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CARBON SEQUESTRATION TECHNOLOGIES

HEARING

BEFORE THE

SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND INNOVATION

OF THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
UNITED STATES SENATE

ONE HUNDRED TENTH CONGRESS

FIRST SESSION

NOVEMBER 7, 2007

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SENATE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

ONE HUNDRED TENTH CONGRESS

FIRST SESSION

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CONTENTS

	Page
Hearing held on November 7, 2007	1
Statement of Senator Dorgan	3
Statement of Senator Ensign	5
Prepared statement	6
Statement of Senator Kerry	1
Statement of Senator Klobuchar	60
Statement of Senator Stevens	4
Prepared statement	4
Statement of Senator Thune	74

WITNESSES

Benson, Professor Sally M., Executive Director, Global Climate and Energy Project, Stanford University	22
Prepared statement	24
Burruss, Dr. Robert C., Research Geologist, Energy Resources Team, U.S. Geological Survey, U.S. Department of the Interior	27
Prepared statement	28
Fox, Charles E., Vice President, Kinder Morgan CO_2 Company	11
Prepared statement	12
Hannegan, Bryan, Vice President, Environment, Electric Power Research Institute (EPRI)	30
Prepared statement	32
Herzog, Ch.E., Howard, Principal Research Engineer, Laboratory for Energy and the Environment, Massachusetts Institute of Technology	6
Prepared statement	8
Wolfe, Ron, Corporate Forester and Natural Resource Manager, Sealaska Corporation	52
Prepared statement	53

APPENDIX

Alstom Power, Inc., prepared statement	77
Friedmann, Dr. S. Julio, Leader, Carbon Management Program, Lawrence Livermore National Laboratory, prepared statement	82
Response to written questions submitted by Hon. John Thune to:	
Charles Fox	89
Howard Herzog, Ch.E.	89

CARBON SEQUESTRATION TECHNOLOGIES

WEDNESDAY, NOVEMBER 7, 2007

U.S. SENATE,
SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND INNOVATION,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC.

The Subcommittee met, pursuant to notice, at 2:35 p.m. in room SR–253, Russell Senate Office Building, Hon. John F. Kerry, Chairman of the Subcommittee, presiding.

OPENING STATEMENT OF HON. JOHN F. KERRY, U.S. SENATOR FROM MASSACHUSETTS

Senator KERRY. Thank you very much for being here. I apologize for being a little late, I had a meeting on the House side, and it takes a little longer to get over here.

I want to thank the witnesses for joining us here today for this. This will be a single panel presentation on the critical issue of carbon sequestration and the technologies that apply to it.

This is one of a series of hearings that this Subcommittee is engaged in on this topic. In April, we held a hearing on clean coal and carbon capture, focusing on the electric power industry, and today we're looking specifically on the sequestration issue. We intend to hold a hearing sometime in the not-too-distant future on gasification and capture technologies. It may be very early next year that we wind up doing that.

Everybody, the concept of climate change is on everybody's tongue tips these days, with greater or lesser degrees of understanding, depending upon who's talking about it, and what sort of effort they've made to look at the science and the background on it.

This Committee, I'm proud to say, right here, Al Gore and I and a few others, and very few others, held the very first hearings on climate change in 1987. And subsequently, we went to Rio for the Global Climate Conference, the Earth Summit as it was known, and from there to Buenos Aires, and ultimately to Kyoto. Now we're here, 20 years later, without a whole lot of progress, and without any real major government initiative and commitment to this urgent issue. That, in itself, is pretty stupefying.

When you measure the science now, with respect to this issue, I think about a year and a half ago, 2 years ago, scientists were warning us that you needed to keep the concentration of greenhouse gases down to about 550 parts per million, and you could

maybe tolerate a 3 degree centigrade increase in the earth's temperature.

Because of the feedback from Earth itself over the course of these last years, we are now seeing reevaluations of all of those estimates, stark reevaluations.

The IPCC study, on which most nations have based their initiatives, had a cutoff date of 2005. So, we've had almost 2 years now of subsequent data. And, it's interesting, the other day I did a compilation of the scientific reports that have come out in those intervening 2 years. With respect to insect infestation in forests in Canada, Alaska, and northern Wyoming, Montana and elsewhere, with respect to understanding the importance of tropical forests, and the amount of deforestation that has taken place, that is adding to the amount of CO_2. With respect to the melting of the Antarctic and West Antarctic and Greenland ice sheet, 100 billion metric tons of melt a year, for an ice sheet that was stable in 1990.

With respect to the Super El Niño effects, with respect to the melt of the floating ice sheets on the Arctic, elsewhere, which is exposing more ocean to warming, and to therefore, not a cycle of reflection of the sun's rays, but of absorption of them, and therefore a faster rate of warming—you can run down the list, folks.

I met with the Audubon the other day, and they talked about how their members are telling them of a hundred-mile vegetation movement, already discerned in the United States with respect to what grows where and how. So, things are changing, and they're changing fast.

And the bottom line is that they now estimate that we can only tolerate a 2 degree centigrade increase before you reach the tipping point, the catastrophic tipping point, and 450 parts per million is the allowable level.

Now, that's a concern, for the simple reason that, since the Industrial Revolution, we've gone from 270 to 370, 380 parts per million right now, right now. And what's already up in the atmosphere will continue to do damage for the next 80 to 100 years, and nobody knows exactly what, or how, or how it compounds, so applying a precautionary principle, and being smart as public people is sort of screaming out at us, even as we still face some flat Earth caucus members, here in the Senate and elsewhere.

This kind of gathering is really important, because in the end, we're looking at coal as one of the most critical components of dealing with this issue. We have 164 years of coal reserves, compared to about 41 years of oil reserves, by most estimates. And we have huge amounts of it in the United States, and China has huge amounts of it.

At the rate we're going today, without a big change, we are going to produce somewhere between 600 to 900 parts per million of greenhouse gases at the current rate of burning fossil fuels. So, we've got a gigantic challenge. And everybody who is talking about use of coal is now talking about carbon capture and sequestration, CCS, as it's known.

Today we want to hear the thoughts of those here, I know North Dakota, they already do some CCS, they use carbon for enhanced-oil recovery. The industry has used it for some 30 years. But we need to know, what is the ability to capture, what's the ability to

store, what length of time, what amounts, and how quickly can we achieve that?

I will be introducing legislation today that will establish 3 to 5 commercial-scale sequestration facilities, and 3 to 5 coal-fired demonstration plants, with carbon capture and establish an interagency process to determine a regulatory framework for CCS, direct USGS to perform a capacity assessment of sequestration potential, and establish an aggressive CCS R&D program at DOE.

Most people have suggested to me that we can only do this if we really kick in to high gear, in terms of demonstration projects and commercialization efforts. I think there's a lot we can do. We also need to authorize technology-sharing agreements with China, India, and other coal-intensive developing countries, and move on this in a joint fashion.

So, we welcome our panel, Senator Dorgan, do you have any opening comment?

STATEMENT OF HON. BYRON L. DORGAN, U.S. SENATOR FROM NORTH DAKOTA

Senator DORGAN. Mr. Chairman, briefly, I regret I can't stay for the entire hearing, I have a meeting in the Leader's Office at three o'clock. The question is not whether we engage in carbon capture and sequestration, the question is how. Half of our electricity in this country comes from coal-based resources. We're going to continue to use coal, the question is—how do we use coal, and how do we capture and sequester?

In North Dakota we have the Nation's only synthetic gasification plant, making synthetic natural gas from coal. We capture 50 percent of the carbon, put it in a pipe and move it to Canada for the purpose of enhanced oil recovery. So that, I think is the world's largest project of its kind, but we need to do a lot of that, we need to do a lot of things to understand what works and what doesn't.

Frankly, the President, for example, in his budget, did not request nearly enough funding. I'm the Chairman of the Energy and Water Appropriations Subcommittee, I increased the funding for fossil fuels by 30 percent over the President's request. The only way we're going to get to where we need to get is to invest in the research and development, to make real investments in these projects. So, I've increased the funding by 30 percent. The President's complaining about those increases, but I think if we're going to solve this, it's absolutely essential that we provide the funding for the research.

And just one final point, if I might, I think the solution, in many ways, to be able to continue to use our coal resources, is going to be in new technologies and new approaches. And sometimes they might represent old inquiries.

I met a fellow who has left the government and is now with a company in Massachusetts, Senator Kerry, engaged in algae issues, you know, single-celled pond scum. Pond scum, called algae, is produced with sunlight and CO_2. Well, guess what? This guy worked 17 years for our National Energy Lab in algae and then the funding was discontinued. I've just continued the funding in the ETL for algae research.

But the interesting thing about algae is it feeds on CO_2, and produces a super-fuel. Wouldn't it be interesting if we discover that we can use wastewater and produce algae, which increases in bulk in hours, and sequester the CO_2, I should say, capture and use the CO_2 to produce algae which, essentially, destroys the CO_2 and produces a super fuel.

And they were telling me, if you take soy beans, and produce ethanol, an acre of soy produces about 80 gallons of ethanol. An acre of corn produces about four or five hundred gallons of ethanol. An equivalent amount of algae would produce four to five thousand gallons of ethanol or super fuel.

Wouldn't it be interesting if we unlocked the mystery of all of this, and used technology to solve some of these issues? I just mention that as one idea, but there are a series of them that are going to come from research. If we don't do the research, we're not going to unlock the opportunities.

And I would say to my colleague, Senator Kerry, thank you for your leadership. You're absolutely correct, 20 years ago you were talking about these issues, I'm now talking about the need to continue to use coal, and use it the right way, by sequestering, capturing and sequestering carbon, because that's essential, in my judgment.

So, I'm sorry I can't stay for the entire hearing, but I'll have a chance to read the testimony, and I appreciate this excellent group of witnesses being with us today.

Senator KERRY. Senator Dorgan, let me just say that the meeting Senator Dorgan has to go to, I'm going to have to pop out too, very briefly, at three o'clock. It happens to be a meeting on this subject, with 30 CEOs of major groups involved in the issue of this alternative energy. So I will go out and come back. During it, Senator Stevens will be here, and he's agreed to cover for me during that, and I appreciate it.

Senator Stevens, do you have any opening?

STATEMENT OF HON. TED STEVENS, U.S. SENATOR FROM ALASKA

Senator STEVENS. I'll just put my statement in the record. I'd be pleased to introduce Mr. Wolfe when the time comes. But, this is an area in which I'm pleased to say, there ought to be bipartisan support, and I look forward to working with you on the whole prospect of getting some demonstration plants to go into this whole subject of carbon sequestration.

I think it's one of the things we ought to know—if the technology is there, and if it works.

Thank you.

[The prepared statement of Senator Stevens follows:]

PREPARED STATEMENT OF HON. TED STEVENS, U.S. SENATOR FROM ALASKA

Mr. Chairman, thank you for holding this hearing today on carbon sequestration technologies. I would like to thank the witnesses for their testimony.

In particular, I would like to welcome Ron Wolfe. Mr. Wolfe is Sealaska's corporate forester and manager of the Office of Natural Resources. Mr. Wolfe has had a long and proud history of serving the Juneau community and Alaska as a whole. Prior to joining Sealaska, he was the forester for the Central Council of Tlingit and Haida Indian Tribes of Alaska and Chief Forester for the Klukwan Corporation. As

a member of the Alaska Board of Forestry, Mr. Wolfe will provide valuable insight into forestry's critical role in carbon capture and sequestration and I look forward to hearing his testimony.

Energy is the lifeblood of our economy, without it, our ability to compete globally would be lost. Therefore, it is vital that our country's energy needs continue to be met if we are to maintain a competitive edge in today's global economy. By expanding our alternative energy portfolio, improving efficiency, and developing ways to exploit more cleanly our abundant natural resources, I believe we can achieve environmental stability while still allowing the economy to prosper. Carbon capture and sequestration is one such technology that may provide part of the solution.

This technology, while helping to reduce the amount of carbon dioxide entering the atmosphere, can also aid in recovering reserves of petroleum previously thought to be unrecoverable. Doing so will become more and more important as global oil reserves diminish and as petroleum prices rise. Further, forestry offers the widely understood option of capturing atmospheric carbon by growing more trees. This solution helps not only the environment, *but also* the economy and culture of many communities that depend on healthy forest management.

While the promises of carbon sequestration technology are great, I believe it is important to have a full understanding of this technology before implementing it. For instance, understanding how long-term sequestration may affect ground water supplies is just one of many issues of vital importance. Further, we must also realize that different regions require different solutions.

The Nation's energy needs must be met through a variety of solutions. The 21st century will be the proving ground for our commitment to achieve both energy independence and new, clean fuels. We can solve our current energy crisis through a combination of initiatives. Increased domestic production, conservation, and the development of alternative sources of energy will all be part of the broader solution, but the appropriate balance must be found between all options. Carbon capture, in its several forms, will inevitably be part of this balance.

Senator KERRY. Thank you, Senator Stevens, and your statement will be put in the record.

Senator Ensign?

STATEMENT OF HON. JOHN ENSIGN, U.S. SENATOR FROM NEVADA

Senator ENSIGN. Mr. Chairman, I'll put my formal statement also in the record, without objection but the—just a couple of quick comments.

We all know the abundance of coal that we have in the United States, and in this world that we live in today, we're relying more and more on countries that are not exactly favorable to the United States. So, if we can develop more coal power plants, other uses for coal in our energy portfolio into the future, and we can do it in an environmentally sound way, it—from so many different ways, it makes sense for the United States.

So, I appreciate you holding this important hearing, I do think this is a place where Republicans and Democrats can come together, with environmentalists, with industry folks, and try to work out some solutions.

As much as we'd all like to have wind and solar, and geothermal and the rest of the renewables, we know that there is, they're not abundant enough with the current technology that exists, so we have to have some fossil fuels, so we can get carbon, as a fossil fuel, to be much more environmentally sound, we should be pursuing that with everything that we have.

So, thanks for holding this hearing.

[The prepared statement of Senator Ensign follows:]

PREPARED STATEMENT OF JOHN ENSIGN, U.S. SENATOR FROM NEVADA

Mr. Chairman, I would like to thank you for holding this hearing today on coal and carbon capture technologies.

It is widely recognized that continued reliance on Middle East oil is neither smart energy policy nor smart security policy. In order to meet the rapidly growing energy needs of this country we must develop the resources that are available domestically. This cannot be done using only one fuel or one technology. It must be done by using all of the resources at our disposal including coal.

Coal is both abundant and inexpensive. In the United States alone, coal-fired power plants satisfy more than half of the Nation's energy needs and this percentage is likely to increase in the future.

The key is to ensure that we are employing this resource in the most efficient and environmentally responsible manner possible. New technologies to make this possible are on the horizon. Carbon capture and sequestration is just one of many processes already in development. Groundbreaking research is being conducted to develop ways to burn coal in order to maximize energy yield and employ cleaner and more efficient processes.

Nevada is a prime example of a state dedicated to doing its part to meet our growing energy needs and has been a national leader in the generation of renewable energy. Nevada also recognizes that there will be times when the wind is not blowing and the sun is not shining that people will still need electricity. In order to respond, Nevada is committed to keeping its energy supply diverse and is planning to build two state-of-the-art, environmentally compliant, clean pulverized coal plants. Both of these plants will be built to accommodate retrofits when large scale carbon capture and sequestration (CCS) technologies are demonstrated feasible.

This project is an important part of Nevada's ongoing strategy to develop and maintain a balanced energy portfolio and reduce our emissions footprint. The plants in Nevada will be the catalyst for the development of more renewable energy resources (particularly wind energy in the mountains of eastern Nevada) by providing transmission access to northern and southern Nevada via a proposed 250-mile transmission line between the two operating companies.

Like many of the alternative energy technologies currently in development, no one single solution will solve the problem of meeting energy needs in a responsible manner. However, if the technology proves commercially feasible and environmentally responsible, we should continue to explore the benefits clean coal can offer to our economy. I look forward to all of our witnesses' testimony and their insight into how we can achieve this goal.

Senator KERRY. Thank you, Senator Ensign, your statement will also be put into the record.

Thank you, members of the panel, for being patient with us, and we look forward to your testimonies.

If you could try to summarize them in 5 minutes, the full written statement will be placed in the record, as if read in full. We appreciate the summaries, they give us a little more time to have some give and take.

Mr. Herzog, would you begin, and we'll just run down the line? Introduce yourselves, and go to work.

STATEMENT OF HOWARD HERZOG, CH.E., PRINCIPAL RESEARCH ENGINEER, LABORATORY FOR ENERGY AND THE ENVIRONMENT, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Mr. HERZOG. Howard Herzog, Principal Research Engineer at MIT.

Mr. Chairman, and Members of the Committee, thank you for this opportunity to appear before you today to discuss carbon sequestration technologies, or more specifically, the sequestration of carbon dioxide into geologic formations.

I've been involved with carbon dioxide capture and storage, referred to as CCS, for over 18 years.

Senator KERRY. Can you pull the mic a little closer, I think we'll get a little more.

Mr. HERZOG. I was coordinating lead author on the Intergovernmental Panel on Climate Change, Special Report on Carbon Dioxide Capture and Storage, as well as a co-author on the MIT report, *The Future of Coal.* Over the past few years, I've also been a U.S. delegate to the Carbon Sequestration Leadership Forum.

Coal is a critical fuel for the world, as you have just said in your statements. It supplies a majority of electricity at inexpensive prices in many countries, including the U.S., China and India.

However, coal is responsible for about 40 percent of the world's carbon dioxide emissions. In the MIT *Future of Coal* study we concluded that carbon dioxide capture and sequestration is the critical enabling technology that will reduce carbon dioxide emissions significantly, while also allowing the world to meet its pressing energy needs.

So, while we recognize that CCS is not a silver bullet, we do view it as a critical component in a portfolio of climate change mitigation options.

For geologic sequestration, the MIT Coal Study finds current evidence indicates it is scientifically feasible to store large quantities of carbon dioxide in geologic formations. This statement is based on actual field experience with carbon sequestration; other types of carbon dioxide injections such as enhanced oil recovery or injection of other buoyant fluids like natural gas for seasonal storage; pilot tests; as well as modeling and assessment studies.

However, to scale up from what we refer to as the current megaton, or millions of tons per year scale to the required gigaton, or billions of tons per year scale, is a major challenge and should not be underestimated. To move forward, we need to address the scientific and regulatory uncertainties associated with geologic storage at scale.

The MIT coal study states that in order to address outstanding technological issues that need to be resolved to confirm CCS as a major mitigation option, and to establish public confidence that large-scale sequestration is practical and safe, it is urgent to undertake a number of large-scale experimental projects in reservoirs that are instrumented, monitored and analyzed to verify the practical reliability and implementation of sequestration.

Specifically, we recommend about 10 sequestration demonstrations worldwide, with a minimum of 3 projects in the U.S. to represent the range of U.S. geology.

It should be noted that all of the world's current large sequestration projects are offshoots of commercial projects, with the science coming as an afterthought. We need the next round of sequestration demonstrations designed with scientific data collection as a primary goal to enable us to reach the gigaton scale.

In additional to the demonstration program, other key recommendations from the coal study are that the U.S. Geological Survey, and the DOE should embark on an assessment of U.S. geological storage capacity. The DOE should accelerate its research program in CCS science and technology, and that a regulatory capacity needs to be built.

Regulations need to cover the injection of carbon dioxide accounting and crediting as part of a climate regime, and site closure and monitoring.

While geologic sequestration is scientifically feasible, it is not technologically or institutionally ready. If the recommendations given above are pursued aggressively, we should be able to achieve technological readiness in 8 to 10 years.

There's urgency to start moving sequestration demonstrations forward as quickly as possible. The goal should be to achieve technological readiness by the time climate legislation creates market opportunities for CCS technologies. Unfortunately, we are currently not on that path.

The number one impediment to moving ahead is lack of funding. To achieve technological readiness both capture and sequestration, the MIT coal study recommends about a billion dollars a year for the U.S. CCS program. This is about 3 to 4 times the existing level of commitment into the current R&D and demonstration programs.

At current funding levels, demonstration projects will be forced to cut corners, which can result in a process to simply demonstrate we can inject carbon dioxide into the ground, which we routinely do right now, but will not advance the cause of technological readiness.

Climate change is a challenge mankind must address for at least the coming decades, and possibly centuries. Even when policies to deal with climate change are implemented, the inherent dynamics of both the energy and climate system means that the benefits from our actions may take decades to appear. Therefore, while the debate on climate change proceeds, it seems both prudent and relatively inexpensive to strive toward technological readiness. We don't want to add further delays into the system by not having technological options available when needed. This is why there's urgency to get on the path to technological readiness now.

Thank you.

[The prepared statement of Mr. Herzog follows:]

PREPARED STATEMENT OF HOWARD HERZOG, CH.E., PRINCIPAL RESEARCH ENGINEER, LABORATORY FOR ENERGY AND THE ENVIRONMENT, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Mr. Chairman and Members of the Committee, thank you for the opportunity to appear before you today to discuss carbon sequestration technologies or more specifically, the sequestration of CO_2 into geologic formations. I have been involved with CO_2 capture and sequestration (CCS) for over 18 years. I started my first research project in CCS in 1989. In 1992–93, under Department of Energy (DOE) funding, I led a 2-year effort that produced the first comprehensive research needs assessment in the field (see DOE/ER–30194). More recently, I was a coordinating lead author on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Dioxide Capture and Storage (see *www.ipcc.ch*), as well as one of 13 co-authors on the just released MIT report on *The Future of Coal* (see *www.mit.edu/coal*). For the past few years, I have also been a U.S. delegate to the Technical Group of the Carbon Sequestration Leadership Forum (see *www.cslforum.org*).

Coal is a critical fuel for the world. It supplies the majority of electricity at inexpensive prices in countries like the U.S., China, and India. However, coal also is responsible for about 40 percent of the world's CO_2 emissions. In the MIT *Future of Coal* Study, *"we conclude that CO_2 capture and sequestration (CCS) is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs."* So while we recognize that CCS is not a silver bullet, we do view it as a critical component in a portfolio of climate change mitigation options.

For geological sequestration, the MIT *Coal Study* finds: *"current evidence indicates that it is scientifically feasible to store large quantities of CO_2"* in geologic formations. This statement is based on actual field experience with CO_2 sequestration (*e.g.,* Sleipner, Weyburn, In-Salah), other types of CO_2 injections (*e.g.,* enhanced oil recovery, acid gas disposal), injection of other buoyant fluids (*e.g.,* natural gas storage), and pilot tests (*e.g.,* Frio Brine), as well as modeling and assessment studies. However, to scale up from what we refer to as the current megaton (*i.e.,* millions of tons per year) scale to the required gigaton (*i.e.,* billions of tons per year) scale is a major challenge and should not be underestimated. To move forward, we need to address the scientific and regulatory uncertainties associated with geologic storage at scale.

