen with little overpotential offer an exciting new approach for dramatic improvements in fuel cell cathode performance. To achieve these gains, new approaches for synthesizing nanoscale hybrid materials are needed to incorporate the essential features of naturally occurring oxygen-reducing catalysts into robust, synthetic hosts. Hybrid materials have high potential for dramatic improvements in materials performance by taking advantage of nanoscale interfaces between dissimilar materials, such as inorganic/organic or conducting/insulating, to build specialized functionalities and architectures for specific applications.

The field of nanoscience is moving rapidly as basic research discovers new features in nanosize structure/property relationships. Nanoscale structures can be varied widely, for example, by size, morphology, ordered or disordered assembly and composition, and interfacial structure, resulting in properties that may be changed profoundly from those of the parent bulk material. Rapid advances in nanoscale synthesis and processing allow us to control and tailor these structures and properties. Key materials properties for application to hydrogen production, storage, and use will benefit from these advances. While the challenges to achieve a hydrogen economy are great, nanomaterials offer an unusually promising opportunity to discover and develop tomorrow's hydrogen technology.

Impact

Ultimately, hydrogen production, storage, and utilization processes must be embodied in efficient physical devices with practical durability. Discovery of new materials with unique properties resulting from nanostructured design could provide critical breakthroughs with broad impact. Understanding and controlling the synthesis and processing of materials will allow the design of materials tailored to optimize performance in a particular end application. Materials could also be designed that incorporate multiple features, such as nanostructured fuel cell electrodes with three interpenetrating networks of catalyst/electrical conductor, ionic conductor, and open porosity, all designed to optimize electrochemical performance and reduce sensitivity to impurities.

MEMBRANES AND SEPARATIONS

Overview

Many of the processes involved in exploiting hydrogen as an energy carrier involve separating gases (e.g., separating hydrogen, produced by natural gas reforming, from contaminating carbon monoxide) or selectively controlling gas or ion transport between reaction compartments (e.g., allowing protons but not hydrogen or oxygen to cross between the chambers of a fuel cell). For kinetic reasons, selectively permeable membrane barriers are often the best design for meeting these requirements. Today's membrane materials are often insufficiently selective to eliminate critical contaminants or to prevent leakage transport between compartments in a fuel cell that robs efficiency. For instance, carbon monoxide that normally contaminates hydrogen produced in reforming processes requires several other complex, large, and heavy purification stages to reduce the carbon monoxide to below the 20 parts per million (ppm) level, which is sufficient to poison the anode of low-temperature proton exchange membrane fuel cells (PEMFCs). A simple membrane that would exclude carbon monoxide but not hydrogen would greatly simplify hydrogen purification. The Nafion™ membrane material that is presently the best available for separating PEMFC chambers is not only expensive, it also allows enough gas transport to reduce efficiency. Oxide ion transport, which is necessary for higher-temperature fuel cells that are less sensitive to poisoning by carbon monoxide, is inefficient in membranes that are currently available and operate at the lower temperatures that would be needed for use in transportation. Finally, separation membranes that could operate in the rigorous chemical environment of a thermal cycle hydrogen generator (i.e., gaseous H_2SO_4 at temperatures above 700°C) would be of substantial value but are essentially unknown at present. In general, membranes with improved selectivity, transport rates, and stability under various operating conditions could improve the efficiency and feasibility of many key steps in hydrogen production, storage and use. Developing these membranes will require improvements in membrane materials, in understanding and design of permeation catalysts, and in technical strategies for constructing membranes with hybrid organic and inorganic composition and with nanostructured features.

Research Needs

Advances in membrane separations will be driven by the synthesis and functional analysis of new nanoporous materials and the characterization and modeling of the molecular phenomena associated with sorption and transport. A fundamental understanding of these chemical and physical processes would allow both the selectivity and the kinetics of the separation process to be enhanced by design. This selectivity could potentially be achieved by using novel synthetic techniques to produce tailored two- and three-dimensional materials incorporating oriented nanocatalytic domains. Improvements in fuel cells as well as in electrolytic and photocatalytic hydrogen generator performance will require improved control over the three-phase reaction surface in which electrons at the electrode surface, liquid (e.g., water and solvated protons), and gas reactants (hydrogen and oxygen) interact. Self-assembling systems, such as di- and tri-block copolymers, mesostructured inorganic solids, and thin films assembled layer-by-layer, have the potential to organize these networks effectively. Membranes that incorporate nanocatalysts and nanocatalyst supports could provide the key for developing efficient, selective transport functions, such as the faster oxide ion conductors needed to enable solid oxide fuel cells to function at the lower operating temperatures (500–600°C) required for transportation applications. Proton-conducting membranes that operate essentially in the absence of water (at temperatures above 100°C) would enable the design of intermediate-temperature fuel cells that potentially combine advantages and avoid the disadvantages of PEMFCs and solid oxide fuel cells. Robust inorganic membranes with high selectivity and high transport rates are needed to enhance the efficiency of high-temperature separations, as required for hydrogen production via thermal water splitting cycles.

Impact

Fundamental advances in membrane separation technologies could reduce the high cost of meeting the hydrogen purity requirements of PEMFCs. This is an important near-term objective that stands in the way of commercializing hydrogen energy systems with current hydrogen generation, storage, and fuel cell technologies. The potential for combining membrane materials with catalytic materials in nanostructured architectures opens the possibility of entirely new approaches to hydrogen production, such as membranes containing embedded photocatalytic reaction centers that produce high-purity hydrogen when immersed in water and exposed to sunlight. Similarly, new membrane/electrode assemblies designed to improve ionic, electronic, and chemical conduction at the surface of electrodes can improve both the energy efficiency and economic performance of fuel cells.

CHARACTERIZATION AND MEASUREMENT TECHNIQUES

Overview

Insight into both the chemical and physical characteristics of materials at the nano scale can enable revolutionary new capabilities for hydrogen production, storage, and use. An especially challenging need is to increase the sensitivity of analytical tools to permit characterization and measurement of processes involving nanophase materials. For example, new analytical techniques will be needed to determine how much hydrogen is adsorbed on a nanostructure, such as a nanotube or a nanohorn. In addition to improved sensitivity, new analytical tools are needed that provide high selectivity and resolution in order to fully satisfy the need to study nanoscale materials and processes at the atomic and molecular levels. Novel sensors will also be needed for sensitive and specific detection of hydrogen and other chemical elements and compounds, especially in support of meeting safety-related concerns, such as those arising from hydrogen leaks and materials failures.

Research Needs

New tools are needed to allow chemical and physical characterization of nanostructured materials with atomic-level resolution. Reactions that occur at interfaces with these nanostructured materials require characterization techniques with both enhanced spatial and multidimensional spectral resolution to characterize interactions and reaction dynamics occurring at these surfaces. Furthermore, characterization and analysis tools are required to study reactions under realistic conditions, with reactants and products present at concentrations, temperatures, and pressures employed in specific applications. These conditions may also include use of extreme temperatures, corrosive/reactive chemicals, and high pressures that are not typically compatible with today's analytical techniques. Tools are also needed to understand ion and mass transport, thermophysical, mechanical, and other chemical and physical properties at the nano scale. Also, techniques are needed for measuring proton conduction in low- or zero-water environments. With the incorporation of large-scale combinatorial synthesis techniques, new characterization methods will be required to rapidly screen synthesized materials with respect to chemical and physical properties, reactivities, and other benchmarking parameters. Sensors for micron- and submicron-length scales with fast time response will be needed to monitor processes at various length and time scales. In addition, entire systems of sensors will be needed to integrate information from multifunctional processes.

Along with new characterization tools, standards will be needed to assure the ability to compare results across the research community. An especially challenging need is to increase the sensitivity of analytical tools to permit characterization and measurement of processes involving nanophase materials. Advances in scanning probes and electron microscopy will make it possible to characterize materials at the atomic level; these sensitive techniques have, for example, been used to study novel nanocatalysts. Revolutionary advances in sensitivity are being achieved by scaling down analytical devices to the micro and nano scales, as demonstrated with micro-electromechanical system and nano-electrochemical system devices. Devices, such as microfluidic lab-on-a-chip devices, nanocantilevers, and others, have already exhibited femtomole and lower detection sensitivities in materials. This technology can provide sensors that can monitor an experiment continuously, providing detailed information on atomic- and molecular-level processes.

Impact

Reliable characterization and measurement techniques, including hydrogen-specific sensors, are essential in the implementation of all aspects of a hydrogen economy. Sensitive new tools are needed that can provide atomic and molecular information at the nano scale to support fundamental research that has promise to ultimately yield the new materials and processes required for establishing a hydrogen-based economy. Together with computational tools, the results of these experimental measurements can provide an unprecedented understanding of the full range of chemical and physical parameters required for the prediction and development of materials and processes needed for efficient hydrogen production, storage, and use.

THEORY, MODELING, AND SIMULATION

Overview

Theoretical modeling, including computational simulation and analysis, will impact all research areas essential for the development of effective hydrogen energy systems. A strong, synergistic relationship between theory and experiments on well-defined systems will provide insight into mechanisms, predict trends, identify promising new materials and reaction processes, and guide new experiments. Successful efforts in these areas will significantly enhance our ability to meet the key technical challenges of the hydrogen economy in hydrogen production, storage, and use.

Research Needs

New computational approaches are needed to integrate across disparate time and length scales that are important for hydrogen production, storage, and use. For example, modeling has traditionally been carried out separately for increments of length scales using quantum mechanics (0.1 to 10 nm), statistical mechanics (1 to 1,000 nm), mesoscale (0.1 to 100 μm), and continuum mechanics (1 mm to 10 m). Time scales range from quantum mechanical methods (10^{-15} s) to continuum methods (1 to 10^5s). There is a critical need for theoretical modeling and simulation to span all these length and time scales seamlessly to meet the needs of hydrogen research. New first-principle algorithms are required to simulate and model condensed-phase phenomena with higher accuracy. This will enable experimental measurements to be assessed for the identification of trends that will aid in the development of new materials and processes for specific applications. For example, computational tools could aid in the identification of elements or compounds that could be added to nanostructured hydrogen storage materials to help improve the rate of hydrogen release. Simulations could then be used to understand the molecular-level processes responsible for the observed improvements.

Computational methods can be used in the design of novel biologically inspired components for catalysis, for example, and to predict the structure and mechanisms of these processes. Computational methods are also needed to understand the structure of materials and interfacial regions, interactions in composites, and ionic and electronic transport within and across phase boundaries. Predictive modeling will be required to provide an atomic-scale understanding of catalytic sites and of the mechanisms involved in catalysis to allow tailored design of catalysts on the nano scale. For hydrogen storage, computational methods are needed to understand how hydrogen reacts with the surface, interface, grain boundaries, and bulk defects of a particular storage material. In fuel cell research, fundamental understanding of ionic transport properties of electrolytes used in membranes and the detailed reduction processes of oxygen at the cathode electrocatalyst-electrolyte interface, for example, are needed to develop improved electrode and electrolyte materials. Understanding electron transfer processes at interfaces is needed to enhance photocatalysis and electrocatalysis processes involved in fuel cells and hydrogen production.

Impact

Coupled with new characterization techniques that will yield unprecedented amounts of detailed information about atomic and molecular processes, new computational methods for theory, modeling, and simulation have the potential to revolutionize the design of materials at the nanoscale and to expedite the discovery of molecular-level processes critical for hydrogen energy systems. Development of these novel materials and processes is critical for attaining the full suite of technologies necessary for a hydrogen economy. The time horizon for the development of practical hydrogen energy systems is short and cannot be met without a strong investment in theory and modeling in parallel with a significant investment in basic experimental research.

SAFETY AND ENVIRONMENTAL ISSUES

Overview

Safety and environmental issues impact all aspects of hydrogen utilization. Moving toward a hydrogen economy will require production, storage, and utilization of large quantities of hydrogen under various operating conditions. The accidental release of hydrogen poses significant risks that differ from those associated with fossil fuels. Hydrogen ignites more readily than propane, and a high-pressure leak can be self-igniting, burning with an invisible flame. Its high diffusivity and buoyancy normally prevent the buildup of flammable concentrations in the open air, but in enclosed spaces, the risk of fire or explosion can be serious. With large quantities of hydrogen in everyday use, we must be able to predict the behavior of hydrogen under many conditions, including enclosed garages, covered parking structures, enclosed or partially ventilated cars, and windless or windy open air. In each case, we should understand the hydrodynamics well enough to predict the threshold of flammable or explosive concentrations, and understand the combustion dynamics well enough to predict the magnitude of the released of heat and blast. Of paramount importance to the safe handling of hydrogen is the training of skilled personnel and extensive public education. In addition, improved materials are needed that address issues related to hydrogen exposure, such as embrittlement, weld failures, and general materials compatibility. Developed technologies must also incorporate safeguards and processes that protect the environment from hydrogen leaks and potentially hazardous by-products of hydrogen production, storage, and use.

A large part of the interest in adopting hydrogen for use as an energy carrier arises from its potential for reducing the negative environmental impacts of our energy systems. However, in planning the development of any technology system that is intended to be implemented on a large scale, it is prudent to anticipate potential deleterious environmental impacts as well. If hydrogen were to become established as the primary carrier in the worldwide energy economy, the additional amount of hydrogen cycled each year would exceed the known amount cycled by all present-day geochemical, biological and atmospheric processes. If 10% of the hydrogen in use were to escape to the atmosphere, the amount of hydrogen entering the atmosphere from all sources would more than double. Hydrogen is rapidly mixed into the atmosphere and has a relatively short turnover time (~2 yr), being consumed in atmospheric processes and by soil microorganisms. The potential consequences of doubling the annual inputs into these processes need careful scientific study.

Research Needs

The need to understand the behavior of hydrogen under a wide variety of conditions demands better theory and modeling of its hydrodynamics and combustion dynamics. Such models would allow predictive capability for assessing the risk of fire or explosion under the many possible leak and failure scenarios that would be found in the hydrogen economy. These predictive models of hydrogen accumulation, ignition, and combustion will form the basis for establishing comprehensive safety standards and procedures. The fundamentals of the interactions of hydrogen with specific materials need to be understood, as well as the mechanisms involved in materials failure. Embrittlement in metals, the role of grain boundaries and other microstructure in promoting or retarding materials degradation, and the effect of hydrogen in weakening welds and joints need to be examined to anticipate catastrophic failures in the hydrogen infrastructure. Studies are needed to fully assess requirements for materials compatibility. Sensors are needed to detect trace amounts of hydrogen escaping into public places and to warn of potential flammable accumulations in enclosed spaces. Such sensors should be highly selective and highly sensitive to hydrogen, providing quantitative as well as qualitative information.

The fate of hydrogen that escapes to the atmosphere needs to be studied in greater detail so that the consequences of increased releases can be accurately modeled and projected. The capacity of soil and various aqueous microbial ecosystems to take up the increased hydrogen flux must be assessed. To make an accurate assessment, the properties of hydrogen-metabolizing organisms and microbial consortia need to be much better understood. The impact of any increased microbial uptake on the diversity and stability of their ecosystems and of increased accumulation of their metabolic by-products, such as methane, must also be assessed. These data are needed for projecting whether or not the net content of hydrogen in the atmosphere would rise. The consequences of increasing atmospheric hydrogen must be carefully studied, including an assessment of its impact on other atmospheric processes.

Impact

The ability to model the hydrodynamics and combustion dynamics of hydrogen in the open air and in enclosed spaces will enable reliable risk assessment of the many potential hydrogen-human contact situations that would occur in a hydrogen economy. Understanding the causes and evolution of hydrogen embrittlement of metals and weld joints at the atomic level will enable prediction and prevention of mechanical failures within the hydrogen infrastructure and the accidental release of hydrogen to the environment. Development of inexpensive and effective sensors for the presence and concentration of hydrogen will provide early warning of dangerous hydrogen concentrations before they reach the ignition point. Data concerning potentially deleterious environmental impacts of hydrogen energy systems are critically needed for developing rational hydrogen emission standards so that the costs of containment are known *before* the technology is adopted on a large scale.

CONCLUSIONS

CONCLUSIONS

The hydrogen economy offers a grand vision for energy management in the future. Its benefits are legion, including an ample and sustainable supply, flexible interchange with existing energy media, a diversity of end uses to produce electricity through fuel cells or heat through controlled combustion, convenient storage for load leveling, and freedom from harmful environmental pollutants. These benefits provide compelling motivation for a broad effort across the research, development, engineering, and industrial sectors to implement hydrogen as the fuel of the future.

The challenges to reach a hydrogen economy, however, are enormous, considering today's state of knowledge and technical capabilities. The hydrogen economy consists of many physical and chemical processes linked in an interdependent network that connects production, distribution, storage, and use. Hydrogen in its various forms flows throughout the network, linking primary sources like hydrocarbons or seawater to storage media like alanates to end-use functions like fuel cells. Many of the processes in the network have been demonstrated in laboratory or prototype tests at some level, but nearly all of these processes remain to be proved in competitive environments against existing technology for cost, performance, and reliability.

The gap between present-day technology and commercial viability is vast. To be economically competitive with the present fossil fuel economy, the cost of fuel cells must be lowered by a factor of 10 or more, the cost of producing hydrogen by a factor of 4, and the performance and reliability of hydrogen technology for transportation and other uses must be improved dramatically (Abraham 2003). This gap cannot be bridged by incremental advances of the present state of the art. Bridging the gap requires not only creative engineering, but also revolutionary conceptual breakthroughs in understanding and controlling the physical and chemical processes that govern the interaction of hydrogen with materials. Such breakthroughs can only come from comprehensive basic research focused on the behavior of hydrogen at the atomic level, exploiting the remarkable recent advances in materials synthesis capabilities, forefront characterization tools, and creative theory and modeling. The best scientists from universities and national laboratories and the best engineers and scientists from industry must work in interdisciplinary groups to find breakthrough solutions to the fundamental problems of hydrogen production, storage, and use. The formulation of such a basic research program must be coordinated with the needs of applied research and development and have coupled experimental and theoretical components for maximum impact. The hope is that these discoveries and related conceptual breakthroughs from basic research will provide a foundation for the innovative design of materials and processes that will produce qualitative improvements in the performance, cost, and reliability of the production, storage, and use of hydrogen so that an economically competitive hydrogen economy can eventually be realized.

Secretary of Energy Spencer Abraham outlined four research challenges for achieving the hydrogen economy in his address to the National Hydrogen Association (Abraham 2003):

- Dramatically lower the cost of fuel cells for transportation,
- Develop a diversity of sources for hydrogen production at energy costs comparable to gasoline,

- Find viable methods of onboard storage of hydrogen for transportation uses, and
- Develop a safe and effective infrastructure for seamless delivery of hydrogen from production to storage to use.

The findings of the three panels and the high-priority research directions presented in this Report address these challenges.

As we ponder the benefits of a hydrogen economy, we also must consider other factors. The time scale required to develop the technology and the infrastructure needed to produce the amount of hydrogen required for a hydrogen economy is significant. In recognition of this long-term focus, we must consider complementary routes for achieving significant energy savings and environmental benefits in the near term, such as internal combustion/electric hybrid vehicles. This Report, however, focuses on the long-term context of the hydrogen economy and the high-priority basic research directions needed to achieve it.

The technical challenges of the hydrogen economy consist of a microcosm of modern interdisciplinary basic science. Fuel cells require electrocatalysts, ionic membranes, and electrical conductors in complex and demanding architectures. Hydrogen storage materials involve special bulk structures, complex surface chemistry, and special catalysts to achieve high storage capacity simultaneously with rapid kinetics. Production of hydrogen from water using either solar photocatalytic and photochemical reactions or heat from nuclear reactors requires nanoscale semiconductor/metal/dye hybrids or complex chemical cycles with sophisticated separation membranes. The specific challenges described in some detail in this Report cannot be met by research within a single field of knowledge; rather, they require coordinated research efforts at the intersection point of traditional chemistry, physics, biology, materials science, and engineering science.

The preceding chapters not only go into some detail about the great technical challenges of the hydrogen economy, but also consider high-priority research directions that offer promise for addressing these challenges. Looking across these high-priority research directions, several broad themes emerge: materials and nanoscale architectures, catalysis, membranes, bio-inspiration, modeling and simulation, and advanced measurements techniques. These themes capture both the technical limitations of current hydrogen technology and the promise for revolutionary conceptual innovations that would enable significantly higher performance at reduced cost. Comprehensive efforts in each of these broad areas will impact key issues across the hydrogen economy, as well as other needs for long-term energy security (Basic Energy Sciences [BES] Advisory Committee 2003).

The basic research that will help to realize a commercially viable hydrogen economy requires an integrated approach, connecting progress in the critical areas of hydrogen production, storage, and use. Major advancement toward the goal of a hydrogen economy can be achieved only with concomitant scientific breakthroughs in each of these critical areas. The integrated research approach emphasized in this Report not only identifies key barriers to success in each of the critical areas, but also promotes broad interdisciplinary efforts, cross-cutting solutions, strong coupling and coordination between basic and applied science, and cooperative efforts among

Basic Energy Sciences and the Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy Program Offices of the U.S. Department of Energy. Each of these offices will play a decisive role in a future hydrogen economy; the research needs of each office must be folded into the formulation of the basic research program.

Materials discovery, performance, and design are identified in this Report as overarching areas of a grand challenge with opportunities for broad impact on enabling the transition to a hydrogen economy. The success to date, the current limitations on performance, and the prospect for dramatic advances in achieving the hydrogen economy all center on materials behavior. Basic research understanding of the mechanisms for proton and oxygen ion conduction, of gas separation, and of surface behavior at interfaces is fundamental to the design of new approaches to hydrogen production, storage, and use. A key materials issue is the integration of functions in hybrid materials, such as gas permeability with catalysis and electron and ion mobility in fuel cells. Another fertile area for research is the self-assembly of polymer and/or inorganic materials into complex composite structures that could enable and optimize many of the processes needed for production, storage, and use of hydrogen. These complex materials open sweeping horizons for variations of structure and function with high potential for revolutionary advances.

Nanoscience introduces a powerful and virtually untapped new dimension to the broad research directions identified in this Report because of the radically new properties that materials exhibit at the nano scale. This theme permeates nearly all the materials and process issues of the hydrogen economy. The dependence of catalytic activity on size and shape of some nanoparticles may provide a powerful knob for increasing the reaction rate and selectivity, while decreasing the cost of catalysts. The intimate interaction of electrons, ions, catalysts, and gases in fuel cells requires complex nanoscale architectures for effective control. In storage media, large surface areas with catalytically enhanced absorption and desorption rates are a key element in obtaining reasonable kinetics and storage densities. These are fundamentally nanoscience phenomena requiring atomic and nanoscale understanding and control to achieve the qualitative advances needed for a viable hydrogen economy. This Report identifies nanoscale science and technology as a high-payoff research direction with the potential for revolutionary breakthroughs in lowering the cost and raising the performance and reliability of technology for hydrogen production, storage, and use in fuel cells.

Present catalytic performance limits many essential elements of the hydrogen economy, including fuel cell efficiency, storage kinetics, and production capacity. Fundamental understanding of the catalytic process at the atomic level in any of these areas would drive collateral progress in all three. Major effort needs to be expended to synthesize less expensive, nonpoisoning, robust catalysts with much higher activities, selectivities, impurity tolerance, and capabilities for operating under extreme environments. These research directions should exploit newly emerging capabilities in the synthesis of size-controlled and patterned nanostructures and composite assemblies. Catalysis research should seek guidance from state-of-the-art modeling and simulation calculations to point the way to the selection of promising approaches to the design of catalysts for specific applications. Catalysis cuts across all areas of hydrogen research. It has high potential for the revolutionary breakthroughs in hydrogen production, storage, and use that will enable a viable hydrogen economy.