"In order to address outstanding technical issues that need to be resolved to confirm CCS as a major mitigation option, and to establish public confidence that large scale sequestration is practical and safe, it is urgent to undertake a number of large scale (on the order of 1 million tonnes/year injection) experimental projects in reservoirs that are instrumented, monitored, and analyzed to verify the practical reliability and implementation of sequestration." Specifically, the MIT Coal Study recommends about ten sequestration demonstrations worldwide, with about three projects in the U.S. to represent the range of U.S. geology. It should be noted that the world's current large sequestration projects operating today are all offshoots of commercial projects, with the science coming as an afterthought. We need the next round of sequestration demonstrations designed with scientific data collection as a primary goal to enable us to start scaling up to the gigaton scale.

In addition to the demonstration program, other key recommendations from the coal study are:

- The U.S. Geological Survey and the DOE should embark on a 3 year "bottom-up" analysis of U.S. geological storage capacity assessments.
- The DOE should accelerate its research program for CCS Science and Technology.
- A regulatory capacity covering the injection of CO_2, accounting and crediting as part of a climate regime, and site closure and monitoring needs to be built.

Summing up the situation, while geologic sequestration is scientifically feasible, it is not technologically or institutionally ready. If the recommendations given above are pursued aggressively, we should be able to achieve technological readiness in about 8–10 years. There is urgency to start moving the sequestration demonstrations forward as quickly as possible. The goal should be to achieve technological readiness by the time climate legislation creates market opportunities for CCS technologies. Unfortunately, we are not currently on that path.

The number one impediment to moving ahead is lack of funding. To achieve technological readiness for both capture and sequestration, the MIT Coal Study recommends about $1 billion/yr for the U.S. CCS program. This is about 3–4 times the existing level of commitment for current R&D and demonstration programs. The current funding levels will require proposed demonstrations to cut corners, which can result in projects that demonstrate we can inject CO_2 into the ground (which we already know we can do), but will not advance the cause of technological readiness.

In summary, climate change will not be solved overnight. Rather, it will be a challenge mankind must address for at least the coming decades and possibly centuries. Even when policies to deal with the climate challenge are implemented, the inherent dynamics of both the energy and climate systems means that the benefits from our actions may take decades to appear. Therefore, while the debate on climate policy proceeds, it seems both prudent and relatively inexpensive to achieve technological readiness. We don't want to add further delays into the system by not having technological options available when needed. That is why there is urgency to get on the path to technological readiness now.

Thank you.

ATTACHMENT

For more details on these topics, please see the MIT Coal Study at *www.mit.edu/coal*. Chapter 4 deals with the topic of geological sequestration. Below are the introduction and recommendations of that chapter.

Introduction

Carbon sequestration is the long term isolation of carbon dioxide from the atmosphere through physical, chemical, biological, or engineered processes. The largest potential reservoirs for storing carbon are the deep oceans and geological reservoirs

in the earth's upper crust. This chapter focuses on geological sequestration because it appears to be the most promising large-scale approach for the 2050 timeframe. It does not discuss ocean or terrestrial sequestration.

In order to achieve substantial GHG reductions, geological storage needs to be deployed at a large scale. For example, 1 Gt C/yr (3.6 Gt CO_2/yr) abatement, requires carbon capture and storage (CCS) from 600 large pulverized coal plants (~1000 MW each) or 3,600 injection projects at the scale of Statoil's Sleipner project. At present, global carbon emissions from coal approximate 2.5 Gt C. However, given reasonable economic and demand growth projections in a business-as-usual context, global coal emissions could account for 9 Gt C [by 2050]. These volumes highlight the need to develop rapidly an understanding of typical crustal response to such large projects, and the magnitude of the effort prompts certain concerns regarding implementation, efficiency, and risk of the enterprise.

The key questions of subsurface engineering and surface safety associated with carbon sequestration are:

Subsurface issues:

- Is there enough capacity to store CO_2 where needed?
- Do we understand storage mechanisms well enough?
- Could we establish a process to certify injection sites with our current level of understanding?
- Once injected, can we monitor and verify the movement of subsurface CO_2?

Near surface issues:

- How might the siting of new coal plants be influenced by the distribution of storage sites?
- What is the probability of CO_2 escaping from injection sites? What are the attendant risks? Can we detect leakage if it occurs?
- Will surface leakage negate or reduce the benefits of CCS?

Importantly, there do not appear to be unresolvable open technical issues underlying these questions. Of equal importance, the hurdles to answering these technical questions well appear manageable and surmountable. As such, it appears that geological carbon sequestration is likely to be safe, effective, and competitive with many other options on an economic basis. This chapter explains the technical basis for these statements, and makes recommendations about ways of achieving early resolution of these broad concerns.

* * * * * * *

Recommendations

Our overall judgment is that the prospect for geological CO_2 sequestration is excellent. We base this judgment on 30 years of injection experience and the ability of the earth's crust to trap CO_2. That said, there remain substantial open issues about large-scale deployment of carbon sequestration. Our recommendations aim to address the largest and most important of these issues. Our recommendations call for action by the U.S. government; however, many of these recommendations are appropriate for OECD and developing nations who anticipate the use CCS.

1. The U.S. Geological Survey and the DOE, and should embark of a 3 year "bottom-up" analysis of U.S. geological storage capacity assessments. This effort might be modeled after the GEODISC effort in Australia.

2. The DOE should launch a program to develop and deploy large-scale sequestration demonstration projects. The program should consist of a minimum of three projects that would represent the range of U.S. geology and industrial emissions with the following characteristics:

- Injection of the order of 1 million tons CO_2/year for a minimum of 5 years.
- Intensive site characterization with forward simulation, and baseline monitoring.
- Monitoring MMV arrays to measure the full complement of relevant parameters. The data from this monitoring should be fully integrated and analyzed.

3. The DOE should accelerate its research program for CCS S&T. The program should begin by developing simulation platforms capable of rendering coupled models for hydrodynamic, geological, geochemical, and geomechanical processes. The geomechanical response to CO_2 injection and determination or risk probability-density functions should also be addressed.

4. A regulatory capacity covering the injection of CO_2, accounting and crediting as part of a climate regime, and site closure and monitoring needs to be built. Two possible paths should be considered—evolution from the existing EPA UIC program or a separate program that covers all the regulatory aspects of CO_2 sequestration.

5. The government needs to assume liability for the sequestered CO_2 once injection operations cease and the site is closed. The transfer of liability would be contingent on the site meeting a set of regulatory criteria (see recommendation 4 above) and the operators paying into an insurance pool to cover potential damages from any future CO_2 leakage.

Senator KERRY. That's very helpful, thank you, Mr. Herzog.

Mr. Fox?

STATEMENT OF CHARLES E. FOX, VICE PRESIDENT, KINDER MORGAN CO_2 COMPANY

Mr. FOX. Mr. Chairman, Members of the Subcommittee, thank you for giving me the opportunity to testify on carbon capture sequestration technologies, also known as CCS.

My name is Chuck Fox, and I serve as Vice President of Kinder Morgan CO_2 Company. I've submitted a more detailed statement to the Committee, and ask it be made a part of the record.

I will summarize my remarks along five specific categories. Kinder Morgan's background with CCS is related to technologies, carbon capture science issues, transportation technology issues, storage issues, and finally, non-technical barriers to creating CCS in the U.S.

Kinder Morgan is one of the largest midstream energy companies in the U.S. It operates more than 30,000 miles of natural gas and products pipelines across the U.S., Canada and Mexico.

Kinder Morgan CO_2 Company is the largest pipeline transporter of CO_2 in the world, the second largest CO_2 EOR company, and the third largest oil producer in Texas. We have extensive experience in transporting CO_2 and injecting it into the ground.

Also, as a supplier of CO_2 we have reviewed the capture processes in order to locate new sources.

Of the various CCS components, capture is the most costly. Today, there are two viable processes—post-combustion capture, and pre-combustion capture, and one developing process—oxy-fuel combustion.

Post-combustion capture has been practiced for more than 60 years. The technology is well-known, but unfortunately is costly. CO_2 is captured by bubbling flue gas through a chemical absorbent. This process is energy intensive, since post-combustion gases have low concentrations of CO_2.

Flue gas is primarily composed of nitrogen, a major constituent of air. Large volumes of flue gases must be managed. The pre-combustion capture and oxy-fuel processes seek to cut costs by reducing the flue gas volume by removing nitrogen from the system.

In pre-combustion capture, fossil fuel is injected with steam and air or oxygen to produce two gas streams—hydrogen and CO_2. Pre-combustion capture could be used with IGCC's power plants. In fact, the gasification process is being used by the Dakota Gasification Company to splice CO_2 to an oil field in Canada.

In oxy-fuel combustion, oxygen is used instead of air for combustion of fuels, thereby eliminating nitrogen from the flue gas. The flue gas is composed primarily of water and CO_2. Unfortunately,

combusting with fuel and oxygen creates an extremely high-temperature flame, and existing steel cannot handle it. Given the relative cost, only the pre-combustion process seems to be viable for large-scale capture in the near term.

The most economical way to transport large volumes of CO_2 is by pipelines. CO_2 has been transported safely for over 35 years. CO_2 is not as dangerous to transport by pipeline as other gases. It is not flammable, explosive or poisonous. Few accidents or leaks have been reported on CO_2 pipelines. None of the dozen leaks that have occurred between 1986 and 2006 resulted in injuries. There are a few technical issues that must be resolved, regarding the transportation, and I made some suggestions in my written testimony.

Geological storage may present the most formidable challenge of any CCS development. Like transport, storage has a well-established and documented history, through established EOR activities. Though the science and engineering knowledge gained through EOR are well-understood, the technology was not developed to store CO_2 for long periods. Relatively little is known, for example, about saline aquifers, the largest and most widespread of CO_2 storage options. These aquifers need to be characterized.

In addition, technology created for EOR must be extended, so that the migration of CO_2 through the subsurface can be monitored, and the ultimate fate of CO_2 can be determined.

Although some technological barriers exist that could delay the economical application of CCS to mitigate climate change, non-technical barriers must also be surmounted. Of all CCS issues, none is as contentious or as critical as the issue of ultimate liability. Companies may not be willing to enter the storage business unless there is some relief from an eternal and unlimited liability.

Another topic discussed in the recent IOGCC report on CCS is ownership of the storage site. The issue of mineral rights versus surface rights must be settled prior to the creation of sites. In addition, the use of eminent domain to create storage sites and pipeline right-of-ways, must be defined by the states or Federal Government.

In addition, much of the pipeline industry has migrated toward the Master Limited Partnership, or MLP structure. The current tax law may not define revenues received for transportation of CO_2 for CCS to be qualifying income. As such, the tax structure would not support the development of a CCS transportation infrastructure.

Even with these challenges, I believe that industry is prepared to respond positively to society's call to find economical methods to mitigate climate change.

Thank you.

[The prepared statement of Mr. Fox follows:]

PREPARED STATEMENT OF CHARLES E. FOX, VICE PRESIDENT, KINDER MORGAN CO_2 COMPANY

Mr. Chairman and Members of the Subcommittee, thank you for giving me the opportunity to testify on carbon capture sequestration technologies, also known as carbon capture and storage or CCS. My name is Charles E. Fox and I serve as Vice President of Kinder Morgan. This is my full written statement and this document covers several topics related to carbon sequestration also known as carbon capture and storage: the development of the related CO_2 enhanced oil recovery (EOR) tech-

nology; the practical science behind carbon capture and sequestration technologies, the technical barriers to implementing such technologies and finally the non-technical barriers to creating a carbon capture and storage business in the United States.

First, as introduction, Kinder Morgan is one of the largest midstream energy companies in the U.S., operating more than 30,000 miles of natural gas and products pipelines across the United States, Canada and Mexico. Kinder Morgan CO_2 Company LLP is the largest transporter of CO_2 in the world; the second largest producer of oil through CO_2 enhanced oil recovery processes, and the third largest oil producer in Texas. Mr. Fox is the Vice President of Operations and Technology for Kinder Morgan CO_2 Company and co-authored the monograph, *Practical Aspects of CO_2 Flooding,* for the Society of Petroleum Engineers.

Development of CO_2 Enhanced Oil Recovery

The oil industry has over thirty-five years of experience producing and transporting CO_2. Commercial scale CO_2 enhanced oil recovery (EOR) began in 1972 in the Permian Basin which is located in west Texas and eastern New Mexico (see Figure 1). Anthropogenic[1] CO_2 was recovered from natural gas plants in the Val Verde Basin in Texas and then pipelined to the Chevron operated SACROC and Shell operated North Cross oil fields. During the 1970s the commerciality of CO_2 EOR was established which set the stage for a major expansion in the 1980s. Major oil companies such as Shell, Mobil, Exxon, Amoco and Arco funded the construction of the Permian Basin infrastructure to source CO_2 for their own oil fields. Natural, nearly pure, underground sources at the McElmo Dome (Colorado), Bravo Dome (New Mexico) and Sheep Mountain (Colorado) fields were developed. The major pipelines were laid (Cortez, Bravo and Sheep Mountain). Also during this decade Exxon began capturing anthropogenic CO_2 from the natural gas and helium Shute Creek plant at the LaBarge (Wyoming) and began to supply the Chevron operated Rangley field in Colorado. Shell also developed the Jackson Dome field in Mississippi to supply its oil fields in Mississippi and Louisiana. In the 1990s Great Plains Gasification Company began capturing anthropogenic CO_2 from its coal gasification plant in North Dakota and built a line to Saskatchewan to supply the Pan Canadian operated Weyburn oil field.

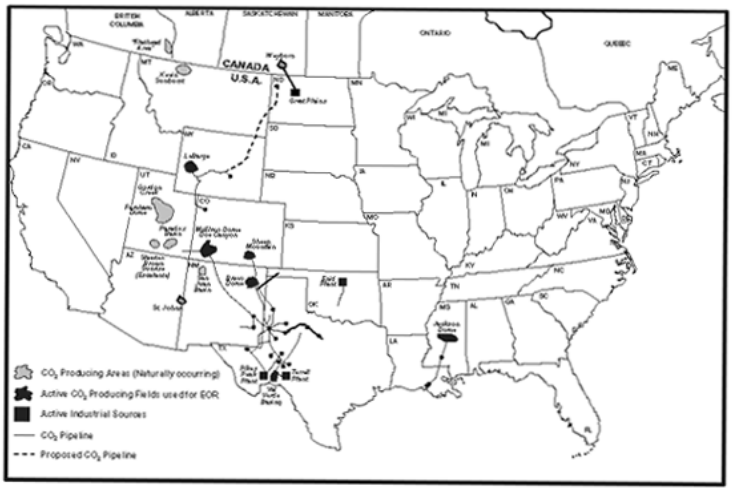

Figure 1. Source: Figure 1.9 from "Practical Aspects of CO2 Flooding," Jarrell et.al., Society of Petroleum Engineers 2002.

[1] Anthropogenic CO_2 (CO_2a) is defined as man-made CO_2 that is captured from an emissions source that otherwise would have been released to the atmosphere. Natural CO_2 (CO_2n) is CO_2 which is produced from naturally occurring underground sources that are primarily operated to supply CO_2. CO_2 produced from McElmo Dome is CO_2n. CO_2 captured from a natural gas plant in the Val Verde basin is CO_2a because even though the CO_2 occurs naturally with the natural gas, the CO_2 is a byproduct of the natural gas production operations.

During this period several short lived or intermittent sources were developed. Fertilizer plants which emit pure CO_2 at atmospheric pressures supplied small fields in Oklahoma and Texas. Of note was a capture project at the Lubbock Power and Light, Holly Street Plant. CO_2 was captured from the flue stack, and a CO_2 pipeline was laid to the Garza oil field.

The oil price collapse in 1986 made the CO_2 flooding uneconomic without inexpensive CO_2. While the natural sources and the Val Verde basin capture plants with lower variable costs were able to offer CO_2 for sale at reduced prices and stay in business, the Lubbock power plant was unable to sell CO_2 at a price its customer could afford and the CO_2 project was discontinued.

From the 1970s to the 1990s, major oil companies (Shell, Mobil, Exxon, Amoco, Arco, etc.) had research centers which conducted much of the research and development that was needed to initiate the new CO_2 EOR process. They and universities such as Stanford, the University of Texas, New Mexico Tech and the University of Alberta conducted research in topics such as intrinsic CO_2 properties, simulation of the underground movement of CO_2, corrosion processes and its mitigation, flow through piping and separation of CO_2 from impure sources. By the time many of the industry research facilities were shut down during the downturn in oil prices and the consolidation of the industry, the essential research was complete.

Today more than 200,000 BOPD are being produced in the U.S. due to the injection of CO_2. Approximately 37 million metric tons per year are purchased for injection into these fields. Approximately 7 million metric tons per year (19 percent) are from anthropogenic sources (Val Verde Basin—1.4, LaBarge—4.1, Dakota Gasification 1.8 million metric tons per year). To date, more than one billion barrels have been produced in the U.S. due to CO_2 EOR.

Carbon Capture Science

There are three pieces to the carbon capture and storage business: capture, transportation and storage. This document touches briefly on capture which Kinder Morgan has studied in order to locate economical sources of CO_2 and focuses more on transportation and storage in which Kinder Morgan has more expertise.

Capture of CO_2 is the first part of the process. Research has identified three main types of capture processes: post combustion capture, pre-combustion capture and oxyfuel combustion. Pre-combustion capture appears to have the most promise for wide spread, economical capture of CO_2.

Post-Combustion Capture

Having been practiced for over 60 years, though not for the primary purpose of capturing CO_2, post-combustion capture is the most mature technology for CO_2 capture. It involves removing the CO_2 from air-fired flue gas after the combustion of fossil fuels (natural gas, coal, oil) or biomass. The capture pieces are located downstream of the combustor to separate and remove the CO_2 from the flue gas. Air-fired combustors generally emit flue gases with low concentrations of CO_2 (3–15 percent by volume). This fact plus the high gas flow rates and low pressures means that post-combustion capture plants must have large equipment in order to process huge amounts of flue gas. Due to the low concentration of CO_2, chemical absorption appears to the most efficient means of separation.

Before the CO_2 can be removed by chemical absorption; however, the flue gas stream must be pretreated. First, the flue gas must be cooled. Next, acid gases like SO_X (sulfur oxides) and NO_X (nitrogen oxides), must be removed or significantly reduced. These acid gases react with the chemical solvent and reduce the solvent's ability to capture the CO_2. Different levels of SO_X and NO_X are tolerable depending on the cost of the chemical solvent.

Chemical absorption with amine solvents is usually used for the CO_2 separation. Not only does it execute high capture efficiency, chemical absorption can also be utilized with relatively low costs and energy consumption in comparison to other existing post-combustion capture processes. One of the most common absorbents used is monoethanolamine (MEA).

The MEA chemical absorption process can recover 85–95 percent[2] of the CO_2 in the flue gas and produce a stream of CO_2 with a purity of 99 percent by volume at low pressure. Unfortunately, large amounts of energy are consumed in the heating and regenerating the lean solvent, the steam production for stripping, the compression for transport, as well as in the powering of flue gas fans and pumps. As a result, there is a large energy penalty. 1–1.5 MW can be consumed in regenerating

[2] *http://www.netl.doe.gov/technologies/carbon_seq/partnerships/phase1/pdfs/CarbonSeparationCapture.pdf.*

the solvent for every metric ton of CO_2 recovered.[3] Other problems with the MEA process include equipment corrosion, solvent degradation due to the presence of oxygen, and the formation of heat-stable salts when SO_X and NO_X molecules are allowed to react with the amine solution. Furthermore, if particulates (fly ash) are not satisfactorily removed prior to entering the absorber foaming and degradation of the solvent can occur. After cooling and dehydrating for water removal, the highly concentrated CO_2 stream that results is compressed for transport and sequestration. Primarily due to the energy penalty, other technologies for carbon capture are being pursued.

Pre-Combustion Capture

It is possible to capture CO_2 before combustion. There are three main components to pre-combustion decarbonization. First, the fossil fuel is reacted with steam and air or oxygen to produce a synthesis gas primarily composed of hydrogen and carbon monoxide. Second, the carbon monoxide is reacted with steam to form CO_2 and additional hydrogen in a catalytic reactor called a shift converter. Third, the CO_2 can be separated, usually by physical or chemical absorption, creating two gas streams: one of CO_2 and one of hydrogen.[4] The CO_2 is condensed and transported and the hydrogen is used as fuel gas in a gas turbine or boiler. Pre-combustion capture could be used in conjunction with (coal) integrated gasification combined cycle (IGCC) power plants that already produce syngas prior to combustion.

Physical absorption can also used for CO_2 separation (and hydrogen sulfide removal) from syngas by using solvents such as Selexol (dimethylether of polyethylene glycol) or Rectisol (cold methanol). Physical absorption works best when high partial pressures of CO_2 are applied at low temperatures. For example, absorption with Selexol occurs at temperatures of 0–5 degrees Celsius.[5] The solvents are then regenerated by heating or reduction of pressure thereby releasing the CO_2.

Chemical absorption is an alternative technique that can be used to capture the CO_2 from the syngas. The most common solvent used for pre-combustion chemical absorption is methyl-diethanolamine (MDEA). Although it is more expensive than MEA, the chemical solvent commonly used in post-combustion, MDEA is more attractive in pre-combustion decarbonization because the chemical bonds that form with the CO_2 are weaker and easier to break and thus less energy/heat is required in the regenerator. While chemical absorption is feasible, physical absorption is a more energy efficient capture option in pre-combustion capture.

Pre-combustion appears to be very advantageous for many reasons. First, hydrogen can be used as a chemical or refining feedstock in addition to a fuel. Second, the higher concentrations of CO_2 can lead to more compact, less expensive equipment since less gas volume must be treated. Third, the high partial pressure of the CO_2 means that it is easier to separate CO_2 from the gas streams. Solvents that form weaker bonds (like MDEA) which require lower energy to restore/regenerate are suitable thereby reducing the cost of capture. Last, pre-combustion capture can be accomplished with techniques that are currently available. Natural gas reforming is currently practiced, and IGCC plants have been successfully demonstrated. All of these reasons make pre-combustion the best and cheapest option strictly for carbon capture. However, building the new IGCC plants would be more expensive from an overall perspective than building conventional plants without capture.

Oxy-fuel Combustion

In oxy-fuel combustion, pure or nearly pure oxygen gas is used instead of air for combustion of fuels or biomass thereby eliminating nitrogen from the flue gas. The combusted gas is primarily composed of water and CO_2. When fuel is burned in pure oxygen, the flame temperature is extremely high and the system has to be adapted in some way to withstand such heat. Combusting fuel in pure oxygen can occur at temperatures as high as 3500 degrees Celsius. Unfortunately, gas turbines can only withstand combustion temperatures of 1300–1400 degrees Celsius and oxy-fuel coal-fired boilers can withstand temperatures of 1900 degrees Celsius. CO_2-rich flue gas recycling and water stream injections are two proposed methods to moderate combustion temperature.[6] After a flue gas clean up and cooling of the resulting flue gas to condense and separate out the water vapor, the flue gas has a CO_2 concentration

[3] *http://www.aseanenvironment.info/Abstract/41013970.pdf.*
[4] *http://www.ipcc.ch/activity/srccs/SRCCS_Chapter3.pdf.*
[5] *http://www.delphi.ca/apec/Modules/Module2.pdf.*
[6] *http://www.delphi.ca/apec/Modules/Module3.pdf.*

of 80–98 percent. This CO_2 rich stream can then be compressed, dried, and further purified before storage or use.[7]

Advantages of this system include lower investment costs, higher concentrations of CO_2 and smaller flue gas volumes that must be separated. Impurities like SO_X, NO_X, and mercury are more concentrated in the lower volumes of flue gas, making purification easier and cheaper. Furthermore, there is a reduction in NO_X since nitrogen was eliminated when oxygen is used for combustion.

The oxygen required for this system is currently produced by low-temperature (cryogenic) air separation. First, air is compressed and cooled and water vapor is removed. Additional water vapor and CO_2 are removed by adsorption in molecular sieves. Next, the stream is sent through a heat exchanger and is cooled to -300 degrees Fahrenheit via refrigeration. Then high and low pressure distillation columns are used to separate the air streams into oxygen and nitrogen. Cryogenic oxygen production generates oxygen with concentrations as high as 99.9 percent possible.[8] It is an expensive process.

Transportation

The most economical way to transport large volumes of CO_2 is by pipelines, which is where Kinder Morgan CO_2 Company's expertise lies and, thus, will be the focus of this testimony in regards to CO_2 transportation.

Safety

CO_2 is not as dangerous to transport by pipeline as other gases. It is not flammable, explosive, or poisonous. The main safety concern with transporting CO_2 is asphyxiation resulting from oxygen being displaced in the surrounding air with CO_2 originating from a leak in the pipeline. In addition, CO_2 is denser than air, and should it leak from a pipe, it would collect in areas of low elevation. However, few accidents/leaks have been reported in CO_2 pipelines. None of the dozen leaks that occurred between 1986 and 2006 resulted in any injuries to people.[9]

Although CO_2 is not flammable or explosive, when in the supercritical, dense phase, it is extremely sensitive to temperature fluctuations. In basic terms, as temperature increases, so does pressure. However, this is not a linear relationship in the supercritical region (where the CO_2 has the characteristics of both liquids and gases). Relatively slight increases in temperature can result in relatively large increases in pressure, thus potentially exceeding the yield stress of the steel pipeline causing a rupture. This is easily avoided with properly designed and installed pressure relief devices.

In circumstances where hydrogen sulfide is present in the stream, considerations must be made regarding protection from hydrogen sulfide releases. This is done in part by correct material selection, properly designed and installed monitoring systems, and education of the operators and the public about exposure to hydrogen sulfide.

Costs

In 2003, an estimate for the annual cost of transporting CO_2 was \$1.5–\$2/metric-ton of CO_2 per 62 miles for a mass flow rate of 2.16 MM metric-tons of CO_2 per year.[10] Pipeline costs can vary in different regions. Pipelines built near heavily populated centers or in areas with mountains, rivers, and other obstacles tend to have higher costs. Onshore pipelines are generally less expensive than offshore pipelines that operate at higher pressures and lower temperatures.[11] Transportation cost rates also tend to drop when the amount of CO_2 (throughput) and distance covered is increased. As a result, it is more economically efficient to transport large amounts of CO_2 over substantial distances.

Operation and Quality Specifications

CO_2 is transported in pipelines as a supercritical, dense phase fluid, operating above the critical pressure or temperature. The critical pressure for CO_2 is 1,071 pounds per square inch (psi) and the critical temperature is 88 degrees F. If a fluid is above its critical pressure then no matter how much the temperature changes, there will be no condensation or vaporization *i.e.,* two phases will never exist at the same time. This is important because transporting and metering a two phase mixture (liquid and gas) is difficult. Normally CO_2 is transported between 60–90 degrees F and between 1,500–2,200 psig; although, CO_2 pipelines often operate at

[7] *http://www.ipcc.ch/activity/srccs/SRCCS_Chapter3.pdf.*
[8] *http://gcep.stanford.edu/pdfs/RxsY3908kaqwVPacX9DLcQ/kobayashi_coal_mar05.pdf.*
[9] *http://opencrs.cdt.org/rpts/RL33971_20070419.pdf.*
[10] *http://www.delphi.ca/apec/Modules/Module4.pdf.*
[11] *http://www.ipcc.ch/activity/srccs/SRCCS_Chapter4.pdf.*

higher pressures to overcome for the frictional losses as the CO_2 flows through the pipes.

Before it can be moved through a pipeline, the CO_2 must first be dehydrated to remove water from the stream, which is usually accomplished by standard glycol dehydration. Water content is significant because when CO_2 dissolves in water it forms carbonic acid which causes corrosion. In addition, hydrates can form that could cause blockages in the pipes and heat exchangers. To avoid these issues, the maximum allowable water content in CO_2 pipeline transportation is typically 30 lb/MMscf.[12]

Pipeline integrity is maintained using standard pipeline techniques. The most common method to determine the condition of a pipeline is in-line inspection also known as smart pigging. Intelligent pig technology is successfully used in pipelines transporting products other than CO_2, but has not been sufficiently developed for CO_2 pipelines. To prevent internal corrosion in a CO_2 pipeline, the water is removed in the process plants by the use of dehydration systems. The water content is continuously monitored to maintain the pipeline water content specification. In pipelines upstream of dehydration, non-corroding materials are used.

In addition to water, CO_2 can also contain impurities such as hydrogen sulfide (H_2S), SO_X, NO_X, oxygen, nitrogen, and hydrocarbons. The presence of any of these in the fluid stream can create challenges not only in CO_2 transportation but in EOR injection as well; *i.e.,* minimum miscibility pressure (MMP) requirements,[13] selection of construction materials, required treatment processes, etc. Oil field operators normally want to inject CO_2 that will be miscible with the reservoir oil at the reservoir conditions. To mitigate such challenges, the following should be taken into consideration:

Constituent	Maximum Recommended	Concern
Water	30 lbs/MMscf	Corrosion
Hydrogen Sulfide	10–20 ppm	Safety/Materials
Oxygen	10 ppm	Corrosion
Nitrogen	4%	Increases MMP
Hydrocarbons	5%	Increases MMP
Glycol	0.3 gal/MMscf	Operations
Temperature	120 deg F	Materials

Reasons for these limits are provided:

Water—CO_2 and free water combine to form carbonic acid which is very corrosive. Transporters of CO_2 want to transport a completely non-corrosive substance. 30 lbs/MMscf is a standard limit for CO_2 to avoid moisture dropout at lower pressures.

Hydrogen Sulfide—10 ppm is the maximum concentration of hydrogen sulfide that a person can work in for 8 continuous hours in the United States based on Occupational Safety and Health Administration (OSHA) standards. Thus, new pipeline specifications for H_2S may be a maximum of 10 ppm. The old OSHA standard was 20 ppm, so pipelines establishing an H_2S specification during that time period may have 20 ppm as the upper limit. Special materials must be used to mitigate the potential for sulfide stress cracking if the H_2S concentration is too high. In typical CO_2 pipeline applications operating at or below 2,200 psia, the H_2S concentration can be up to 20 ppm without special metallurgical considerations.

Oxygen—Oxygen is limited due to corrosion concerns.

Nitrogen—Nitrogen in CO_2 increases the minimum miscibility pressure of the oil/CO_2 mixture.

Hydrocarbons—Methane in CO_2 increases the minimum miscibility pressure of the oil/CO_2 mixture.

Glycol—Pipeline operations are more difficult when glycol is slugging through the pipe. Glycol plugs instrumentation lines, clogs pump seal faces and is harmful to some analyzers.

Temperature—120 degrees F is chosen because higher temperatures degrade polymers utilized in pipeline coatings.

CO_2 custody transfer meters are typically orifice meters, which is a well known, long standing technology. They are accurate to within 1 percent. Other meters are also used to measure CO_2, including turbine meters and wedge meters, although their use is not as accepted for custody transfer but are often used for allocation purposed downstream of the custody transfer meter.

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[12] *http://uregina.ca/ghgt7/PDF/papers/poster/350.pdf.*

[13] The MMP is the pressure at which CO_2 EOR works at maximum efficiency.

If the CO_2 is not pure, an important part of accurate measurement is determining the density and molecular weight of the CO_2 mixture. The density is important because it is used in determining the flow rate. Density can either be measured with an in-line densitometer or it can be calculated based on a compositional analysis and the static pressure. Where the composition barely changes (underground source fields), the industry moved away from using densitometers to using compositional analysis, first utilizing in-line chromatographs and then by taking monthly samples. Where the CO_2 composition is variable (processing plant sources), densitometers are used.

Material Selection

Selection of materials is critical when designing and constructing CO_2 processing and transportation facilities. Three key focuses are on internal pipeline corrosion, elastomer materials, and the presence of hydrogen sulfide.

According to *Practical Aspects of CO_2 Flooding* (SPE Monograph, 2002), "Corrosion has been a concern in CO_2 flooding from its inception. It is well known that when CO_2 dissolves in water, a small fraction hydrolizes to form carbonic acid. (The remainder exists as physically dissolved carbon dioxide). Carbonic acid dissociates to form bicarbonate ions, and hydrogen ions. Carbonic acid is quite corrosive to most carbon steels." In addition, "the combination of hydrogen sulfide (H_2S) and CO_2 dissolved in water causes higher corrosion rates than either acid gas alone." [14]

Thus, when water is present, Kinder Morgan utilizes certain materials to mitigate internal pipeline and piping corrosion. Most commonly used is stainless steel due to its corrosion resistant properties; however, the high material cost makes it less economical. An alternative to stainless steel is carbon steel lined with a high-density polyethylene (HDPE). The HDPE liner creates an adequate barrier between the corrosive fluid and the carbon steel. Internally coated carbon steel piping is also used, although not as frequently due to certain logistical and economic challenges. All of these alternatives have a history of success in CO_2 operations; the driving factor in determining which technology to use is cost, availability, and constructability.

Another key issue to consider is that CO_2 will diffuse into elastomeric compounds under pressure and temperature. Repeated pressurizing and depressurizing of CO_2 into an elastomer can cause the phenomenon called explosive decompression which will cause damage to the physical properties of the elastomer. This damage is known as blistering or fracturing.

Three factors effecting explosive decompression are: the rate of decompression, the permeability of the elastomer and the strength of the elastomer. It is difficult to control the rate of decompression but one may be able to control the number of decompressions which occur. Commonly used elastomers are rated as follows: Nitrile, Epichlorohydrine, Fluorocarbon (Viton), and EPDM. Most of these have some permeability to CO_2.

Kinder Morgan is not aware of any consensus among industry engineers and operations personnel concerning the "right" elastomer to use. There is general agreement, however, that an effective way to reduce explosive decompression is to increase the hardness (strength) of the elastomeric compound. Usually a durometer rating of at least 90 is specified. Further research into elastomer technology would benefit future CO_2 operation and development.

As is the case in any pipeline or piping system containing hydrogen sulfide, one must take into consideration the general principals, requirements, and recommendations for selection of cracking resistant materials as provided in the NACE International Standard NACE MR0175/ISO 15156.

Storage

Some sedimentary basins are more suitable for CO_2 storage than others. Ideal CO_2 storage formations generally have sufficient storage capacities, injection sites, seals, and stable geological environments. This means that sedimentary basins in the middle of tectonic plates, where there is less geological disturbance, are generally more secure. In addition, colder basins are preferred because they can store dense CO_2 at relatively shallow depths of 2,000 to 3,000 feet underground.[15] Mature storage formations like oil and gas fields are currently the most economic option for CO_2 storage. Oil and gas fields are well defined, their natural ability to store hydrocarbons for thousands of years proves their integrity, and an infrastructure is in place. Depleting oil and gas reservoirs and unmineable coal beds are the best near term storage options because they are mature storage formations and have value

[14] "CO_2 Surface Facilities", Version PF81–P–03–02–06. John M. Campbell & Co., 2006.
[15] *http://www.ipcc.ch/activity/srccs/SRCCS_Chapter5.pdf.*

added production of oil and methane (or other gases). Deep saline reservoirs are the best long term storage options because they represent the largest storage potential.

Depleted Oil and Gas Fields

Depleted oil and gas fields are promising geologic storage options for many reasons. First, oil and natural gases have been naturally stored in them for millions of years which prove that there is a natural seal. Second, there are years of industrial experience in the injection of CO_2 and the disposal of acid gas which contains CO_2. Third, many abandoned oil and gas fields have been studied at length. These containers have considerable storage capacity. In the U.S. alone, depleted oil and gas fields have been estimated to have the capacity to theoretically store 47 Gt of CO_2. Worldwide, these containers could theoretically hold a total of 820 Gt of CO_2.

Trapping mechanisms usually employed in oil and gas reservoirs are structural and stratigraphic, residual, mineral, and solubility.[16] CO_2 is generally compressed and injected into porous rock that is isolated by a layer of non-porous rock. After injection, some of the CO_2 will go into solution and some will react with the rock to form stable carbonates.

There are a few problems that exist with storing CO_2 in oil and gas fields. For example, the process can be costly when the distance between the fields and capturing source can be significant. Leakage is also a concern. Poorly plugged wells could allow the CO_2 to escape. Furthermore the injection pressure must be closely monitored so the process does not fracture the cap-rock.

Unmineable Coal Beds and CO_2 *Enhance Coal Bed Methane Production*

Deep unmineable coal beds provide another set of possible CO_2 storage containers. It is estimated that there are 6 trillion tons of coal sources in the U.S. and 90 percent of them are considered to by unmineable.[17] Located anywhere from 1,000 to 5,000 feet deep, these coal seams could theoretically store 140 Gt of CO_2 globally and 30 Gt of CO_2 in just the U.S.[18]

The trapping mechanism employed in coal beds is primarily chemical adsorption.[19] Coal is naturally fractured. Coal beds often have methane adsorbed onto (and weakly bonded to) pore surfaces and drilling wells can extract this coal bed methane (CBM). Additional methane can be recovered by injecting of CO_2 gas to displace the methane. Coal has a higher affinity for CO_2 than it does for methane. When a stream of CO_2 is sent through the fracture system of a coal bed, it is selectively adsorbed onto the surfaces of the coal, effectively releasing the previously adsorbed methane. The selectively adsorbed CO_2 is less likely to move. For every 2 or 3 molecules of CO_2 adsorbed, one molecule of methane is released.[20]

After rapid surface adsorption, the CO_2 begins to slowly diffuse into the coal as it is absorbed in the internal structure of the coal. When coal adsorbs a certain amount of CO_2, some scientists think that the glass-to-rubber transition temperature of the coal is lowered. As a result, some of the coal will become plasticized, allowing for increased diffusion of CO_2 through the molecular network. As pressure increases, more CO_2 is thought to be adsorbed by the coal and thus the easier the coal is plasticized and even more CO_2 can be absorbed and sequestered.[21]

Some scientists also theorize that as pressure increases, swelling of the coal increases. Coal swelling can be problematic in enhanced coal bed methane (ECBM) recovery. When CO_2 is adsorbed, it swells making the coal much less permeable. This inhibits the flow of CO_2 and thus limits the recovery of methane and the storage of CO_2.

Storage capacity of coal beds depends on many factors. For example, since adsorption increases at higher pressures, one would expect a greater storage capacity of a deeper coal bed. Higher temperatures, however, decrease the storage capacity. The water content of a coal bed can also affect the CO_2 storage capacity of a coal bed. When CO_2 mixes with water, compounds can form which can plug up the coal microstructure and restrict CO_2 flow throughout the coal bed system. Drier coal beds can,

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[16] *http://www.pnl.gov/gtsp/docs/ccs_report.pdf.*

[17] *http://www.fossil.energy.gov/programs//sequestration/geologic/index.html* or *http://www.netl.doe.gov/publications/proceedings/98/98ps/ps4-8.pdf.*

[18] *http://www.pnl.gov/gtsp/docs/ccs_report.pdf.*

[19] *http://www.pnl.gov/gtsp/docs/ccs_report.pdf.*

[20] *http://www.netl.doe.gov/technologies/carbon_seq/index.html.*

[21] *http://www.netl.doe.gov/publications/carbon_seq/presentations/awma-2003CriticalReview.pdf.*

thus, store more CO_2.[22] Dewatering of a coal bed is often required prior to CBM recovery.

Enhanced coal bed methane recovery can potentially increase the amount of methane produced up to 90 percent of the original amount.[23] This increased production of methane reduces the cost of CO_2 storage in coal beds. The injected CO_2 does not need to be pure. In fact, flue gas can be directly injected into the coal formation.

Saline Formations

Deep saline formations are the largest and most widespread of the CO_2 storage options. These formations represent an enormous potential for CO_2 storage. An advantage of the common aquifers is that the distance from the CO_2 capturing source can be small. In fact, one source estimates that 65 percent of CO_2 from U.S. power plants can be injected into saline formations without long pipeline transport.[24] These formations of porous sedimentary rock are saturated with brine and can contain high concentrations of dissolved salts.[25]

The CO_2 must be injected below 2,500 feet so that it is in a dense phase, either liquid or supercritical. Many of these storage sites are located 12,000 feet underground far below the reservoirs containing drinkable water. While the actual amount of CO_2 that can be stored is yet to be determined, the fact that they are the largest potential reservoirs is widely accepted and educated guesses have been made. One estimate predicts that 500 billion tons of CO_2 could potentially be stored in these formations in the U.S.[26] Another source estimates that there is a potential global storage capacity of 350–11,000 Gt of CO_2.[27]

The important trapping mechanisms for aquifers include structural/stratigraphic, hydrodynamic, solubility, and mineral trapping. Initially, CO_2 is contained mostly by physical trapping mechanisms, but after enough time has passed for CO_2 to react with the surrounding rock and fluid, solubility and mineral trapping means prove to be the primary trapping mechanisms.

Technical Barriers to Implementing Carbon Capture and Storage

This section will discuss several of the technical barriers to an economic CCS process. It is divided into three subsections: capture, transportation and storage.

Capture

The primary technical barriers to implementing CCS are economic. We know how to capture CO_2, but the cost is prohibitive for society. Advances in several technologies could significantly reduce the cost of capture.

Post-Combustion Capture

Due to the elevated costs, post-combustion capture is unlikely to become the technology of choice. Nevertheless, the installed base of power plants and industrial processes makes research into reducing costs in this area advisable. Specific research topics could include creating chemical absorbents which are better able to tolerate impurities and regenerate at lower energy cost. Research could also be conducted on producing steel which corrodes less quickly in the presence of these chemical absorbents.

Pre-Combustion Capture

Pre-combustion capture may be the most productive area of research. We know that gasification and similar processes work; however, due to a cost premium in a non-carbon constrained world, these processes are not widely pursued. Demonstration projects such as FutureGen would assist industry in designing more economical power plants.

Oxy-Fuel Combustion

Oxy-fuel combustion seems further from commercialization than gasification (post combustion capture). Nevertheless, research into lowering the cost of producing pure oxygen and into developing materials that can withstand higher temperatures could prove productive.

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[22] *http://www.netl.doe.gov/publications/carbon_seq/presentations/awma-2003CriticalReview .pdf.*

[23] *http://www.ipcc.ch/activity/srccs/SRCCS_Chapter5.pdf.*

[24] *http://www.netl.doe.gov/publications/carbon_seq/presentations/awma-25002003CriticalReview .pdf.*

[25] *http://www.ipcc.ch/activity/srccs/SRCCS_Chapter5.pdf.*

[26] *http://www.fossil.energy.gov/programs//sequestration/geologic/index.html.*

[27] *http://www.netl.doe.gov/publications/carbon_seq/presentations/awma–2003CriticalReview.pdf.*

Transportation

Better tools with which to inspect CO_2 pipelines are needed. The most common method to determine the condition of a pipeline is in-line inspection also known as smart pigging. When pigs are sent through a CO_2 pipeline, the CO_2 entrains into the sealing elements which keep the CO_2 from contacting the electronics in the tool. When pigs are pulled from the pipeline, the elastomers swell and often destroy the pig. The pipeline industry has successfully tested smart pigs in smaller diameter pipelines, but larger diameter pigs need to be built and the industry needs to determine if smart pigging CO_2 pipelines has unique elements.

Transporting flue gas may be required. Since flue gas is highly corrosive, some research into this technology may be warranted.

Storage

While CO_2 has been injected into the ground for many years, the energy industry focused on monitoring the CO_2 over the span of years or decades not centuries. Several technologies already should be enhanced to better track the movement of CO_2 in the subsurface. Seismic and a related technology, cross well tomography, can be better tuned to detect the presence of CO_2 and therefore monitor the movement of CO_2. Reservoir simulation can be improved to better model the movement of CO_2 and the interaction of the CO_2 with the rock. Mineralization, the process by which CO_2 converts from a gas or liquid into rock needs more study.

General

Several technologies which can be improved are common across the CCS processes. These technologies include compression, seal elements/elastomer selection and corrosion control. Compression is one of the largest costs in CCS. More efficient methods of compression could significantly reduce costs. CO_2, due to its low viscosity and tendency to remove hydrocarbon based sealants like grease, has a propensity to escape through valves. Improving sealing elements or elastomers would reduce CO_2 losses to the atmosphere. CO_2 and water form carbonic acid a highly corrosive substance. Where the CO_2 cannot remain dehydrated, improved coatings and metals would reduce costs and inadvertent losses to the environment.

Non-Technical Barriers to Implementing Carbon Capture and Storage

There are three categories of non-technical barriers to implementing carbon capture and storage: economic, legal and commercial. At this time, it is generally not economic to engage in carbon capture activities. Some legal uncertainties must be clarified before CCS can move forward, and commercial terms between various parties must be negotiated. Government action at the Federal and state level is needed to solve the first two barriers. Commercial issues can be worked between private parties once the playing field has been defined.

Some of these barriers can be illustrated by examining how CCS and CO_2 EOR could combine. When we talk about widespread CCS, people envision capturing CO_2 from power plants and storing it in the ground. Because there is an economic benefit to using CO_2 for EOR, and because the legal framework for EOR is already in place, many people think that EOR will a first step in developing the business; however, even with EOR, CCS cannot proceed without significant government action.

When CO_2 is used in EOR, it is an industrial commodity that must be supplied in relative abundance at an economic price. The only successful sources of CO_2 for EOR have been natural underground CO_2 fields, natural gas plants where nearly pure CO_2 is stripped from the gas stream to make natural gas saleable, and a coal gasification plant. The reason is cost.

For the past 25 years the price that oil producers have been willing to pay for CO_2 is 3–4 percent of the oil price where the oil price is measured in $/barrel of oil and the CO_2 is priced in terms of dollars per thousand cubic feet (MCF). This is based on personal knowledge of CO_2 prices and oil prices over the period plus a series of economic evaluations of oil field projects while I worked at Shell and Kinder Morgan. That doesn't mean that today, with prices trending toward $100 per barrel, producers are willing to buy CO_2 at $3–$4 per MCF ($57.75–$77.00 per metric ton). At this time, most producers are unwilling to bet on $100 oil. With respect to investments in CO_2 floods, they seem to be betting on $50 oil over the long haul which means that CO_2 prices must be in the $30–$40 per metric ton range.