Biological and bio-inspired energy conversion designs have produced remarkable innovations that integrate light harvesting, charge separation and transport, and charge transfer for fuel formation and stability into model systems. Particular microbes have been identified for biophotolysis, along with component redox enzymes, proteins, cofactors, and regulatory pathways for producing and metabolizing hydrogen and other fuels (e.g., carbon monoxide, methane) using inspiration from nature's evolutionary prowess. Biomimetic catalysts devoid of noble metals and protein-modeled maquettes designed for electron tunneling and proton exchange offer promise for incorporation into fuel cell electrodes. Furthermore, these novel bio-like structures can be bonded onto nanoengineered surfaces to amplify their effectiveness through self-assembly and enhanced surface area. Since kinetic constraints severely limit the practical utility of present hydrogen energy systems in so many ways, basic research into the fundamental principles underlying biological hydrogen metabolism and oxygen reduction could lead to crucial breakthroughs along the path toward development of large-scale, hydrogen-based energy systems. In this vein, research is needed for understanding the mechanisms that underlie the bio-genesis, maintenance, and integrated activity of the enzymes and cofactors that support biological hydrogen metabolism and oxygen reduction, as well as to transform this understanding to the development of biomimetic or bio-inspired synthetic catalysts. Nature chose hydrogen as the energy carrier for development of the biosphere some three billion years ago. Through evolution, nature has developed powerful and clever approaches for manipulating hydrogen in the natural environment. Basic research into biological and bio-inspired energy conversion is an untapped high-risk/high-payoff opportunity for dramatic breakthroughs spanning all phases of hydrogen production, storage, and use.

Separation technology is a key determinant of efficiency in both hydrogen production and use. The needs for very high permeability and selectivity in gas separations, high ionic conductivity with minimal fuel crossover in fuel cell membranes, and membranes with much improved durability that are capable of separations at high temperatures under extreme chemical environments call for an intensive effort in materials synthesis, characterization, and modeling. Basic research is sorely needed to enhance the efficiency of separations for the production of ultra-pure hydrogen and for direct use in fuel cells of hydrogen made by steam reforming, to enable novel intermediate- and high-temperature fuel cell designs by means of advanced polymeric and inorganic ion-conducting membranes, and to develop robust inorganic membranes to enable thermal water splitting cycles as a viable means of hydrogen production. Research that is likely to have high impact will seek advances in nanostructured porous materials; robust inorganic membranes for high-temperature separations in corrosive environments; electronically conductive gas diffusion membranes for PEM fuel cell applications; low-cost, high-conductivity proton conductors for higher-temperature use; and fast oxide-ion conductors for solid oxide fuel cells.

Sensitive tools are needed for the detection, characterization, and measurement of hydrogen as it interacts with materials, particularly with nanostructures, under a wide range of realistic operating conditions of temperature, pressure, and chemically reactive environments. Included are imaging tools like scanning probes and transmission electron microscopes, as well as scattering tools like neutron and synchrotron diffractometers and spectrometers. The development of novel, low-cost, and selective sensors for hydrogen gas will also be needed for safety-related applications connected with the detection of hydrogen leaks and for the prevention of hydrogen-embrittlement–related materials failures.

Theory, simulation, and computation are critical for bridging the vast gap between the science and technology necessary for a competitive hydrogen economy and our present capability for implementing hydrogen production, storage, and use. To bridge this gap, it is necessary to couple theory and experiment in basic research to gain a fundamental understanding of the basic interactions of hydrogen with materials. Theory and computation can be used not only to understand experimental results, but also to guide them. The first step in this direction is to understand the interaction of hydrogen with surfaces and associated step edges and crystal defects, and how hydrogen diffuses on the surface. The sites that hydrogen atoms occupy in the bulk; the energy barriers for its diffusion, including their effect on the electronic structure of the host and their interaction with lattice defects (e.g., vacancies, voids, impurities, grain boundaries, and dislocations); and the effect of temperature and pressure on phenomena are all important for a comprehensive understanding of hydrogen in materials. It is important to understand how alloying can change the bonding between hydrogen and metal atoms in light complex metal hydrides. Similarly, an understanding of the role of catalysts and dopants in altering the nature of hydrogen bonding in these hydrides is needed. In nanostructured materials, it is important to study the effect of size and shape on the nature of hydrogen bonding and binding energies. In porous materials, one needs to know whether hydrogen remains in molecular form or if it bonds atomically. A multiscale approach is needed to understand the electronic structure, dynamics, and energetics of hydrogen in materials. Recent advances in methodology (theory and algorithms) and increases in computational power have opened up new possibilities for theoretical studies of the hydrogen-materials interaction over a wide range of length and time scales. This study sees great promise for theory/simulation/calculations to make major headway in bridging the gap between present capabilities and the needs of a hydrogen economy.

This study paid special attention to safety in the hydrogen economy, because of the high diffusivity, buoyancy, and inflammability of hydrogen. Hydrogen embrittlement of materials after extended exposure, together with possible explosive scenarios for hydrogen accumulation in enclosed spaces, is a concern. It is concluded that the study of hydrogen embrittlement; the hydrodynamics of the combustion of hydrogen in enclosed spaces and when mixed with other gases; and the development of sensitive, selective sensors for hydrogen gas are important research areas. Public education about the safe use of hydrogen and suitable training of personnel working with hydrogen are both needed in planning for a hydrogen economy.

Attention is also given to environmental issues — in particular, assessing to what degree a hydrogen economy would be truly environmentally friendly. Because of the large potential increase in atmospheric hydrogen, high-priority research was identified for assessing the effect of such an increase in hydrogen on present-day geochemical, biological, and atmospheric processes.

The panels assembled to carry out this study started their investigation by focusing on the large gap between present knowledge and technology and the requirements of a hydrogen economy. As the panels carried out their investigations, however, optimism increased, indicating that the many recent advances in chemistry, materials research, and computation have opened exciting new research opportunities with the potential for having a significant impact on diminishing the gap between knowledge and technology. At the same time, concerns about possible safety and environmental risks led the panels to propose additional research agendas in these areas that should be pursued.

Whereas others have emphasized the huge knowledge and technology gap (Davis et al. 2003; Weiss et al. 2003) separating us from the hydrogen economy, this Report takes the position that a serious long-range basic research effort could have a large impact on significantly narrowing this gap. Furthermore, most of the research directions identified in this Report are expected not only to make progress in achieving a hydrogen economy, but also to have a dramatic impact on many other aspects of the DOE efforts to provide the nation with a secure energy supply for the future (BES Advisory Committee 2003).

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APPENDIX

Workshop on Basic Research Needs for the Hydrogen Economy

Doubletree Hotel and Executive Meeting Center
Rockville, Maryland
May 13–15, 2003

Agenda for Plenary Sessions

Tuesday Afternoon, May 13

Time	Topic	Speaker or Location
1:00 - 1:15 pm	Welcome and Introduction	Mildred Dresselhaus, Workshop Chair, Massachusetts Institute of Technology
1:15 - 1:30 pm	Overview of the Office of Basic Energy Sciences	Patricia Dehmer, Director, Office of Basic Energy Sciences
1:30 - 2:15 pm	President's Hydrogen Initiative	Steven Chalk, Program Manager, DOE/EERE Hydrogen, Fuel Cells and Infrastructure Technologies Program
2:15 - 3:00 pm	Hydrogen Storage: State of the Art	George Thomas, Consultant, Sandia National Laboratories
3:00 - 3:30 pm	Onboard Hydrogen Storage: Who's Driving and Where Are We Going?	Scott Jorgensen, Manager, Energy Storage Systems Group/General Motors R&D
3:30 - 3:45 pm	Break	
3:45 - 4:15 pm	Hydrogen and Climate Change	Jae Edmonds, Senior Staff Scientist, Pacific Northwest National Laboratory
4:15 - 5:00 pm	Science of Hydrogen Safety	Jay Keller, Department Manager, Sandia National Laboratories/Combustion in Engines and Hydrogen Energy
5:00 - 5:15 pm	Overview of Hydrogen Production Breakout Session	Tom Mallouk, Penn State University, and Laurie Mets, The University of Chicago
5:15 -5:30 pm	Overview of Hydrogen Storage and Distribution Breakout Session	Kathy Taylor, General Motors (retired), and Puru Jena, Virginia Commonwealth University
5:30 - 5:45 pm	Overview of Fuel Cells and Novel Fuel Cell Materials Breakout Session	Frank DiSalvo, Cornell University, and Tom Zawodzinsky, Case Western Reserve University
6:00 - 7:00 pm	Reception (cash bar)	Plaza Ballroom Foyer
7:00 pm	Working Dinner	Plaza I

Agenda for Plenary Sessions (Cont.)

Wednesday, May 14, and Thursday Morning, May 15

No Plenary Sessions; see Agenda for Breakout Sessions.

Thursday Afternoon, May 15

Time	Topic	Speaker or Location
1:30 - 1:45 pm	Concluding Remarks	Mildred Dresselhaus, Workshop Chair Massachusetts Institute of Technology
1:45 - 2:30 pm	Summary of Hydrogen Production Breakout Session	Tom Mallouk, Penn State University Laurie Mets, University of Chicago
2:30 - 3:15 pm	Summary of Hydrogen Storage and Distribution Breakout Session	Kathy Taylor, General Motors (retired) Puru Jena, Virginia Commonwealth University
3:15 - 3:30 pm	Break	
3:30 - 4:15 pm	Summary of Fuel Cells and Novel Fuel Cell Materials Breakout Session	Frank DiSalvo, Cornell University Tom Zawodzinsky, Case Western Reserve University
4:15 - 4:45 pm	Cross-cutting Issues and Summary	Workshop Associate Chairs: George Crabtree, Argonne National Lab Michelle Buchanan, Oak Ridge National Lab
5:00 pm	Adjourn	

Agenda for Hydrogen Production Breakout Session

Wednesday, May 14

Time	Topic	Speaker or Location
8:30 - 9:00 am	Solar Production	Allan Bard, University of Texas, Austin
9:10 - 9:40 am	Biological and Biomimetic Production	Charles Dismukes, Princeton
9:50 - 10:10 am	Bio/inorganic Interfaces	Leonard Tender, Naval Research Lab
10:20 - 10:50 am	Break	
10:50 - 11:20 am	Fossil Production	Jennifer Holmgren, UOP
11:30 am - 12:00 pm	Nuclear Production	Ken Schultz, General Atomic
12:10 - 1:30 pm	Working Lunch	Executive Dining Room
1:30 - 3:30 pm	Panel Discussions	
3:30 - 4:00 pm	Break	
4:00 - 7:00 pm	Meetings of Subgroups to Draft Reports	
7:00 pm	Working Dinner	Regency
Evening after Dinner	Meetings to Assess Progress	

Thursday Morning, May 15

Time	Topic	Speaker or Location
8:30 - 10:00 am	Meetings of Subgroups to Finalize Reports	
10:00 am - 12:00 noon	Consolidation of the Reports/Preparation for Presentation	
12:00 - 1:00 pm	Working Lunch	Executive Dining Room

Agenda for Hydrogen Storage Breakout Session

Wednesday, May 14

Time	Topic	Speaker or Location
8:30 - 8:45 am	General Objectives	Kathy Taylor, General Motors (Retired)
8:45 - 9:20 am	Key Issues	Scott Jorgensen, General Motors
9:20 - 9:55 am	Metal and Compound Hydrides	Robert Bowman, Jet Propulsion Laboratory
9:55 - 10:30 am	Theory and Computation	Karl Johnson, University of Pittsburgh
10:30 - 11:00 am	Break	
11:00 – 11:35 am	Nanostuctured Hydrides	Thomas Lassen, GKSS-Research Center
11:35 am - 12:05 pm	Carbon-related Materials	Peter Eklund, Penn State University
12:05 - 1:30 pm	Working Lunch	Executive Dining Room
1:30 - 3:00 pm	Panel Discussions	
3:00 - 3:30 pm	Break	
3:30 - 5:30 pm	Meetings of Subgroups to Draft Reports	
7:00 pm	Working Dinner	Regency
Evening after Dinner	Meetings to Assess Progress (tentative)	

Thursday Morning, May 15

Time	Topic	Speaker or Location
8:30 - 10:00 am	Meetings of Subgroups to Finalize Reports	
10:00 am - 12:00 noon	Consolidation of the Reports/Preparation for Presentation	
12:00 noon - 1:00 pm	Working Lunch	Executive Dining Room

Agenda for Fuel Cells and Novel Fuel Cell Materials Breakout Session

Wednesday, May 14

Time	Topic	Speaker or Location
8:00 - 8:30 am	Loading of Presentations onto Computer, Check of Audio-Visual Equipment	All Speakers
8:30 - 8:45 am	Introduction and Welcome	Frank DiSalvo and Tom Zawodzinski
8:45 - 9:15 am	Overview: The Fuel Cell Prospect	Shimshon Gottesfeld, MTI
9:15 - 9:45 am	Bio-fuel Cells	Adam Heller
9:45 - 10:15 am	SOFC	Ray Gorte
10:15 - 10:45 am	Break	
10:45 - 11:15 am	Fuel Processing	Levi Thompson
11:15 - 11:45 am	Electrocatalysis and Auto Needs	Hubert Gasteiger
11:45 am - 12:15 pm	Polymers in Fuel Cells	Jim McGrath
12:15 - 1:30 pm	Working Lunch	Executive Dining Room
1:30 - 2:00 pm	Status of Theory for Fuel Cell Processes	Woods Halley
2:00 - 3:30 pm	Panel Reflections, Summaries, Additions	15 min from Member of Each Panel
3:30 - 4:00 pm	Break	
4:00 - 7:00 pm	Meetings to Draft Reports	Low-T Fuel Cells, High-T Fuel Cells, Reformers
7:00 pm	Working Dinner	Regency
Evening after Dinner	Meetings to Draft Reports	

Thursday Morning, May 15

Time	Topic	Speaker or Location
8:30 - 10:00 am	Meetings to Draft Reports, Joining Sections When Possible	
10:00 am - 12:00 noon	Preparation for Presentation	
12:00 noon - 1:00 pm	Working Lunch	Executive Dining Room

Workshop on Basic Research Needs for the Hydrogen Economy

Doubletree Hotel and Executive Meeting Center
Rockville, Maryland
May 13-15, 2003

Invited Participants

Workshop Chair	Mildred Dresselhaus, Massachusetts Institute of Technology
Associate Chairs	George Crabtree, Argonne National Laboratory Michelle Buchanan, Oak Ridge National Laboratory

Pre-Workshop Briefing Presenters

Mark Paster, Department of Energy/Energy Efficiency and Renewable Energy
JoAnn Milliken, Department of Energy/Energy Efficiency and Renewable Energy
Nancy Garland, Department of Energy/Energy Efficiency and Renewable Energy

Plenary Session Speakers

Steve Chalk, Department of Energy/Energy Efficiency and Renewable Energy
George Thomas, Sandia National Laboratories - California
Scott Jorgensen, General Motors
Jae Edmonds, Pacific Northwest National Laboratory
Jay Keller, Sandia National Laboratories - California

Hydrogen Production Panel Chairs

Tom Mallouk, Pennsylvania State University
Laurie Mets, The University of Chicago

Speakers

Allen Bard, University of Texas, Austin
Charles Dismukes, Princeton University
Jennifer Holmgren, UOP
Ken Schultz, General Atomics
Lenny Tender, NRL

Panelists

Michael Adams, University of Georgia
Les Dutton, University of Pennsylvania
Charles Forsberg, Oak Ridge National Laboratory
Heinz Frei, Lawrence Berkeley National Laboratory
Tom Moore, Arizona State University
Jens Nørskov, Technical University of Denmark
Arthur J. Nozik, National Renewable Energy Laboratory
K. Lee Peddicord, Texas A&M University
Tom Rauchfuss, University of Illinois
John A. Turner, National Renewable Energy Laboratory
Luping Yu, The University of Chicago

Hydrogen Storage Panel

Chairs

Kathy Taylor, General Motors, retired
Puru Jena, Virginia Commonwealth University

Speakers

Robert Bowman, Jet Propulsion Laboratory
Karl Johnson, University of Pittsburgh
Peter Eklund, Pennsylvania State University
Scott Jorgensen, General Motors
Thomas Klassen, GKSS-Research Center, Germany

Panelists

Mike Baskes, Los Alamos National Laboratory
Björgvin Hjörvarsson, Uppsala University, Sweden
Hannes Jonsson, University of Washington
Vitalij Pecharsky, Ames Laboratory
James Ritter, University of South Carolina
Seiji Suda, Kogakun University, Japan
George Thomas, Sandia National Laboratory, (Retired)
John Wolan, University of South Florida

Fuel Cells and Novel Fuel Cell Materials

Chairs

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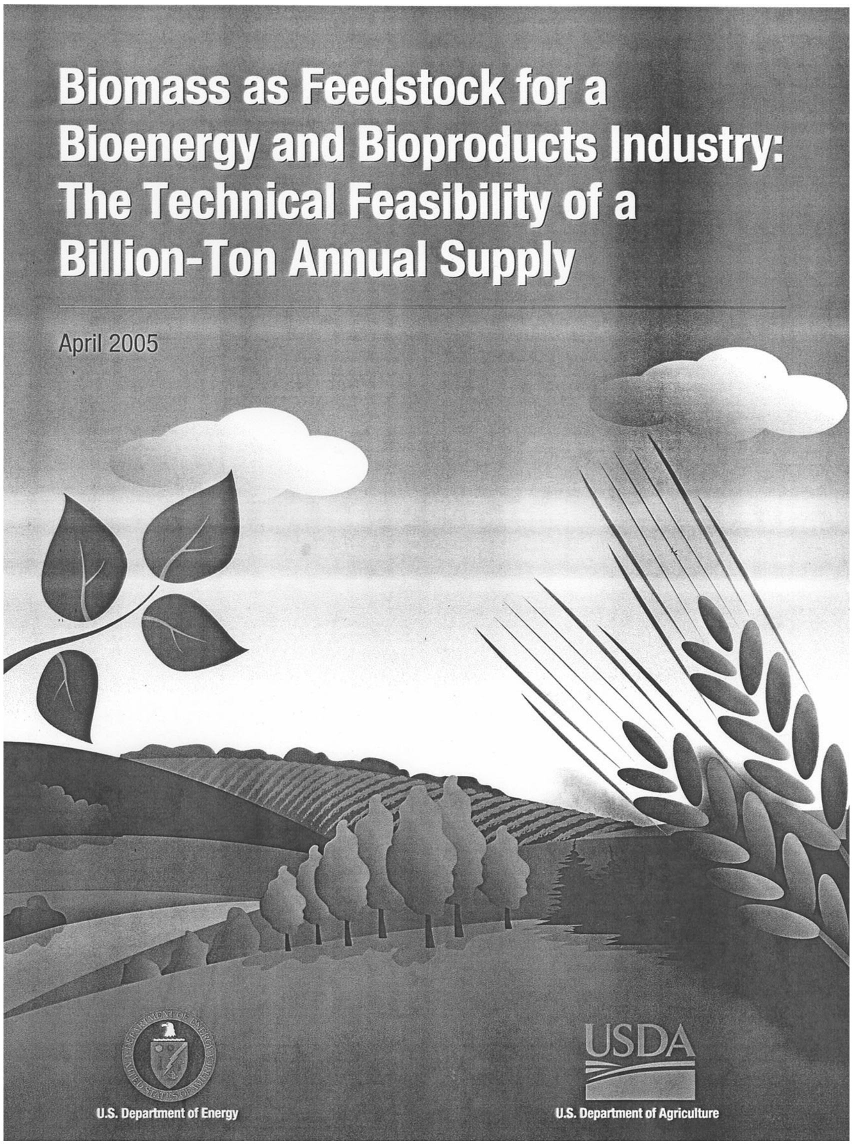

Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply

April 2005

U.S. Department of Energy

U.S. Department of Agriculture

Foreword

The United States Department of Agriculture (USDA) and the United States Department of Energy (DOE) both place high importance on developing resources and conversion technologies for producing fuels, chemicals and power from biomass. The two departments are working together on several aspects of bioenergy. This report is the third to be produced from joint collaboration. This and other reports can be found at: http://www.eere.energy.gov/biomass/publications.html.

The website for biomass feedstock research sponsored by the DOE's Office of Energy Efficiency and Renewable Energy Office of the Biomass Program (OBP) can be found at: http://bioenergy.ornl.gov/. More general information about OBP's feedstock research program can be found at: http://www.eere.energy.gov/biomass/biomass_feedstocks.html.

The website for research and development sponsored by the USDA Forest Service can be found at: http://www.fs.fed.us/research/.

The website for bioenergy research sponsored by the USDA Agricultural Research Service can be found at: http://www.ars.usda.gov/research/programs/programs.htm?NP_CODE=307.

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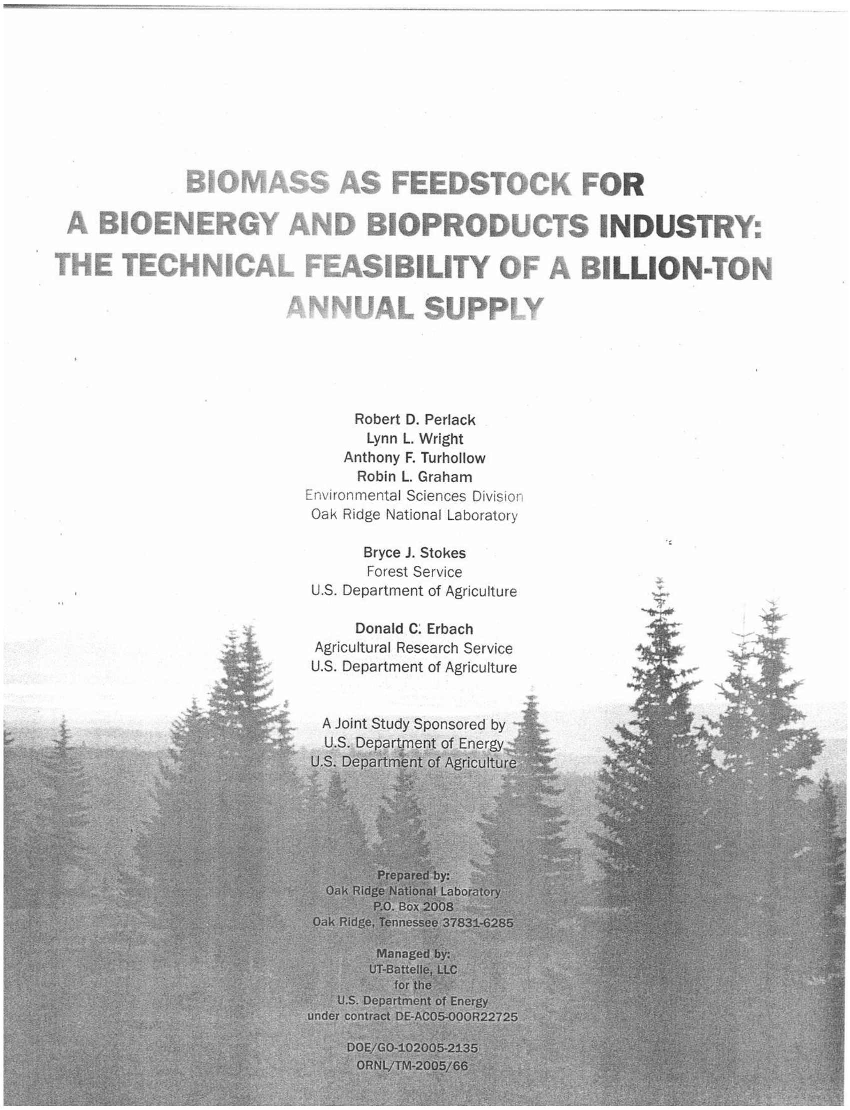

BIOMASS AS FEEDSTOCK FOR A BIOENERGY AND BIOPRODUCTS INDUSTRY: THE TECHNICAL FEASIBILITY OF A BILLION-TON ANNUAL SUPPLY

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Abbreviations and Acronyms

CAFO	confined animal feeding operation
CRP	Conservation Reserve Program
DOE	U.S. Department of Energy
EERE	Energy Efficiency and Renewable Energy
FIA	Forestry Inventory and Analysis (USDA program)
FTE	Fuel Treatment Evaluator
HFRA	Healthy Forest Restoration Act
LBS	large biomass soybean
MSW	municipal solid waste
NCGA	National Corn Growers Association
OBP	Office of the Biomass Program
quad	quadrillion (10^{15}) BTUs
R&D	research and development
RMR	residue maintenance requirement
RUSLE	Revised Universal Soil Loss Equation
SCI	Soil Conditioning Index
TPO	Timber Product Output
USDA	U.S. Department of Agriculture

Executive Summary

The U.S. Department of Energy (DOE) and the U.S. Department of Agriculture (USDA) are both strongly committed to expanding the role of biomass as an energy source. In particular, they support biomass fuels and products as a way to reduce the need for oil and gas imports; to support the growth of agriculture, forestry, and rural economies; and to foster major new domestic industries — biorefineries — making a variety of fuels, chemicals, and other products. As part of this effort, the Biomass R&D Technical Advisory Committee, a panel established by the Congress to guide the future direction of federally funded biomass R&D, envisioned a 30 percent replacement of the current U.S. petroleum consumption with biofuels by 2030.