The Intergovernmental Panel on Climate Change (IPCC) published a Special Report on CO_2 Capture and Storage. In it they compared cost estimate for carbon capture for several technologies: retrofit of existing pulverized coal (PC) plants for capture ($31–$56 per metric ton), installation of capture facilities in of new PC plants ($23–$35 per metric ton), retrofit of natural gas combined cycle plants for capture and installation of capture facilities in new NGCC plants ($33–$57 per metric ton)

and installation of capture equipment in new integrated gasification and combined cycle plants (IGCC) ($11–$32 per metric ton). Only the gasification plant could reliably supply CO_2 at price where the buyer could afford to transport the CO_2 to an oil field.[28]

Because EOR provides an economic offset to carbon capture and storage, it may provide a first step for storage in some parts of the country. The legal framework regulating the injection of CO_2 into oil fields exists; however, some legal issues present themselves when an EOR project progresses to a storage project. The right to inject CO_2 arises from the right to capture the minerals. Oil companies may inject CO_2 in order to recover the minerals. On the other hand, oil companies have not purchased the right to access the pore space to store CO_2. There is now some consensus that the pore space is owned by the surface owner and not the mineral owner. How does one define when EOR becomes storage? Can a surface owner block an EOR project from progressing to a storage project?

Similar issues arise with respect to injection into saline aquifers. While there may be no competing mineral interests, at least with oil fields, a land area had been set aside for development. A large area may be needed to store the CO_2. Will CO_2 storage operators need to use condemnation in order to gather an appropriate injection area? What rights would condemnation give an operator to use the surface?

Also of note is the liability for the storage site. This is both a commercial and legal challenge. The public does not want to pay for storage that is ineffective. Companies do not want to incur an eternal liability. Insurance companies may not be willing to insure facilities for leakage.

Commercial terms must be developed between the power companies, capture companies, transportation companies, storage companies and monitoring companies. For example, the power companies prefer not to pay for removal of hydrogen sulfide from the CO_2. Transportation companies prefer not to handle high concentrations of hydrogen sulfide because it is deadly at low concentrations. With respect to the structure of the industry, it is possible that power companies may vertically integrate from capture to storage. There will always need to be a third party to verify to the public and government that the storage site is operated properly.

Finally, the public will need to feel that its safety is not compromised and that the environment will not be unduly affected. Finally the public needs to accept CCS as safe and effective. The public trusts the government and academia more than industry. They must take the lead in selling this carbon control solution to the public.

Senator KERRY. Thank you very much, Mr. Fox, those were interesting questions.

Dr. Benson?

STATEMENT OF PROFESSOR SALLY M. BENSON, EXECUTIVE DIRECTOR, GLOBAL CLIMATE AND ENERGY PROJECT, STANFORD UNIVERSITY

Dr. BENSON. Good afternoon, Mr. Chairman, and Members of the Subcommittee, thank you for the opportunity to talk with you today. I am Sally Benson, a Professor at Stanford University, and Executive Director of the Global Climate and Energy Project.

The science behind carbon sequestration builds on concepts developed over a century in the oil and gas industry. Safe and secure sequestration can be achieved by injecting carbon dioxide into porous rocks, and trapping it underneath thick and continuous fine-textured rock, or so-called seals.

Two mechanisms are responsible for trapping, and we know they are effective, because these are the exact same mechanisms that are responsible for the existence of oil and gas reservoirs. On this

[28] The IPCC cost estimates were made in 2003–2005. During that period, based on the oil prices of that time, the CO_2 price delivered at the field needed to be in the range of $12–$38 per metric ton. Since transportation costs are about $10 per metric ton per 100 miles, transportation costs are about $10 per metric ton per 100 miles, only IGCC can supply CO_2 at economic prices. Also note that since 2005, construction costs and energy costs which are the drivers of capture costs, have increased significantly.

basis, it's straightforward to conclude that sequestration in oil and gas reservoirs is feasible.

So, what about other types of formations that have been proposed for sequestration? Saline aquifers are extremely important sequestration resources, because they have the largest capacity, and are located closer to more emission sources. The sealing mechanisms for saline aquifers are the same as for oil and gas reservoir, but here we need scientific proof that the seals are sufficiently thick, have uniformly good sealing properties, and are not penetrated by active faults.

While in principle, sequestration is straightforward, in practice, there is a great deal of science and engineering that underpins safe and effective sequestration, for example, seismic imaging for assessing and monitoring sequestration projects, and computer simulation models to predict sequestration performance.

In addition, while there are many reasons to conclude that sequestration is feasible, the question of scale can not be ignored. Today, there are three active sequestration projects. To make a significant impact on emissions reductions, thousands of projects will be needed, and each of these will be from five to ten times larger than any of the existing projects. The potential for unforeseen consequences of large-scale sequestration must be assessed, and methods to avoid them developed.

Worldwide, public and private research efforts continue to make steady progress on these issues. For example, last summer the Department of Energy funded an experiment to answer the question, what's the smallest leak that could be detected? Field testing results proved that a number of existing and innovative techniques have the sensitivity needed for reliable monitoring.

As another example, over the past several years, the Department of Energy has funded two pilot tests in Texas. These tests demonstrated that the location of the plume could be tracked and modeled. The regional sequestration partnerships will replicate these tests in different geological environments, providing valuable firsthand knowledge and experience for state and local regulators, who will one day be called upon to oversee these projects.

As a final example, the Global Climate and Energy Project has developed new theoretical models to predict how quickly secondary trapping mechanisms could permanently immobilize carbon dioxide, thus further reducing the potential for leakage.

There is also an urgent need for demonstration projects at a scale commensurate with the five to ten million tons per year of carbon dioxide emitted from a large coal-fired power plant. Plans are underway for a number of publicly and privately funded demonstration projects, and it is important that these get started now. Without definitive results from these, and even larger scale tests, policymakers, investors and society will not have the confidence to proceed with widespread deployment of CCS.

As interest in sequestration has grown, so too has the concern about long-term stewardship and liability. Who will be responsible for long-term monitoring? Who will pay to remediate a site if it starts to leak 100 years from now? The prospects of long-term stewardship and long-term financial responsibility make investors nerv-

ous, and if not addressed, will create a barrier to widespread deployment.

In part, answers to these questions are legal and institutional in nature. However, scientific research has a role to play in bounding the probability of unforeseen events, in providing a scientific framework for addressing these issues.

In particular, naturally occurring secondary trapping mechanisms, such as converting the carbon dioxide into solid minerals, can provide additional storage security, and these processes become more effective as time passes. Fundamental research is needed to quantify the potential and framework for completely reducing the risk of leakage, and for learning how to accelerate these processes, if needed.

Long-term stewardship and financial responsibility are much less daunting if the risk of unforeseen events can be shown to predictably decrease with time.

Now, coming to your final question—are there gaps in the public and private research activities? Certainly growth in Federal support for sequestration research has been impressive over the past decade, increasing from nearly nothing 10 years ago, to over $100 million in 2007.

Industrial support is also growing. But while growth in interest and support is encouraging, at the current pace of progress, convincing answer about safety and effectiveness may not be available for more than a decade. Accelerating the pace of progress requires commitment to a parallel development pathway, simultaneously building a strong, fundamental science program, providing sufficient financial resources for the pilot projects, in order to learn as much as possible from them, and expediting full-scale demonstration projects.

In closing, carbon sequestration is a promising and necessary technology. Thank you very much for the opportunity to discuss this important topic with you.

[The prepared statement of Dr. Benson follows:]

PREPARED STATEMENT OF PROFESSOR SALLY M. BENSON, EXECUTIVE DIRECTOR, GLOBAL CLIMATE AND ENERGY PROJECT, STANFORD UNIVERSITY

Good afternoon. Senator Kerry and Members of the Subcommittee, thank you for the opportunity to talk with you today. I am Sally Benson, a Professor at Stanford University and Executive Director of Stanford's Global Climate and Energy Project.

The Science Behind Safe and Effective Sequestration

The science behind safe and effective carbon dioxide sequestration builds on concepts developed from over a century of experience in the oil and gas and groundwater supply industries. Safe and secure sequestration can be achieved by injecting carbon dioxide into porous rocks and trapping it underneath thick and continuous fine-textured rocks or so-called "seals."[1] Two mechanisms are responsible for trapping[2] and we know they are effective because these are the exact same mechanisms that are responsible for the existence of oil and gas reservoirs.

[1] Since the density of carbon dioxide is less than water, unimpeded, when injected underground, it would migrate back to the land surface. Therefore "seals" are needed to trap carbon dioxide underground.

[2] Two mechanisms are responsible for effective trapping by seals: extremely low permeability—which limits the rate of flow through the seals; and extremely high capillary entry pressure—which prevents any separate phase carbon dioxide from moving into the seal (IPCC Special Report on Carbon Dioxide Capture and Storage, 2005, Cambridge University Press).

On this basis, it is straight forward to conclude that sequestration in oil and gas reservoirs is feasible. So what about the other types of formations that have been proposed for sequestration?

Saline aquifers are extremely important sequestration resources because they have the largest capacity and are located closer to more emission sources. The sealing mechanisms for saline aquifers are the same as for oil and gas reservoirs—but here we need scientific proof that the seals are sufficiently thick, have uniformly good sealing properties, and are not penetrated by active faults.

While, in principle, sequestration is straight forward—in practice there is a great deal of science and engineering that underpin safe and effective sequestration, for example: geophysical imaging to locate and assess sequestration reservoirs and seals; computer simulation models to predict sequestration performance; and geophysical monitoring technology to assure that the carbon dioxide remains sequestered.

In addition, while there many reasons to conclude that sequestration is feasible—the question of scale cannot be ignored. Today there are three active sequestration projects.[3] To make a significant impact on emission reductions, thousands of projects will be needed—and each of the projects will be from 5 to 10 times larger than any of the existing projects. The potential for unforeseen consequences of large scale sequestration must be assessed and methods to avoid them developed.

Progress on Research and Development

World-wide, public and private research efforts continue to make steady progress on basic and applied research that address these issues. For example:

- Last summer, the Department of Energy funded an experiment to answer the question—what is the smallest leak that could be detected?[4] Field testing results proved that a number of existing and innovative techniques could detect and quantify extremely low leakage rates—and have the sensitivity needed for reliable monitoring.
- As another example, over the past several years, the U.S. DOE has funded two pilot tests in Texas—the so-called Frio I and Frio II tests.[5] These tests demonstrated that high-resolution seismic methods successfully tracked migration of the plume and that, after calibration, computer simulation models could predict where and how fast the carbon dioxide moved. The U.S. DOE Regional Partnerships will replicate these types of tests in a number of different geological environments, providing valuable first-hand knowledge and experience for state and local regulators who will one day be called upon to oversee these projects.
- As a final example, the Global Climate and Energy Project at Stanford University[6] has developed new theoretical concepts to predict how quickly secondary trapping mechanisms[7] could permanently immobilize carbon dioxide—thus fur-

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[3] The three existing sequestration projects are the Sleipner Project off-shore of Norway, the Weyburn Project in Saskatchewan, and the In Salah Project in Algeria. The Sleipner Project began in 1996 and sequesters 1 Mt/year of CO_2 in a saline aquifer. The Weyburn Project, which began in 2000, is a combined CO_2 EOR and sequestration project that injects about 2 Mt/yr into an oil reservoir. The In Salah Project began in 2004 and sequesters about 1 Mt/yr in a depleting gas reservoir. A fourth project, the Snohvit Project, is expected to begin injecting 0.7 Mt/yr into a saline aquifer under the Barents Sea in 2007.

[4] The Detection Verification Facility is collaboration between several universities and national laboratories lead by Montana State University. The experiment showed that leakage of 100 kg/day over a 100 m long feature could be detected and quantified using flux accumulation chambers. A second experiment demonstrated that 300 kg/day could be detected and quantified by several methods.

[5] The Frio Pilot Tests, lead by the University of Texas at Austin, are a collaboration between university and national laboratory scientists. The first test in 2003 injected about 1,600 tons of carbon dioxide. The second test in 2006 injected about 500 tons. Extremely valuable scientific results were gained from the small-scale pilot tests, including new methods for tracking migration of carbon dioxide movement in the surface, fundamental insights about multi-phase flow of carbon dioxide and brine, and geochemical interactions between carbon dioxide and the reservoir rocks.

[6] The Global Climate and Energy Project at Stanford University funded by ExxonMobil, GE, Toyota and Schlumberger, performs fundamental breakthrough research to develop a wide range of low-carbon and carbon-free energy supply technologies—including carbon sequestration. *http://gcep.stanford.edu/*.

[7] Secondary trapping mechanisms include dissolutions of CO_2 in brine, capillary trapping and mineralization (IPCC Special Report on Carbon Dioxide Chapter and Storage, Cambridge University Press, 2005).

ther reducing the potential for leakage, even if, for example, degrading cement in an old abandoned well breached the reservoir seal.

There is a also an urgent need for demonstration projects—at a scale commensurate with sequestering the 5 to 10 million tons of carbon dioxide emitted annually from a typical coal-fired power plant. Plans have been announced or are now underway in the U.S. for at number of publicly [8] and privately [9] funded mid-to-large scale demonstration projects—and it is important they get started now. Without definitive results from these and even larger scale tests, policymakers, investors and society will not have the confidence needed to proceed with widespread deployment of CCS.

Barriers to Implementing Geological Storage

As interest in sequestration has grown, so too has the concern about long term stewardship and liability grown. Who will be responsible for long term monitoring? Who will pay to remediate a site if it starts to leak 100 years from now? The prospects for long term stewardship and long term financial responsibility make investors nervous—and if not addressed they will create a barrier to widespread deployment. In part, answers to these questions are legal and institutional in nature. However, scientific research has a large role to play in bounding the potential for unforeseen events and providing a scientific framework for addressing these issues.

In particular, naturally occurring secondary trapping mechanisms such as dissolving carbon dioxide into water, forming minerals, and capillary trapping can provide additional storage security—and these processes become more effective as time passes. Fundamental research is needed quantify the potential and time-frame for completely reducing the risk of leakage and for learning how accelerate these processes if needed. Long term stewardship and financial responsibility are much less daunting if the risk of unforeseen events can be shown to predictably decrease with time.

Gaps in Public and Private Research Activities

Now, coming to your final question—are there gaps in public and private research activities? Certainly, growth in Federal support for sequestration research has been impressive over the past decade—increasing from nearly nothing 10 years ago to over $100 M in 2007. Industrial support is also growing. But, while growing interest and support is encouraging, at the current pace of progress, convincing answers about safety and effectiveness may not be available for more than a decade. Accelerating the pace of progress requires commitment to a parallel development pathway, simultaneously

- building a strong fundamental scientific program; [10]
- providing sufficient financial resources for the pilot projects in order to learn as much as possible from them; and
- expediting full-scale demonstration projects.

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[8] Federally funded project include FutureGen and 3 recently announced sequestration projects carried out by the Plains Carbon Dioxide Reduction Partnership; Southeast Regional Carbon Sequestration Partnership; and Southwest Regional Partnership for Carbon Sequestration. All will conduct large volume tests for the storage of one million tons of carbon dioxide (CO_2) in deep saline reservoirs.

[9] Announcements for privately funded mid-to-large scale projects in the U.S. have been made by a number of companies. Examples include the BP Carson project and AEP's projects in West Virginia and Oklahoma. All of these are in the planning stage.

[10] DOE's Office of Science conducted a workshop in research opportunities in the geosciences related to sequestration (Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems, *http://www.sc.doe.gov/bes/reports/files/GEO_rpt.pdf*). Five priorities for improving our understanding of multiphase flow were identified:

- New approaches are needed to accurately predict migration of multiple fluid phases in environments that are highly heterogeneous, from the pore scale to the basin scale—over large spatial scales and long time-frames.
- Methods to quantify and predict rates of geochemical reactions between multi-phase, multi-component fluids and minerals are needed to understand how quickly dissolution and mineralization will occur.
- Fundamental scientific understanding of basin-scale geomechanical processes is needed to predict shallow crustal deformation and basin scale brine displacement caused by large and rapid anthropogenic perturbations such as injection or extraction of multiphase fluids in the subsurface.
- A new multi-disciplinary approach is needed to assess the multi-phase flow properties of membrane seals, faults and fractures—in order to determine whether or not a geological reservoir has an adequate seal.
- Dynamic field-scale imaging is needed to test and validate multi-phase flow models.

Effective communication and coordination of these three parallel development pathways will also maximize progress and ensure efficient use of resources.

In closing, carbon sequestration is a promising and necessary technology. Thank you very much for the opportunity to discuss this important topic with you.

Senator KERRY. Thank you very much, Dr. Benson.

Dr. Burruss?

STATEMENT OF DR. ROBERT C. BURRUSS, RESEARCH GEOLOGIST, ENERGY RESOURCES TEAM, U.S. GEOLOGICAL SURVEY, U.S. DEPARTMENT OF THE INTERIOR

Dr. BURRUSS. Mr. Chairman and Members of the Subcommittee, I'm Robert Burruss, a research geologist with the U.S. Geological Survey. Thank you for the opportunity to present testimony on geological sequestration of carbon dioxide. I will also briefly discuss terrestrial carbon sequestration.

Of particular importance is the evaluation of the potential geologic storage capacity for CO_2 and understanding the impact of the natural carbon cycle on the role of terrestrial sequestration to limit accumulation of CO_2 in the atmosphere.

Fossil fuel usage, a major source of carbon dioxide emissions into the atmosphere will continue in both industrialized and developing nations. The fraction of carbon emissions from all sources that must be eliminated to impact climate is large. For example, scenarios that stabilize CO_2 concentrations at about 550 parts per million, suggest that emissions may need to be reduced by as much as 70 percent. Reductions of this magnitude will involve many types of carbon management, including geologic and terrestrial sequestration, but also shifts from fossil fuels to biofuels, increased electricity generation from solar, wind and nuclear power, and increased efficiency of generation, transmission and end-use.

In geologic sequestration, carbon dioxide is separated from flue gas and injected into subsurface rock formations at depths of one to three kilometers. At these depths, CO_2 has the properties of a low-density liquid, it displaces the fluid that initially occupied the porous space, and rises buoyantly until it is retained beneath a non-permeable rock formation, otherwise known as a seal.

A critical issue for evaluation of storage capacity is the integrity and effectiveness of these seals, especially in saline reservoirs. The IPCC Special Report on Carbon Dioxide Capture and Storage, concluded that the global storage capacity of geologic formations may be able to accommodate a large fraction of the captured carbon dioxide necessary to stabilize atmospheric concentrations between 250 and 750 ppm.

However, geologic storage capacity varies on a regional and national scale, and better understanding of storage capacity is needed to address this knowledge gap. USGS experience with national and international assessments of natural resources provides the basis to develop a peer-reviewed set of methods to assess the distribution of the Nation's capacity for geologic storage of CO_2.

In addition, USGS knowledge of regional groundwater aquifer systems and groundwater chemistry will allow development of methods to assess the storage capacity of saline reservoirs. Saline reservoirs have the potential for very large storage capacities, but

the extent to which these capacities can be utilized remains unknown.

There are research questions that are important for addressing the performance and risks associated with wide scale deployment of geologic sequestration. These include understanding the capabilities of seals to recoup carbon dioxide, the potential role of abandoned wells to act as migration pathways for CO_2 and formation water, and the potential for injected CO_2 to mobilize naturally occurring trace metals and organic materials.

Carbon can also be stored in the biosphere. Terrestrial sequestration attempts to enhance transfer and retention of CO_2 from the atmosphere into vegetation and soils.

While terrestrial storage of carbon can be enhanced by appropriate land use and soil management practices, the potential reductions in atmospheric CO_2 are closely tied to the natural processes of the global carbon cycle. Although we know that naturally stored carbon is vulnerable to release to the atmosphere in a changing climate, the processes that preserve carbon in soils are poorly understood and represent a critical knowledge gap in evaluating the potential of terrestrial carbon sequestration to limit accumulation of CO_2 in the atmosphere.

In conclusion, it is clear that the challenge of reducing atmospheric carbon dioxide levels through both geological and terrestrial sequestration is a complex issue, evaluation of geologic storage capacity for carbon dioxide is needed to determine the full impact of this technology on climate change.

This information, combined with research on the feedbacks between terrestrial carbon sequestration, the carbon cycle, and climate change, will provide a scientific foundation for decisions regarding all types of carbon management.

Thank you for the opportunity to present this testimony, and I will be pleased to answer any questions you and the Members of the Committee have.

[The prepared statement of Dr. Burruss follows:]

PREPARED STATEMENT OF DR. ROBERT C. BURRUSS, RESEARCH GEOLOGIST, ENERGY RESOURCES TEAM, U.S. GEOLOGICAL SURVEY, U.S. DEPARTMENT OF THE INTERIOR

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to present testimony on terrestrial sequestration and geologic capture and storage of carbon dioxide and their role in reducing atmospheric carbon. In addition to these topics, I also plan to discuss in my statement today the role of science in evaluating the potential geologic storage capacity for industrial carbon dioxide and in furthering our understanding of the carbon cycle.

Introduction

Let me begin by saying that the challenges of addressing carbon dioxide accumulation in the atmosphere are significant. Fossil fuel usage, a major source of carbon dioxide emissions to the atmosphere, will continue in both industrialized and developing nations. Therefore, a variety of strategies are being investigated to reduce emissions and remove carbon dioxide from the atmosphere. Such strategies include the facilitated sequestration of carbon from the air to terrestrial biomass, including soils and the capture and storage of carbon dioxide in geologic formations.

The current atmospheric carbon dioxide concentration is approximately 380 parts per million volume and rising at a rate of approximately 2 parts per million volume annually, according to the most recent information from the Intergovernmental Panel on Climate Change (IPCC). The fraction of carbon emissions from all sources that must be eliminated or sequestered to impact the magnitude of climate change is large. For example, to stabilize carbon dioxide concentrations at about 550 parts

per million volume, the extent to which carbon dioxide emissions would need to be reduced may be as much as 70 percent. Reductions of this magnitude could involve implementation of several mechanisms, including geologic storage and biological sequestration, fuel shifts from fossil sources to renewable biological sources, increased electricity generation from solar and wind systems and nuclear power, and increased efficiency of power generation, transmission, and end use. Each of these mechanisms has distinct geological, hydrological, ecological, economic and social implications that should be assessed on a wide range of scales, from molecular to basin scales, to allow informed policy discussions and decisions on implementation and deployment of technologies.

Geologic Storage of Carbon

The 2005 IPCC Special Report on *Carbon Dioxide Capture and Storage* concluded that, in emissions reductions scenarios striving to stabilize global atmospheric carbon dioxide concentrations at targets ranging from 450 to 750 parts per million volume, the global storage capacity of geologic formations may be able to accommodate most of the captured carbon dioxide. However, geologic storage capacity may vary on a regional and national scale, and a more refined understanding of geologic storage capacity is needed to address this knowledge gap.