Biomass — all plant and plant-derived materials including animal manure, not just starch, sugar, oil crops already used for food and energy — has great potential to provide renewable energy for America's future. Biomass recently surpassed hydropower as the largest domestic source of renewable energy and currently provides over 3 percent of the total energy consumption in the United States. In addition to the many benefits common to renewable energy, biomass is particularly attractive because it is the only current renewable source of liquid transportation fuel. This, of course, makes it invaluable in reducing oil imports — one of our most pressing energy needs. A key question, however, is how large a role could biomass play in responding to the nation's energy demands. Assuming that economic and financial policies and advances in conversion technologies make biomass fuels and products more economically viable, could the biorefinery industry be large enough to have a significant impact on energy supply and oil imports? Any and all contributions are certainly needed, but would the biomass potential be sufficiently large to justify the necessary capital replacements in the fuels and automobile sectors?

The purpose of this report is to determine whether the land resources of the United States are capable of producing a sustainable supply of biomass sufficient to displace 30 percent or more of the country's present petroleum consumption – the goal set by the Advisory Committee in their vision for biomass technologies. Accomplishing this goal would require approximately 1 billion dry tons of biomass feedstock per year.

The short answer to the question of whether that much biomass feedstock can be produced is yes. Looking at just forestland and agricultural land, the two largest potential biomass sources, this study found over 1.3 billion dry tons per year of biomass potential (Figure 1) — enough to produce biofuels to meet more than one-third of the current demand for transportation fuels. The full resource potential could be available roughly around mid-21st century when large-scale bioenergy and biorefinery industries are likely to exist. This annual potential is based on a more than seven-fold increase in production from the amount of biomass currently consumed for bioenergy and biobased products. About 368 million dry tons of sustainably removable biomass could be produced on forestlands, and about 998 million dry tons could come from agricultural lands.

Forestlands in the contiguous United States can produce 368 million dry tons annually. This projection includes 52 million dry tons of fuelwood harvested from forests, 145 million dry tons of residues from wood processing mills and pulp and paper mills, 47 million dry tons of urban wood residues including construction and demolition debris, 64 million dry tons of residues from logging and site clearing operations, and 60 million dry tons of biomass from fuel treatment operations to reduce fire hazards. All of these forest resources are sustainably available on an annual basis. For estimating the residue tonnage from logging and site clearing operations and fuel treatment thinnings, a number of important assumptions were made:

- all forestland areas not currently accessible by roads were excluded;
- all environmentally sensitive areas were excluded;
- equipment recovery limitations were considered; and
- recoverable biomass was allocated into two utilization groups – conventional forest products and biomass for bioenergy and biobased products.

From agricultural lands, the United States can produce nearly 1 billion dry tons of biomass annually and still continue to meet food, feed, and export demands. This projection includes 428 million dry tons of annual crop residues, 377 million dry tons of perennial crops, 87 million dry tons of grains used for biofuels, and 106 million dry tons of animal manures, process residues, and other miscellaneous feedstocks. Important assumptions that were made include the following:

- yields of corn, wheat, and other small grains were increased by 50 percent;
- the residue-to-grain ratio for soybeans was increased to 2:1;
- harvest technology was capable of recovering 75 percent of annual crop residues (when removal is sustainable);
- all cropland was managed with no-till methods;
- 55 million acres of cropland, idle cropland, and cropland pasture were dedicated to the production of perennial bioenergy crops;
- all manure in excess of that which can applied on-farm for soil improvement under anticipated EPA restrictions was used for biofuel; and
- all other available residues were utilized.

The biomass resource potential identified in this report can be produced with relatively modest changes in land use, and agricultural and forestry practices. This potential, however, should not be thought of as an upper limit. It is just one scenario based on a set of reasonable assumptions. Scientists in the Departments of Energy and Agriculture will explore more advanced scenarios that could further increase the amount of biomass available for bioenergy and biobased products.

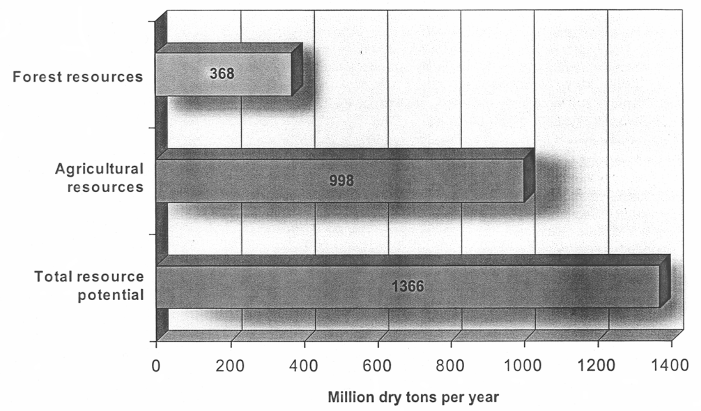
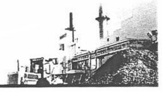


Figure 1: Annual biomass resource potential from forest and agricultural resources



1. Introduction

Biomass is already making key energy contributions in the United States, having supplied nearly 2.9 quadrillion Btu (quad) of energy in 2003. It has surpassed hydropower as the largest domestic source of renewable energy. Biomass currently supplies over 3 percent of the total energy consumption in the United States – mostly through industrial heat and steam production by the pulp and paper industry and electrical generation with forest industry residues and municipal solid waste (MSW). In addition to the many benefits common to any renewable energy use, biomass is particularly attractive because it is the only current renewable source of liquid transportation fuel. This, of course, makes it an invaluable way to reduce oil imports – one of our nation's most pressing energy and security needs. Biomass also has great potential to provide heat and power to industry and to provide feedstocks to make a wide range of chemicals and materials or bioproducts.

Feedstock Resource Vision Goals Established by the Biomass Research & Development Technical Advisory Committee (Source: BTAC, 2002a)

Biopower – Biomass consumption in the industrial sector will increase at an annual rate of 2% through 2030, increasing from 2.7 quads in 2001 to 3.2 quads in 2010, 3.9 quads in 2020, and 4.8 quads in 2030. Additionally, biomass consumption in electric utilities will double every 10 years through 2030. Combined, biopower will meet 4% of total industrial and electric generator energy demand in 2010 and 5% in 2020.

Biobased Transportation Fuels – Transportation fuels from biomass will increase significantly from 0.5% of U.S. transportation fuel consumption in 2001 (0.0147 quad) to 4% of transportation fuel consumption in 2010 (1.3 quads), 10% in 2020 (4.0 quads), and 20% in 2030.

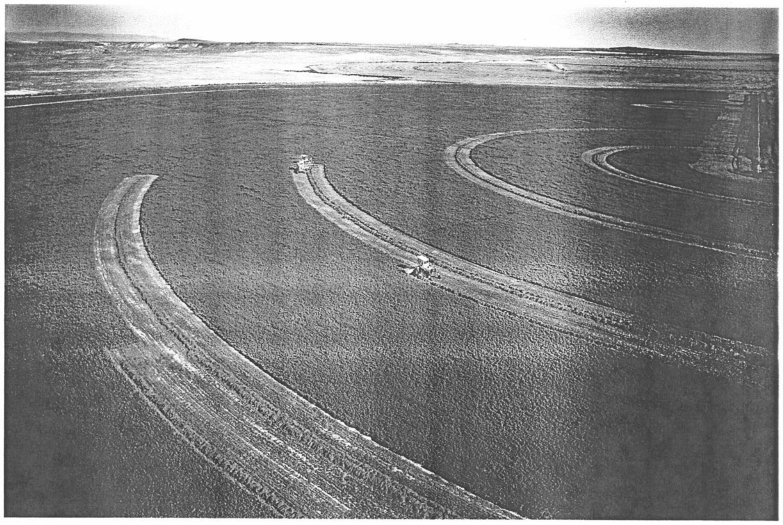
Biobased Products – Production of chemicals and materials from biobased products will increase substantially from approximately 12.5 billion pounds or 5% of the current production of target U.S. chemical commodities in 2001, to 12% in 2010, 18% in 2020, and 25% in 2030.

The overall mission of the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) is to strengthen the nation's energy security, environmental quality, and economic vitality in public-private partnerships that enhance energy efficiency and productivity; bring clean, reliable and affordable energy technologies to the marketplace; and make a difference in the everyday lives of Americans by enhancing their energy choices and their quality of life. Consistent with this mission, DOE-EERE's Biomass Program supports a research agenda to develop biomass feedstock production and conversion technologies capable of providing for significant fractions of domestic demands for transportation fuels, electric power, heat, chemicals and materials.

The U.S. Department of Agriculture (USDA) through its agencies and offices has similar goals of reducing foreign oil dependence, improving the environment through the development of new sources of energy, increasing the use of agricultural crops and forest resources as feedstocks for bioenergy and bioproducts, and creating jobs and enhancing income in America's rural sector.

The Biomass Research and Development Act of 2000 created the Biomass R&D Technical Advisory Committee to provide advice to the Secretaries of Agriculture and Energy on program priorities and to facilitate cooperation among various federal and state agencies, and private interests. The Technical Advisory Committee also established a national vision for bioenergy and biobased products. Included in its vision was the setting of a very challenging goal: biomass will supply 5 percent of the nation's power, 20 percent of its transportation fuels, and 25 percent of its chemicals by 2030. The goal is equivalent to 30 percent of current petroleum consumption and will require more than approximately one billion dry tons of biomass feedstock annually – a fivefold increase over the current consumption (DOE, 2003).

The purpose of this report is to assess whether the land resources of the United States have the potential to produce a sustainable supply of biomass that can displace 30 percent of the country's current petroleum consumption. This report does not attempt to outline R&D and policy agendas to attain this goal, nor does it attempt to assess the economic competitiveness of a billion-ton bioenergy and bioproducts industry, and its potential impacts on the energy, agriculture (food and feed production), and forestry sectors of the economy. Many of these issues are partially addressed in the roadmap that accompanied the biomass vision (BTAC, 2002b). The roadmap explores the technical research, development, and demonstrations needed to achieve advances in biomass systems and outlines the institutional and policy changes needed to remove the barriers to economically and environmentally sound development of sustainable biomass systems. To provide some perspective, the next section of this resource assessment report summarizes current biomass consumption and the biomass feedstock resource base. The biomass feedstock resource base from forests and agricultural lands are then discussed in more detail in the main body of the report.



2. The Biomass Feedstock Resource Base

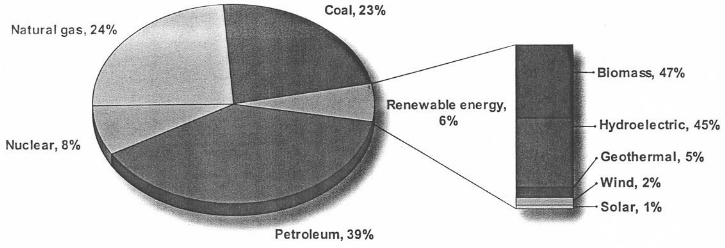
2.1 Land Resources for Biomass Production

The land base of the United States encompasses nearly 2,263 million acres, including the 369 million acres of land in Alaska and Hawaii. About 33 percent of the land area is classified as forest land, 26 percent as grassland pasture and range, 20 percent as cropland, 8 percent as special uses (e.g., public facilities), and 13 percent as miscellaneous uses such as urban areas, swamps, and deserts (Vesterby and Krupa, 2001; Alig et al., 2003). About one-half of this land has some potential for growing biomass. This percentage is nearly 60 percent without Alaska and Hawaii.

Currently, slightly more than 75 percent of biomass consumption in the United States (about 142 million dry tons) comes from forestlands. The remainder (about 48 million dry tons), which includes biobased products, biofuels and some residue biomass, comes from cropland.

2.2 Biomass Feedstock Consumption

In 2003, biomass contributed nearly 2.9 quadrillion BTU (quad) to the nation's energy supply, nearly 3 percent of total U.S. energy consumption of about 98 quads (EIA, 2004a). At 47 percent of total renewable energy consumption, biomass is the single largest renewable energy resource, recently surpassing hydropower (Figure 2). More than 50 percent



Biomass Consumption	Million dry tons/year
Forest products industry	
Wood residues	44
Pulping liquors	52
Urban wood and food & other process residues	35
Fuelwood (residential/commercial & electric utilities)	35
Biofuels	18
Bioproducts	6
Total	**190**

- Forestlands and agricultural lands contribute 190 million dry tons of biomass - 3% of America's current energy consumption.

Source: EIA, 2004a & b

Figure 2: Summary of biomass resource consumption

of this biomass comes from wood residues and pulping liquors generated by the forest products industry. Currently, biomass accounts for approximately

- 13 percent of renewably generated electricity,
- nearly all (97 percent) the industrial renewable energy use,
- nearly all the renewable energy consumption in the residential and commercial sectors (84 percent and 90 percent, respectively), and
- 2.5 percent of transport fuel use.

A relatively significant amount of biomass (~6 to 9 million dry tons) is also currently used in the production of a variety of industrial and consumer bioproducts that directly displace petroleum-based feedstocks (Energetics, 2003). The total annual consumption of biomass feedstock for bioenergy and bioproducts together currently approaches 190 million dry tons (Figure 3).

2.3 Composition of the Current Resource Base

The biomass resource base is composed of a wide variety of forestry and agricultural resources, industrial processing residues, and municipal solid and urban wood residues (Figure 3). The forest resources include residues produced during the harvesting of forest products, fuelwood extracted from forestlands, residues generated at primary forest product processing mills, and forest resources that could become available through initiatives to reduce fire hazards and improve forest health. The agricultural resources include grains used for biofuels production, animal manures and residues, and crop residues derived primarily from corn and small grains (e.g., wheat straw). A variety of regionally significant crops, such as cotton, sugarcane, rice, and fruit and nut orchards can also be a source of crop residues. Municipal and urban wood residues are widely available and include a variety of materials — yard and tree trimmings, land-clearing wood residues, wooden pallets, packaging materials, and construction and demolition debris.

Forest Resources

Primary
- Logging residues from conventional harvest operations and residues from forest management and land clearing operations
- Removal of excess biomass (fuel treatments) from timberlands and other forestlands
- Fuelwood extracted from forestlands

Secondary
- Primary wood processing mill residues
- Secondary wood processing mill residues
- Pulping liquors (black liquor)

Tertiary
- Urban wood residues — construction and demolition debris, tree trimmings, packaging wastes and consumer durables

Agricultural Resources

Primary
- Crop residues from major crops — corn stover, small grain straw, and others
- Grains (corn and soybeans) used for ethanol, biodiesel, and bioproducts
- Perennial grasses
- Perennial woody crops

Secondary
- Animal manures
- Food/feed processing residues

Tertiary
- MSW and post-consumer residues and landfill gases

The resource base includes a wide range of primary resources, and secondary and tertiary residues. This report emphasizes primary resources.

Figure 3: The biomass resource base

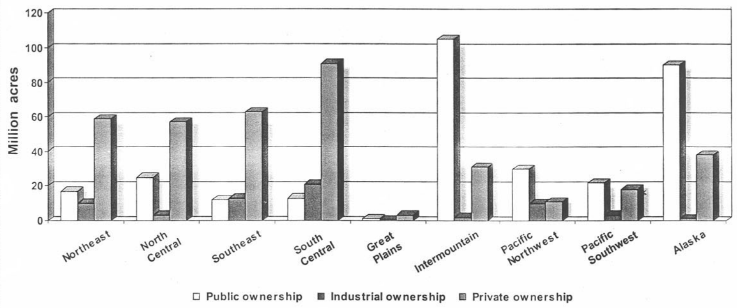
The remainder of this report addresses the potential availability of biomass feedstock projected over a long term — roughly around mid-21st century when large-scale bioenergy and biorefinery industries are likely to exist. The report emphasizes primary sources of forest- and agriculture-derived biomass such as logging residues, fuel treatment thinnings, crop residues, and perennially grown grasses and woody crops. These primary sources have the greatest potential to supply large, sustainable quantities of biomass. While the primary sources are emphasized, secondary and tertiary (or residue) sources of biomass are also addressed in the report.

The amount of forest-derived biomass is based on an analysis of extant resources and trends in the demand for forest products. The biomass resource potential from agricultural land is based on creating scenarios that extrapolate from current agriculture and research and development trends. While the forestland area is much larger, agricultural land has a greater biomass resource potential due to a much higher level of management intensity. Forestlands, especially those held publicly, will always be managed less intensively than agricultural lands because forests are expected to provide multiple-use benefits including wildlife habitat, recreation, and ecological and environmental services. By contrast, active cropland and, to a lesser extent, idle cropland and cropland pasture are intensively managed, with crops and management practices changing on a year-to-year basis and land moving in and out of active production.

3. Forest-Derived Biomass Resource Assessment

3.1 Forestland Resource Base

The total forestland in the United States is approximately 749 million acres – about one-third of the nation's total land area. Most of this land is owned by private individuals or by the forest industry (Figure 4). Two-thirds of the forestland (504 million acres) is classified as timberland which, according to the Forest Service, is land capable of growing more than 20 ft^3 per acre of wood annually (Smith et al., 2004). Although timberland is not legally reserved from harvesting, much of it is inaccessible or inoperable by forestry equipment. In addition, there are 168 million acres of forestland that the Forest Service classifies as "other." This "other" forestland is generally incapable of growing 20 ft^3 per acre of wood annually. The lower productivity is due to a variety of factors or site conditions that adversely affect tree growth (e.g., poor soils, lack of moisture, high elevation, and rockiness). As a result, this land tends to be used for livestock grazing and extraction of some non-industrial wood products. The remaining 77 million acres of forestland are reserved from harvesting and are intended for a variety of non-timber uses, such as parks and wilderness.



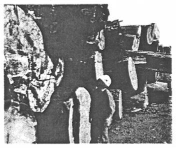
- Of the 504 million acres of U.S. timberland, about 29% is publicly owned, 13% is owned by the forest industry, and the remaining 58% is privately owned.
- Timberland ownership varies considerably among regions of the country. The East United States tends to be dominated by private ownership and the West by public land ownership.

Source: Alig et al., 2003

Figure 4: Ownership break-up of U.S. forestland by region

The total forestland base considered for this resource analysis includes the 504 million acres of timberland and the 168 million acres of other forestland. The timberland acreage is the source of nearly all current forest-derived bioenergy consumption and the source of most of the potential. The other forestland is included because it has accumulated excess biomass that poses wildland fire risks and hazards. Much of this excess biomass is not suitable for conventional wood products but could be used for a variety of bioenergy and biobased product uses.

3.2 Forest Resources



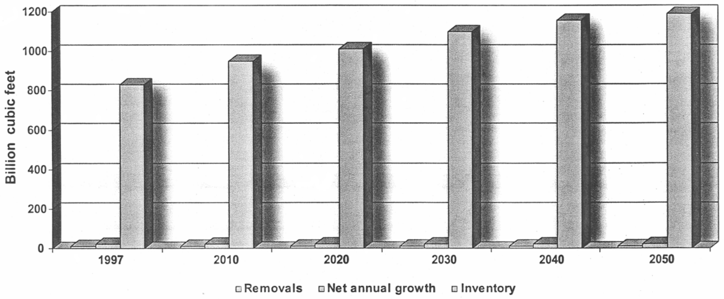
The processing of harvested forest products, such as sawlogs and pulpwood, generates significant quantities of mill residues and pulping liquors. These secondary forest residues constitute the majority of biomass in use today (Figure 3). Secondary residues generated in the processing of forest products account for 50 percent of current biomass energy consumption. These materials are used by the forest products industry to manage residue streams, produce energy, and recover important chemicals. Fuelwood extracted from forestlands for residential and commercial use and electric utility use accounts for about 35 million dry tons of current consumption. In total, the amount of harvested wood products from timberlands in the United States is less than the annual forest growth and considerably less than the total forest inventory (Figure 5), suggesting substantial scope for expanding biomass resource base from forestlands.

In addition to these existing uses, forestlands have considerable potential to provide biomass from two primary sources:

- residues associated with the harvesting and management of commercial timberlands for the extraction of sawlogs, pulpwood, veneer logs, and other conventional products; and
- currently non-merchantable biomass associated with the standing forest inventory.

This latter source is more difficult to define, but generally would include rough and rotten wood not suitable for conventional forest products and excess quantities of smaller-diameter trees in overstocked forests. A large amount of this forest material has been identified by the Forest Service as needing to be removed to improve forest health and to reduce fire hazard risks (USDA-FS, 2003; Miles, 2004).

These two categories of forest resources constitute what is defined as the primary source of forest residue biomass in addition to the fuelwood that is extracted for space heating applications in the residential and commercial sectors and



- Removals from the forest inventory are a small fraction of the total standing inventory. Current removals are also less than net annual forest growth.
- Forest inventories are projected to increase relative to removals despite a loss of about 3% (23 million acres) of U.S. forestland by the year 2050. The projected loss is expected as a result of land conversion to urban and developed uses driven primarily by population and income growth (Alig et al., 2003).

Source: Haynes, 2003

Figure 5: Projections of timber removals, growth, and inventory

for some feedstocks by electric utilities. Perennial woody crops (also referred to as short-rotation woody crops) are also a potential primary biomass resource. Because these woody crops would be grown on agricultural lands, they are discussed in the agricultural resources section that follows (Section 4.0).

There is also a relatively large tertiary, or residue, source of forest biomass in the form of urban wood residues – a generic category that includes yard trimmings, packaging residues, discarded durable products, and construction and demolition debris.

All of these forest resources can contribute an additional 226 million dry tons to the current forest biomass consumption (approximately 142 million dry tons) – an amount still only a small fraction of the total biomass timberlands inventory of more than 20 billion dry tons (Figure 6). Specifically, these forest resources include the following:

- **The recovered residues generated by traditional logging activities and residues generated from forest cultural operations or clearing of timberlands.** Currently, about 67 million dry tons of residues are generated annually from these activities (Smith et al., 2004; USDA-FS, 2004a). About 41 million dry tons of this biomass material is potentially available for bioenergy and biobased products after consideration of equipment recovery limitations (Tables A.1 to A.3, Appendix A).

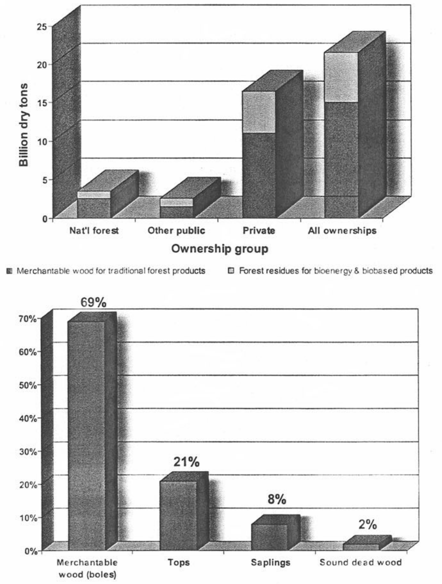
- **The recovered residues generated from fuel treatment operations on timberland and other forestland.** Well over 8 billion dry tons of biomass has been identified for fuel treatment removal (Miles, 2004). The amount of this biomass potentially available for bioenergy and biobased product uses is estimated at 60 million dry tons annually. This estimate takes into consideration factors affecting forest access, residue recovery, and the merchandizing of the recoverable biomass into higher-value fractions (conventional wood products) and lower-value fractions (the biomass suitable for bioenergy and biobased product uses) (Tables A.5 to A.7, Appendix A). The fraction that could be available for bioenergy and biobased products is less than 1 percent of the total size of the fuel treatment biomass resource.

- **The direct conversion of roundwood to energy (fuelwood) in the residential, commercial, and electric utility sectors.** Thirty-five million dry tons of biomass is currently extracted by the residential and commercial sectors and by the electric power sector. Most of the fuelwood used by the residential and commercial sectors is used for space- and process-heating applications.

- **Forest products industry residues and urban wood residues.** Utilization of unused residues generated by the forest products industry (8 million dry tons); urban wood residues discarded from construction and demolition activities (20 million dry tons); and residues from the disposal of tree trimmings, packaging residues, and wood-based consumer durables (8 million dry tons) can annually provide 36 million dry tons to the current 108 million dry tons currently used.

- **Forest growth and increase in the demand for forest products.** In the long term, a continuation of current trends in the demand and supply of forest products could increase the potential contribution of forest biomass by another 89 million dry tons annually. The additional 89 million dry tons result from a combination of sources and changing circumstances. An increase in the harvest of traditional forest products will create additional logging residues, and more efficient equipment will allow the recovery of a greater fraction of the logging residue. However, this increase will be offset somewhat by more efficient logging practices that will generate less wood residue per unit volume of the harvested forest products (Haynes, 2003). Demand growth for conventional forest products will create additional mill residue, and pulping liquor and urban wood residues. However, the rate of increase in these secondary and tertiary forest residue sources will be tempered by product substitution, recycling and reuse, and more efficient manufacturing processes.

A summary of the amounts of biomass available annually and on a sustainable basis from forest resources is summarized in Figure 7. The approximate total quantity is 368 million dry tons annually. As noted, this includes about 142 million dry tons of biomass currently being used primarily by the forest products industry, as well as the 89 million dry tons that could result annually from a continuation of demand and supply trends in the forest products industry.



- The merchantable wood or the conventional forest products component includes the boles and sound dead wood.
- The forest residue fraction suitable for bioenergy and biobased products includes the tops and some fraction of saplings considered to be overstocked.
- The total forest residue resource is about 6.7 billion dry tons.

Source: Smith et al., 2004

Figure 6: Total timberland biomass and forest residue inventory

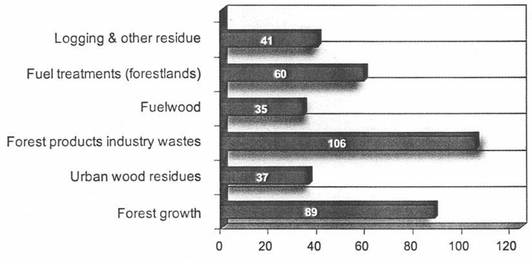


Figure 7: Estimate of the sustainably recoverable forest biomass

3.3 Increasing Biomass Resources from Forests

3.3.1 Logging Residues and Other Removals from the Forest Inventory

A recent analysis shows that the annual removals from the forest inventory totaled nearly 20.2 billion ft^3. Of this volume, 78 percent was for roundwood products, 16 percent was logging residue, and slightly more than 6 percent was classified as "other removals" (Smith et al., 2004). The total annual removals constitute about 2.2 percent of the forest inventory of timberland and are less than net annual forest growth (Figure 5). The logging residue fraction is biomass removed from the forest inventory as a direct result of conventional forest harvesting operations. This biomass material is largely tree tops and small branches left on site because these materials are currently uneconomical to recover either for product or energy uses (Figure 8). The remaining fraction, other removals, consists of timber cut and is burned in the process of land conversion or cut as a result of cultural operations such as precommercial thinnings and timberland clearing.

Data on the total amount of logging residue and other removals are available from the USDA Forestry Inventory and Analysis (FIA) program's Timber Product Output (TPO) Database Retrieval System (USDA-FS, 2004a). This database provides volumetric information on roundwood products (e.g., sawlogs, pulpwood, veneer logs, and fuelwood), logging residues, other removals, and mill residues. For the United States, total logging residue and other removals currently amount to nearly 67 million dry tons annually: 49 million dry tons of logging residue and 18 million dry tons of other removal residue (Table A.1, Appendix A).

Forest Inventory and Analysis

The Forest Inventory and Analysis (FIA) program of the Forest Service is the nation's forest census and has been in continuous operation since 1930 under various names (Forest Survey, Forest Inventory and Analysis). Its mission is to "make and keep current a comprehensive inventory and analysis of the present and prospective conditions of and requirements for the renewable resources of the forest and rangelands of the United States." FIA reports on status and trends in forest areas and locations; on the species, size, and health of trees; on total tree growth, mortality, and removals by harvest; on wood production and utilization rates by various products; and on forest land ownership. FIA is the only program which provides consistent, credible, and periodic forest data for all forest lands (public and private) within the United States. FIA covers all U.S. forestlands, including Alaska, Hawaii, Puerto Rico, the U.S. Virgin Islands, and the U.S. Pacific territories. The FIA program is managed by the R&D organization within the USDA Forest Service in cooperation with state and private forestry and national forest systems. More information can be found at http://www.fia.fs.fed.us/. This analysis uses data from the FIA databases.

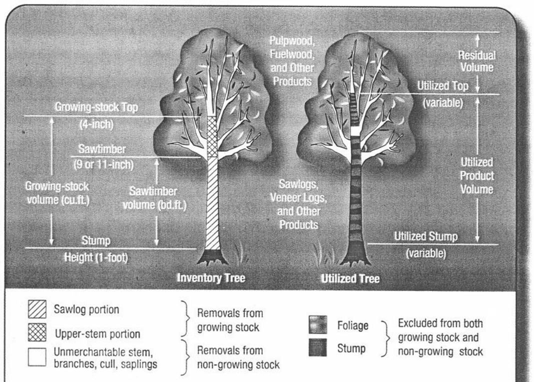
Not all of this resource is potentially available for bioenergy and biobased products (Figure 8). Generally, these residues tend to be relatively small pieces consisting of tops, limbs, small branches, and leaves. Stokes reported a wide range of recovery percentages, with an average of about 60 percent potential recovery behind conventional forest harvesting systems (Stokes, 1992). With newer technology, it is estimated that the current recovery is about 65 percent. Other removals, especially from land-clearing operations, usually produce different forms of residues and are not generally as feasible or as economical to recover. It is expected that only half of the residues from other removals can be recovered. Of course, not all of this material should be recovered. Some portion of this material, especially the leaves and parts of tree crown mass, should be left on site to replenish nutrients and maintain soil productivity.

Since many forest operations involve the construction of roads that provide only temporary access to the forest, it is assumed that these residues are removed at the same time as the harvest or land clearing operations that generate the residues. Limiting the recoverability of logging and other removal residue reduces the size of this forest resource from about 67 million to 41 million dry tons (Tables A.2 and A.3, Appendix A). About three-fourths of this material would come from the logging residue. Further, because of ownership patterns most of the logging residue and nearly all residues from other sources (e.g., land clearing operations) would come from privately owned land (Figure 9).

3.3.2 Forest Residues from Fuel Treatment Thinning

Vast areas of U.S. forestland are overstocked with relatively large amounts of woody materials. This excess material has built up over years as a result of forest growth and alterations in natural fire cycles. Over the last ten years, federal agencies have spent more than $8.2 billion fighting forest fires, which have consumed over 49 million acres (Figure 10). The cost of fighting fires does not include the costs of personal property losses, ecological damage, loss of valuable forest products, or the loss of human life. The Forest Service and other land management agencies are currently addressing the issue of hazardous fuel buildups and looking at ways to restore ecosystems to more fire-adaptive conditions. The removal of excess woody material would also improve forest health and productivity (Graham, et al., McCaffrey, and Jain, 2004).

In August 2000, the National Fire Plan was developed to help respond to severe wildland fires and their impacts on local communities while ensuring sufficient firefighting capacity for future fires. The National Fire Plan specifically addresses firefighting capabilities, forest rehabilitation, hazardous fuels reduction, community assistance, and accountability. Recently, the Healthy Forest Restoration Act (HFRA) of 2003 was enacted to encourage the removal of hazardous fuels and utilization of the material, and protect, restore and enhance forest ecosystem components. HFRA is also intended to support R&D to overcome both technical and market barriers to greater utilization of this resource for bioenergy and other commercial uses from both public and private lands. Removing excess woody material has the potential to make available relatively large volumes of forest residues and small-diameter trees for bioenergy and biobased product purposes.

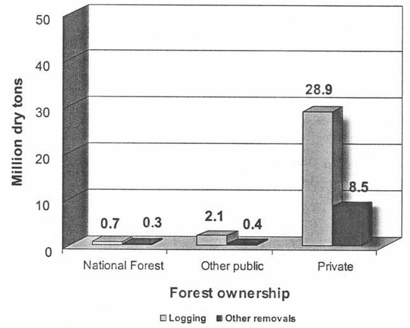


- Logging residue includes the unmerchantable tops and small branches.

Source: Northeastern Forest Inventory & Analysis Program

Figure 8: Forest utilization relationships

The Forest Service has identified timberland and other forestland areas that have tree volumes in excess of prescribed or recommended stocking densities that require some form of treatment or thinning operation to reduce fire risks and hazards, and are in close proximity to people and infrastructure (USDA-FS, 2003b). For timberlands, this was accomplished using the Fuel Treatment Evaluator or FTE (USDA-FS, 2004c; Miles, 2004), an assessment tool developed to identify, evaluate, and prioritize fuel treatment opportunities and facilitate the implementation of HFRA on all timberland areas.



- 41 million dry tons of logging and other removal residue is currently available annually for recovery.
- Most of this resource would come from privately owned timberland

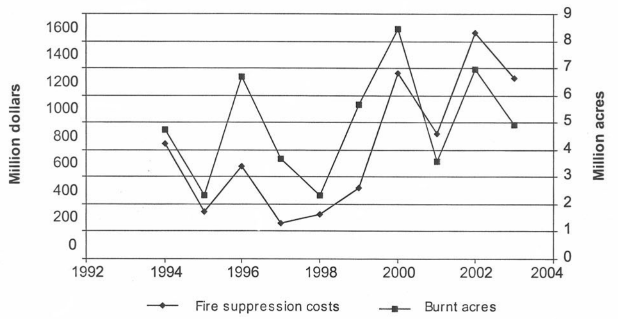
Figure 9: Logging and other removal residues

The FTE uses a stand density index approach to identify stands that are minimally fully stocked. Stands that exceed this threshold are identified as potential candidates for thinning treatment. Treatable land areas are then sorted into fire regime condition classes to measure the extent a given area has departed from natural wildfire conditions. The condition classes range from minimally altered areas to areas that are significantly altered from historical norms and pose significant fire risks due to the heavy fuel loadings.

The FTE program requires individual tree data. Because this information was not collected for all "other forestland" areas prior to 1998, Forest Service personnel implemented FTE procedures manually for other forestland areas where individual tree data were available. The results for these areas were then extrapolated to similar areas, based on forest type and ecoregion, where individual tree data were not available. Since 1998, the FIA program has been collecting individual tree data on all forestland nationwide.

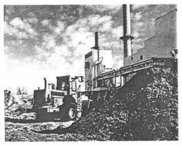
The FTE identified nationwide about 7.8 billion dry tons of treatable biomass on timberland and another 0.6 billion dry tons of treatable biomass on other forestland (Figure 11; Table A.5, Appendix A). Only a fraction of this approximately 8.4 billion dry tons is considered potentially available for bioenergy and biobased products on a sustainable annual basis. Many factors reduce the size of this primary biomass resource (USDA-FS, 2003).

The first of these limiting factors is accessibility to the material from the standpoint of having roads to transport the material and operate logging/collection systems (Table A.6, Appendix A). This is rarely a technology-limited factor since there is equipment for nearly any type of terrain and for removing wood a long distance, even without roads (e.g., via helicopters, two-stage hauling, or long-distance cableways). However, there are usually economic and political constraints that inhibit working in roadless areas and more difficult terrain. Estimates of operational accessibility assume conventional types of operations by limiting the areas for consideration to roaded forestland. About 60 percent of the North American temperate forest is considered accessible (not reserved or high-elevation and within 15 miles of major transportation infrastructure) (FAO, 2001). The Forest Service's final environmental impact statement for roadless area conservation indicates that about 65 percent of Forest Service acreage falls within roaded or non-restricted designations (USDA-FS, 2004b). Road density is much higher in the eastern United States, and in most cases, the topography is more accessible.



- On average, nearly 5 million acres have been burned each year over the last 10 years.
- Fire suppression costs average nearly $170 per acre burned.

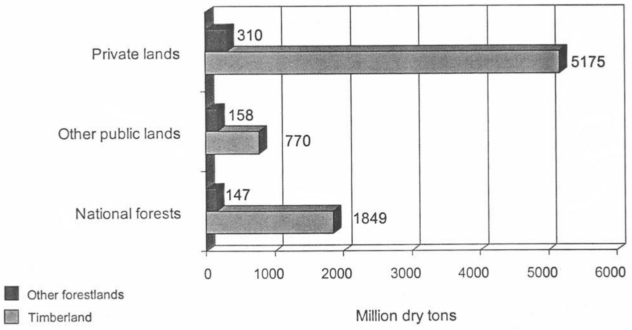
Figure 10: Fire suppression cost and acres burned



Operational accessibility is further limited by the need to avoid adverse impacts to soil and water. Steep slopes, sensitive sites, regeneration difficulty, or lack of adequate resource information may exclude an area from operational treatments. A summary of national forest land management plans from 1995 indicated about 60 percent of the western national forest timberland base to be "suitable" for timber production operations (Timko, 2003). This would be a conservative estimate for other landowners as well, and an even more conservative estimate for eastern U.S. timberlands.

A more significant restriction is economic feasibility. Operating in steep terrain, in unroaded areas, or with very low-impact equipment is expensive. The value of the biomass (in its broad sense, meaning a combination of product value and treatment value) has to be weighed against the cost of removing the material. For example, May and LeDoux (1992) compared FIA data for hardwood inventory with economic modeling of the cost of harvest and concluded that only 40 percent of the inventory volume in Tennessee was economically available. Biomass, with a lower product value, would be even less available if the biomass has to cover the entire cost of the operation. If the biomass were to be produced as part of an integrated operation, it would be at most 40 percent available in the eastern hardwood example. The primary economic factor is the cost of transportation to processing mills.

The recoverability (i.e., the fraction of standing biomass removed offsite) of wood for bioenergy and biobased products is a function of tree form, technology, and timing of the removal of the biomass from the forests. In most cases, merchantable wood is removed, and the forest residues — in the form of limbs and tops, and small non-merchantable trees — remain scattered across the harvest area. This practice reduces recoverability when the biomass is removed in a second pass. However, when all biomass is harvested and processed using an integrated system, recovery is usually greatly improved, even greater than 90 percent. For example, a study by Stokes and Watson (1991) found that 94 percent of the standing biomass could be recovered when using a system to recover multiple products if the biomass from in-woods processing was actually utilized for bioenergy.



- About 8.4 billion dry tons of treatable biomass is potentially available for bioenergy and biobased products.

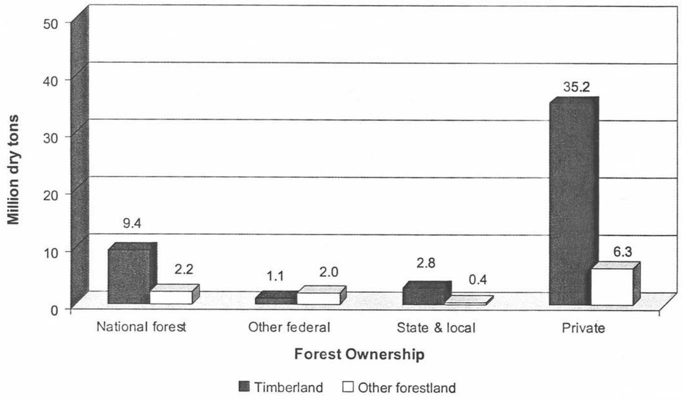
Figure 11: Total treatable biomass resource on timberlands and other forestlands

There is a concern about removal of large quantities of biomass from stands because of reduced long-term site productivity and loss of diversity and habitat associated with down-wood debris. Although the consequences are very site-specific, most negative impacts can be eliminated or minimized by leaving leaves, needles, and a portion of the woody biomass on site (Burger 2002).

The 8.4 billion dry tons of treatable biomass that is potentially available for bioenergy and biobased products was reduced by the following factors (Table A.6, Appendix A):

- To allay any concerns about site impacts, recovered material using an integrated system is limited to 85 percent.
- Only 60 percent of the identified treatable areas are assumed to be accessible.
- Fuel treatment material is recovered on a 30-year cycle before any sites are re-entered.
- Harvested fuel treatment biomass is allocated into two utilization groups: (1) merchantable trees suitable for conventional or higher-value forest products as well as rotten trees, brush and understory, small saplings, and polewood trees; (2) the residues (e.g., tops, limbs, and branches) from the harvested larger trees suitable for bioenergy and biobased product uses. The conventional forest products fraction assumed is 70 percent, and the residue or bioenergy and biobased product fraction is 30 percent (USDA-FS, 2003).

The combination of these factors significantly reduces the amount of fuel treatment biomass that can be sustainably removed on an annual basis. About 49 million dry tons can potentially be removed annually from timberlands, and about 11 million dry tons can be removed annually from other forestlands (Figure 12; Table A.7, Appendix A). Most of the fuel treatment biomass from timberlands would come from privately owned lands; slightly less than 20 percent of the material would come from national forests. In contrast, proportionately more of the fuel treatment biomass allocated to bioenergy and biobased products on other forestland land would come from publicly held lands. Most of



- About 60 million dry tons can be removed from timberlands and other forestlands for fuel treatments.

Figure 12: Fuel treatments on timberland and other forestland

these lands are located in the western regions of the country. The 60 million dry tons of fuel treatment biomass assumes that a relatively large percentage (70 percent) goes to higher-valued products. If feedstock prices for biomass were to increase relative to conventional forest products, the amount of biomass available for bioenergy and biobased products could increase substantially.

3.3.3 Forest Products Industry Processing Residues

3.3.3.1 Primary Wood Processing Mills

The Forest Service classifies primary mill residues into three categories — bark, coarse residues (chunks and slabs), and fine residues (shavings and sawdust). In each of these categories, residues are further segmented into hardwoods and softwoods. Data on residue quantities are reported at any user-specified spatial scale, ranging from data of individual counties to state and national totals. Primary mill residues are desirable for energy and other purposes because they tend to be clean, uniform, and concentrated and have a low moisture content (< 20 percent). These desirable physical properties, however, mean that nearly all of these materials are currently used as inputs in the manufacture of products or as boiler fuel. Very little of this resource is currently unused. According to Forest Service estimates, about 80 percent of bark is used as fuel and about 18 percent is used in low-value products such as mulch (USDA-FS, 2004a). For coarse residues, about 85 percent is used in the manufacture of fiber products and about 13 percent is used for fuel. About 55 percent of the fine residues are used as fuel and 42 percent used in products.

Primary timber processing mills (facilities that convert roundwood into products such as lumber, plywood, and wood pulp) produced 91 million dry tons of residues in the form of bark, sawmill slabs and edgings, sawdust, and peeler log cores in 2002 (USDA-FS, 2004a). Nearly all of this material is recovered or burned, leaving slightly less than 2 million dry tons available for other bioenergy and biobased product uses (Table A.8, Appendix A).

3.3.3.2 Secondary Wood Processing Mills

Residues are also generated at secondary processing facilities — mills utilizing primary mill products. Examples of secondary wood processing mill products include millwork, containers and pallets, buildings and mobile homes, furniture, flooring, and paper and paper products. Since these industries use an already processed product, they generate smaller quantities of residues. In total, the secondary mill residue resource is considerably smaller than the primary mill resource (Rooney, 1998; McKeever, 1998). The types of residues generated at secondary mills include sawdust and sander dust, wood chips and shavings, board and cut-offs, and miscellaneous scrap wood.

At the larger secondary mills, most of the residue produced is used on site to meet energy needs (such as heat for drying operations) or is recycled into other products. This is in contrast to practices at the smaller mills where much of the residue material goes unused (Bugelin and Young, 2002). The recovery of residue at smaller mills is more constrained because it may be generated seasonally and may be more dispersed.

Neither the Forest Service nor any other federal agency systematically collects data on secondary mill residue. One of the few estimates of the amount of secondary mill residue available is provided by Fehrs (1999). He estimates that 15.6 million dry tons is generated annually, with about 40 percent of this potentially available and recoverable. The remaining fraction is used to make higher-valued products and is not available (Table A.8, Appendix A).

3.3.3.3 Pulp and Paper Mills

In the manufacture of paper products, wood is converted into fiber using a variety of chemical and mechanical pulping process technologies. Kraft (or sulfate) pulping is the most common processing technology, accounting for over 80 percent of all U.S.-produced pulp. In Kraft pulping, about half the wood is converted into fiber. The other half becomes black liquor, a by-product containing unutilized wood fiber and valuable chemicals.

Pulp and paper facilities combust black liquor in recovery boilers to produce energy (i.e., steam), and, more importantly, to recover the valuable chemicals present in the liquor. The amount of black liquor generated in the pulp and paper industry is the equivalent of 52 million dry tons of biomass (Table A.8, Appendix A). Because the amount of black liquor generated is insufficient to meet all mill needs, recovery boilers are usually supplemented with fossil and wood residue–fired boilers. The pulp and paper industry utilizes enough black liquor, bark, and other wood residues to meet nearly 60 percent of its energy requirements. Currently, the forest products industry along with DOE are looking at black liquor gasification to convert pulping liquors and other biomass into gases that can be combusted much more efficiently.

3.3.4 Urban Wood Residues

There are two principal sources of urban wood residues: MSW and construction and demolition debris. MSW consists of a variety of items ranging from organic food scraps to discarded furniture and appliances. In 2001, nearly 230 million tons of MSW was generated (EPA, 2003). Wood and yard and tree trimmings are the two sources within this residue stream that are potentially recoverable for bioenergy and biobased product applications. The wood component includes discarded furniture, pallets, containers, packaging materials, lumber scraps (other than new construction and demolition), and wood residuals from manufacturing. McKeever (2004) estimates the total wood component of the MSW stream at slightly more than 13 million dry tons (Table A.9, Appendix A). About 55 percent of this material is either recycled as compost, burned for power production, or unavailable for recovery because of excessive contamination. In total, about 6 million dry tons of MSW wood is potentially available for recovery for bioenergy and biobased products. The other component of the MSW stream — yard and tree trimmings — is estimated at 9.8 million dry tons. However, only 1.7 million dry tons is considered potentially available for recovery after accounting for what is currently used and what is unusable.

The other principal source of urban wood residue is construction and demolition debris. These materials are considered separately from MSW since they come from much different sources. These debris materials are correlated with economic activity (e.g., housing starts), population, demolition activity, and the extent of recycling and reuse programs. McKeever (2004) estimates annual generation of construction and demolition debris at 11.6 and 27.7 million dry tons, respectively. About 8.6 million dry tons of construction debris and 11.7 million dry tons of demolition debris are considered potentially available for bioenergy and biobased products (Table A.9, Appendix A). Unlike construction debris, which tends to be relatively clean and can be more easily source-separated, demolition debris is often contaminated, making recovery much more difficult and expensive.

Additional Potential from Commercial Forest Thinnings in the U.S. South

This analysis does not include wood that is currently merchantable at the lower size and quality specifications for conventional products, such as pulpwood and small sawlogs. Depending on local market conditions, i.e., low-price wood and/or high-price oil markets, this resource could move between these markets and be an additional potential resource for bioenergy and biobased products. As an example, the southern U.S. has vast acreages of forests that are being commercially thinned to improve stand quality. Most of the wood goes to pulpwood, while some is used to make lumber and composite boards. It is projected that approximately 8 million dry tons could be available annually from such thinnings in the South.

Forest Stand Type	Million Dry Tons
Planted pine	6.7
Natural pine	1.1
Oak-Pine	<0.01
Lowland Hardwood	0.1
Upland Hardwood	<0.001
Total	**7.9**

Notes:
Volumes are merchantable bole wood to a 4-inch top, inside bark. Residues from thinning, including tops and small-diameter trees are already accounted for in other sections of this report. For pine, it was assumed that 50% of the output would be pulpwood and that this material could possibly be used for energy (Clark and Shiver 2005). For the hardwood, 70% of the volumes were assumed to be the potentially available for bioenergy and biobased products.

Source: Mills (2005)

All these sources of urban wood residue total 28 million dry tons. As noted by McKeever (1998), many factors affect the availability of urban wood residues, such as size and condition of the material, extent of commingling with other materials, contamination, location and concentration, and, of course, costs associated with acquisition, transport, and processing.