Geological storage of carbon dioxide in porous and permeable rocks involves injection of carbon dioxide into a subsurface rock unit and displacement of the fluid or formation water that initially occupied the pore space. This principle operates in all types of potential geological storage formations such as oil and gas fields, deep saline water-bearing formations, or coal beds. Because the density of injected carbon dioxide is less than the density of formation water, carbon dioxide will be buoyant in pore space filled with water and rise vertically until it is retained beneath a nonpermeable barrier (seal). A critical issue for evaluation of storage capacity is the integrity and effectiveness of these seals.

Terrestrial Carbon Sequestration

Terrestrial carbon sequestration practices seek to effect the transfer of carbon between the atmosphere and terrestrial biosphere (the earth and the living organisms that inhabit it) to reduce atmospheric carbon dioxide concentrations. Land management practices in the United States can affect the transfer of carbon from terrestrial systems into the atmosphere. Land conversion, especially deforestation, continues to be a significant source of global carbon dioxide emissions. Good land stewardship practices can reverse this and enhance biological uptake of carbon dioxide from the atmosphere, an approach termed terrestrial sequestration. Many of these practices, including tree planting and conservation tillage, are widely adopted and well understood. The Department of Agriculture is promoting the adoption of these practices through conservation programs implemented under the Farm Bill. The knowledge gained on the benefits of terrestrial sequestration will improve our understanding of the duration and extent to which the biological uptake of atmospheric carbon dioxide can be enhanced to reduce atmospheric concentration of carbon dioxide.

Role of the U.S. Geological Survey

While the USGS currently has no experience assessing the national geologic storage capacity, USGS-generated data and information were included in the Carbon Sequestration Atlas of the United States and Canada developed by the Department of Energy. In addition, our experience with national and international assessments of natural resources could allow USGS to develop geologically based methodologies to assess the national capacity for geologic storage of carbon dioxide. We envision the national geologic carbon dioxide storage assessment methodology would be largely analogous to the peer-reviewed methodologies used in USGS oil, gas, and coal resource assessments. In addition, the USGS' knowledge of regional groundwater aquifer systems and groundwater chemistry would allow USGS to develop methods to assess potential carbon storage in saline aquifers. Previous studies have postulated the existence of very large carbon dioxide storage capacities in saline aquifers, but the extent to which these capacities can be utilized remains unknown.

The USGS could create a scientifically based, multi-disciplinary methodology for geologic carbon dioxide storage assessment that can be consistently applied on a national scale. Some potential areas for further study include understanding the capabilities of seals to retain carbon dioxide and the role of abandoned wells that may act as migration pathways for carbon dioxide and formation water; defining the potential for mobilization of trace metals and organic materials by carbon dioxide reactions with minerals or dissolution of organic compounds; and understanding the role of bacteria and other microorganisms in water-rock-carbon dioxide interactions relevant to storage.

There are also a number of potential issues for further study pertaining to terrestrial sequestration, including the natural processes that affect carbon cycling. It is now widely recognized that the global carbon cycle and climate varied together, before human influence, as interactive components in a highly complex system of global feedbacks. These feedbacks have profound implications for the response of climate to anthropogenic carbon dioxide emissions, and for the potential response of the carbon cycle to changes in climate.

Along with our partners in the Department of Agriculture, the Department of Energy, and other agencies, ongoing USGS research addresses these issues. In particular, USGS research on soil carbon dynamics focuses on soil development and the buildup and stabilization of soil organic matter, a large carbon reservoir in the terrestrial biosphere, which play key roles in water distribution, and in turn control both sediment transport and carbon production and respiration. This research is critically important in explaining the processes affecting the flow of carbon dioxide from soils. The response of soils to human land use is a significant component in the global carbon dioxide budget, and their response to climate change may cause significant feedback on a global scale. Land use—particularly agriculture—significantly alters patterns of terrestrial carbon storage and transport, nutrient cycles, and erosion and sedimentation. Current models of the terrestrial carbon cycle do not adequately account for the interactions among changes in erosion, sedimentation, and soil dynamics. Additional research on variable scales (local to global) of carbon flow would provide a more thorough understanding of the carbon cycle.

Conclusion

It is clear that addressing the challenge of reducing atmospheric carbon dioxide and understanding the effect of global climate change is a complex issue with many interrelated components. A better understanding of geologic storage potential for carbon dioxide combined with research to understand the implications of terrestrial carbon sequestration on the carbon cycle would provide a scientific foundation for future decisions regarding carbon management. We believe additional study of geologic and terrestrial opportunities will better prepare decisionmakers as they deal with these issues. Thank you for the opportunity to present this testimony. I am pleased to answer questions you and other Members of the Committee might have.

Senator KERRY. Thank you, Dr. Burruss.

Dr. Hannegan?

STATEMENT OF DR. BRYAN HANNEGAN, VICE PRESIDENT, ENVIRONMENT, ELECTRIC POWER RESEARCH INSTITUTE (EPRI)

Dr. HANNEGAN. Thank you, Mr. Chairman, and Members of the Subcommittee, my name is Bryan Hannegan, and I am Environment Vice President for the Electric Power Research Institute, a non-profit, collaborative, R&D organization based in California, Tennessee and North Carolina. EPRI appreciates the opportunity to provide testimony to the Committee this afternoon on the topic of carbon sequestration technologies, and there is considerable detail in our written testimony, submitted for the record.

I would like to summarize that testimony in a few key points. The first is that advanced coal power plant technologies with integrated CO_2 capture and storage will be crucial to reducing future U.S. electric power sector CO_2 emissions.

As slide one, attached to my testimony and shown on the screen here demonstrates, a recent EPRI study looking at the technical potential for CO_2 reductions from the U.S. electric sector identified that with aggressive development and deployment of low-carbon electricity technologies, and end-use efficiency, it is technically feasible to return those emissions back to their 1990 levels, sometime around 2025, and dramatically reduce those future emissions significantly in the decades thereafter. A key technology as shown by

the red and the orange contributions on that chart is advanced coal technologies with CO_2 capture and storage.

The second point I'd like to make is that the availability of advanced coal power in integrated CO_2 capture and storage and other technologies will dramatically reduce the projected increases in the cost of wholesale electricity under any given carbon constraint going forward.

If I could get slide two, the impact under two scenarios we looked at with a macroeconomic model, on the left-hand side showing a world in which we had not advanced the ball with respect to R&D in these low-carbon energy technologies, and the right-hand one in which we had aggressively pushed energy technology R&D forward, you can see the differences between the generation mix, the limited case being defined primarily by switching to natural gas, which has its own set of challenges, as this Committee well knows, as well as significant amounts of demand reduction, which are fostered by a high price of wholesale electricity.

On the right-hand side, if you invest in energy technologies, you drive an expansion in electric energy with CO_2 capture and storage on coal plants, and with an advancement in nuclear power. The result is a difference in the price increase for delivered wholesale power between two and a half times today's value in real costs, in the limited case, and only the incremental cost of R&D in the advanced case. So, significantly, with the same amount of CO_2 abatement, the cost to the U.S. economy and to the U.S. consumer are significantly less.

The key point to proving CCS capability is going to be—as others on the panel have mentioned, the large-scale deployment of both pre- and post-combustion capture with storage, in a variety of technologies. And we envision large combined demonstrations should be encouraged in different regions, with different coals and technologies.

As shown on slide three, EPRI's *CoalFleet for Tomorrow®* program has identified the R&D pathways to demonstrate after 2020 a full portfolio of economically attractive and commercial-scale advanced coal power opportunities, suitable for use with a broad range of U.S. coal types and geologies around the Nation. The identified R&D is estimated to cost somewhere between $8 and $17 billion cumulatively between now and 2020.

While there are well-proven methods for capturing CO_2, resulting from coal gasification, no IGCC yet captures CO_2. IGCC technology is still relatively new, and needs more commercial installation.

Senator KERRY. What's the figure you gave there?

Dr. HANNEGAN. It's an EPRI-derived figure for the incremental cost of additional investment to realize the promise of this development timeline by 2020.

Senator KERRY. And what was it?

Dr. HANNEGAN. Between $8 and $17 billion between now and 2020.

Senator KERRY. Big, big, big.

Dr. HANNEGAN. In contrast to IGCC, pulverized coal technologies already mature, but it's the capture technologies which are not.

So, it's important to avoid choosing between coal technology options, and any effort we make, both public and private, should foster a full portfolio.

The final point I want to make is that in addition to the challenge of capturing the CO_2, we also faced the challenges my colleagues have mentioned of the storage issues. And there are major, non-technical barriers associated with storage, that must be addressed concurrently, before CCS can become a commercial opportunity.

That includes the permitting challenge, that includes public acceptance in the demonstration of no significant environmental impact, that includes the legal framework around the liability and who controls the pore space, and who takes liability in the event of a leakage, and it also means looking—as my colleagues have mentioned—at possible new uses of CO_2. We've been able to turn sulfur into wallboard, it's quite possible we could turn CO_2 into a useable by-product.

My testimony entails many more details behind my comments, and I look forward to your questions.

[The prepared statement of Dr. Hannegan follows:]

PREPARED STATEMENT OF DR. BRYAN HANNEGAN, VICE PRESIDENT, ENVIRONMENT, ELECTRIC POWER RESEARCH INSTITUTE (EPRI)

Introduction

Thank you, Mr. Chairman, Ranking Member Ensign, and Members of the Subcommittee. I am Bryan Hannegan, Vice President of Environment for the Electric Power Research Institute (EPRI), a non-profit, collaborative R&D organization. EPRI has principal locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee. EPRI appreciates the opportunity to provide testimony to the Committee on the topic of carbon sequestration technologies.

Through the development and deployment of advanced coal plants with integrated CO_2 capture and storage (CCS) technologies, coal power can become part of the solution to satisfying both our energy needs and our global climate change concerns. However, a sustained RD&D program at heightened levels of investment and the resolution of legal and regulatory unknowns for long-term geologic CO_2 storage will be required to achieve the promise of advanced coal with CCS technologies. The members of EPRI's *CoalFleet for Tomorrow®* program—a research collaborative comprising more than 60 organizations representing U.S. utilities, international power generators, equipment suppliers, government research organizations, coal and oil companies, and a railroad—see crucial roles for both industry and governments worldwide in aggressively pursuing collaborative RD&D over the next 20+ years to create a full portfolio of commercially self-sustaining, competitive advanced coal power generation and CCS technologies.

The key points I will make today include:

- Advanced coal power plant technologies with integrated CO_2 capture and storage (CCS) will be crucial to lowering U.S. electric power sector CO_2 emissions. They will also be crucial to substantially lowering world CO_2 emissions.
- The availability of advanced coal power and integrated CCS and other technologies could dramatically reduce the projected increases in the cost of wholesale electricity under a carbon cap, thereby saving the U.S. economy as much as $1 trillion by 2050.
- It is important to avoid choosing between coal technology options. We should foster a full portfolio of technology options.
- While there are well proven methods for capturing CO_2 resulting from coal gasification, no integrated gasification combined cycle (IGCC) yet captures CO_2. IGCC technology is still relatively new and needs more commercial installations. In contrast, pulverized coal (PC) technology is already well proven commercially in the power industry; the need is for demonstration of post-combustion capture at a commercial and affordable scale.

- There will inevitably be additional costs associated with CCS. EPRI's latest estimates suggest that the levelized cost of electricity (COE) from new coal plants (IGCC or supercritical PC) designed for capture, compression, transportation and storage of the CO_2 will be 40–80 percent higher than the COE of a conventional supercritical PC (SCPC) plant.
- EPRI's technical assessment work indicates that the preferred technology and the additional cost of electricity for CCS will depend on the coal type, location and the technology employed. Without CCS, supercritical pulverized coal (SCPC) has an advantage over IGCC. However, the additional CCS cost is generally lower with IGCC than for SCPC.
- Some studies show an advantage for IGCC with CCS with bituminous coal. With lignite coal SCPC with CCS is generally preferred. With sub-bituminous coals, SCPC with CCS and IGCC with CCS appear to show similar costs.
- Our initial work with post-combustion CO_2 capture technologies suggests we can potentially reduce the current estimated 30 percent energy penalty associated with CCS to about to 15 percent over the longer-term. Improvements in IGCC plants offer the same potential for reducing cost and energy penalty as well.
- The key to proving CCS capability is the demonstration of CCS at large-scale (on the order of 1 million tons CO_2/year) for both pre- and post-combustion capture with storage in a variety of geologies. Large combined capture and storage demonstrations should be encouraged in different regions and with different coals and technologies.
- EPRI's *CoalFleet for Tomorrow®* program has identified the RD&D pathways to demonstrate, by 2025, a full portfolio of economically attractive, commercial-scale advanced coal power and integrated CCS technologies suitable for use with the broad range of U.S. coal types. Some technologies will be ready for some fuels sooner, but the economic benefits of competition will not be realized until the full portfolio is developed.
- The identified RD&D is estimated to cost $8 billion between now and 2017 and $17 billion cumulatively by 2025, and we need to begin immediately to ensure that these climate change solution technologies will be fully tested at scale by 2025.
- Major non-technical barriers associated with CO_2 storage must be addressed before CCS can become a commercial reality, including resolution of regulatory and long-term liability uncertainties.

Background

Coal currently provides over half of the electricity used in the United States, and most forecasts of future energy use in the United States show that coal will continue to have a dominant share in our electric power generation for the foreseeable future. Coal is a stably priced, affordable, domestic fuel that can be used in an environmentally responsible manner. Through development of advanced pollution control technologies and sensible regulatory programs, emissions of criteria air pollutants from new coal-fired power plants have been reduced by more than 90 percent over the past three decades. And by displacing otherwise needed imports of natural gas or fuel oil, coal helps address America's energy security and reduces our trade deficit with respect to energy.

By 2030, according to the Energy Information Administration, the consumption of electricity in the United States is expected to increase by approximately 40 percent over current levels. At the same time, to responsibly address the risks posed by potential climate change, we must substantially reduce the greenhouse gas emissions intensity of our economy in a way which allows for continued economic growth and the benefits that energy provides. This is not a trivial matter—it implies a substantial change in the way we produce and consume electricity. Technologies to reduce CO_2 emissions from coal will necessarily be one part of an economy-wide solution that includes greater end-use efficiency, increasing renewable energy, more efficient use of natural gas, expanded nuclear power, and similar transformations in the transportation, commercial, industrial and residential sectors of our economy. In fact, our work at EPRI on climate policy has consistently shown that non-emitting technologies for electricity generation will likely be less expensive than technologies for limiting emissions of direct fossil fuel end-uses in other sectors. Paradoxically, as we seek greater limits on CO_2 across our economy, our work at EPRI suggests we will see greater amounts of electrification—but only if the technologies to do so with near-zero emissions are at hand.

The Role of Advanced Coal Generation with CO_2 Capture and Storage in a Carbon-Constrained Future

EPRI's "Electricity Technology in a Carbon-Constrained Future" study suggests that it is technically feasible to reduce U.S. electric sector CO_2 emissions by 25–30 percent relative to current emissions by 2030 while meeting the increased demand for electricity. The study showed that the largest single contributor to emissions reduction would come from the integration of CCS technologies with advanced coal-based power plants coming on-line after 2020.

Economic analyses of scenarios to achieve the study's emission reduction goals show that in 2050, a U.S. electricity generation mix based on a full portfolio of technologies, including advanced coal technologies with integrated CCS and advanced light water nuclear reactors, results in wholesale electricity prices at less than half of the wholesale electricity price for a generation mix without advanced coal/CCS and nuclear power. In the case with advanced coal/CCS and nuclear power, the cost to the U.S. economy of a CO_2 emissions reduction policy is $1 trillion less than in the case without advanced coal/CCS and nuclear power, with a much stronger manufacturing sector. Both of these analyses are documented in the 2007 EPRI Summer Seminar Discussion paper, "The Power to Reduce CO_2 Emissions—the Full Portfolio," available at *http://epri-reports.org/DiscussionPaper2007.pdf*.

Accelerating RD&D on Advanced Coal Technologies with CO_2 Capture and Storage—Investment and Time Requirements

The portfolio aspect of advanced coal with integrated CCS technologies must be emphasized because no single advanced coal technology (or any generating technology) has clear-cut economic advantages across the range of U.S. applications. The best strategy for meeting future electricity needs while addressing climate change concerns and minimizing economic disruption lies in developing a *full portfolio* of technologies from which power producers (and their regulators) can choose the option best suited to local conditions and preferences and provide power at the lowest cost to the customer. Toward this end, four major technology efforts related to CO_2 emissions reduction from coal-based power systems must be undertaken:

1. Increased efficiency and reliability of integrated gasification combined cycle (IGCC) power plants.
2. Increased thermodynamic efficiency of pulverized-coal (PC) power plants.
3. Improved technologies for capture of CO_2 from coal combustion- and gasification-based power plants.
4. Reliable, acceptable technologies for long-term storage of captured CO_2.

Identification of mechanisms to share RD&D financial and technical risks and to address legal and regulatory uncertainties must take place as well.

In short, a comprehensive recognition of all the factors needed to hasten deployment of competitive, commercial advanced coal and integrated CO_2 capture and storage technologies—and implementation of realistic, pragmatic plans to overcome barriers—is the key to meeting the challenge to supply affordable, environmentally responsible energy in a carbon-constrained world.

A typical path to develop a technology to commercial maturity consists of moving from the conceptual stage to laboratory testing, to small pilot-scale tests, to larger-scale tests, to multiple full-scale demonstrations, and finally to deployment in full-scale commercial operations. For capital-intensive technologies such as advanced coal power systems, each stage can take years or even a decade to complete, and each sequential stage entails increasing levels of investment. As depicted in Figure 1, several key advanced coal power and CCS technologies are now in (or approaching) an "adolescent" stage of development. This is a time of particular vulnerability in the technology development cycle, as it is common for the expected costs of full-scale application to be higher than earlier estimates when less was known about scale-up and application challenges. Public agency and private funders can become disillusioned with a technology development effort at this point, but as long as fundamental technology performance results continue to meet expectations, and a path to cost reduction is clear, perseverance by project sponsors in maintaining momentum is crucial.

Unexpectedly high costs at the mid-stage of technology development have historically come down following market introduction, experience gained from "learning-by-doing," realization of economies of scale in design and production as order volumes rise, and removal of contingencies covering uncertainties and first-of-a-kind costs. An International Energy Agency study led by Carnegie Mellon University (CMU) observed this pattern of cost-reduction-over-time for power plant environmental controls, and CMU predicts a similar reduction in the cost of power plant

CO_2 capture technologies as the cumulative installed capacity grows.[1] EPRI concurs with their expectations of experience-based cost reductions and believes that RD&D on specifically identified technology refinements can lead to greater cost reductions sooner in the deployment phase.

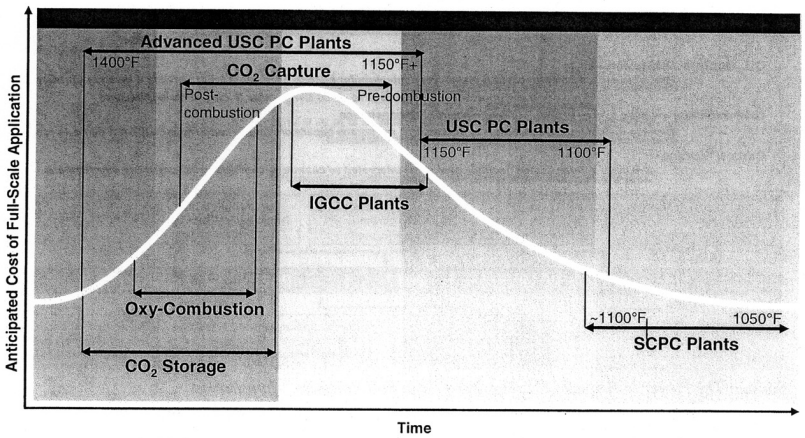
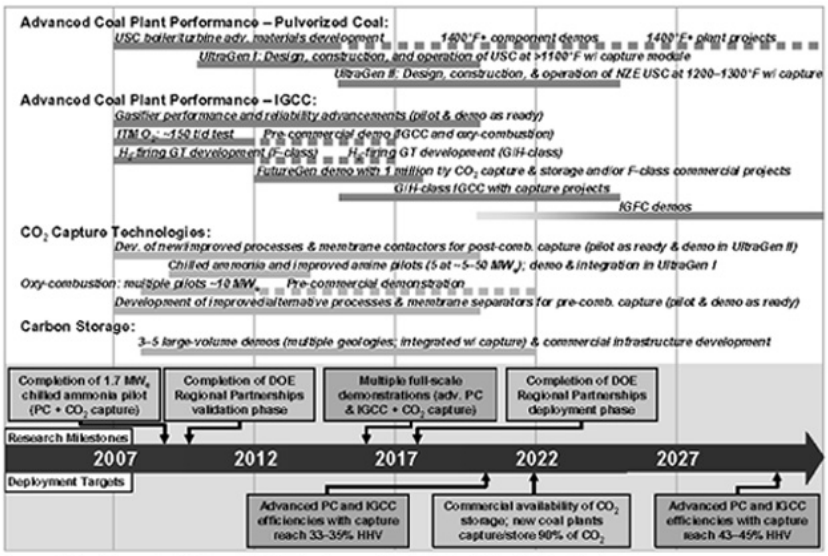


Figure 1 – Model of the development status of major advanced coal and CO_2 capture and storage technologies (temperatures shown for pulverized coal technologies are turbine inlet steam temperatures)

Of the coal-based power generating and carbon sequestration technologies shown in Figure 1, only supercritical pulverized coal (SCPC) technology has reached commercial maturity. It is crucial that other technologies in the portfolio—namely ultra-supercritical (USC) PC, integrated gasification combined cycle (IGCC), CO_2 capture (pre-combustion, post-combustion, and oxy-combustion), and CO_2 storage—be given sufficient support to reach the stage of declining constant dollar costs *before* society's requirements for greenhouse gas reductions compel their application in large numbers.

Figure 2 depicts the major activities in each of the four technology areas that must take place to achieve a robust set of integral advanced coal/CCS solutions. Important, but not shown in the figure, are the interactions between RD&D activities. For example, the ion transport membrane (ITM) oxygen supply technology shown under IGCC can also be applied to oxy-combustion PC units. Further, while the individual goals related to efficiency, CO_2 capture, and CO_2 storage present major challenges, significant challenges also arise from complex interactions that occur when CO_2 capture processes are integrated with gasification- and combustion-based power plant processes.

[1] IEA Greenhouse Gas R&D Programme (IEA GHG), "Estimating Future Trends in the Cost of CO_2 Capture Technologies," 2006/5, January 2006.



Source: The Power to Reduce CO2 Emissions – the Full Portfolio," http://epri-reports.org/DiscussionPaper2007.pdf

Figure 2 – Timing of advanced coal power system and CO_2 capture and storage RD&D activities and milestones

Reducing CO_2 Emissions Through Improved Coal Power Plant Efficiency—A Key Companion to CCS that Lowers Cost and Energy Requirements

Improved thermodynamic efficiency reduces CO_2 emissions by reducing the amount of fuel required to generate a given amount of electricity. A two-percentage point gain in efficiency provides a reduction in fuel consumption of roughly 5 percent and a similar reduction in flue gas and CO_2 output. Because the size and cost of CO_2 capture equipment is determined by the volume of flue gas to be treated, higher power block efficiency reduces the capital and energy requirements for CCS. Depending on the technology used, improved efficiency can also provide similar reductions in criteria air pollutants, hazardous air pollutants, and water consumption.