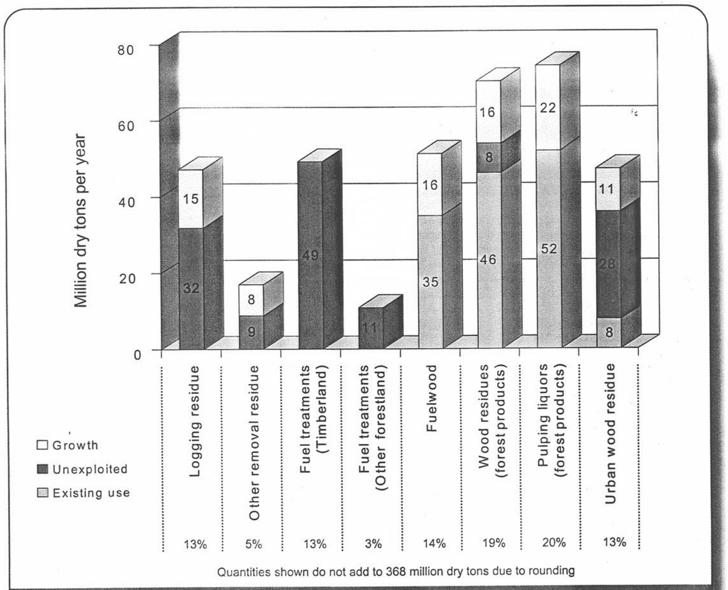
3.3.5 Forest Growth and Increase in the Demand for Forest Products

The Fifth Resources Planning Act Timber Assessment projects the continued expansion of the standing forest inventory despite the estimated conversion of about 23 million acres of timberland into more developed uses (Haynes, 2003). The size of the standing forest inventory will increase because annual forest growth will continue to exceed annual harvests and other removals from the inventory. The forest products industry will continue to become more efficient in the way it harvests and processes wood products. The demand for forest products are also projected to increase. However, the increase will be less than historical growth owing to a general declining trend in the use of paper and paperboard products relative to GNP and the relatively stable forecast of housing starts (Haynes, 2003). The increase in the consumption of forest products will be met by an increase in timber harvests; an increase in log, chip, and product imports; and an increase in the use of recovered paper. Further, consumers will become more efficient in the use of wood products by generating fewer wood residues and increasing recycling rates.

These changes and trends will affect the availability of forest residues for bioenergy and biobased products. An overall increase in the amount of biomass available due to changes in the demand and supply of forest products will increase the availability and use of forest residues by about 89 million dry tons annually by mid-21st century. Specifically, the availability of logging and other removal residues could increase by about 23 million dry tons over the current annual resource estimate of 41 million dry tons. Fuelwood harvested for space- and process-heat applications could increase by another 16 million dry tons over current levels. Wood residues and pulping liquors generated by the forest products industry could increase by about 16 and 22 million dry tons, respectively. And, the amount of urban wood waste generated could increase by 11 million dry tons over currently available amounts.

3.4 Forest Resources Summary

Biomass derived from forestlands currently contributes about 142 million dry tons to the total annual consumption in the United Sates of 190 million dry tons. Based on the assumptions and conditions outlined in this analysis, the amount of forestland-derived biomass that can be sustainably produced is approximately 368 million dry tons annually – more than 2.5 times the current consumption. The distribution of this resource potential is summarized in Figure 13. This estimate includes the current annual consumption of 35 million dry tons of fuelwood extracted from forestland for residential, commercial and electric utility purposes, 96 million dry tons of residues generated and used by the forest products industry, and 11 million dry tons of urban wood residue. As discussed previously, there are relatively large amounts of forest residue produced by logging and land clearing operations that goes uncollected (41 million dry tons per year) and significant quantities of forest residues that can be collected from fuel treatments to reduce fire hazards (60 million dry tons per year). Additionally, there are some unutilized residues from wood processing mills and unutilized urban wood. These sources total about 36 million dry tons annually. About 48 percent of these resources are derived directly from forestlands (primary resources). About 39 percent are secondary sources of biomass from the forest products industry. The remaining fraction would come from tertiary or collectively from a variety of urban sources.



Quantities shown do not add to 368 million dry tons due to rounding

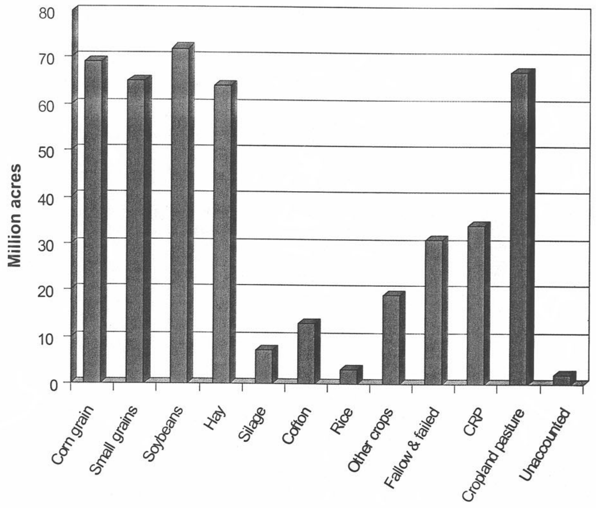
Figure 13: Summary of potentially available forest resources

4. Agriculture-Derived Biomass Resources

4.1 Agricultural Land Resource Base

Agriculture is the third largest single use of land in the United States. In 1997, the year of the most recent complete land inventory, agricultural land totaled some 455 million acres — 349 million acres of land in active use to grow crops, 39 million acres of idle cropland (including land enrolled in the Conservation Reserve Program or CRP), and 67 million acres of cropland used as pasture (Figure 14) (USDA-NRCS, 2003a). The amount of agricultural land actively used to grow crops has varied from 330 to 380 million acres over the last 30 years. Cropland tends to move in and out of active production because of soil and weather conditions at planting time, expected crop prices, and the presence of government programs. Some cropland is also permanently converted to other nonagricultural uses. Between 1997 and 2001, seven million acres of active cropland were lost to other uses (USDA-NRCS 2003a).

The agricultural land base considered for this resource analysis includes 342 million acres of active cropland, 39 million acres of idle cropland, and 67 million acres of cropland used as pasture (448 million acres total). All cropland acres are assumed to be potential contributors to agriculturally derived biomass feedstocks. Permanent pasture land might be another potential resource, but it is not considered in this analysis.



Source: Vesterby and Krupa, 2001

- Corn grain, small grains (primarily wheat), and soybeans account for 60% of cropland use.

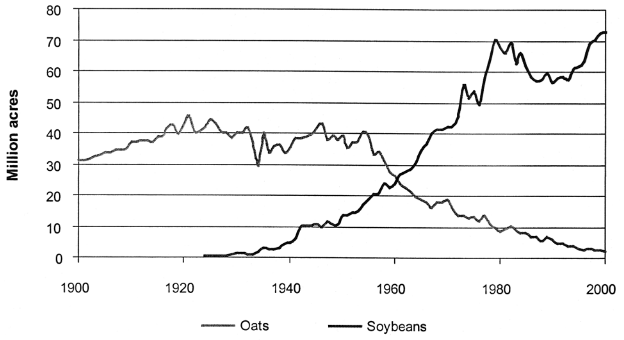
Figure 14: Summary of cropland uses, idle cropland, and cropland pasture in the contiguous United States

4.2 Agricultural Resources

Grains and oilseeds are the primary feedstocks used to produce most of the ethanol, biodiesel, and bioproducts consumed today. Food and feed processing residues and tertiary post-consumer residues are also used to generate a modest amount of electricity. These agriculture-derived biomass resources account for nearly 25 percent of the current biomass consumption. This amount of biomass, however, is small relative to currently available agricultural biomass resources and tiny relative to agriculture's full potential. With appropriate economic incentives, and improved cropping practices and technologies, such as higher-yielding plants and more efficient harvest equipment, significant amounts of agricultural crop residues, and food and feed processing residues could be sustainably produced. Moreover, the amount of sustainable biomass derived from agricultural land could be increased further by dedicating some land to the production of perennial grass and woody crops.

U.S. agriculture has changed considerably since the early part of the 20th century (USDA-NASS, 2003a). The key technological drivers of this change were mechanization and dramatically increased yields of major grain and fiber crops. Mechanization dramatically reduced the need for horses for "horsepower," and consequently oat production (for animal food) greatly declined. In the same time frame, soybean production increased but for different reasons (Figure 15). Increased crop yields were a direct result of research such as corn and wheat hybridization, and governmental price support policies. Agriculture also became more productive in the use of inputs to grow crops (Figure 16). A substantial increase in livestock production, especially cattle and poultry, also occurred.

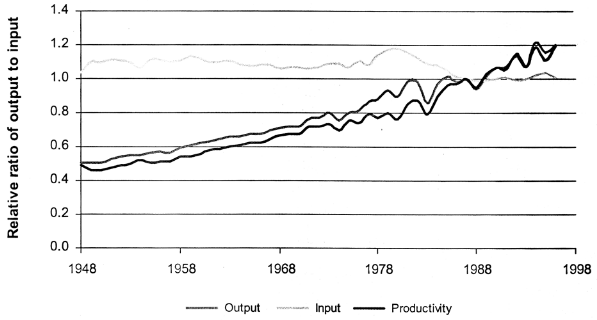
Driven by a need to reduce erosion, maintain soil structure and nutrients, and build soil carbon levels, agriculture adopted sounder environmental and conservation practices. For example, no-till cultivation, the most environmentally friendly production system, is now practiced on more than 62 million acres, and another 50 million acres are part of another conservation tillage system (CTIC, 2004). Crop rotation is also much more common. In the mid-1990s for instance, the practice of rotating corn with soybeans increased from nearly half to about two-thirds of the planted corn acreage.



- Major changes in crop use allocations have occurred over the past 60 years.

Source: USDA-NASS, 2003a

Figure 15: Harvested acres of oats and soybeans, 1900-2000



- Agricultural productivity - a measure of output to input - has increased steadily over the last half century.

Source: USDA-NASS, 2003a

Figure 16: Agricultural productivity, 1948-1996

Agriculture is expected to continue to change and adapt to new technologies and circumstances. Biotechnology, for example, is transforming agriculture by making available genetically altered varieties of corn and soybeans. Biotech hybrids of corn now account for 40 percent of the total planted acreage (National Corn Growers Association, 2004).

The future could also see agriculture becoming a more important supplier of bioenergy and biobased products to the U.S. economy. The production of ethanol from corn and other grains is projected to continue to grow (USDA-OCE, 2004, 2005). Biodiesel production has also grown significantly and could increase substantially in the future under an EPA mandate to reduce sulfur in diesel fuel (Stroup, 2004). The demand for new biobased products is also expanding. For example, innovative carbon-based technologies, such as the development of carbon-annotate fibers, could provide new markets for biomass.

4.3 Evaluating the Biomass Potential of Agriculture

To assess the potential biomass contribution from agriculture, a number of scenarios were evaluated. These scenarios include various combinations of changes in the following:

- yields of crops grown on active cropland,
- crop residue-to-grain or -seed ratios,
- annual crop residue collection technology and equipment,
- crop tillage practices,
- land use change to accommodate perennial crops (i.e., grasses and woody crops),
- biofuels (i.e., ethanol and biodiesel), and
- secondary processing and other residues.

Crop yields are of particular importance because they affect the amount of residue generated and the amount of land needed to meet food, feed, and fiber demands.

The following three scenarios are summarized in this report:

Scenario 1: current availability of biomass feedstocks from agricultural land;

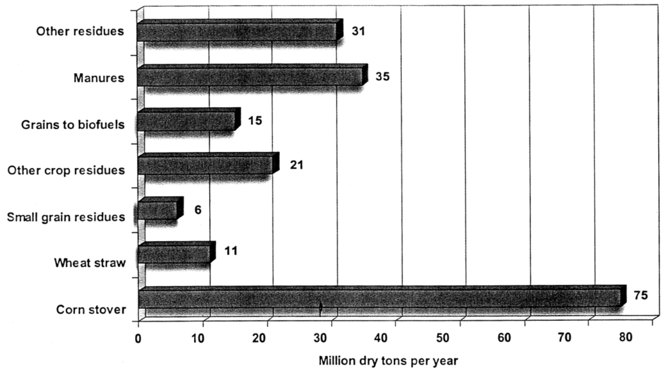
Scenario 2: biomass availability through a combination of technology changes focused on conventional crops only; and

Scenario 3: biomass availability through technology changes in both conventional crops and new perennial crops together with significant land use change.

The types of crop technology changes assumed include yield increases, more efficient harvest technology, changes in tillage practice, and, for scenario three only, changes in residue to grain ratios. The agricultural biomass resources considered for each of these scenarios include residues from major crops, grains and oilseeds used for ethanol and biodiesel production, and residues and waste resources. Switchgrass and hybrid poplars are assumed for perennial crops, but any fast growing grasses or trees could be used. For the three major crops (corn, wheat, and soybeans), a comparison among the USDA baseline and Scenarios 2 and 3 is summarized in Table B.1, Appendix B.

4.3.1 Scenario 1: Current Sustainable Availability of Biomass from Agricultural Lands

Current availability is the baseline that summarizes sustainable biomass resources under current crop yields, tillage practices (20-40 percent no-till for major crops), residue collection technology (~40 percent recovery potential), grain to ethanol and biodiesel production, and use of secondary and tertiary residues. In sum, the amount of biomass currently available for bioenergy and bioproducts is about 194 million dry tons annually (Table B.2, Appendix B). This is about 16 percent of the 1.2 billion dry tons of plant material produced on agricultural land. It includes 113 million dry tons of crop residues, 15 million dry tons of grain (starch) used for ethanol production, 6 million dry tons of corn fiber, and 60 million dry tons of animal manures and residues (e.g., MSW and animal fats). The single largest source of this current potential is corn residues or corn stover (Figure 17; Table B.2, Appendix B), totaling close to 75 million dry tons.

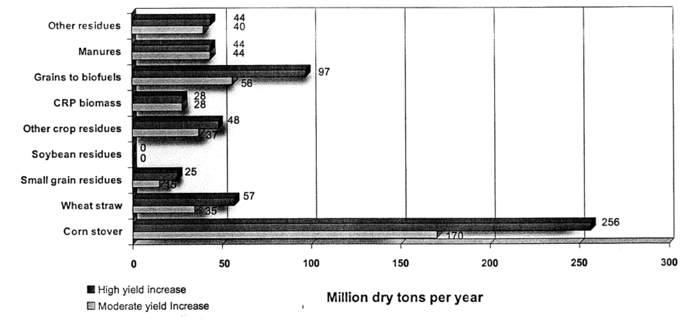


- The total current availability of biomass from cropland is approximately 194 million dry tons/year.
- Slightly more than one-fifth of this biomass is currently used.
- Corn stover is a major untapped source of agriculture-derived biomass.
- Small grain residues include sorghum, barley, oats, and rice. Other crop residues include cotton, other oil seeds (e.g., sunflower, peanuts, canola), tobacco, sugar crops, potatoes, beans, miscellaneous root crops, and double crops. Other residues include secondary agricultural processing residues, MSW, and fats and greases.

Figure 17: Current availability of biomass from agricultural lands

4.3.2 Scenario 2: Technology Change with Conventional Crops Only (No Land Use Change)

Scenario 2 assumes an increase in crop yields for corn by 25-50 percent. Yields of wheat and other small grains, sorghum, soybeans, rice, and cotton are assumed to increase at rates lower than for corn. The rates of increase of all crops are the same as those used by USDA-OCE (2004, 2005) in their Baseline Projections (The USDA baseline for three major crops is summarized in Table B.1, Appendix B.). Acres for each crop are fixed at levels predicted for 2014 by USDA-OCE (2005). Soybeans contribute no crop residue under a moderate yield increase (~ 13 percent) but make a small contribution with a high yield increase (~23 percent). Collection equipment is assumed to be capable of recovering as much as 60 percent of residue under the moderate yield increases and 75 percent under the high yield increases but the actual removal amounts depend on the sustainability requirements. No-till cultivation is assumed to be practiced on approximately 200 million acres under moderate yield increases and all of active cropland under high yields. The amount of corn and soybeans available for ethanol, biodiesel or other bioproducts was calculated by first subtracting amounts needed to meet food requirements plus feed and export requirements. All remaining grain was assumed to be available for biofuels. This worked out to a more than three-fold increase over 2001 levels under the moderate yield increase and more than a five-fold increase under the high yield increase. Soy oil used for biodiesel increases dramatically from the 2001 level under both moderate and high yield increases. Further, about 75 million dry tons of manure and other secondary and tertiary residues and wastes, and 50 percent of the biomass produced on CRP lands (17 to 28 million dry tons) are assumed to be available for bioenergy production. Attaining these levels of crop yield increase and collection will require a continuation of research, deployment of new technologies, and incentives. Past trends indicate that such increases are certainly doable. This intensive scenario for use of crop residue results in the annual production of 423 million dry tons per year under moderate yields and 597 million dry tons under high yields (Figure 18; Tables B.3 and B.4, Appendix B). In this scenario, about two-thirds to three-fourths of total biomass are from crop residues.

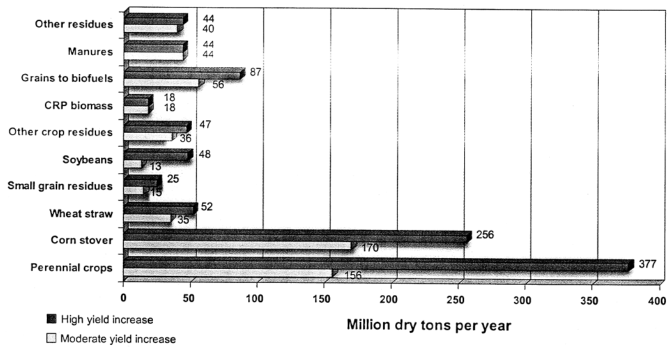


- Total availability of biomass from cropland ranges from 423 to 597 million dry tons per year at crop yield increases of 25% (moderate) and 50% (high) for corn and various rates of increase for other crops. Moderate and high changes in tillage practices and residue collection technology and equipment are also assumed. (Quantities shown do not add to 423 and 597 million dry tons due to rounding.)
- No changes in the current allocation of cropland are required to attain these levels of biomass.
- Small grain residues include sorghum, barley, oats, and rice. Other crop residues include cotton, other oil seeds (e.g., sunflower, peanuts, canola), tobacco, sugar crops, potatoes, beans, miscellaneous root crops, and double crops. Other residues include secondary agricultural processing residues, MSW, and fats and greases.

Figure 18: Availability of biomass under increased crop yields and technology changes

4.3.3 Scenario 3: Technology Change with Perennial Crops And Land Use Change

Scenario 3 assumes the addition of perennial crops to the landscape, land use changes and changes in soybean varieties, as well as the technology changes assumed under the previous scenario. Soybean varieties are assumed to transition from an average residue-to-grain ratio of 1.5 to a ratio of 2.0 as current varieties are partially replaced with varieties that produce 50 to 100 percent more residue but maintain similar grain yields. The land use changes include the conversion of either 40 or 60 million acres to perennial crop production associated with moderate and high yield increases, respectively. Woody crops produced for fiber are expanded from 0.1 million acres to 5 million acres, where they can produce an average annual yield of 8 dry tons per acre. Twenty-five percent of the wood fiber crops are assumed to be used for bioenergy and the remainder for other, higher-value conventional forest products. Perennial crops (trees or grasses) grown primarily for bioenergy expand to either 35 million acres at 5 dry tons per acre per year or to 55 million acres with average yields of 8 dry tons per acre per year. Ninety-three percent of the perennial crops are assumed available for bioenergy and the remainder for other products. A small fraction of the available biomass (10 percent) is assumed lost during the harvesting operations. This scenario results in the production of 581 to 998 million dry tons (Figure 19; Tables B.5 and B.6, Appendix B). Crop residues increase even though conventional cropland is less because of the addition of more soybean residue together with increased yields. The single largest source of biomass is the crop residue, accounting for nearly 50 percent of the total produced. Perennial crops account for about 30 to 40 percent depending on the crop yield increase (i.e., moderate or high).

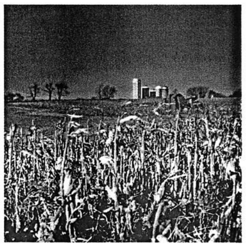


- Total availability of biomass from cropland, idle cropland, and cropland pasture ranges from 581 to 998 million dry tons per year at crop yield increases of 25% (moderate) and 50% (high) for corn and various rates for other crops. Changes in tillage practices, residue to grain and seed ratios, and residue collection technology and equipment are also assumed. (Quantities shown do not add to 581 million dry tons due to rounding.)
- The allocation of some active cropland, idle cropland, and cropland pasture to perennial crops is required to attain this level of annual biomass production.
- Small grain residues include sorghum, barley, oats, and rice. Other crop residues include cotton, other oil seeds (e.g., sunflower, peanuts, canola), tobacco, sugar crops, potatoes, beans, miscellaneous root crops, and double crops. Other residues include secondary agricultural processing residues, MSW, and fats and greases.

Figure 19: Availability of biomass under increased crop yields, technology changes, and inclusion of perennial crops

4.4 Factors Increasing Biomass Resources from Agriculture

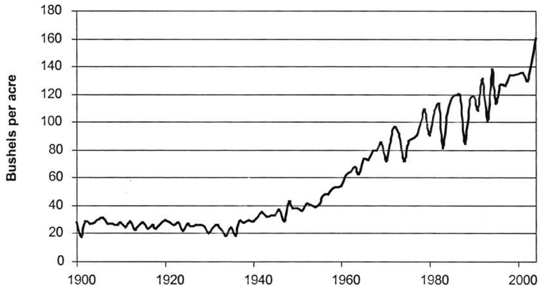
4.4.1 Crop Yields



Corn grain yields have risen dramatically and steadily over the past 35 years (1965-2000) at an average annual change of 1.7 bushels per acre even while fertilizer inputs have declined (Figure 20) (Dobermann et al., 2002). Continuing increases at the level currently used by USDA for projections (1.8 bushels per acre) will result in a 25 percent yield increase (173 bushels per acre) by 2020 and a 50 percent yield increase (207 bushels per acre) by 2043. This translates to an actual crop yield rate of increase that is less than the current rate of nearly 1.2 percent per year to about 0.9 percent per year by 2030 – a prediction made by FAO (2003). Crop yields and acreage for 2001 were obtained from published agricultural statistics (USDA-NASSa; USDA-NRCS, 2003a). Acreage for conventional crops in the future scenarios are based on the acres projected to be in production in 2014 by USDA-OCE (2005).

The high yield expectation of 207 bushels per acre is very reasonable (even conservative) given that this yield level remains well below the projected average corn yield potential of about 300 bushels per acre in both irrigated and rainfed corn belt areas, where soil moisture is generally not a limiting factor. This is based on corn yield simulation models developed at the University of Nebraska (Arkebauer et al., 2004). In recent years, record corn yields have been virtually the same between irrigated and rainfed acreage (Doberman et al. 2003). The adoption of new varieties with many genetic improvements, including the Bt genetic modification and increases in corn planting density, have been crucial in achieving these results.

Recent corn selection techniques have optimized genotype/environment interactions leading to increased yield stability and stress tolerance (e.g., tolerance to higher planting densities) (Tollenaar and Lee, 2002). Research results



- Corn grain yields have increased steadily throughout the latter half of the 20th century.

Source: USDA-NASS, 2003a

Figure 20: Average corn yields, 1900-1999

and recommendations by Pioneer Hi-Bred Ltd. suggest that increasing the density of corn plantings is a trend that will continue since it can increase profit in many situations (Paszkiewicz and Butzen, 2003).

Increasing wheat grain yields by 25 to 50 percent is considered doable but probably not in the same time frame as corn. The most recent estimates from the Wheat Improvement Center in Mexico City (CIMMYT, 2002) show annual yield increasing by 1.7 percent per year in the United States for 1988-2000, higher than the average yield increase rate of 1.3 percent observed in the 1977-988 period. However, a concern is that most genetic research on wheat in the United States currently focuses on developing dwarf varieties (which would reduce residue-to-grain ratios), and increasing disease resistance rather than yields. Only a small amount of research is focused on improving tall wheat varieties. The rate of yield increase assumed by USDA for the next 10 years is about 1.3 percent per year, resulting in a 20 percent increase in wheat grain yields by 2020.

The big unknown factor for wheat and other small grains is the effect of biotechnology. A technology being aggressively pursued that could affect wheat is asexual reproduction (Pollack, 2000). Asexual reproduction would allow seeds to be exact genetic copies, or clones, of the parent. If commercially successful, this technique would accelerate breeding, allow genetic adaptation of plants to specific micro-climates, and allow the ability to create and stabilize new genetic combinations. Major biotechnology and seed companies as well as the USDA, universities, and small private groups were all actively pursuing research in the late 1990s (GRAIN, 2001). However, according to Doanes Agricultural Report (February 25, 2005), many research groups are hesitating to pursue biotechnology advancements in wheat due to declining profit margins, for example, Monsanto Company has shelved its plans to offer herbicide resistant wheat. The same Doanes report indicated that the National Association of Wheat Growers is supportive of the use of biotechnology advancements to stay competitive. Wheat Associates is initiating a plan to begin promoting the safety and benefits of biotech wheat.

Among the plant growth factors that pose barriers to yield increase, soil moisture is the most limiting factor. Thus, continued selection for stress tolerance, including tolerance to moisture deficits, will be critically important to achieving a crop's potential yield. While climate change could modify yield potential, a review of climate change impacts on agriculture suggests that the net effects of a doubling of carbon dioxide levels on agriculture may be small if the agricultural community is adaptive (Adams et al. 1999).

4.4.2 Residue-to-Grain or -Seed Ratios

The ratio of crop residues to grain is a key variable that has a significant effect on estimates of the availability of biomass. Since grain yields are reported annually, but "biomass" yields are not, an estimate of the relationship between the two is necessary for estimating biomass yields. A wide variation in residue-to-grain ratios exists in the literature. For this analysis, the baseline ratio of crop residues to grain is derived from the Soil Conditioning Index (SCI) of the USDA National Resource Conservation Service Soil (USDA-NRCS, 2003b). If different ratios are given for the same crop, the one associated with conditions that represented the largest crop acreage was used.

Clearly, the ratio of residue to grain (or its inverse, the harvest index) does vary within crops from year to year and according to the time of harvest, variety, and density of planting. Prihar and Stewart (1990) indicate that harvest index increases with increasing total yields and decreasing crop stresses. This tendency was also shown in experiments in Minnesota reported by Linden et al. (2000). However, these results contrast with those published by Doberman et al. (2003), where harvest index was found to decrease slightly under the highest yield conditions in Nebraska experiment trials. The salient difference is that the highest yield conditions in Nebraska were associated with higher-density plantings. Tollenar and Lee (2002) report that the corn harvest index has not shown a clear trend in the past seven decades except where plants are grown at higher densities, in which case it decreases. The lowest harvest index measured in the Nebraska experiments, even at the highest density, was 0.49 (Yang et al., 2004). In this analysis, it is assumed that corn stover-to-grain ratios remain at 1:1 on a dry weight basis under all scenarios. It was necessary to adjust the weights published for crops in agricultural statistics (USDA-NASS, 2003b) to a dry weight based on assumed moisture content at harvest (Gupta, 1979). Information on moisture contents were found in Hellevang (1995).

A change in the residue-to-grain ratio is a possible technology change that could occur for any crop. In this assessment, however, a ratio change was assumed only for soybeans which presently do not contribute to the removable residue estimates. Most, if not all, soybean residue needs to be left on the ground to meet conservation practice requirements. USDA genetic improvement research in soybeans at Beltsville, Maryland has focused on developing varieties that have a higher ratio of straw to beans, grow taller, have improved lodging resistance, have a better over-winter residue persistence, and are able to attain these traits without genetic transformation (Figures 21 and 22). Originally the soybean program was geared to develop larger biomass soybeans for forage production and resulted in three varieties (Devine and Hatley, 1998a, 1998b, 1998c). A recently released variety for the southeast, Tara (Devine and McMurtrey, 2004), has the characteristics of a 1.75 residue-to-grain ratio without sacrificing expected levels of grain yield. It is evident from data on the forage soybean varieties that the potential exists to produce 100 percent more crop residue and thus provide more soil conservation benefits than the conventional varieties (Wu et al., 2004). It cannot be predicted whether farmers will adopt these new varieties, but clearly the technology will be available. Potentially, with such varieties soybean acreage could contribute to the availability of residues for bioenergy and biobased products.

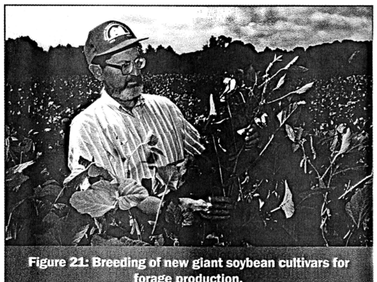


Figure 21: Breeding of new giant soybean cultivars for forage production.
(Photo by Scott Bauer, USDA, Agricultural Research Service, Beltsville, Maryland)

4.4.3 Residue Collection Technology for Annual Crops

Most residue recovery operations today pick up residue left on the ground after primary crops have been harvested. Collection of residues from these crops involves multiple passes of equipment over fields and results in no more than 40 percent removal of stover or straw on average. This low recovery amount is due to a combination of collection equipment limitations, contour ridge farming, economics, and conservation requirements. It is possible under some conditions to remove as much as 60-70 percent of corn stover with currently available equipment. However, this level of residue collection is economically or environmentally viable only where land is under no-till cultivation and crop yields are very high. This analysis assumes that the harvest technology and the percentage of cropland under no-till management are increased simultaneously.

Future residue collection technology with the potential of collecting up to 75 percent of the residue is envisioned (DOE, 2003). These systems are likely to be single-pass systems that would reduce costs by collecting the grain and residue together. Single-pass systems will also address concerns about soil compaction from multiple pieces of residue collection equipment, unless the single pass system is heavier than the current grain harvesters (Wilhelm et al. 2004). Further, one-pass systems for corn and grain will need to have selective harvesting capability so that some portions of the residue stream can be reapplied to the field to meet conservation requirements.

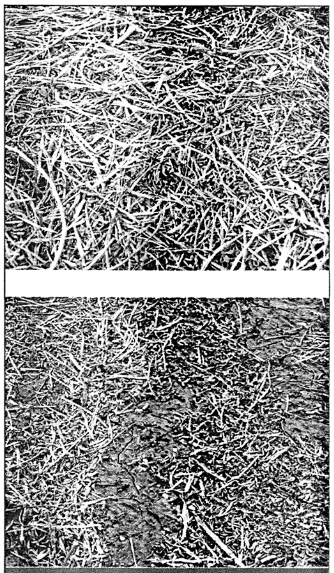


Figure 22: Soybean residues from large biomass (top) and conventional soybeans (bottom)
(Source: Wu et al., 2004)

4.4.4 Cropland Tillage

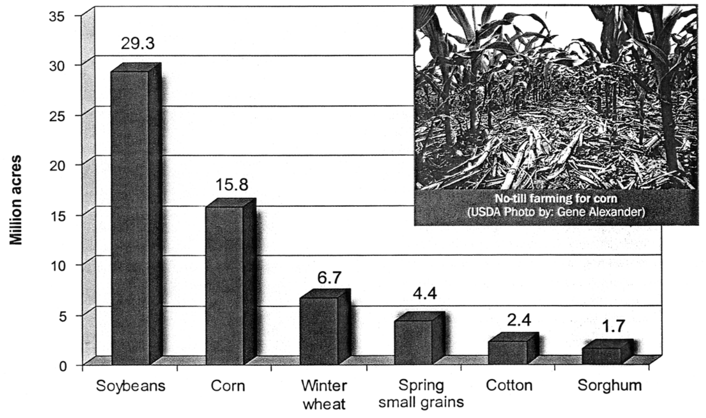
No-till planting systems are now used on more than 60 million acres in the United States, surpassing mulch till as the favored form of conservation tillage (Figure 23) (CTIC, 2004). With the concerted effort by USDA to educate farmers and conservation advisors, it is anticipated that acres designated for no-till cultivation and other types of conservation tillage will increase in the future. One example of the USDA effort is the CORE4 Conservation Training Practices Guide (USDA-NRCS, 1999).

Developing a single national estimate of the amount of residue that must remain on the ground to maintain soil sustainability for any given set of conditions is a challenge. Residue maintenance requirements (RMRs) are most properly estimated at the individual field level with models such as RUSLE (Revised Universal Soil Loss Equation), used together with the SCI (soil conditioning index) tool as described in the National Agronomy Manual (USDA-NRCS, 2002). However, using this approach to provide a national estimate would require actual data from hundreds of thousands of specific locations. Nelson (2002) developed a methodology for making a national estimate that reflected the RUSLE/SCI modeling approach in that it considered soils, rainfall, crop and rotation choices, and tillage choices in determining the amount of residue required to minimize erosion to T (tolerance) levels recommended by USDA. Nelson is a co-author on the Graham et al., (2004) analysis that produced estimates of residue maintenance requirements on land with corn as a rotation crop (using 1995 to 2000 data). Walsh (2004) also relied on Nelson's approach in developing updated estimates of corn and wheat residue. Both the unpublished Graham et al. and Walsh analysis studies were used to derive national estimates of average RMRs for corn and wheat land.

Estimating national-level RMRs under various scenarios for corn land was done by creating factors using the Graham et al., (2004) analysis. Thus, the calculation –

(Sustainably Available Residue Estimate/Total Residue) / Acres Harvested

– gave an average national RMR factor (in lbs or tons/acre) for minimizing erosion on corn land for current till and all no-till cases. The current-till RMR factor was used in the 2001 base case; the all-no-till RMR factor was used in the land



Source: Conservation Technology Information Center (www.ctic.purdue.edu)

Figure 23: Crops under no-till cultivation

change–high yield scenario; and an RMR factor halfway between was used in the land change–moderate yield scenario. This resulted in estimation of removal rates of 33 percent, 54 percent, and 68 percent respectively under current tillage mix, increased no-till and all no-till scenarios. For wheat, a similar development of RMR factors was done using results from the updated 2004 analysis by Walsh. Estimated sustainable removal rates were 14 percent, 34 percent, and 48 percent respectively. Development of the soybean RMR factors relied on first calculating an average of the residue maintenance requirements found in the SCIVER25 worksheet from the top five soybean-producing states, adjusting that value based on the soybean residue equivalency value (to corn), and finally, further adjusting the value for no-till conditions for conventional and large biomass soybean (LBS) varieties based on discussions in 2004 with Jim McMurtrey, a member of the soybean research team in Beltsville, Maryland. McMurtrey et al. (in press) found that LBS varieties provided 40-100 percent more residue cover than conventional soybeans, not only because of higher biomass but also because the decomposition of the LBS varieties is slower. Estimated sustainable removal rates were 0 percent for conventional soybeans in all scenarios and 0 percent, 7.4 percent, and 30 percent respectively for LBS varieties under current tillage mix, increased no-till, and all no-till scenarios.

The current goal of soil conservation is not just to manage for minimizing erosion but also to increase soil carbon (Puckett, 2003). Practices that enhance soil carbon include high biomass yields, cover crops, reduced or no tillage, rotational grazing, and establishment of perennial crops. All practices except grazing also have the potential of increasing sustainably removable biomass, although the requirements for maintaining or increasing soil carbon may be higher in some locations than the requirements for meeting the soil loss tolerance (T) levels. With annual crop production, the largest increases in soil organic matter will result from continuous no-till cultivation. Leaving the root structure of plants undisturbed is vital to the success of no-till cultivation in increasing soil carbon, in most cases, more so than leaving crop residues on the surface (USDA-NRCS, 1999). Research results on factors affecting soil organic matter or soil carbon are varied depending on soil types, rainfall conditions, crop types and varieties, and tillage methods; thus, work is needed by agronomists and soil scientists to develop recommendations on removal rates that consider specific site conditions (Wilhelm et al. 2004). Nevertheless, it is safe to say that some residue will nearly always need to be left to maintain soil moisture and quality (i.e., nutrients and organic matter), limit rainfall and wind erosion, and maintain or increase soil carbon levels, but the amount that can be taken off sustainably is expected to increase as crop yields and total residue produced increase.

4.4.5 Allocation of Cropland Acres to Perennial Crops

It is assumed that significant amounts of land could shift to the production of perennial crops if a large market for bioenergy and biobased products emerges. Studies by de la Torre Ugarte et al. (2003) and McLaughlin et al. (2002) indicate that this could happen today if the price for energy crops were high enough to attract the interest of farmers. These authors report that if a farmgate price of about $40 per dry ton were offered to the farmers, perennial grass crops producing an average of 4.2 dry tons per acre (a level attainable today) would be competitive with the current crops on about 42 million acres of cropland and CRP land.

The high-yield scenario for perennial crops in this assessment assumes an average crop yield of 8 dry tons per acre, an amount considered feasible by grass researchers provided there is a concomitant increase in R&D. Current average annual yields from switchgrass clones tested in small plots over multiple years at twenty-three locations in the United States range from a low of 4.2 dry tons per acre to a high of 10.2 dry tons per acre, with most locations having an average between 5.5 and 8 dry tons per acre (McLaughlin and Kszos, 2005). Yields from the best clones were generally 8 dry tons per acre or higher. The highest observed yield at any location or in any year was 15.4 dry tons per acre. The best-performing clones were often the same at a majority of the twenty-three sites spread over the Great Plains, the Midwest, and the South. None of the test plots were irrigated. Assuming an intensive genetic selection and research program on grasses, the feasibility of attaining average yield of 8 dry tons per acre over millions of acres is supported by modeling (McLaughlin and Kszos, 2005). For woody crops, annual yields have been generally 5 dry tons per acre in most locations and are currently achieving more than 8 dry tons per acre in commercial plantings in the Pacific Northwest. These test data alone suggest that future yields estimated for perennial crops are well within reason, if not conservative. Yields from small plots are not likely to be representative of average yields across the millions of acres assumed in the perennial crop scenarios. However, with the genetic variability existing in switchgrass and woody crops, the potential for continued yield increases and attainment of 8 dry tons per acre averaged over millions of acres is very high.

The technology change with land use change scenario (Scenario 3, Section 4.3.3) assumes that as many as 60 million acres of cropland, cropland pasture, and CRP are shifted to perennial crop production, including grass and woody crops. Forest Service projections of possible expansion of short-rotation woody crop technology were used as the basis for assuming that 5 million acres are shifted to woody crops (Ince, 2001). It was assumed, however, that 75 percent of the harvested wood goes to fiber and 25 percent is available for energy. On the remaining 55 million acres, it is assumed that 93 percent of the perennial crops are used for energy less losses in harvesting operations. Whether the perennial crops are primarily wood or grass may depend on whether the bioenergy emphasis is on fuels or power. Figure 24 summarizes the change in land use among the three broad categories of agricultural land (i.e., active cropland, idle cropland, and cropland pasture) among scenarios under moderate and high crop yield increases. In all cases, USDA baseline projections for food and feed demands continue to be met.

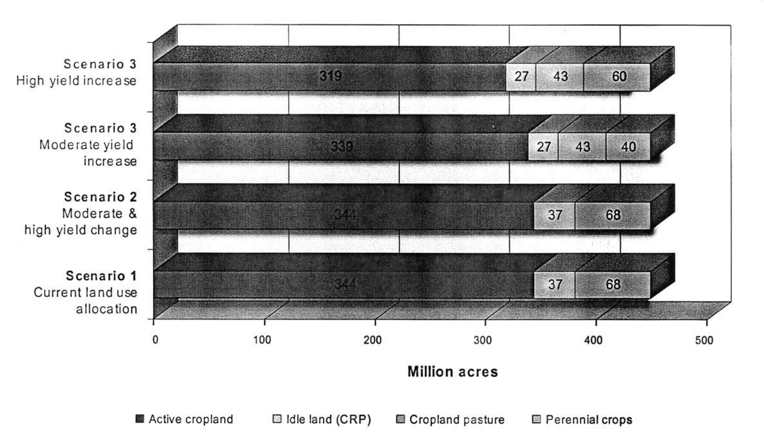
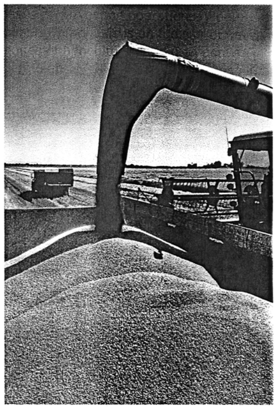


Figure 24: Summary of the allocation of agricultural land under alternative scenarios

4.4.6 Grain to Ethanol or Bioproducts and Soybeans to Biodiesel

The USDA Office of the Chief Economist projects that under business-as-usual conditions, acreage planted for the eight major crops grown in the United States will decrease by 1 million acres between 2003 and 2013 but harvested acres will increase by 9 million acres (USDA-OCE, 2004). This would suggest that fewer crop failures are expected. All crop use categories increase, with grain to ethanol showing the largest relative increase and exports also significantly increasing. To create scenarios beyond 2013, world population and crop yield trends published by the United Nations Food and Agricultural Organization were considered (UN, 2003 and FAO, 2003). Projections suggest that the North American population will increase by 37 percent between 2001 and 2050 while the world population increase will be only slightly higher. Thus, in the highest crop yield scenarios, corn required for food in the United States is assumed to increase by 37 percent over the 2001 value.



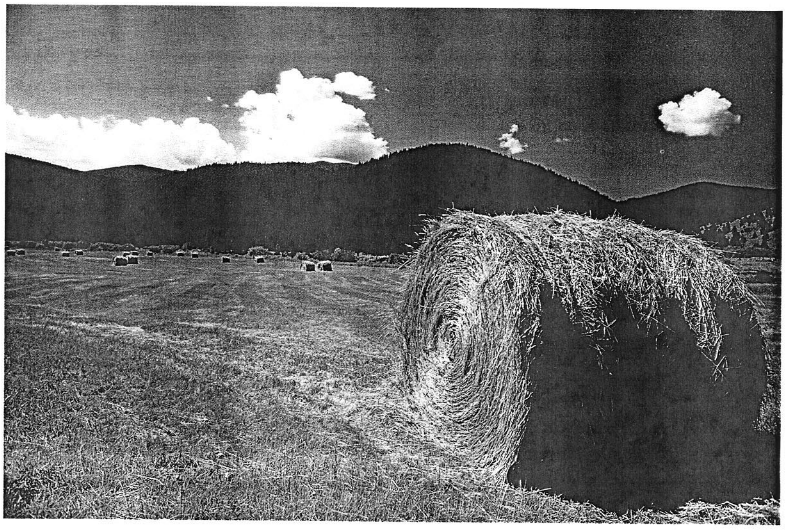
The FAO (2003) predicts that export demands from industrial countries will continue to increase through 2030 but at a slowing rate. The USDA-OCE (2005) predicts that export demand for corn through 2014 will rise, primarily because of increasing demand for animal feed. This evaluation assumes that corn exports rise by another 10 percent in the high corn yield scenarios. The USDA-OCE (2005) also predicts that exports of wheat and soybeans will remain level through 2014 because of increasing foreign competition. The scenarios assume level export demand after 2014 in wheat and soybeans.

The USDA-OCE (2005) projects that demand for corn grain for ethanol will increase from 714 million bushels in 2001 to 1750 million bushels in 2014 or from 7.5 percent to about 14 percent of total corn grain production (Table B.1, Appendix B). This evaluation assumes that food, feed, and export demands are met first and then ethanol (or other bioproducts) is produced from the remaining grain. The results show that with a 50 percent increase in corn yield and land at the 2014 level, over 3,950 million bushels of grain would be available for ethanol or bioproducts. Urbancheck (2001) projected that ethanol use could increase to 8.8 billion gallons in the future; this amount would require 2,464 million bushels. Thus, significant potential exists for meeting increased corn grain demand for both ethanol and bioproducts.

The USDA-OCE (2005) projections to 2014 show domestic use of soybeans increasing due to more demand for pork and poultry, but planted and harvest acres of soybeans are projected to decline slightly because of increasing yields. Although the USDA-OCE reports do not project soybean use for biodiesel, biodiesel production from soybeans has already more than doubled from 12.5 million gallons in 2001 to more than 25 million gallons in 2004. Expectations are that demand will continue to rise. Stroup (2004) noted that a "big looming potential for biodiesel is the use of biodiesel blends for transportation fuel" – a possibility that could result from a proposed EPA mandate to reduce sulfur in diesel fuel. This assessment assumes that all soybeans not needed for food, feed, or export could be used to make biodiesel or other industrial products. The maximum amount available is 297 million bushels under the high-yield, no perennial crop scenario which could result in 415 million gallons of pure biodiesel. Soybeans available for biodiesel are reduced to a negative value when 8 million acres of soybeans are assumed to be converted to perennial crops and food requirement demands are also increased by 37 percent similar to corn. Market conditions would determine whether reductions would actually occur in the food, feed, export, or fuel components or indeed whether the acreage reduction would occur in other land uses.

4.4.7 Secondary Processing and Other Residues

The largest potential single source of biomass from food/feed processing and post consumer wastes is animal manure. Manure can be readily collected from confined animal feeding operations (CAFOs), which continue to increase in number and size. In the recent past, CAFOs for cattle and hogs have increased slightly while those for poultry increased considerably.



Data published by USDA on manure production in CAFOs (USDA-ERS, 2001) and studies estimating the amounts of recoverable nitrogen and phosphorus (Kellog et al., 2000; Gollehon, 2002) were used to determine collectable and recoverable dry weights of manure. All future scenarios assume some increase in manure collected. One could assume that all collectable manure is available for bioenergy, however, it was assumed that only the portion in excess of the amounts that can be applied on-farm without exceeding EPA mandated criteria, is available. Estimates of that excess amount are also derived by Kellog et al. (2000) and Gollehon (2001). Of course, manure will need to be handled differently than most other biomass resources. Its use is dependent on development of appropriate technologies and would be best utilized on farm or very close to the source.

Approximately 20 percent of the corn kernel is not utilized in the production of ethanol and other starch based products, such as sweeteners and high-fructose corn syrup. It is an excellent near-term biomass resource for bioproducts. Based on NCGA information, it appears that about 90 percent of all corn grain grouped by USDA in the category of food, seed and industrial uses is being processed in a way that results in corn fiber production. The corn fiber produced as a byproduct of ethanol dry mills, DDG (dry distillers grain) is sold for animal feed. It is estimated that about half of the corn fiber produced is (or will be used) for animal feed while the remainder is (or could be) used for bioproducts. The amount of corn fiber available for bioproducts in 2001 was a little over 6 million dry tons. With corn yield increases of 25 percent, corn fiber not used for cattle feed increases to over 8 million dry tons, and with a 50 percent corn yield increase, it increases to over 12 million dry tons.

The utilization of other secondary sources of wastes from food and feed processing and tertiary wastes, such as MSW and gas, may be important at a few locations but were not large enough overall to include in a significant way in this evaluation.

4.5 Agricultural Resources Summary

The amount of biomass sustainably removable from agricultural lands is currently about 194 million dry tons annually. This amount can be increased fivefold to nearly 1 billion dry tons within 35 to 40 years through a combination of technology changes (e.g., higher crop yields and improved residue collection technology), adoption of no-till cultivation, and changes in land use to accommodate large-scale production of perennial crops. These results are graphically summarized in Figure 25. By comparison, the total amount of biomass produced on this acreage is 2.1 billion dry tons. There is a large increase both in total amount of plant matter produced due to higher crop yields and in the available biomass due to changes in tillage practices and harvest technology. Without the addition of perennial crops targeted toward biomass production, the maximum amount of sustainably removable biomass would be about 600 million dry tons under the high technology change assumptions. Approximately the same amount of biomass could be produced on agricultural lands within 15-20 years with moderate changes in future yields (e.g., 25 percent for corn), less residue recovery, and less no-till cultivation, *provided* perennial biomass crops are substituted for other land uses on at least 40 million acres of land. Most of this land could come from idle land (summer fallow and CRP) and cropland pasture. Use of about 15 million acres of active cropland is assumed.

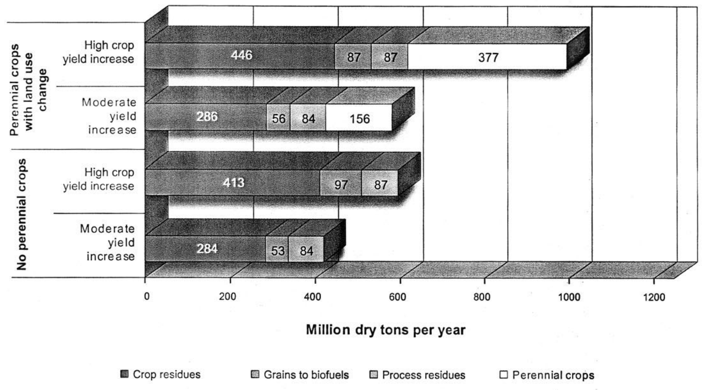
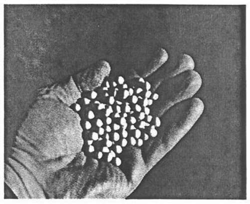


Figure 25: Summary of potentially available agricultural resources

Some factors not considered could limit the maximum amount of biomass estimated to be available. First, if demand for meat production increases (rather than remaining level), it will be more difficult to convert conventional cropland into perennial crop production. Of course, greater animal production would result in more byproducts from the animals (manures, and oils and grease from animal rendering). Second, higher export demands for wheat and soybeans could limit conversion of cropland to perennials. Third, if the total cropland base becomes less due to encroachment of urban populations, cropland conversion will also be less likely to occur. Fourth, the process used for adjusting residue availability as a function of tillage may not fully account for amounts needed to maintain or increase carbon in soils. This assessment also did not account for the use of residues by cattle for forage, which was estimated to equal about 12 million dry tons based on 1997 cattle populations (Gallagher et al., 2003). With the trend toward increasing the proportion of cattle reared in CAFOs, the demand for forage is likely to be decreasing.