A typical baseloaded 500 MW (net) coal plant emits about 3 million metric tons of CO_2 per year. Individual plant emissions vary considerably given differences in plant steam cycle, coal type, capacity factor, and operating regimes. For a given fuel, however, a new supercritical PC unit built today might produce 5–10 percent less CO_2 per megawatt-hour (MWh) than the existing fleet average for that coal type.

With an aggressive RD&D program on efficiency improvement, new ultra-supercritical (USC PC) plants could reduce CO_2 emissions per MWh by up to 25 percent relative to the existing fleet average. Significant efficiency gains are also possible for IGCC plants by employing advanced gas turbines and through more energy-efficient oxygen plants and synthesis (fuel) gas cleanup technologies.

EPRI and the Coal Utilization Research Council (CURC), in consultation with DOE, have identified a challenging but achievable set of milestones for improvements in the efficiency, cost, and emissions of PC and coal-based IGCC plants. The EPRI–CURC Roadmap projects an overall improvement in the thermal efficiency of state-of-the art generating technology from 38–41 percent in 2010 to 44–49 percent by 2025 (on a higher heating value [HHV] basis; see Table 1). As Table 1 indicates, power-block efficiency gains (*i.e.,* without capture systems) will be offset by the energy required for CO_2 capture, but as noted, they are important in reducing the overall cost of CCS. Coupled with opportunities for major improvements in the energy efficiency of CO_2 capture processes per se, aggressive pursuit of the EPRI–CURC RD&D program offers the prospect of coal power plants *with* CO_2 capture in 2025 that have net efficiencies meeting or exceeding current-day power plants without CO_2 capture.

It is also important to note that the numeric ranges in Table 1 are not simply a reflection of uncertainty, but rather they underscore an important point about dif-

ferences among U.S. coals. The natural variations in moisture and ash content and combustion characteristics between coals have a significant impact on attainable efficiency. An advanced coal plant firing Wyoming and Montana's Powder River Basin (PRB) coal, for example, would likely have an HHV efficiency 2 percentage points lower than the efficiency of a comparable plant firing Appalachian bituminous coals. Equally advanced plants firing lignite would likely have efficiencies 2 percentage points lower than their counterparts firing PRB. Any government incentive program with an efficiency-based qualification criterion should recognize these inherent differences in the attainable efficiencies for plants using different ranks of coal.

Table 1.—Efficiency Milestones in EPRI–CURC Roadmap

	2010	2015	2020	2025
PC & IGCC Systems *(Without CO_2 Capture)*	38–41% HHV	39–43% HHV	42–46% HHV	44–49% HHV
PC & IGCC Systems *(With CO_2 Capture*)*	31–32% HHV	31–35% HHV	33–39% HHV	39–46% HHV

**Efficiency values reflect impact of 90 percent CO_2 capture, but not compression or transportation.*

New Plant Efficiency Improvements—IGCC

Although IGCC is not yet a mature technology for coal-fired power plants, chemical plants around the world have accumulated a 100-year experience base operating coal-based gasification units and related gas cleanup processes. The most advanced of these units are similar to the front end of a modern IGCC facility. Similarly, several decades of experience firing natural gas and petroleum distillate have established a high level of maturity for the basic combined cycle generating technology. Nonetheless, ongoing RD&D continues to provide significant advances in the base technologies, as well as in the suite of technologies used to integrate them into an IGCC generating facility.

Efficiency gains in currently proposed IGCC plants will come from the use of new "FB-class" gas turbines, which will provide an overall plant efficiency gain of about 0.6 percentage point (relative to IGCC units with FA-class models, such as Tampa Electric's Polk Power Station). This corresponds to a decrease in the rate of CO_2 emissions per MWh of about 1.5 percent. Alternatively, this means 1.5 percent less fuel is required per MWh of output, and thus the required size of pre-combustion water-gas shift and CO_2 separation equipment would be slightly smaller.

Figure 3 depicts the anticipated time-frame for further developments identified by EPRI's *CoalFleet for Tomorrow®* program that promise a succession of significant improvements in IGCC unit efficiency. Key technology advances under development include:

- larger capacity gasifiers (often via higher operating pressures that boost throughput without a commensurate increase in vessel size).
- integration of new gasifiers with larger, more efficient G- and H-class gas turbines.
- use of ion transport membrane or other more energy-efficient technologies in oxygen plants.
- warm synthesis gas cleanup and membrane separation processes for CO_2 capture that reduce energy losses in these areas.
- recycle of liquefied CO_2 to replace water in gasifier feed slurry (reducing heat loss to water evaporation).
- hybrid combined cycles using fuel cells to achieve generating efficiencies exceeding those of conventional combined cycle technology.

Improvements in gasifier reliability and in control systems also contribute to improved annual average efficiency by minimizing the number and duration of startups and shutdowns.

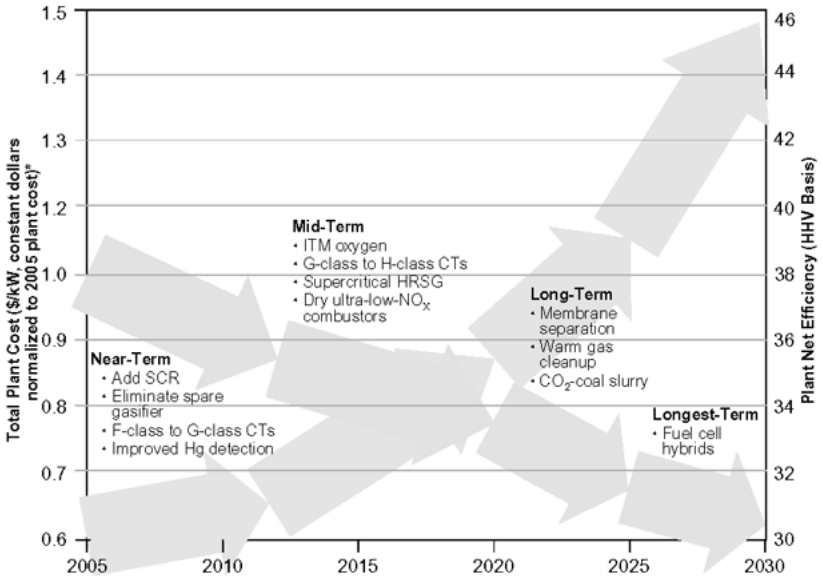


Figure 3 – RD&D path for capital cost reduction (falling arrows) and efficiency improvement (rising arrows) for IGCC power plants with 90% CO_2 capture

** For a slurry-fed gasifier designed for 90% unit availability and 90% pre-combustion CO_2 capture using Pittsburgh #8 bituminous coal; cost normalization using Chemical Engineering Plant Cost Index or equivalent. A similar trend is observed in analyses of dry-fed gasifiers using Power River Basin subbituminous coal, although the absolute values vary somewhat from those shown.*

Counteracting Gas Turbine Output Loss at High Elevations. IGCC plants designed for application in high-elevation locations must account for the natural reduction in gas turbine power output that occurs where the air is thin. This phenomenon is rooted in the fundamental volumetric flow limitation of a gas turbine, and can reduce power output by up to 15 percent at an elevation of 5,000 feet (relative to a comparable plant at sea level). EPRI is exploring measures to counteract this power loss, including inlet air chilling (a technique used at natural gas power plants to mitigate the power loss that comes from thinning of the air on a hot day) and use of supplemental burners between the gas turbine and steam turbine to boost the plant's steam turbine section generating capacity.

Larger, Higher Firing Temperature Gas Turbines. For plants coming on-line around 2015, the larger size G-class gas turbines, which operate at higher firing temperatures (relative to F-class machines) can improve efficiency by 1 to 2 percentage points while also decreasing capital cost per kW capacity. The H-class gas turbines coming on-line in the same timeframe, which also feature higher firing temperatures as well as steam-based internal cooling of hot turbine components, will provide a further increase in efficiency and capacity.

Ion Transport Membrane-Based Oxygen Plants. Most gasifiers used in IGCC plants require a large quantity of high-pressure, high purity oxygen, which is typically generated onsite with an expensive and energy-intensive cryogenic process. The ITM process allows the oxygen in high-temperature air to pass through a membrane while preventing passage of non-oxygen atoms. According to developers, an ITM-based oxygen plant consumes 35–60 percent less power and costs 35 percent less than a cryogenic plant. EPRI is performing a due diligence assessment of this technology in advance of potential participation in technology scale-up efforts.

Supercritical Heat Recovery Steam Generators. In IGCC plants, hot exhaust gas exiting the gas turbine is ducted into a heat exchanger known as a heat recovery steam generator (HRSG) to transfer energy into water-filled tubes producing steam to drive a steam turbine. This combination of a gas turbine and steam turbine power cycles produces electricity more efficiently than either a gas turbine or steam turbine alone. As with conventional steam power plants, the efficiency of the steam cycle in a combined cycle plant increases when turbine inlet steam temperature and

pressure are increased. The higher exhaust temperatures of G- and H-class gas turbines offer the potential for adoption of more-efficient supercritical steam cycles. Materials for use in a supercritical HRSG are generally established, and thus should not pose a barrier to technology implementation once G- and H-class gas turbines become the standard for IGCC designs.

Synthesis Gas Cleaning at Higher Temperatures. The acid gas recovery (AGR) processes currently used to remove sulfur compounds from synthesis gas require that the gas and solvent be cooled to about 100 °F, thereby causing a loss in efficiency. Further costs and efficiency loss are inherent in the process equipment and auxiliary steam required to recover the sulfur compounds from the solvent and convert them to useable products. Several DOE-sponsored RD&D efforts aim to reduce the energy losses and costs imposed by this recovery process. These technologies (described below) could be ready—with adequate RD&D support—by 2020:

- The Selective Catalytic Oxidation of Hydrogen Sulfide process eliminates the Claus and Tail Gas Treating units, along with the traditional solvent-based AGR contactor, regenerator, and heat exchangers, by directly converting hydrogen sulfide (H_2S) to elemental sulfur. The process allows for a higher operating temperature of approximately 300 °F, which eliminates part of the low-temperature gas cooling train. The anticipated benefit is a net capital cost reduction of about $60/kW along with an efficiency gain of about 0.8 percentage point.
- The RTI/Eastman High-Temperature Desulfurization System uses a regenerable dry zinc oxide sorbent in a dual loop transport reactor system to convert H_2S and COS to H_2O, CO_2, and SO_2. Tests at Eastman Chemical Company have shown sulfur species removal rates above 99.9 percent, with 10 ppm output versus 8000+ ppm input sulfur, using operating temperatures of 800–1000 °F. This process is also being tested for its ability to provide a high-pressure CO_2 by-product. The anticipated benefit for IGCC, compared with using a standard oil-industry process for sulfur removal, is a net capital cost reduction of $60–$90 per kW, a thermal efficiency gain of 2–4 percent for the gasification process, and a slight reduction in operating cost. Tests are also under way for a multi-contaminant removal processes that can be integrated with the transport desulfurization system at temperatures above 480 °F.

Liquid CO_2-Coal Slurrying for Gasification of Low-Rank Coals. Future IGCC plants with CCS may recycle some of the recovered liquid CO_2 to replace water as the slurrying medium for the coal feed. This is expected to increase gasification efficiency for all coals, but particularly for subbituminous coal and lignite, which have naturally high moisture contents. The liquid CO_2 has a lower heat of vaporization than water and is able to carry more coal per unit mass of fluid. The liquid CO_2-coal slurry will flash almost immediately upon entering the gasifier, providing good dispersion of the coal particles and potentially yielding the higher performance of a dry-fed gasifier with the simplicity of a slurry-fed system.

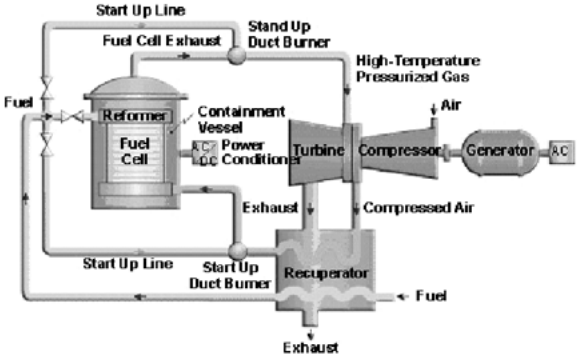
Traditionally, slurry-fed gasification technologies have a cost advantage over conventional dry-fed fuel handling systems, but they suffer a large performance penalty when used with coals containing a large fraction of water and ash. EPRI identified CO_2 coal slurrying as an innovative fuel preparation concept 20 years ago, when IGCC technology was in its infancy. At that time, however, the cost of producing liquid CO_2 was too high to justify the improved thermodynamic performance. Requirements for CCS change that, as it will substantially reduce the incremental cost of producing a liquid CO_2 stream.

To date, CO_2-coal slurrying has only been demonstrated at pilot scale and has yet to be assessed in feeding coal to a gasifier, so the estimated performance benefits remain to be confirmed. It will first be necessary, however, to update previous studies to quantify the potential benefit of liquid CO_2 slurries with IGCC plants designed for CO_2 capture. If the predicted benefit is economically advantageous, a significant amount of scale-up and demonstration work would be required to qualify this technology for commercial use.

Fuel Cells and IGCC. No matter how far gasification and turbine technologies advance, IGCC power plant efficiency will never progress beyond the inherent thermodynamic limits of the gas turbine and steam turbine power cycles (along with lower limits imposed by available materials technology). Several IGCC-fuel cell hybrid power plant concepts (IGFC) aim to provide a path to coal-based power generation with net efficiencies that exceed those of conventional combined cycle generation.

Along with its high thermal efficiency, the fuel cell hybrid cycle reduces the energy consumption for CO_2 capture. The anode section of the fuel cell produces a stream that is highly concentrated in CO_2. After removal of water, this stream can be compressed for sequestration. The concentrated CO_2 stream is produced without having to include a water-gas shift reactor in the process (see Figure 4). This fur-

ther improves the thermal efficiency and decreases capital cost. IGFC power systems are a long-term solution, however, and are unlikely to see full-scale demonstration until about 2030.



Source: U.S. Department of Energy; http://www.netl.doe.gov/technologies/coalpower/fuelcells/hybrids.html

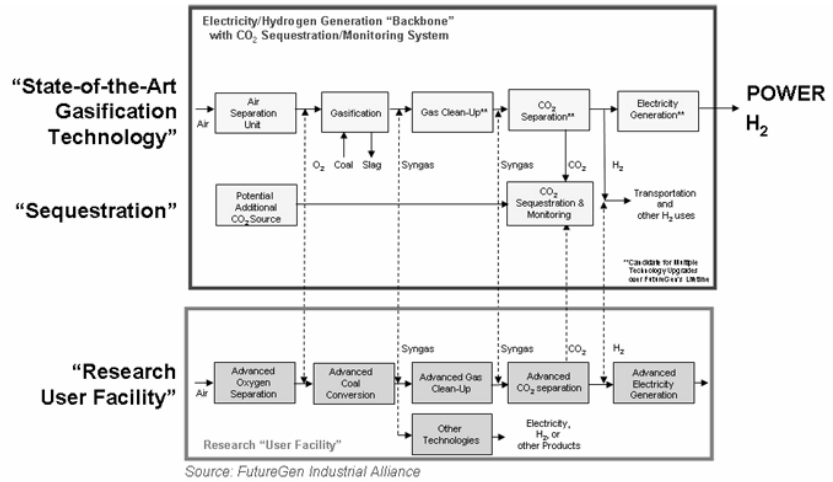
Figure 4 – Schematic of fuel cell-turbine hybrid

Role of FutureGen. The FutureGen Industrial Alliance and DOE are building a first-of-its-kind, near-zero emissions coal-fed IGCC power plant integrated with CCS. The commencement of full-scale operations is targeted for 2013. The project aims to sequester CO_2 in a representative geologic formation at a rate of at least one million metric tons per year.

The FutureGen design will address scaling and integration issues for coal-based, zero emissions IGCC plants. In its role as a "living laboratory," FutureGen is designed to validate additional advanced technologies that offer the promise of clean environmental performance at a reduced cost and increased reliability. FutureGen will have the flexibility to conduct full-scale and slipstream tests of such scalable advanced technologies as:

- Membrane processes to replace cryogenic separation for oxygen production.
- An advanced transport reactor sidestream with 30 percent of the capacity of the main gasifier.
- Advanced membrane and solvent processes for H_2 and CO_2 separation.
- A raw gas shift reactor that reduces the upstream clean-up requirements.
- Ultra-low-NO_X combustors that can be used with high-hydrogen synthesis gas.
- A fuel cell hybrid combined cycle pilot.
- Challenging first-of-a-kind system integration.
- Smart dynamic plant controls including a CO_2 management system.

Figure 5 provides a schematic of the "backbone" and "research platform" process trains envisioned for the FutureGen plant.



Source: FutureGen Industrial Alliance

Figure 5 – FutureGen technology platforms

Figure 6 summarizes EPRI's recommended major RD&D activities for improving the efficiency and cost of IGCC technologies with CO_2 capture.

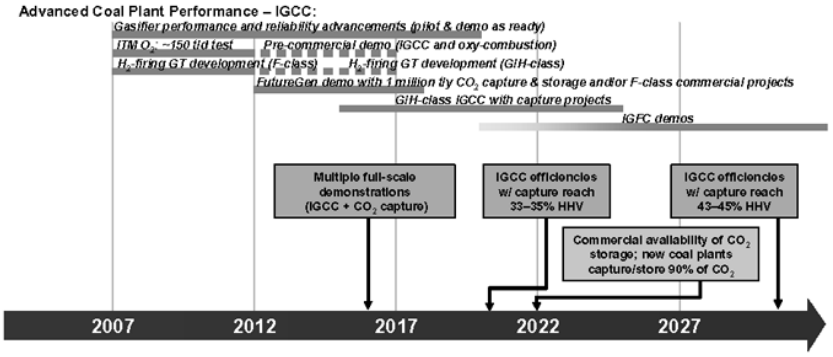


Figure 6 – Timing of advanced IGCC and CO_2 capture integration RD&D activities and milestones

New Plant Efficiency Improvements—Advanced Pulverized Coal

Pulverized-coal power plants have long been a primary source of reliable and affordable power in the United States and around the world. The advanced level of maturity of the technology, along with basic thermodynamic principles, suggests that significant efficiency gains can most readily be realized by increasing the operating temperatures and pressures of the steam cycle. Such increases, in turn, can be achieved only if there is adequate development of suitable materials and new boiler and steam turbine designs that allow use of higher steam temperatures and pressures.

Current state-of-the-art plants use supercritical main steam conditions (*i.e.,* temperature and pressure above the "critical point" where the liquid and vapor phases of water are indistinguishable). SCPC plants typically have main steam conditions up to 1100 °F. The term "ultra-supercritical" is used to describe plants with main steam temperatures in excess of 1100 °F and potentially as high as 1400 °F.

Achieving higher steam temperatures and higher efficiency will require the development of new corrosion-resistant, high-temperature nickel alloys for use in the boiler and steam turbine. In the United States, these challenges are being address by the Ultra-Supercritical Materials Consortium, a DOE R&D program involving En-

ergy Industries of Ohio, EPRI, the Ohio Coal Development Office, and numerous equipment suppliers. EPRI provides technical management for the consortium. Results are applicable to all ranks of coal. As noted, higher power block efficiencies translate to lower costs for post-combustion CO_2 capture equipment.

It is expected that a USC PC plant operating at about 1300 °F will be built during the next seven to 10 years, following the demonstration and commercial availability of advanced materials from these programs. This plant would achieve an efficiency (before installation of CO_2 capture equipment) of about 45 percent (HHV) on bituminous coal, compared with 39 percent for a current state-of-the-art plant, and would reduce CO_2 production per net MWh by about 15 percent.

Ultimately, nickel-base alloys are expected to enable stream temperatures in the neighborhood of 1400 °F and pre-capture generating efficiencies up to 47 percent HHV with bituminous coal. This approximately 10 percentage point improvement over the efficiency of a new subcritical pulverized-coal plant would equate to a decrease of about 25 percent in CO_2 and other emissions per MWh. The resulting saving in the cost of subsequently installed CO_2 capture equipment is substantial.

Figure 7 illustrates a timeline developed by EPRI's *CoalFleet for Tomorrow*® program to establish efficiency improvement and cost reduction goals for USC PC plants with CO_2 capture.

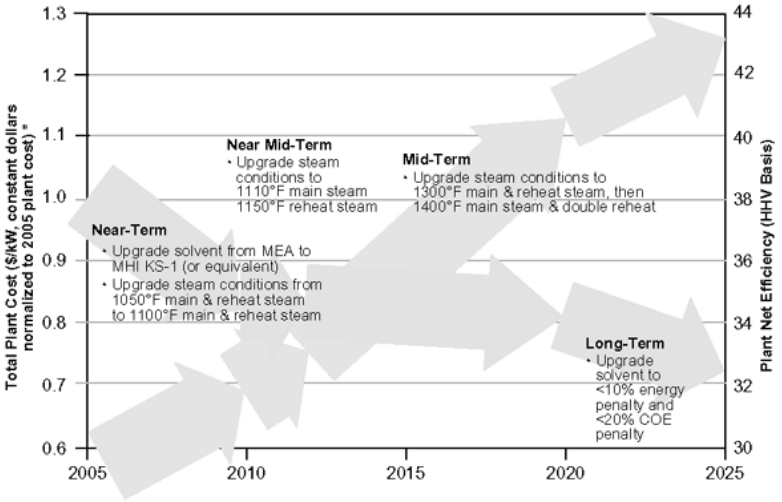


Figure 7 – RD&D path for capital cost reduction (falling arrows) and efficiency improvement (rising arrows) for PC power plants with 90% CO_2 capture

** For a unit designed for 90% unit availability and 90% post-combustion CO_2 capture firing a Pittsburgh #8 bituminous coal; cost normalization using Chemical Engineering Plant Cost Index or equivalent. A similar trend is observed in analyses of PC units with CCS using other U.S. coals, although the efficiency values are up to two percentage points lower for units firing subbituminous coal such as Powder River Basin and up to four percentage points lower for units firing lignite.*

UltraGen Ultra-Supercritical (USC) Pulverized Coal (PC) Commercial Projects. EPRI and industry representatives have proposed a program to support commercial projects that demonstrate advanced PC and CCS technologies. The vision entails construction of two (or more) commercially operated USC PC power plants that combine state-of-the-art pollution controls, ultra-supercritical steam power cycles, and innovative CO_2 capture technologies.

The UltraGen I plant will use the best of today's proven ferritic steels in high-temperature boiler and steam turbine components, while UltraGen II will be the first plant in the United States to feature nickel-based alloys that are able to withstand the higher temperatures of advanced ultra-supercritical steam conditions.

UltraGen I will demonstrate CO_2 capture modules that separate about 1 million tons CO_2/yr using the best established technology. This system will be about 6 times the size of the largest CO_2 capture system operating on a coal-fired boiler today. UltraGen II will double the size of the UltraGen I CO_2 capture system, and may demonstrate a new class of chemical solvent if one of the emerging low-regeneration-energy processes has reached a sufficient stage of development. Both plants will

demonstrate ultra-low emissions. Both UltraGen demonstration plants will dry and compress the captured CO_2 for long-term geologic storage and/or use in enhanced oil or gas recovery operations. Figure 8 depicts the proposed key features of UltraGen I and II.

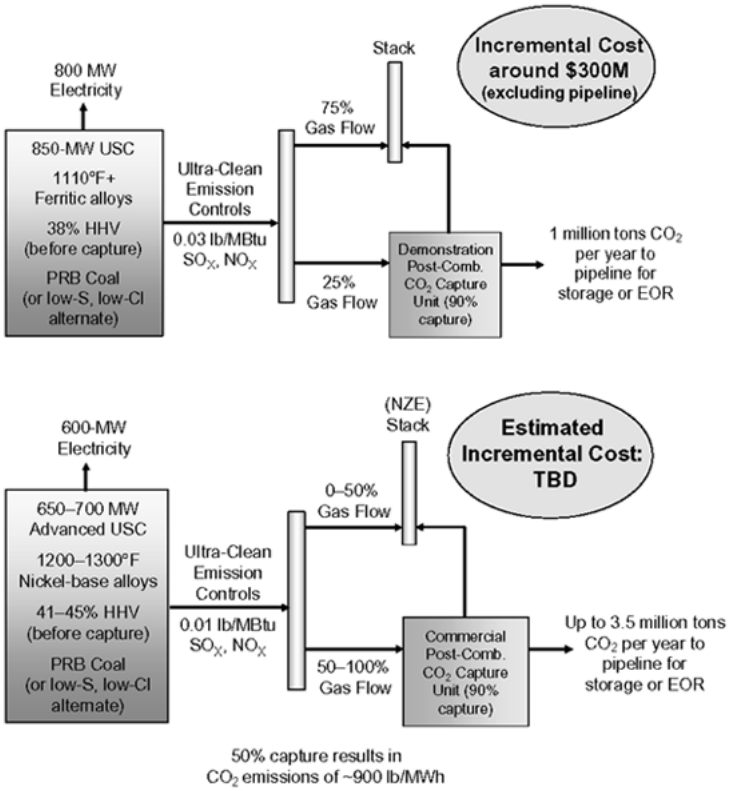


Figure 8 – Key parameters for UltraGen I (upper schematic) and UltraGen II (lower schematic), assuming a subbituminous feed coal such as Powder River Basin

To provide a platform for testing and developing emerging PC and CCS technologies, the UltraGen program will allow for technology trials at existing sites as well as at the sites of new projects. Unlike FutureGen, EPRI expects the UltraGen projects will be commercially dispatched by electricity grid operators. The differential cost to the host company for demonstrating these improved features are envisioned to be offset by any available tax credits (or other incentives) and by funds raised through an industry-led consortium formed by EPRI.

The UltraGen projects represent the type of "giant step" collaborative efforts that need to be taken to advance integrated PC/CCS technology to the next phase of evolution and assure competitiveness in a carbon-constrained world. Because of the time and expense for each "design and build" iteration for coal power plants (3 to 5 years not counting the permitting process and ~$2 billion), there is no room for hesitation in terms of commitment to advanced technology validation and demonstration projects.

The UltraGen projects will resolve technical and economic barriers to the deployment of USC PC and CCS technology by providing a shared-risk vehicle for testing and validating high-temperature materials, components, and designs in plants also providing superior environmental performance.

Figure 9 summarizes EPRI's recommended major RD&D activities for improving the efficiency and cost of USC PC technologies with CO_2 capture.

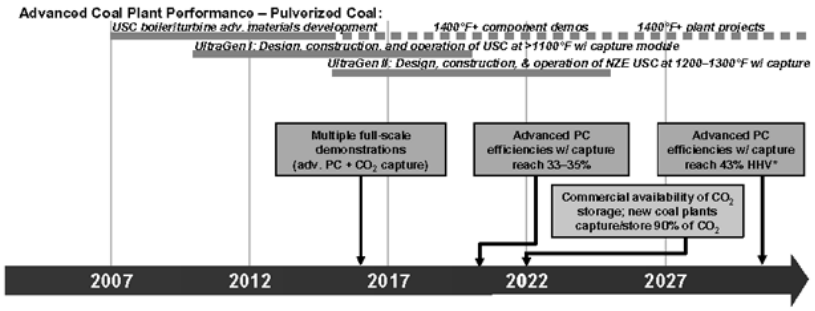


Figure 9 – Timing of advanced PC and CO_2 capture integration RD&D activities and milestones

Efficiency Improvement and CCS Retrofits for the Existing PC Fleet. It would be economically advantageous to operate the many reliable subcritical PC units in the U.S. fleet well into the future. Premature replacement of these units or mandatory retrofit of these units for CO_2 capture en masse would be economically prohibitive. Their flexibility for load following and provision of support services to ensure grid stability makes them highly valuable. With equipment upgrades, many of these units can realize modest efficiency gains, which, when accumulated across the existing generating fleet could make a sizable reduction in CO_2 emissions. For some existing plants, retrofit of CCS will make sense, but specific plant design features, space limitations, and economic and regulatory considerations must be carefully analyzed to determine whether retrofit-for-capture is feasible.

These upgrades depend on the equipment configuration and operating parameters of a particular plant and may include:

- turbine blading and steam path upgrades.
- turbine control valve upgrades for more efficient regulation of steam.
- cooling tower and condenser upgrades to reduce circulating water temperature, steam turbine exhaust backpressure, and auxiliary power consumption.
- cooling tower heat transfer media upgrades.
- condenser optimization to maximize heat transfer and minimize condenser temperature.
- condenser air leakage prevention/detection.
- variable speed drive technology for pump and fan motors to reduce power consumption.
- air heater upgrades to increase heat recovery and reduce leakage.
- advanced control systems incorporating neural nets to optimize temperature, pressure, and flow rates of fuel, air, flue gas, steam, and water.
- optimization of water blowdown and blowdown energy recovery.
- optimization of attemperator design, control, and operating scenarios.
- sootblower optimization via "intelligent" sootblower system use.
- coal drying (for plants using lignite and subbituminous coals).

Coal Drying for Increased Generating Efficiency. Boilers designed for high-moisture lignite have traditionally employed higher feed rates (lb/hr) to account for the large latent heat load to evaporate fuel moisture. An innovative concept developed by Great River Energy (GRE) and Lehigh University uses low-grade heat recovered from within the plant to dry incoming fuel to the boiler, thereby boosting plant efficiency and output. [In contrast, traditional thermal drying processes are complex and require high-grade heat to remove moisture from the coal.] Specifically, the GRE approach uses steam condenser and boiler exhaust heat exchangers to heat air and water fed to a fluidized-bed coal dryer upstream of the plant pulverizers. Based on successful tests with a pilot-scale dryer and more than a year of continuous operation with a prototype dryer at its Coal Creek station, GRE (with U.S. Department of Energy support and EPRI technical consultation) is now building a full suite of

dryers for Unit 2 (*i.e.,* a commercial-scale demonstration). In addition to the efficiency and CO_2 emission reduction benefits from reducing the lignite feed moisture content by about 25 percent, the plant's air emissions will be reduced as well.[2] Application of this technology is not limited to PC units firing lignite. EPRI believes it may find application in PC units firing subbituminous coal and in IGCC units with dry-fed gasifiers using low-rank coals.

Improving CO_2 Capture Technologies

CCS entails pre-combustion or post-combustion CO_2 capture technologies, CO_2 drying and compression (and sometimes further removal of impurities), and the transportation of separated CO_2 to locations where it can be stored away from the atmosphere for centuries or longer.

Albeit at considerable cost, CO_2 capture technologies can be integrated into all coal-based power plant technologies. For both new plants and retrofits, there is a tremendous need (and opportunity) to reduce the energy required to remove CO_2 from fuel gas or flue gas. Figure 10 shows a selection of the key technology developments and test programs needed to achieve commercial CO_2 capture technologies for advanced coal combustion- and gasification-based power plants at a progressively shrinking constant-dollar levelized cost-of-electricity premium. Specifically, the target is a premium of about $6/MWh in 2025 (relative to plants at that time without capture) compared with an estimated 2010 cost premium of perhaps $40/MWh (not counting the cost of transportation and storage). Such a goal poses substantial engineering challenges and will require major investments in RD&D to roughly halve the currently large energy requirements (operating costs) associated with CO_2 solvent regeneration. Achieving this goal will allow power producers to meet the public demand for stable electricity prices while reducing CO_2 emissions to address climate change concerns.

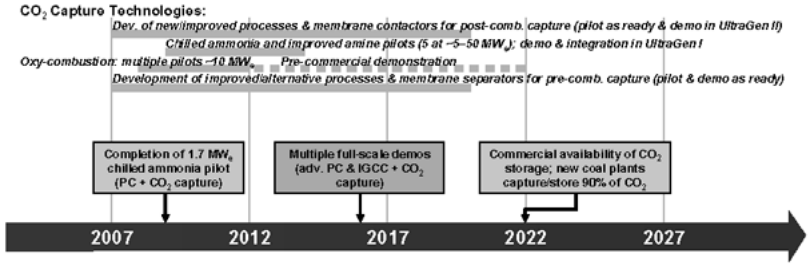


Figure 10 – Timing of CO_2 capture technology development RD&D activities and milestones

Pre-Combustion CO_2 Capture (IGCC)

IGCC technology allows for CO_2 capture to take place via an added fuel gas processing step at elevated pressure, rather than at the atmospheric pressure of post-combustion flue gas, permitting capital savings through smaller equipment sizes as well as lower operating costs.

Currently available technologies for such pre-combustion CO_2 removal use a chemical and/or physical solvent that selectively absorbs CO_2 and other "acid gases," such as hydrogen sulfide. Application of this technology requires that the CO in synthesis gas (the principal component) first be "shifted" to CO_2 and hydrogen via a catalytic reaction with water. The CO_2 in the shifted synthesis gas is then removed via contact with the solvent in an absorber column, leaving a hydrogen-rich synthesis gas for combustion in the gas turbine. The CO_2 is released from the solvent in a regeneration process that typically reduces pressure and/or increases temperature.

Chemical plants currently employ such a process commercially using methyl diethanolamine (MDEA) as a chemical solvent or the Selexol and Rectisol processes, which rely on physical solvents. Physical solvents are generally preferred when extremely high (>99.8 percent) sulfur species removal is required. Although the required scale-up for IGCC power plant applications is less than that needed for scale-up of post-combustion CO_2 capture processes for PC plants, considerable engineering

[2] C. Bullinger, M. Ness, and N. Sarunac, "One Year of Operating Experience with Prototype Fluidized Bed Coal Dryer at Coal Creek Generating Station," 32nd International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, FL, June 10–15, 2007.

challenges remain and work on optimal integration with IGCC cycle processes has just begun.

The impact of current pre-combustion CO_2 removal processes on IGCC plant thermal efficiency and capital cost is significant. In particular, the water-gas shift reaction reduces the heating value of synthesis gas fed to the gas turbine. Because the gasifier outlet ratios of CO to methane to H_2 are different for each gasifier technology, the relative impact of the water-gas shift reactor process also varies. In general, however, it can be on the order of a 10 percent fuel energy reduction. Heat regeneration of solvents further reduces the steam available for power generation. Other solvents, which are depressurized to release captured CO_2, must be re-pressurized for reuse. Cooling water consumption is increased for solvents needing cooling after regeneration and for pre-cooling and interstage cooling during compression of separated CO_2 to a supercritical state for transportation and storage. Heat integration with other IGCC cycle processes to minimize these energy impacts is complex and is currently the subject of considerable RD&D by EPRI and others.

Membrane CO_2 Separation. Technology for separating CO_2 from shifted synthesis gas (or flue gas from PC plants) offers the promise of lower auxiliary power consumption but is currently only at the laboratory stage of development. Several organizations are pursuing different approaches to membrane-based applications. In general, however, CO_2 recovery on the low-pressure side of a selective membrane can take place at a higher pressure than is now possible with solvent processes, reducing the subsequent power demand for compressing CO_2 to a supercritical state. Membrane-based processes can also eliminate steam and power consumption for regenerating and pumping solvent, respectively, but they require power to create the pressure difference between the source gas and CO_2-rich sides. If membrane technology can be developed at scale to meet performance goals, it could enable up to a 50 percent reduction in capital cost and auxiliary power requirements relative to current CO_2 capture and compression technology.

Post-Combustion CO_2 Capture (PC and CFB Plants)

The post-combustion CO_2 capture processes being discussed for power plant boilers in the near-term draw upon commercial experience with amine solvent separation at much smaller scale in the food, beverage and chemical industries, including three U.S. applications of CO_2 capture from coal-fired boilers.

These processes contact flue gas with an amine solvent in an absorber column (much like a wet SO_2 scrubber) where the CO_2 chemically reacts with the solvent. The CO_2-rich liquid mixture then passes to a stripper column where it is heated to change the chemical equilibrium point, releasing the CO_2. The "regenerated" solvent is then recirculated back to the absorber column, while the released CO_2 may be further processed before compression to a supercritical state for efficient transportation to a storage location.

After drying, the CO_2 released from the regenerator is relatively pure. However, successful CO_2 removal requires very low levels of SO_2 and NO_2 entering the CO_2 absorber, as these species also react with the solvent, requiring removal of the degraded solvent and replacement with fresh feed. Thus, high-efficiency SO_2 and NO_X control systems are essential to minimizing solvent consumption costs for post-combustion CO_2 capture; currently the approach to achieving such ultra-low SO_2 concentrations is to add a polishing scrubber, a costly venture. Extensive RD&D is in progress to improve the solvent and system designs for power boiler applications and to develop better solvents with greater absorption capacity, less energy demand for regeneration, and greater ability to accommodate flue gas contaminants.

At present, monoethanolamine (MEA) is the "default" solvent for post-combustion CO_2 capture studies and small-scale field applications. Processes based on improved amines, such as Fluor's Econamine FG Plus and Mitsubishi Heavy Industries' KS–1, await demonstration at power boiler scale and on coal-derived flue gas. The potential for improving amine-based processes appears significant. For example, a recent study based on KS–1 suggests that its impact on net power output for a supercritical PC unit would be 19 percent and its impact on the levelized cost-of-electricity would be 44 percent, whereas earlier studies based on suboptimal MEA applications yielded output penalties approaching 30 percent and cost-of-electricity penalties of up to 65 percent.

Accordingly, amine-based engineered solvents are the subject of numerous ongoing efforts to improve performance in power boiler post-combustion capture applications. Along with modifications to the chemical properties of the sorbents, these efforts are addressing the physical structure of the absorber and regenerator equipment, examining membrane contactors and other modifications to improve gas-liquid contact and/or heat transfer, and optimizing thermal integration with steam turbine and balance-of-plant systems. Although the challenge is daunting, the payoff is poten-

tially massive, as these solutions may be applicable not only to new plants, but to retrofits where sufficient plot space is available at the back end of the plant.

Finally, as discussed earlier, deploying USC PC technology to increase efficiency and lower uncontrolled CO_2 per MWh can further reduce the cost impact of post-combustion CO_2 capture.

Ammonia-Based Processes. Post-combustion CO_2 capture using ammonia-based solvents offers the promise of significantly lower solvent regeneration requirements relative to MEA. In the "chilled ammonia" process currently under development and testing by ALSTOM and EPRI, respectively, CO_2 is absorbed in a solution of ammonium carbonate, at low temperature and atmospheric pressure.

Compared with amines, ammonium carbonate has over twice the CO_2 absorption capacity and requires less than half the heat to regenerate. Further, regeneration can be performed under higher pressure than amines, so the released CO_2 is already partially pressurized. Therefore, less energy is subsequently required for compression to a supercritical state for transportation to an injection location. Developers have estimated that the parasitic power loss from a full-scale supercritical PC plant using chilled ammonia CO_2 capture could be as low as 15 percent, with an associated cost-of-electricity penalty of just 25 percent. Part of the reduction in power loss comes from the use of low quality heat to regenerate ammonia and reduce the quantity of steam required for regeneration. Following successful experiments at 0.25 MW_e scale, ALSTOM and a consortium of EPRI members are constructing a 1.7 MW_e pilot unit to test the chilled ammonia process on a flue gas slipstream at We Energies' Pleasant Prairie Power Plant. The American Electric Power Co. (AEP) has announced plans to test a scaled-up (20 MW_e) design, incorporating the lessons learned on the 1.7 MW_e unit, at its Mountaineer station in West Virginia in the 2009 timeframe.

Other "multi-pollutant" control system developers are also exploring ammonia-based processes for CO_2 removal. For example, Powerspan and NRG Energy, Inc. just last week announced plans to demonstrate a 125 MW_e design of Powerspan's ECO_2 system at the Parish station in Texas starting up in 2012.

Other Processes. EPRI has identified over 40 potential CO_2 separation processes that are being developed by various firms or institutes. They include absorption systems (typically solvent-based similar to the amine and ammonia processes discussed above), adsorbed (attachment of the CO_2 to a solid that is then regenerated and reused), membranes, and biological systems. Funding comes from a variety of sources, primarily DOE or internal funds, but the funding is neither sufficient or well-enough coordinated to advance the most promising technologies at the speed needed to achieve the goals of high CO_2 capture at societally-acceptable cost and energy drain.

Oxy-Fuel Combustion Boilers

Fuel combustion in a blend of oxygen and recycled flue gas rather than in air (known as oxy-fuel combustion, oxy-coal combustion, or oxy-combustion) is gaining interest as a viable CO_2 capture alternative for PC and CFB plants. The process is applicable to virtually all fossil-fueled boiler types and is a candidate for retrofits as well as new power plants.

Firing coal with high-purity oxygen alone would result in too high of a flame temperature, which would increase slagging, fouling, and corrosion problems, so the oxygen is diluted by mixing it with a slipstream of recycled flue gas. As a result, the flue gas downstream of the recycle slipstream take-off consists primarily of CO_2 and water vapor (although it also contains small amounts of nitrogen, oxygen, and criteria pollutants). After the water is condensed, the CO_2-rich gas is compressed and purified to remove contaminants and prepare the CO_2 for transportation and storage.

Oxy-combustion boilers have been studied in laboratory-scale and small pilot units of up to 3 MW_t. Two larger pilot units, at ~10 MW_e, are now under construction by Babcock & Wilcox (B&W) and Vattenfall. An Australian-Japanese project team is pursuing a 30 MW_e repowering project in Australia. These larger tests will allow verification of mathematical models and provide engineering data useful for designing pre-commercial systems.

CO_2 Transport and Geologic Storage

Application of CO_2 capture technologies implies that there will be secure and economical forms of long-term storage that can assure CO_2 will be kept out of the atmosphere. Natural underground CO_2 reservoirs in Colorado, Utah, and other western states testify to the effectiveness of long-term geologic CO_2 storage. CO_2 is also found in natural gas reservoirs, where it has resided for millions of years. Thus, evi-

dence suggests that similarly sealed geologic formations will be ideal for storing CO_2 for millennia or longer.

The most developed approach for large-scale CO_2 storage is injection into depleted or partially depleted oil and gas reservoirs and similar geologically sealed "saline formations" (porous rocks filled with brine that is impractical for desalination). Partially depleted oil reservoirs provide the potential added benefit of enhanced oil recovery (EOR). [EOR is used in mature fields to recover additional oil after standard extraction methods have been used. When CO_2 is injected for EOR, it causes residual oil to swell and become less viscous, allowing some to flow to production wells, thus extending the field's productive life.] By providing a commercial market for CO_2 captured from industrial sources, EOR may help the economics of CCS projects where it is applicable, and in some cases might reduce regulatory and liability uncertainties. Although less developed than EOR, researchers are exploring the effectiveness of CO_2 injection for enhancing production from depleted natural gas fields (particularly in compartmentalized formations where pressure has dropped) and from deep methane-bearing coal seams. DOE and the International Energy Agency are among the sponsors of such efforts. However, at the scale that CCS needs to be deployed to help achieve atmospheric CO_2 stabilization at an acceptable level, EPRI believes that the primary economic driver for CCS will be the value of carbon that results from a future climate policy.

Geologic sequestration as a CCS strategy is currently being demonstrated in several RD&D projects around the world. The three largest projects (which are non-power)—Statoil's Sleipner Saline Aquifer CO_2 Storage project in the North Sea off of Norway; the Weyburn Project in Saskatchewan, Canada; and the In Salah Project in Algeria—each sequester about 1 million metric tons of CO_2 per year, which matches the output of one baseloaded 150–200 MW coal-fired power plant. With 17 collective operating years of experience, these projects have thus far demonstrated that CO_2 storage in deep geologic formations can be carried out safely and reliably. Statoil estimates that Norwegian greenhouse gas emissions would have risen incrementally by 3 percent if the CO_2 from the Sleipner project had been vented rather than sequestered.[3]

Table 2 lists a selection of current and planned CO_2 storage projects as of early 2007. In October 2007, the DOE awarded the first three large scale carbon sequestration projects in the United States. The Plains Carbon Dioxide Reduction Partnership, Southeast Regional Carbon Sequestration Partnership, and Southwest Regional Partnership for Carbon Sequestration, will conduct large volume tests for the storage of one million or more tons of CO_2 in deep saline reservoirs in the U.S.

Table 2.—Select Existing and Planned CO_2 Storage Projects as of Early 2007

Project	CO_2 Source	Country	Start	Anticipated amount injected by:		
				2006	2010	2015
Sleipner	Gas. Proc.	Norway	1996	9 MT	13 MT	18 MT
Weyburn	Coal	Canada	2000	5 MT	12 MT	17 MT
In Salah	Gas. Proc.	Algeria	2004	2 MT	7 MT	12 MT
Snohvit	Gas. Proc.	Norway	2007	0	2 MT	5 MT
Gorgon	Gas. Proc.	Australia	2010	0	0	12 MT
DF–1 Miller	Gas	U.K.	2009	0	1 MT	8 MT
DF–2 Carson	Pet Coke	U.S.	2011	0	0	16 MT
Draugen	Gas	Norway	2012	0	0	7 MT
FutureGen	Coal	U.S.	2012	0	0	2 MT
Monash	Coal	Australia	NA	0	0	NA
SaskPower	Coal	Canada	NA	0	0	NA
Ketzin/CO_2 STORE	NA	Germany	2007	0	50 KT	50 KT
Otway	Natural	Australia	2007	0	100 KT	100 KT
Totals				16 MT	35 MT	99 MT

Source: Sally M. Benson (Stanford University GCEP), "Can CO_2 Capture and Storage in Deep Geological Formations Make Coal-Fired Electricity Generation Climate Friendly?" Presentation at Emerging Energy Technologies Summit, UC Santa Barbara, California, February 9, 2007. [Note: Statoil has subsequently suspended plans for the Draugen project and announced a study of CO_2 capture at a gas-fired power plant at Tjeldbergodden. BP and Rio Tinto have announced the coal-based "DF–3" project in Australia.]