In contrast, other scenario assumptions could increase the maximum amounts of biomass estimated to be available. For instance, the crop yield increases assumed are essentially business-as-usual expectations. None of the scenarios consider the possibility that technology could overcome yield limitations caused by drought and pests or increase nutrient use efficiency. Also, adoption of new cropping technologies in developing countries could further reduce export demands on the United States. Second, it is just as logical to assume that future meat demands will decline rather than increase. Populations will be aging, thus requiring less protein for sustenance. Further, trends towards healthier eating practices may cause reduced meat demand, at least in the industrialized countries.

These results are believed to be reasonable, if not conservative, estimates of future biomass potential in the United States.

5. Potential Concerns and Impacts

Forestland and cropland resources have the potential to provide for a seven-fold increase in the amount of biomass currently consumed for bioenergy and biobased products. This annual potential exceeds 1.3 billion dry tons – the equivalent of more than one-third of the current demand for transportation fuels. More than 25 percent of this potential would come from extensively managed forestlands and about 75 percent from intensively managed croplands. The major primary resources would be logging residues and fuel treatments from forestland, and crop residues and perennial crops from agricultural land. Some additional quantities of biomass would be available from secondary sources; however, most of this biomass would be expected to be used by the forest products industry and food processing industries. Tertiary or residue sources of biomass are small relative to the primary sources. A sizeable fraction of this potential would be captive to existing uses. Examples are most of the biomass resource generated by the forest products industry, fuelwood extracted from forestlands, some urban wood residues, grains used in the production of biofuels, and some agricultural residues. Excluding these captive uses of biomass from the total resource potential still shows 220 million dry tons of forestland biomass (logging residue, fuel treatments, urban wood residues) and, depending on crop yield improvements, 450 to nearly 850 million dry tons of cropland biomass (agricultural residues, perennial crops, and most process residues) as potentially available for new bioenergy and biobased product uses (Figure 26).

Producing one billion tons or more of feedstock annually will require technologies that can increase the utilization of currently available and underutilized feedstocks, such as agricultural residues and forest residues. It will require the development of perennial crops as an energy resource on a relatively large scale. It will require changes in agricultural and silvicultural crop management systems. Production yields from these systems will need to be increased and costs lowered. Changes in the way biomass feedstocks are collected or harvested, stored and transported, and pre-processed will also have to be made. Accomplishing these changes will obviously require investments and policy initiatives as well as the coordinated involvement of numerous stakeholder groups to gain broad public acceptance. Much more program coordination among the Departments of Energy and Agriculture and other federal, state, and local agencies will be necessary to attain the billion-ton feedstock goal.

The utilization of a significant amount of these biomass resources would also require a concerted R&D effort to develop technologies to overcome a host of technical, market, and cost barriers. Demonstration projects and incentives (e.g., tax credits, price supports, and subsidies) would be required. Additional analyses would be required to discern the potential impact that large-scale forest and crop residue collection and production of perennial crops could have on traditional markets for agricultural and forest products. These policy considerations are very important but were certainly well beyond the limited technical scope of this resource assessment. The remainder of this assessment focuses on utilization issues and analysis limitations.

5.1 Forest-Derived Biomass Resources

The three key forest resources identified for this assessment are residues from logging and other removals, fuel treatments, and urban wood residues. There are particular issues associated with the utilization of each of these resources.

- Accessibility, terrain (e.g., steep slopes), and environmentally sensitive areas limit fuel treatment operations. Where treatment operations are appropriate, costs associated with the removal of the excess biomass may be prohibitive. Separating and marketing larger-diameter trees for conventional (higher-valued) forest products would be necessary to help defray the costs of dealing with large numbers of small-diameter material (USDA-FS, 2003). Removing large trees, however, can create unfavorable public opinion and opposition to fuel treatment operations.

- Transportation costs, usually in the range of $0.20 to $0.60 per dry ton-mile, could severely limit haul distances, if based solely on bioenergy and biobased product values. The availability of markets within viable transport distances may limit the practicality of removing fuel treatment biomass for bioenergy and biobased products.

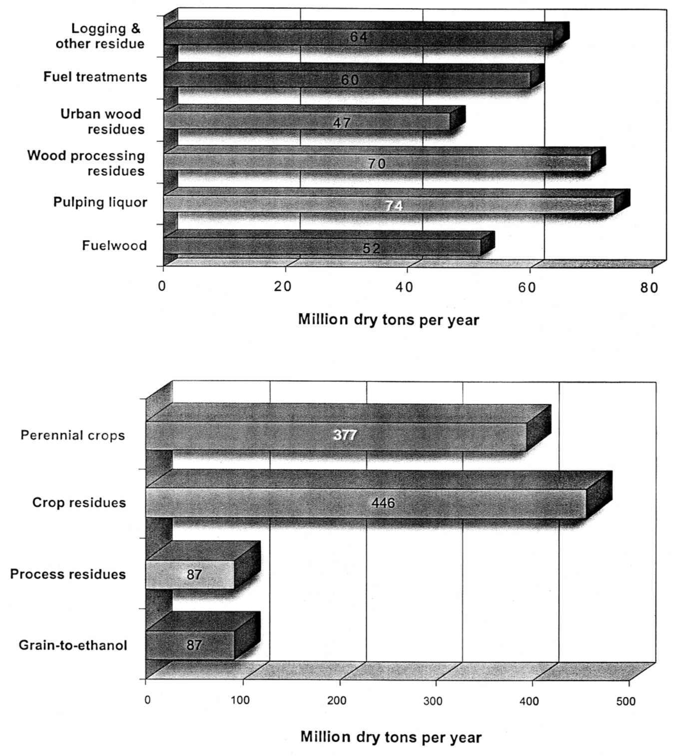


Figure 26: Summary of potential forest and agricultural resources

- Labor availability may be a key constraint in fuel treatment operations. The strategic fuel treatment assessment for the western states notes that there is a disparity between the distribution of skilled forestry workers and the forestlands requiring fuel treatments (USDA-FS, 2003). Mobilizing forestry workers and equipment across large distances can increase costs and reduce competition for contracted projects.

- Fuel treatment operations have the potential to create environmental impacts, especially if sites are severely disturbed. The impact of erosion and consequent movement of sediments into surface waters is a particular concern. However, studies suggest that there is often a much higher flow of sediments into surface waters as a consequence of wildfires than as a consequence of fuel treatment thinning operations (USDA-FS, 2003).

- More cost-effective fuel treatment operations and recovery of logging and other removal residue will require the development of more efficient and specialized equipment that can accommodate small-diameter trees. The availability of more efficient equipment will make the recovery of biomass for bioenergy and biobased products much more cost-effective.

- Federal funding for forestry programs for such activities as private tree planting, forest stand management, and technical assistance are a small fraction (<0.5 percent) of direct agricultural payments to farmers (Alig et al., 2003). Given the size of private forestland ownership, well-crafted policies aimed at providing incentives for landowners to manage their holdings could attract large quantities of biomass. Of course, any policies must be based on good science and call for meeting all sustainability requirements.

- The availability of urban wood residues is largely governed by the size of tipping fees. Where such fees are high (due in part to the lack of land for landfills), recycling is often higher. Also, high tipping fees provide economic incentives to utilize these resources.

- Some urban wood residues are highly dispersed, making economical recovery potentially costly. Seasonality of the generated residue can also affect the viability of this source.

- Contamination and commingling of urban wood residues with non-wood products, especially demolition residues and some construction residues, can limit uses. Contamination with dirt and rocks is also a potential issue with yard and tree trimmings.

Can the same amount of biomass be produced with more environmentally beneficial approaches?

The agricultural scenarios assumed are an improvement over current agricultural practices because they include higher levels of conservation tillage, more efficient use of nutrients, and the introduction of perennial crops on some land currently producing annual crops. These benefits are in addition to the benefits attained by displacing fossil fuels with biofuels. As cellulosic ethanol production and other bioenergy and bioproduct markets increase the value of biomass, making it more profitable to displace annual crops with perennial crops, further environmental benefits are possible. Replacement of some corn production with perennial trees and grasses would significantly reduce fertilizer use and improve soil carbon, for example. However, the amount of biomass produced by perennial crops will have to be more than 10 dry tons per acre in order to exceed the harvestable biomass (residue and grain) from corn producing at yields of 207 bushels per acre. Thus, it will be difficult to increase total biomass by replacing corn acres. Replacement of other annual corps with perennial crops would clearly generate more biomass.

3.2 Agriculture-Derived Biomass Resources

Annual crop residues, perennial crops, and, to a lesser extent, processing residues (e.g., animal manures) have the potential to sustainably contribute more than 900 million dry tons of biomass annually. This number is in addition to biomass that is currently used and likely to be used in the future, such as biofuel production from grains. Issues associated with these resources are as follows.

- Utilizing crop residues and growing perennial crops on a large scale would require significant changes in current crop yields, tillage practices, harvest/collection technologies, and transportation. The yield and harvest efficiency increases are plausible within reasonable time frames based on current trends and research directions. While no-till management is also increasing, some question that it would ever be adopted on all cropland due to significant transition costs in the form of initial lower yields, possible increase in disease problems, and simple resistance to change. A strong market for bioenergy, however, could be a key to changing attitudes.

- There are long-term economic and environmental concerns associated with the removal of large quantities of residues from cropland. Removing any residue on some soils could reduce soil quality, promote erosion, and lead to a loss of soil carbon which in turn lowers crop productivity and profitability. On other soils, some level of removal can be sustainable and even beneficial (Wilhelm et al, 2004). Establishment and communication of research-based guidelines is necessary to ensure that removal of residue biomass is done in a sustainable manner.

- A particular concern has been raised regarding the effect of removing the nutrients embodied in residues. At a minimum, there is a cost associated with supplying the lost nutrients through fertilizer applications. If residue removal results in larger fertilizer applications, then the environmental and economic costs associated with producing and acquiring those fertilizers (nitrogen, phosphorous and potassium as well as micro-nutrients) must be considered. Production of nitrogen from natural gas is becoming more expensive. Higher application of fertilizers could exacerbate the problem of nutrient runoff and development of the "dead zone" in the Gulf (Raloff, 2004b). Unless current levels of nutrient runoff are voluntarily reduced, farmers are likely to face increasing regulation to control the problem (Raloff, 2004a).

- One of the proposed solutions to the nutrient runoff problem has been to increase the acres of perennial crops relative to annual crops. Perennial crops require fewer applications of pesticides and fertilizers. When strategically placed, they can absorb the runoff from annual crop plantings. Other benefits of perennial crops include less erosion and less soil compaction due to less soil disturbance. Perennial crops also provide better habitat for many birds, such as migratory song birds and for several types of mammals.

- Annual crops are quite variable in yield, particularly at a local level. A key requirement to attaining targeted crop yields is the availability of sufficient water and nutrients. Genetic selection continues to move toward crops that are more stable in yield and more efficient in their use of water and nutrients. However, for specific bioenergy facilities, it will be necessary to consider excess production, storage, and ability to utilize multiple feedstocks in order to ensure adequate supplies in any given year.

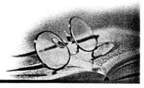
- Redirecting large quantities of animal manure to bioenergy uses can lessen nutrient runoff and reduce contamination of surface water and groundwater resources.

- The use of biomass has considerable potential to reduce emissions of greenhouse gases, especially if perennial crops are a large component of the resource mix. Depending how the biomass resources are utilized, there could also be reductions in regional and locally significant air emissions. The expanded use of forest- and agriculture-derived biomass resources could result in improvements in water quality (at least relative to wildfires and annual crops) and reduced soil erosion.

- With increased production of ethanol from corn and small grains, the amount of dry distillers grains, gluten feed and gluten meal will increase. Also, soybean meal will increase as more soybeans are crushed for biodiesel. The co-products of biofuels production can be used as a protein supplement for livestock in place of corn grain. It is also assumed in this evaluation that perennial grasses are processed to remove proteins prior to their utilization as a low-cost ethanol feedstock. With all of these protein sources, there is sufficient feed material for livestock under all scenarios.

- Finally, this evaluation of the technical feasibility of changes in agricultural systems cannot determine whether markets would respond in a way that would support the biomass potential outlined.

6. Summarized Findings



The U.S. Department of Energy and the U.S. Department of Agriculture are both strongly committed to expanding the role of biomass as an energy source. In particular, they support biomass fuels and products as a way to reduce the need for oil and gas imports; as a way of supporting the growth of agriculture, forestry, and rural economies; and as a way to foster major new domestic industries in the form of biorefineries that manufacture a variety of fuels, chemicals, and other products. The purpose of this analysis was to determine if the land resources of the United States are sufficient to support a large-scale biorefinery industry capable of displacing a significant fraction of our nation's petroleum consumption. This study found that the combined forest and agriculture land resources have the potential of sustainably supplying much more than one-third of the nation's current petroleum consumption.

Forest lands, and in particular, timberlands, have the potential to sustainably produce close to 370 million dry tons of biomass annually. This estimate includes the residues generated in the manufacture of various forest products and the residues generated in the use of manufactured forest products. It also includes the harvest of wood for various residential and commercial space-heating applications. With the exception of urban wood residues, most of these sources of forest biomass are currently being utilized and there are significant efforts under way to use these resources much more efficiently. Two potentially large sources of forest biomass not currently being used are logging and other removal residues, and fuel treatment thinnings. These sources can sustainably contribute over 120 million dry tons annually. The logging and other removal residues can easily be recovered following commercial harvest and land clearing operations. Fuel treatment thinnings can also be recovered concomitantly with efforts to reduce forest fire hazards and otherwise improve the health of our nation's forests.

Agricultural lands can provide nearly 1 billion dry tons of sustainably collectable biomass and continue to meet food, feed and export demands. This estimate includes 446 million dry tons of crop residues, 377 million dry tons of perennial crops, 87 million dry tons of grains used for biofuels, and 87 million dry tons of animal manures, process residues, and other residues generated in the consumption food products. The perennial crops are crops dedicated primarily for bioenergy and biobased products and will likely include a combination of grasses and woody crops. Providing this level of biomass will require increasing yields of corn, wheat, and other small grains by 50 percent; doubling residue-to-grain ratios for soybeans; developing much more efficient residue harvesting equipment; managing active cropland with no-till cultivation; growing perennial crops whose output is primarily dedicated for bioenergy purposes on 55 million acres of cropland, idle cropland, and cropland pasture; using animal manure in excess of what can be applied on-farm for soil improvement for bioenergy; and using a larger fraction of other secondary and tertiary residues for bioenergy.

In the context of the time required to scale up to a large-scale biorefinery industry, an annual biomass supply of more than 1.3 billion dry tons can be accomplished with relatively modest changes in land use and agricultural and forestry practices.

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Glossary

Annual removals - The net volume of growing stock trees removed from the inventory during a specified year by harvesting, cultural operations such as timber stand improvement, or land clearing.

Asexual reproduction - The naturally occurring ability of some plant species to reproduce asexually through seeds, meaning the embryos develop without a male gamete. This ensures the seeds will produce plants identical to the mother plant.

Biobased product - The term 'biobased product,' as defined by Farm Security and Rural Investment Act (FSRIA), means a product determined by the U.S. Secretary of Agriculture to be a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.

Bioenergy - Useful, renewable energy produced from organic matter - the conversion of the complex carbohydrates in organic matter to energy. Organic matter may either be used directly as a fuel, processed into liquids and gasses, or be a residual of processing and conversion.

Biodiesel - Fuel derived from vegetable oils or animal fats. It is produced when a vegetable oil or animal fat is chemically reacted with an alcohol.

Biorefinery - A facility that processes and converts biomass into value-added products. These products can range from biomaterials to fuels such as ethanol or important feedstocks for the production of chemicals and other materials. Biorefineries can be based on a number of processing platforms using mechanical, thermal, chemical, and biochemical processes.

Biofuels - Fuels made from biomass resources, or their processing and conversion derivatives. Biofuels include ethanol, biodiesel, and methanol.

Biomass - Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal manure, municipal residues, and other residue materials. Biomass is generally produced in a sustainable manner from water and carbon dioxide by photosynthesis. There are three main categories of biomass - primary, secondary, and tertiary.

Biopower - The use of biomass feedstock to produce electric power or heat through direct combustion of the feedstock, through gasification and then combustion of the resultant gas, or through other thermal conversion processes. Power is generated with engines, turbines, fuel cells, or other equipment.

Black Liquor - Solution of lignin-residue and the pulping chemicals used to extract lignin during the manufacture of paper.

Coarse materials - Wood residues suitable for chipping, such as slabs, edgings, and trimmings.

Commercial species - Tree species suitable for industrial wood products.

Conservation Reserve Program - CRP provides farm owners or operators with an annual per-acre rental payment and half the cost of establishing a permanent land cover in exchange for retiring environmentally sensitive cropland from production for 10 to 15 years. In 1996, Congress reauthorized CRP for an additional round of contracts, limiting enrollment to 36.4 million acres at any time. The 2002 Farm Act increased the enrollment limit to 39 million acres. Producers can offer land for competitive bidding based on an Environmental Benefits Index (EBI) during periodic signups, or can automatically enroll more limited acreages in practices such as riparian buffers, field windbreaks, and grass strips on a continuous basis. CRP is funded through the Commodity Credit Corporation (CCC).

Cropland - Total cropland includes five components: cropland harvested, crop failure, cultivated summer fallow, cropland used only for pasture, and idle cropland.

Cropland used for crops – Cropland used for crops includes cropland harvested, crop failure, and cultivated summer fallow. **Cropland harvested** includes row crops and closely sown crops; hay and silage crops; tree fruits, small fruits, berries, and tree nuts; vegetables and melons; and miscellaneous other minor crops. In recent years, farmers have double-cropped about 4 percent of this acreage. **Crop failure** consists mainly of the acreage on which crops failed because of weather, insects, and diseases, but includes some land not harvested due to lack of labor, low market prices, or other factors. The acreage planted to cover and soil improvement crops not intended for harvest is excluded from crop failure and is considered idle. **Cultivated summer fallow** refers to cropland in sub-humid regions of the West cultivated for one or more seasons to control weeds and accumulate moisture before small grains are planted. This practice is optional in some areas, but it is a requirement for crop production in the drier cropland areas of the West. Other types of fallow, such as cropland planted with soil improvement crops but not harvested and cropland left idle all year, are not included in cultivated summer fallow but are included as idle cropland.

Cropland pasture – Land used for long-term crop rotation. However, some cropland pasture is marginal for crop uses and may remain in pasture indefinitely. This category also includes land that was used for pasture before crops reached maturity and some land used for pasture that could have been cropped without additional improvement.

Cull tree – A live tree, 5.0 inches in diameter at breast height (d.b.h.) or larger that is non-merchantable for saw logs now or prospectively because of rot, roughness, or species. (See definitions for rotten and rough trees.)

d.b.h. – The diameter measured at approximately breast high from the ground.

Feedstock – A product used as the basis for manufacture of another product.

Fiber products – Products derived from fibers of herbaceous and woody plant materials. Examples include pulp, composition board products, and wood chips for export.

Fine materials – Wood residues not suitable for chipping, such as planer shavings and sawdust.

Forest land – Land at least 10 percent stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between heavily forested and nonforested lands that are at least 10 percent stocked with forest trees and forest areas adjacent to urban and built-up lands. Also included are pinyon-juniper and chaparral areas in the West and afforested areas. The minimum area for classification of forest land is 1 acre. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 120 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if less than 120 feet wide.

Fuel Treatment Evaluator (FTE) – A strategic assessment tool capable of aiding the identification, evaluation, and prioritization of fuel treatment opportunities.

Fuelwood – Wood used for conversion to some form of energy, primarily for residential use.

Grassland pasture and range – All open land used primarily for pasture and grazing, including shrub and brush land types of pasture; grazing land with sagebrush and scattered mesquite; and all tame and native grasses, legumes, and other forage used for pasture or grazing. Because of the diversity in vegetative composition, grassland pasture and range are not always clearly distinguishable from other types of pasture and range. At one extreme, permanent grassland may merge with cropland pasture, or grassland may often be found in transitional areas with forested grazing land.

Growing stock – A classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. Cull trees are excluded. When associated with volume, includes only trees 5.0 inches in d.b.h. and larger.

Idle cropland – Land in cover and soil improvement crops, and cropland on which no crops were planted. Some cropland is idle each year for various physical and economic reasons. Acreage diverted from crops to soil-conserving uses (if not eligible for and used as cropland pasture) under federal farm programs is included in this component. Cropland enrolled in the Federal Conservation Reserve Program (CRP) is included in idle cropland.

Industrial wood – All commercial roundwood products except fuelwood.

Live cull - A classification that includes live cull trees. When associated with volume, it is the net volume in live cull trees that are 5.0 inches in d.b.h. and larger.

Logging residues - The unused portions of growing-stock and non-growing-stock trees cut or killed by logging and left in the woods.

Nonforest land - Land that has never supported forests and lands formerly forested where use of timber management is precluded by development for other uses. (Note: Includes area used for crops, improved pasture, residential areas, city parks, improved roads of any width and adjoining clearings, powerline clearings of any width, and 1- to 4.5-acre areas of water classified by the Bureau of the Census as land. If intermingled in forest areas, unimproved roads and nonforest strips must be more than 120 feet wide, and clearings, etc., must be more than 1 acre in area to qualify as nonforest land.)

Nonindustrial private - An ownership class of private lands where the owner does not operate wood-using processing plants.

Other forest land - Forest land other than timberland and reserved forest land. It includes available forest land, which is incapable of annually producing 20 cubic feet per acre of industrial wood under natural conditions because of adverse site conditions such as sterile soils, dry climate, poor drainage, high elevation, steepness, or rockiness.

Other removals - Unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing. Does not include volume removed from inventory through reclassification of timberland to productive reserved forest land.

Other sources - Sources of roundwood products that are not growing stock. These include salvable dead, rough and rotten trees, trees of noncommercial species, trees less than 5.0 inches d.b.h., tops, and roundwood harvested from non-forest land (for example, fence rows).

Poletimber trees - Live trees at least 5.0 inches in d.b.h. but smaller than sawtimber trees.

Primary wood-using mill - A mill that converts roundwood products into other wood products. Common examples are sawmills that convert saw logs into lumber and pulp mills that convert pulpwood roundwood into wood pulp.

Pulpwood - Roundwood, whole-tree chips, or wood residues that are used for the production of wood pulp.

Residues - Bark and woody materials that are generated in primary wood-using mills when roundwood products are converted to other products. Examples are slabs, edgings, trimmings, sawdust, shavings, veneer cores and clippings, and pulp screenings. Includes bark residues and wood residues (both coarse and fine materials) but excludes logging residues.

Rotten tree - A live tree of commercial species that does not contain a saw log now or prospectively primarily because of rot (that is, when rot accounts for more than 50 percent of the total cull volume).

Rough tree - (a) A live tree of commercial species that does not contain a saw log now or prospectively primarily because of roughness (that is, when sound cull, due to such factors as poor form, splits, or cracks, accounts for more than 50 percent of the total cull volume) or (b) a live tree of noncommercial species.

Roundwood products - Logs and other round timber generated from harvesting trees for industrial or consumer use.

Salvable dead tree - A downed or standing dead tree that is considered currently or potentially merchantable by regional standards.

Saplings - Live trees 1.0 inch through 4.9 inches in d.b.h.

Secondary wood processing mills - A mill that uses primary wood products in the manufacture of finished wood products, such as cabinets, moldings, and furniture.

Sound dead - The net volume in salvable dead trees.

Timberland - Forest land that is producing or is capable of producing crops of industrial wood, and that is not withdrawn from timber utilization by statute or administrative regulation. Areas qualifying as timberland are capable of producing more than 20 cubic feet per acre per year of industrial wood in natural stands. Currently inaccessible and inoperable areas are included.

Timber Product Output Database Retrieval System (TPO) - Developed in support of the 1997 Resources Planning Act (RPA) Assessment, this system acts as an interface to a standard set of consistently coded TPO data for each state and county in the country. This set of national TPO data consists of 11 data variables that describe for each county the roundwood products harvested, the logging residues left behind, the timber otherwise removed, and the wood and bark residues generated by its primary wood-using mills.

Table A.1: Current availability of logging residue and other removals

Forest Resource	National Forest	Other Public	Private Lands	Total
	million dry tons			
Logging residues	1.1	3.2	44.4	48.8
Other removals	0.5	0.7	17.1	18.3
Total	**1.6**	**3.9**	**61.5**	**67.1**

Note: Conversion of volumetric data assumes an average density of 30 dry lbs/ft^3 (Timber Product Output database)
Source: Timber Product Output database (USDA-FS, 2004a)

Table A.2: Availability factors for logging residue and other removals under current recovery conditions

Forest Resource	Portion of Forest Resource Available				Harvest Frequency
	Accessible Fraction	Recovery Fraction	Biomass Fraction	Total Availability	
Logging residue					
Public	1	0.65	1	0.65	Annually
Private	1	0.65	1	0.65	Annually
Other removals					
Public	1	0.5	1	0.5	Annually
Private	1	0.5	1	0.5	Annually

Notes: Logging residue and residue from other removals are assumed to be 100% accessible provided these materials are removed concurrently with harvest and/or land clearing operations. Recovery fractions are based on field studies and average site conditions. The lower recovery fraction for other removals is because of generally smaller parcel size making collection more difficult. The small and scattered piece-size limits the recovery of this material. All recovered material is assumed to be available as a feedstock for bioenergy and biobased products.

Table A.3: Availability of logging residue and other removals under current recovery conditions

Forest Resource	National Forest	Other Public	Private Lands	Total
	million dry tons			
Logging residues	0.7	2.1	28.9	31.7
Other removals	0.3	0.4	8.5	9.2
Total	**1.0**	**2.5**	**37.4**	**40.9**

Notes: Availability of logging and other removal residue is based on the product of the total resource size (Table A.1) and availability factor (Table A.2).

Table A.4: Availability of logging residue and other removals under future growth and recovery conditions

Forest Resource	National Forest	Other Public	Private Lands	Total
	million dry tons			
Logging residues	1.0	3.1	42.3	46.4
Other removals	0.5	0.7	16.3	17.4
Total	**1.5**	**3.8**	**58.5**	**63.8**

Notes: Under future conditions (mid-century), harvested roundwood products are assumed to increase by 35% and 47% for softwoods and hardwoods, respectively. The amount of logging residue generated is assumed to decline from 6.7% to 6% for softwoods and from 12.4% to 9% for hardwoods. These assumptions are derived from Haynes (2003). The fraction of recoverable logging and other removal residue is assumed to increase by 20%.

Table A.5: Total fuel treatment thinnings resource

Forest Resource	National Forest	Other Public	Private Lands	Total
	million dry tons			
Timberland	1,849	770	5,175	7,794
Other forest land	147	158	310	616
Total	**1,996**	**928**	**5,486**	**8,410**

Note: Conversion of volumetric Forest Inventory Analysis data assumes 30 dry lbs/ft3.
Tree volumes were partitioned into two utilization groups - trees greater than 7 inches taken to a 4 inch minimum top diameter and the remaining smaller material (tops, limbs, small diameter trees). The larger-sized material was assumed merchantable for higher-value products and the smaller-sized material suitable for bioenergy and biobased products.
Source: Fuel Treatment Evaluator (USDA-FS, 2004c)

Table A.6: Assumed availability factors for fuel treatment thinnings

Forest Resource	Portion Of Forest Resource Available				Harvest Frequency
	Accessible	Fraction	Recovery	Fraction	
Timberland					
Public	0.6	0.85	0.3	0.15	30 years
Private	0.8	0.85	0.3	0.20	30 years
Other forest land					
Public	0.6	0.85	0.9	0.46	30 years
Private	0.8	0.85	0.9	0.61	30 years

Notes: These assumptions are based in part on from USDA-FS (2003).

Table A.7: Availability of fuel treatment thinnings

Forest Resource	National Forest	Other Public	Private Lands	Total
	million dry tons			
Timberland	9.4	3.9	35.2	48.6
Other forest land	2.2	2.4	6.3	11.0
Total	**11.7**	**6.3**	**41.5**	**59.6**

Notes: Availability of fuel treatment thinnings is based on the product of the total resource size (Table A.5) and the respective availability factors (Table A.6) divided by the harvest frequency (Table A.6).

Table A.8: Forest products industry processing residues

Source	Energy	Product And Other Uses	Unused	Total
	Mill Residue Byproducts (millon dry tons)			
Primary wood processing mills	39.4	50.3	1.7	93.1
Secondary wood processing mills	—	9.5	6.1	15.6
Pulp and paper mills	52.1	—	—	52.1

Notes: Primary wood processing mills account for 91.3 million dry tons split among bark, coarse wood, and fine wood in the following proportions - 26.5%, 42.9%, and 30.7%, respectively. Mill residues are projected to increase by about 30% and somewhat less for black liquor generated at pulp and paper mills.
Source: Timber Product Output database (USDA-FS, 2004a)

Table A.9: Summary of availability of urban wood residues

Urban Wood Residue Source	Disposition of Residue		
	Generated	Recovered, Combusted For Energy & Unusable	Available
	million dry tons		
Construction residue	11.6	3.0	8.6
Demolition debris	27.7	16.1	11.7
Woody yard trimmings (MSW)	9.8	8.0	1.7
Wood (MSW)	13.2	7.3	6.0
Total	**62.3**	**34.4**	**28.0**

Notes: Woody yard trimmings were converted to dry tons based on 40% moisture content. The amount of urban wood residue generated is estimated to increase by about 30%. This estimate is based on trends associated with residential and nonresidential construction, demolition, and remodeling, as well as in the disposal of durables and packaging residues.
Source: McKeever (2004)

Table B.1: Comparison of USDA baseline for major crops with change scenarios

Major Crop	USDA Baseline		Technology changes without land use change, no perennial crops		Technology changes with land use change to accomodate perennial crops	
	2001	2014	Moderate	High	Moderate	High
Corn						
Harvested acres (millions)	68.8	76.6	76.6	76.6	76.6	76.6
Yield (bushels/acre)	138.2	161.8	172.75	207.3	172.75	207.3
Production (thousand bushels)	9,509,266	12,395,000	13,232,650	15,879,180	13,232,650	15,879,180
Total grain supply (000s bushels)	11,416,000	13,604,000				
Use						
Food, See, Res. (000s bushels)	1,340,000	1,5000,000	1,581,200	1,835,000	1,581,200	1,835,800
Animal Feed (000s bushels)	5,874,000	6,200,000	6,200,000	6,820,000	6,200,000	6,820,000
Export (000s bushels)	1,889,000	2,975,000	2,975,000	3,272,500	2,975,000	3,272,500
Industry/fuel (000s bushels)	714,000	1,750,000	2,476,450	3,950,880	2,476,450	3,950,880
Stocks (000s bushels)	1,599,000	1,179,000				
Total grain Use (000s bushels)	11,416,000	13,604,000	13,232,650	15,879,180	13,232,650	15,879,180
Wheat						
Harvested acres (millions)	48.8	52.3	52.3	52.3	52.3	47.25
Yield (bushels/acre)	40.1	45.9	48.1	55.7	48.1	55.8
Production (thousand bushels)	1,957,043	2,400,000	2,513,760	2,911,772	2,513,760	2,635,579
Total grain supply (000s bushels)	2,941,000	3,032,000				
Use						
Food, Seed, Res. (000s bushels)	1,010,000	1,049,000	1,191,800	1,383,700	1,191,800	1,383,700
Animal Feed (000s bushels)	193,000	230,000	230,000	230,000	230,000	230,000
Export (000s bushels)	961,000	1,200,000	1,200,000	1,200,000	1,200,000	1,200,000
Industry/fuel (000s bushels)	0	0	-108,040	98,072	-108,040	-178,121
Stocks (000s bushels)	777,000	553,000				
Total grain Use (000s bushels)	2,941,000	3,032,000	2,513,760	2,911,772	2,513,760	2,635,579
Soybeans						
Harvested acres (millions)	73.0	71.4	71.4	71.4	71.4	63.4
Yield (bushels/acre)	39.6	43.6	44.748	48.708	44.748	48.708
Production (thousand bushels)	2,890,682	3,115,000	3,195,007	3,477,751	3,195,007	3,088,087
Total grain supply (000s bushels)	3,140,749	3,328,000				
Use						
Food, Seed, Res. (000s bushels)	438,303	467,914	517,197	600,475	517,197	600,475
Animal Feed (000s bushels)	1,084,262	1,307,438	1,307,438	1,307,438	1,307,438	1,307,438
Export (000s bushels)	1,353,835	1,272,500	1,272,500	1,272,500	1,272,500	1,272,500
Industry/fuel (000s bushels)	8,929	35,714	97,872	297,338	97,872	-92,326
Stocks (000s bushels)	254,926	243,533				
Total grain Use (000s bushels)	3,140,254	3,327,099	3,195,007	3,477,751	3,195,007	3,088,087

Table B.2: Current availability of biomass from agricultural lands - baseline summary

Crop	Acres harvested or reserved	Product yield	Fiber yield	Residue yield	Total cropland plant mass	Total residue produced	Residue logistically removable	Residue sustainably removable	Grains used for bioenergy	Secondary & tertiary residues available	Total sustainable biomass
	million acres	dry tons/acre/year			million dry tons/year						
Corn grain	68.8	3.3	na	3.3	450.0	225.0	90.0	74.8	13.5	6.2	94.6
Sorghum	8.6	1.4	na	1.4	24.8	12.4	5.0	0.0	0.5		0.5
Barley	4.3	1.2	na	1.8	12.8	7.7	3.1	0.7	0.2		0.8
Oats	1.9	0.8	na	1.7	4.8	3.2	1.3	0.1	0.0		0.1
Wheat-winter	31.3	1.1	na	1.9	95.4	60.1	24.0	8.8	0.2		8.9
Wheat-spring	17.5	0.9	na	1.2	35.5	20.1	8.0	2.2	0.0		2.2
Soybeans	73.0	1.1	na	1.6	193.0	115.8	46.3	0.0	0.2		0.2
Rice	3.3	2.9	na	4.3	23.7	14.2	5.7	5.7	0.0		5.7
Cotton lint	13.8	0.3	na	1.0	17.7	13.3	2.7	2.7	0.0		2.7
Alfalfa	23.8	3.0	na	0.0	70.6	0.0	0.0	0.0	0.0		0.0
Other Hay	39.7	1.7	na	0.0	67.4	0.0	0.0	0.0	0.0		0.0
Silage corn	6.1	6.6	na	0.0	40.8	0.0	0.0	0.0	0.0		0.0
Silage sorghum	0.3	4.4	na	0.0	1.5	0.0	0.0	0.0	0.0		0.0
Other Crops	20.1	1.0	na	1.0	20.1	20.1	18.1	18.1	0.0		18.1
Double Crops							0.0	0.0	0.0		0.0
Crop failure	10.0	0.5	na	0.0	5.0	0.0	0.0	0.0	0.0		0.0
Summer fallow	21.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Grasses (CRP)	25.4	2.0	na	0.0	50.8	0.0	0.0	0.0	0.0		0.0
Trees (CRP)	2.2	2.0	na	0.0	4.4	0.0	0.0	0.0	0.0		0.0
Environment (CRP)	6.4	2.0	na	0.0	12.7	0.0	0.0	0.0	0.0		0.0
Unaccounted	3.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Pasture	67.5	1.5	na	0.0	101.3	0.0	0.0	0.0	0.0		0.0
Wood fiber	0.1	0.0	6.0	2.0	0.8	0.2	0.2	0.2	0.0		0.2
Perennials	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Manure			na	na	na	54.9				35.1	35.1
Fats & greases						3.5				0.9	0.9
MSW										23.7	23.7
Totals	448.1	37.7	6.0	21.1	1233.1	550.4	204.3	113.2	14.6	65.9	193.7

Table B.3: Summary of biomass from agricultural lands under moderate crop yield increases without land use change

Crop	Acres harvested or reserved	Product yield	Fiber yield	Residue yield	Total cropland plant mass	Total residue produced	Residue logistically removable	Residue sustainably removable	Grains used for bioenergy	Secondary & tertiary residues available	Total sustainable biomass
	million acres	dry/tons/acre/year					million dry tons/year				
Corn grain	76.6	4.1	na	4.1	626.2	313.1	187.9	169.7	46.9	8.6	225.2
Sorghum	6.8	1.7	na	1.7	22.8	11.4	6.8	1.3	1.8		3.1
Barley	3.7	1.5	na	2.2	13.8	8.3	5.0	2.8	0.6		3.4
Oats	1.6	0.9	na	1.9	4.5	3.0	1.8	0.7	0.0		0.7
Wheat-winter	33.3	1.4	na	2.3	121.8	76.7	46.0	27.4	0.0		27.4
Wheat-spring	19.0	1.1	na	1.4	46.3	26.2	15.7	7.4	0.0		7.4
Soybeans	71.4	1.2	na	1.8	213.3	128.0	76.8	0.0	2.6		2.6
Rice	3.4	3.4	na	5.1	28.5	17.1	10.3	10.3	0.0		10.3
Cotton lint	12.3	0.4	na	1.1	18.4	13.8	5.5	5.5	0.0		5.5
Alfalfa	23.8	3.4	na	0.0	81.2	0.0	0.0	0.0	0.0		0.0
Other Hay	34.2	2.0	na	0.0	66.8	0.0	0.0	0.0	0.0		0.0
Silage corn	6.1	7.6	na	0.0	46.9	0.0	0.0	0.0	0.0		0.0
Silage sorghum	0.3	5.1	na	0.0	1.7	0.0	0.0	0.0	0.0		0.0
Other Crops	20.1	1.2	na	1.2	23.1	23.1	20.8	20.8	2.0		22.8
Double Crops							10.0	10.0	2.0		12.0
Crop failure	10.0	0.5	na	0.0	5.0	0.0	0.0	0.0	0.0		0.0
Summer fallow	21.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Grasses (CRP)	25.4	2.0	na	0.0	50.8	0.0	0.0	25.4	0.0		25.4
Trees (CRP)	2.2	2.0	na	0.0	4.4	0.0	0.0	2.2	0.0		2.2
Environment (CRP)	6.4	2.0	na	0.0	12.7	0.0	0.0	0.0	0.0		0.0
Unaccounted	3.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Pasture	67.5	1.5	na	0.0	101.3	0.0	0.0	0.0	0.0		0.0
Wood fiber	0.1	0.0	6.0	2.0	0.8	0.2	0.2	0.2	0.0		0.2
Perennials	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Manure			na	na	na	68.0				43.5	43.5
Fats & greases						5.0				2.0	2.0
MSW										29.4	29.4
Totals	**448.2**	**42.8**	**6.0**	**24.7**	**1490.3**	**693.8**	**386.7**	**283.8**	**55.9**	**83.6**	**423.2**

Table B.4: Summary of biomass from agricultural lands under high crop yield increase without land use change

Crop	Acres harvested or reserved	Product yield	Fiber yield	Residue yield	Total cropland plant mass	Total residue produced	Residue logistically removable	Residue sustainably removable	Grains used for bioenergy	Secondary & tertiary residues available	Total sustainable biomass
	million acres	dry tons/acre/year			million dry tons/year						
Corn grain	76.6	4.9	na	4.9	751.4	375.7	281.8	256.1	74.8	12.3	343.2
Sorghum	6.8	1.9	na	1.9	25.9	12.9	9.7	4.0	2.8		6.8
Barley	3.7	1.7	na	2.6	16.0	9.6	7.2	4.7	0.9		5.7
Oats	1.6	1.0	na	2.1	5.0	3.3	2.5	1.2	0.0		1.2
Wheat-winter	33.3	1.6	na	2.7	141.1	88.8	66.6	44.9	2.5		47.5
Wheat-spring	19.0	1.2	na	1.6	53.6	30.3	22.7	12.2	0.0		12.2
Soybeans	71.4	1.3	na	2.0	232.1	139.3	104.5	0.0	7.9		7.9
Rice	3.4	3.9	na	5.8	32.6	19.6	14.7	14.7	0.0		14.7
Cotton lint	12.3	0.4	na	1.2	19.9	14.9	8.9	8.9	0.0		8.9
Alfalfa	23.8	3.9	na	0.0	91.8	0.0	0.0	0.0	0.0		0.0
Other Hay	34.2	2.2	na	0.0	75.5	0.0	0.0	0.0	0.0		0.0
Silage corn	6.1	8.6	na	0.0	53.1	0.0	0.0	0.0	0.0		0.0
Silage sorghum	0.3	5.8	na	0.0	1.9	0.0	0.0	0.0	0.0		0.0
Other Crops	20.1	1.3	na	1.3	26.1	26.1	23.5	23.5	4.0		27.5
Double Crops								15.0	4.0		19.0
Crop failure	10.0	0.5	na	0.0	5.0	0.0	0.0	0.0	0.0		0.0
Summer fallow	21.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Grasses (CRP)	25.4	2.0	na	0.0	50.8	0.0	0.0	25.4	0.0		25.4
Trees (CRP)	2.2	2.0	na	0.0	4.4	0.0	0.0	2.2	0.0		2.2
Environment (CRP)	6.4	2.0	na	0.0	12.7	0.0	0.0	0.0	0.0		0.0
Unaccounted	3.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Pasture	67.5	1.5	na	0.0	101.3	0.0	0.0	0.0	0.0		0.0
Wood fiber	0.1	0.0	6.0	2.0	0.8	0.2	0.2	0.2	0.0		0.2
Perennials	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Manure			na	na	na	68.0				43.5	43.5
Fats & greases						5.0				2.0	2.0
MSW										29.4	29.4
Totals	448.2	47.7	6.0	28.1	1701.0	793.8	542.3	413.1	97.0	87.2	597.3

Table B.5: Summary of biomass from agricultural lands under moderate crop yield increase with land use change

Crop	Acres harvested or reserved	Product yield	Fiber yield	Residue yield	Total cropland plant mass	Total residue produced	Residue logistically removable	Residue sustainably removable	Grains used for bioenergy	Secondary & tertiary residues available	Total sustainable biomass
	million acres	dry tons/acre/year			million dry tons/year						
Corn grain	76.6	4.1	na	4.1	626.2	313.1	187.9	169.7	46.9	8.6	225.2
Sorghum	6.8	1.7	na	1.7	22.8	11.4	6.8	1.3	1.8		3.1
Barley	3.7	1.5	na	2.2	13.8	8.3	5.0	2.8	0.6		3.4
Oats	1.6	0.9	na	1.9	4.5	3.0	1.8	0.7	0.0		0.7
Wheat-winter	33.3	1.4	na	2.3	121.8	76.7	46.0	27.4	0.0		27.4
Wheat-spring	19.0	1.1	na	1.4	46.3	26.2	15.7	7.4	0.0		4.5
Soybeans	71.4	1.2	na	2.4	255.9	170.6	102.4	12.7	2.6		15.3
Rice	3.4	3.4	na	5.1	28.5	17.1	10.3	10.3	0.0		10.3
Cotton lint	12.3	0.4	na	1.1	18.4	13.8	5.5	5.5	0.0		5.5
Alfalfa	23.8	3.4	na	0.0	81.2	0.0	0.0	0.0	0.0		0.0
Other Hay	34.2	2.0	na	0.0	66.8	0.0	0.0	0.0	0.0		0.0
Silage corn	6.1	7.6	na	0.0	46.9	0.0	0.0	0.0	0.0		0.0
Silage sorghum	0.3	5.1	na	0.0	1.7	0.0	0.0	0.0	0.0		0.0
Other Crops	20.1	1.2	na	1.2	23.1	23.1	20.8	20.8	2.0		22.8
Double Crops								10.0	2.0		12.0
Crop failure	10.0	0.5	na	0.0	5.0	0.0	0.0	0.0	0.0		0.0
Summer fallow	16.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Grasses (CRP)	15.4	2.0	na	0.0	30.8	0.0	0.0	15.4	0.0		15.4
Trees (CRP)	2.2	2.0	na	0.0	4.4	0.0	0.0	2.2	0.0		2.2
Environment (CRP)	6.4	2.0	na	0.0	12.7	0.0	0.0	0.0	0.0		0.0
Unaccounted	3.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Pasture	42.5	1.5	na	0.0	63.8	0.0	0.0	0.0	0.0		0.0
Wood fiber	5.1	0.0	6.0	2.0	40.8	10.2	9.2	9.2	0.0		9.2
Perennials	35.0	0.4	0.0	4.7	175.0	162.8	146.5	146.5	0.0		146.5
Manure			na	na	na	68.0				43.5	43.5
Fats & greases						5.0				2.0	2.0
MSW										29.4	29.4
Totals	448.2	43.2	6.0	30.0	1690.5	909.2	557.8	441.9	55.8	83.6	581.3

Table B.6: Summary of biomass from agricultural lands under high crop yield increase with land use change

Crop	Acres harvested or reserved	Product yield	Fiber yield	Residue yield	Total cropland plant mass	Total residue produced	Residue logistically removable	Residue sustainably removable	Grains used for bioenergy	Secondary & tertiary residues available	Total sustainable biomass
	million acres	dry/tons/acre/year			million dry tons/year						
Corn grain	76.6	4.9	na	4.9	751.4	375.7	281.8	256.1	74.8	12.3	343.2
Sorghum	6.8	1.9	na	1.9	25.9	12.9	9.7	4.0	2.8		6.8
Barley	3.7	1.7	na	2.6	16.0	9.6	7.2	4.7	1.9		6.6
Oats	1.6	1.0	na	2.1	5.0	3.3	2.5	1.2	0.0		1.2
Wheat-winter	30.3	1.6	na	2.7	128.3	80.8	60.6	40.9	0.0		40.9
Wheat-spring	17.0	1.2	na	1.6	48.0	27.1	20.3	10.9	0.0		10.9
Soybeans	63.4	1.3	na	2.6	247.4	164.9	123.7	47.9	0.0		47.9
Rice	3.4	3.9	na	5.8	32.6	19.6	14.7	14.7	0.0		14.7
Cotton lint	12.3	0.4	na	1.2	19.9	14.9	8.9	8.9	0.0		8.9
Alfalfa	23.8	3.9	na	0.0	91.8	0.0	0.0	0.0	0.0		0.0
Other Hay	29.2	2.2	na	0.0	64.5	0.0	0.0	0.0	0.0		0.0
Silage corn	6.1	8.6	na	0.0	53.1	0.0	0.0	0.0	0.0		0.0
Silage sorghum	0.3	5.8	na	0.0	1.9	0.0	0.0	0.0	0.0		0.0
Other Crops	20.1	1.3	na	1.3	26.1	26.1	23.5	23.5	4.0		27.5
Double Crops								15.0	4.0		19.0
Crop failure	8.0	0.5	na	0.0	4.0	0.0	0.0	0.0	0.0		0.0
Summer fallow	16.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Grasses (CRP)	15.4	2.0	na	0.0	30.8	0.0	0.0	15.4	0.0		15.4
Trees (CRP)	2.2	2.0	na	0.0	4.4	0.0	0.0	2.2	0.0		2.2
Environment (CRP)	6.4	2.0	na	0.0	12.7	0.0	0.0	0.0	0.0		0.0
Unaccounted	3.0	0.0	na	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Pasture	42.5	1.5	na	0.0	63.8	0.0	0.0	0.0	0.0		0.0
Wood fiber	5.1	0.0	6.0	2.0	40.8	10.2	9.2	9.2	0.0		9.2
Perennials	55.0	0.6	0.0	7.4	440.0	409.2	368.3	368.3	0.0		368.3
Manure			na	na	na	68.0				43.5	43.5
Fats & greases						5.0				2.0	2.0
MSW										29.4	29.4
Totals	**448.2**	**48.3**	**6.0**	**36.1**	**2108.4**	**1227.4**	**930.4**	**823.0**	**87.4**	**87.2**	**997.7**