[3] *http://www.co2captureandstorage.info/project_specific.php?project_id=26.*

Enhanced Oil Recovery. Experience relevant to CCS comes from the oil industry, where CO_2 injection technology and modeling of its subsurface behavior have a proven record of accomplishment. EOR has been conducted successfully for 35 years in the Permian Basin fields of west Texas and Oklahoma. Regulatory oversight and community acceptance of injection operations for EOR seem well established.

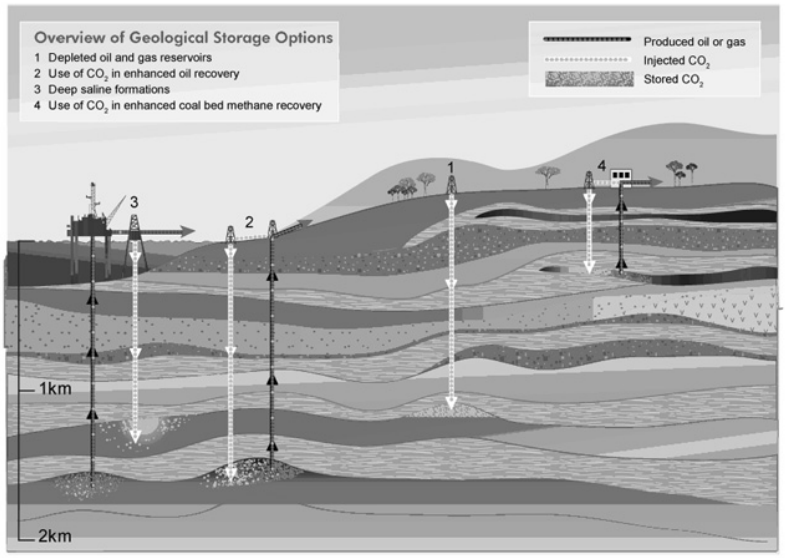
Although the purpose of EOR heretofore has not been to sequester CO_2, the practice can be adapted to include large-volume residual CO_2 storage. This approach is being demonstrated in the Weyburn-Midale CO_2 monitoring projects in Saskatchewan, Canada. The Weyburn project uses captured and dried CO_2 from the Dakota Gasification Company's Great Plains synfuels plant near Beulah, North Dakota. The CO_2 is transported via a 200-mile pipeline constructed of standard carbon steel. Over the life of the project, the net CO_2 storage is estimated at 20 million metric tons, while an additional 130 million barrels of oil will be produced.

Although EOR might help the economics of early CCS projects in oil-patch areas, EOR sites are ultimately too few and too geographically isolated to accommodate much of the CO_2 from widespread industrial CO_2 capture operations. In contrast, saline formations are available in many—but not all—U.S. locations.

CCS in the United States

A DOE-sponsored R&D program, the "Regional Carbon Sequestration Partnerships," is engaged in mapping U.S. geologic formations suitable for CO_2 storage. Evaluations by these Regional Partnerships and others suggest that enough geologic storage capacity exists in the U.S. to hold many centuries' production of CO_2 from coal-based power plants and other large point sources.

The Regional Partnerships are also conducting pilot-scale CO_2 injection validation tests across the country in differing geologic formations, including saline formations, deep unmineable coal seams, and older oil and gas reservoirs. Figure 11 illustrates some of these options. These tests, as well as most commercial applications for long-term storage, will use CO_2 compressed for volumetric efficiency to a liquid-like "supercritical" state; thus, virtually all CO_2 storage will take place in formations at least a half-mile deep, where the risk of leakage to shallower groundwater aquifers or to the surface is usually very low.



Source: Peter Cook, CO2CRC, in Intergovernmental Panel on Climate Change, Special Report "Carbon Dioxide Capture and Storage," http://www.ipcc.ch/pub/reports.htm

Figure 11 – Illustration of potential geological CO_2 storage site types

After successful completion of pilot-scale CO_2 storage validation tests, the Partnerships will undertake large-volume storage tests, injecting quantities of ~1 million metric tons of CO_2 or more over a several year period, along with post-injection

monitoring to track the absorption of the CO_2 in the target formation(s) and to check for potential leakage.

The EPRI–CURC Roadmap identifies the need for several large-scale integrated demonstrations of CO_2 capture and storage. This assessment was echoed by MIT in its recent *Future of Coal* report, which calls for three to five U.S. demonstrations of about 1 million metric tons of CO_2 per year and about 10 worldwide.[4] These demonstrations could be the critical path item in commercialization of CCS technology. In addition, EPRI has identified 10 key topics[5] where further technical and/or policy development is needed before CCS can become fully commercial:

- Caprock integrity.
- Injectivity and storage capacity.
- CO_2 trapping mechanisms.
- CO_2 leakage and permanence.
- CO_2 and mineral interactions.
- Reliable, low-cost monitoring systems.
- Quick response and mitigation and remediation procedures.
- Protection of potable water.
- Mineral rights.
- Long-term liability.

Figure 12 shows that EPRI's recommended large-scale integrated CO_2 capture and storage demonstrations is temporally consistent with the Regional Partnerships' "Phase III" large-volume CO_2 storage test program. EPRI believes that many of the storage demonstrations should use CO_2 that comes from coal-fired boilers to address any uncertainties that may exist about the impact of coal-derived CO_2 on its behavior in underground formations.

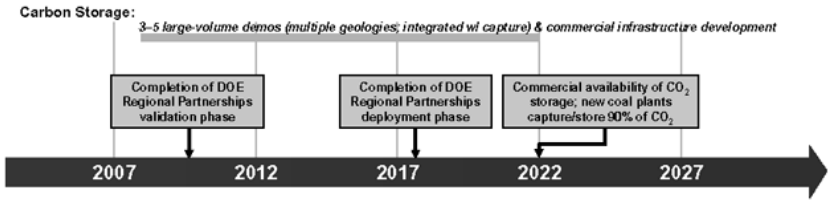


Figure 12 – Timing of CO_2 storage technology RD&D activities and milestones

CO_2 Transportation

Mapping of the distribution of potentially suitable CO_2 storage formations across the country, as part of the research by the Regional Partnerships, shows that some areas have ample storage capacity while others appear to have little or none. Thus, implementing CO_2 capture at some power plants may require pipeline transportation for several hundred miles to suitable injection locations, possibly in other states. Although this adds cost, it should not represent a technical hurdle because long-distance, interstate CO_2 pipelines have been used commercially in oilfield EOR applications. Economic considerations dictate that the purity requirements of coal-derived CO_2 be established so that the least-cost pipeline and compressor materials can be used at each application. From an infrastructure perspective, EPRI expects that early commercial CCS projects will take place at coal-based power plants near sequestration sites or an existing CO_2 pipeline. As the number of projects increases, regional CO_2 pipeline networks connecting multiple industrial sources and storage sites will be needed.

Policy-Related Long-Term CO_2 Storage Issues

Beyond developing the technological aspects of CCS, public policy needs to address issues such as CO_2 storage site permitting, long-term monitoring requirements, and post-closure liability. CCS represents an emerging industry, and the jurisdictional roles among Federal and state agencies for regulations and their relationship to pri-

[4] *http://web.mit.edu/coal/The_Future_of_Coal.pdf* .
[5] EPRI, Overview of Geological Storage of CO_2, Report ID 1012798

vate carbon credit markets operating under Federal oversight has yet to be determined.

Currently, efforts are under way in some states to establish regulatory frameworks for long-term geologic CO_2 storage. Additionally, stakeholder organizations such as the Interstate Oil and Gas Compact Commission (IOGCC) are developing their own suggested regulatory recommendations for states drafting legislation and regulatory procedures for CO_2 injection and storage operations.[5] Other stakeholders, such as environmental groups, are also offering policy recommendations. EPRI expects this field to become very active soon.

A state-by-state approach to sequestration may not be adequate because some geologic formations, which are ideal for storing CO_2, underlie multiple states. At the Federal level, the U.S. EPA published a first-of-its-kind guidance (UICPG #83) on March 1, 2007, for permitting underground injection of CO_2.[6] This guidance offers flexibility for pilot projects evaluating the practice of CCS, while leaving unresolved the requirements that could apply to future large-scale CCS projects.

Long-Term CO_2 Storage Liability Issues

Long-term liability for injected CO_2 will need to be assigned before CCS can become fully commercial. Because CCS activities will be undertaken to serve the public good, as determined by government policy, and will be implemented in response to anticipated or actual government-imposed limits on CO_2 emissions, a number of policy analysts have suggested that the entities performing these activities should be granted a measure of long-term risk reduction assuming adherence to proper procedures during the storage site injection operations and closure phases.

RD&D Investment for Advanced Coal and CCS Technologies

Developing the suite of technologies needed to achieve competitive advanced coal and CCS technologies will require a sustained major investment in RD&D. As shown in Table 3, EPRI estimates that an expenditure of approximately $8 billion will be required in the 10-year period from 2008–17. The MIT *Future of Coal* report estimates the funding need at up to $800–$850 million per year, which approaches the EPRI value. Further, EPRI expects that an RD&D investment of roughly $17 billion will be required over the next 25 years.

Investment in earlier years may be weighted toward IGCC, as this technology is less developed and will require more RD&D investment to reach the desired level of commercial viability. As interim progress and future needs cannot be adequately forecast at this time, the years after 2023 do not distinguish between IGCC and PC.

Table 3.—RD&D Funding Needs for Advanced Coal Power Generation Technologies with CO∞ Capture

	2008–12	2013–17	2018–22	2023–27	2028–32
Total Estimated RD&D Funding Needs *(Public + Private Sectors)*	$830M/yr	$800M/yr	$800M/yr	$620M/yr	$400M/yr
Advanced Combustion, CO_2 Capture	25%	25%	40%	80%	80%
Integrated Gasification Combined Cycle (IGCC), CO_2 Capture	50%	50%	40%		
CO_2 Storage	25%	25%	20%	20%	20%

By any measure, these estimated RD&D investments are substantial. EPRI and the members of the *CoalFleet for Tomorrow®* program, by promoting collaborative ventures among industry stakeholders and governments, believe that the costs of developing critical-path technologies for advanced coal and CCS can be shouldered by multiple participants. EPRI believes that government policy and incentives will also play a key role in fostering CCS technologies through early RD&D stages to achieve widespread, economically feasible deployment capable of achieving major reductions in U.S. CO_2 emissions.

Senator KERRY. Thank you very much, Dr. Hannegan.

[5] *http://www.iogcc.state.ok.us/PDFS/CarbonCaptureandStorageReportandSummary.pdf.*
[6] *http://www.epa.gov/safewater/uic/pdfs/guide_uic_carbonsequestratione_final-03-07.pdf.*

Mr. Wolfe?

STATEMENT OF RON WOLFE, CORPORATE FORESTER AND NATURAL RESOURCE MANAGER, SEALASKA CORPORATION

Mr. WOLFE. Good afternoon, Mr. Chairman, Members of the Subcommittee, my name is Ron Wolfe, and I am Corporate Forester and Natural Resource Manager for Sealaska Corporation. It's my pleasure to be here today to offer testimony on greenhouse gas emissions. I have submitted testimony in written form, and I ask that it be part of the record.

I would like to first begin by introducing Sealaska. Sealaska is an Alaska Native regional corporation that was created as authorized by the Alaska Native Claims Settlement Act for Southeast Alaska. We have over 17,000 Tlingit, Haida and Tsimshian shareholders that are the descendents of the original inhabitants of Southeast Alaska. Our land and natural resources are the very foundation for which we are able to provide benefits to our shareholders, such as education and training, culture preservation, and yes our very economies in our villages.

We see many opportunities to contribute to efforts to curb greenhouse gas emissions. But first we must ask ourselves, why are we sequestering carbon? And ultimately, it is to preserve the Earth's ecological functions. And for that reason, we believe that any program designed to encourage carbon sequestration, must create incentives and rewards for both carbon sequestration and maintenance of ecological functions. Trees are over 50 percent carbon, and forests have a tremendous capacity to take up and store carbon, but they also serve many ecological functions. Wood products store carbons for the duration of their use. A wood 2 by 4 in house construction stores carbon for as long as the house continues to serve as a house, and even, perhaps, longer, depending on what happens to the 2 by 4.

More importantly, wood products require less carbon to manufacture than substitute products, such as aluminum, plastic or concrete. Woody biomass can be converted into ethanol or other renewable fuels, such as fuel pellet wood. All of these offer carbon savings over alternate fossil fuels.

Providing carbon offset savings over fossil fuels will develop the commercialization of these technologies. Forest management practices in doing these things provides commerce and job opportunities to some of the poorest rural and predominantly Alaska Native areas of Southeast Alaska. Active management of these forests fits with the principle that we should first keep what we have.

A program that rewards landowners for only the delta, or the increase in sequestration from carbon practices is not an incentive for keeping forests remaining as forests, and for managing them for the long-term carbon sinks that they can provide.

For these opportunities to occur, the entire carbon forest budget and related ecological co-benefits must be taken into account, so purchasers get what they are paying for, sellers receive fair compensation for what they are providing, and this must be done with the appropriate verification, systems and protocols.

In summary, Mr. Chairman, climate change solutions require a sequestration strategy. However, the ultimate reason to manage

climate change is to preserve the earth's ecological functions. Any forestry sequestration strategy must ensure that we get the right outcome. Single-focus sequestration strategies can negatively impact ecosystem diversity, strategies to provide incentives in sequestration and maintaining co-benefits of ecological functions should be rewarded. A national policy should reward all carbon sequestered in a forest, it should clarify that harvesting forests for renewable fuels and products is within sequestration objectives.

I am happy to answer any questions of the Committee. Thank you, Mr. Chairman.

[The prepared statement of Mr. Wolfe follows:]

PREPARED STATEMENT OF RON WOLFE, CORPORATE FORESTER AND NATURAL RESOURCE MANAGER, SEALASKA CORPORATION

Introduction

Good afternoon Mr. Chairman, Members of the Subcommittee. My name is Ron Wolfe, Corporate Forester and Natural Resource Manager for Sealaska Corporation. Thank you for this opportunity to present testimony on the United States' efforts to control greenhouse gas emissions.

I would like to begin by telling you who we are. Sealaska Corporation (Sealaska) is one of 12 Regional Corporations established pursuant to the Alaska Native Claims Settlement Act (ANCSA) of 1971. Sealaska is the Regional Corporation for Southeast Alaska. Sealaska has over 17,000 shareholders and is the largest private landowner in Southeast Alaska. Our shareholders are the descendants of the original inhabitants of Southeast Alaska, the Tlingit, Haida and Tsimshian Indians. Our land and natural resources provide the foundation for our business strategies to deliver benefits to our Native shareholders. Sealaska also plays an important role in educating and training its Native shareholders, through scholarships and internship programs, and in preserving the culture of the Native people of Southeast Alaska.

Sealaska and other southeast Alaska Native entities own more than 575,000 acres of coastal temperate rainforest located in the panhandle of Southeast Alaska from as far north as Yakutat on the outer coast of the Gulf of Alaska to the Prince of Wales/Dall Island area at Dixon Entrance, the boundary between Alaska and Canada.

Given our substantial forest land holdings, we see many opportunities for Alaska Natives to contribute to the global efforts to address global warming as well as to create economic benefits for themselves and others. My testimony today outlines Sealaska's current thinking with respect to these opportunities.

Our Carbon Mission

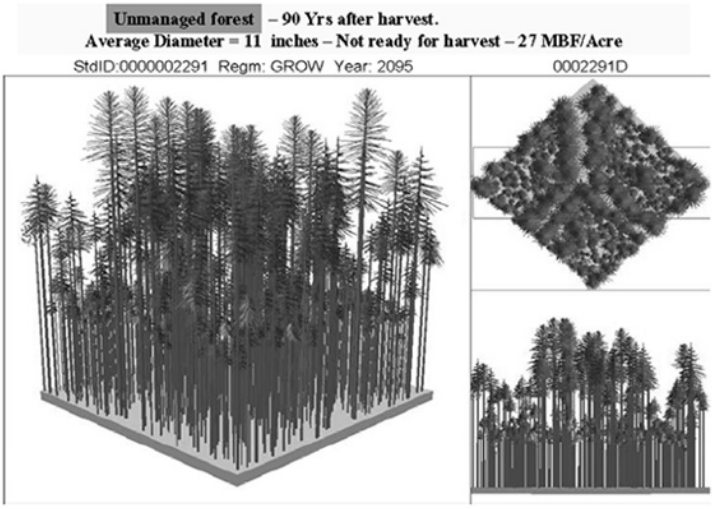
Sealaska strives to manage its natural resource holdings in a manner that maximizes the various multiple uses of those resources. As we consider carbon sequestration strategies and technologies we need to ask what our motivation is for sequestering carbon. Ultimately the goal is to preserve earth's ecological functions. As such we should not focus exclusively on carbon sequestration as a panacea without understanding the ecological consequence of our actions. We believe that any Federal program designed to encourage carbon sequestration must create incentives that reward systems that both sequester carbon and protect and enhance ecological functions.

Trees are mostly carbon, about 50 percent or more by weight (the balance being primarily water), and have a tremendous capacity to take up and store carbon. The forests of Southeast Alaska are a coastal temperate rain forest with few disturbance agents and for several centuries have been free of catastrophic forest fires, creating a relatively stable carbon storage unit. But these forests do much more than store carbon. They also provide clean air, clean water, wildlife habitat, stream habitat, erosion control and soils protection, ecosystem and ecological functions, as well as recreation, hunting and fishing, subsistence, reverent religious experiences and spiritual well being opportunities.

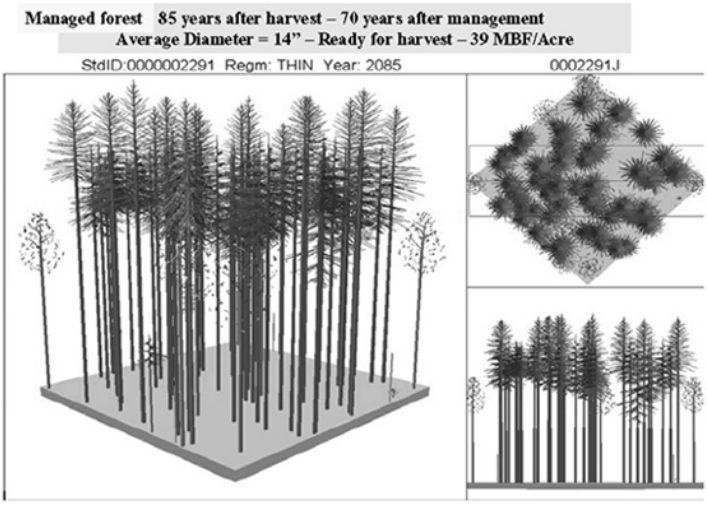
Sealaska has embarked on an effort to document how management of the temperate rainforests of S.E. Alaska sequesters carbon and provide other co-benefits. These efforts can help guide development of policies and regulations that create the right incentives to induce forest land owners to "grow carbon" and to create other co-benefits including ecological functions.

We all understand that carbon sequestration using trees is not a silver bullet that will absorb the huge influx in carbon emissions that needs to occur to stabilize climate change. But, forests can be managed to sequester carbon and to be part of a combination of solutions needed to solve the climate change crisis. To that extent the Committee needs to appreciate that a policy directed to keep forest lands in tree production is an important component of a carbon sequestering strategy. The right policies and inducements can entice forest land owners to manage lands to optimize carbon sequestration.

Our analysis concludes that managing a forest purely for maximum sequestration may cause a deterioration of the ecological functioning of forest lands. I have provided two graphic attachments from a computer model that predicts tree growth. The pictures show the results of two different management strategies. The first illustration depicts a strategy to maximize carbon sequestration:



The second illustration depicts a strategy to optimize carbon retention and protect other ecological functions:



Both forests are the same age, but one has many small trees with less ecological function, whereas the other has larger trees and much better ecological function.

Modern forest managers of today require inventory systems and data capable of planning at both the individual "stand" level and at the landscape level. Sealaska's forest planning software (FPS)[1] is designed to assist us to manage forest stands for optimum benefits. From FPS we are able to provide visual representation of the forest condition over time and to calculate the amount of carbon our forests grow over time for a variety of management regimes and prescriptions.

These diagrams demonstrate two principals:

1. A tree canopy that is dense will block sunlight reaching the forest floor, significantly retarding growth of ground vegetation important for forest diversity. This is the best strategy to maximize carbon sequestration in our forests.

2. Conversely a tree canopy that is managed to create open spaces allows sunlight to reach the forest floor enhancing brush, shrubs and forbs production that serve as food for wildlife and other important ecosystem functions. This is the best strategy to optimize both carbon sequestration and ecological functions.

Close inspection of the diagrams for an unmanaged forest reveals a very densely stocked stand of trees that shuts out virtually all sunlight beginning at age 30 and persists until age 180 when individual trees begin to die and fall to the forest floor; even then little sunlight reaches the forest floor. Compare now a stand that has been thinned early in its development by removing the small trees at age 15; much more sunlight is allowed to reach the forest floor, and this condition persists with time. Herein lies the co-benefits to wildlife and ecosystem functions. While the unmanaged forest shades all sunlight to the forest floor, the managed forest allows the sunlight to reach the forest floor.

Consistent with the ultimate goal of carbon sequestration we believe that any Federal climate change regulatory program should reward for both sequestration of carbon and enhancing ecological function. Likewise, Federal research and development initiatives should be focused on how best to maximize carbon sequestration, while also maintaining and enhancing the other ecological functions provided by the forest.

Mr. Chairman, I would also like to point out that proper management of the forest is not the only way to store and save carbon. Products made from wood store carbon for the duration of their use. A wood 2 x 4 stud used in house construction stores carbon so long as the house stands and perhaps longer depending on what happens to the 2 x 4 when the house is taken down. Further, and perhaps more importantly, a wood 2 x 4 requires less carbon to manufacture than substitute products such as aluminum, cinder blocks, bricks or concrete, creating a savings in carbon.

Similarly, use of forest materials can reduce carbon emissions in the energy sector. Sealaska has investigated a variety of technologies to convert lignocellulosic biomass (wood and bark) into ethanol and other renewable fuels. Our studies with the Department of Energy have proven several viable technologies for creation of renewable fuels. Pellet fuel wood produced from biomass that is currently waste in the forest, or from the manufacture of wood products, also offers savings in carbon over alternate fossil fuels. Providing carbon offset credits for these benefits would facilitate the development and commercialization of these technologies.

Lastly, it is important to point out that active management of forests is not a silver bullet in the total sequestration game, but fits within what should be the first rule of sequestration policy *"keep what you have."* Consistent with this rule, Sealaska believes that any Federal climate change program should provide incentives to forest land owners and managers to keep lands in forest production and not convert forest lands to other uses. The argument that forest land owners should be awarded for only the delta or increase in sequestration from current practices is not an incentive for retaining forest lands and managing to be long-term carbon sinks.

In summary, Mr. Chairman, climate change solutions require a sequestration strategy. However, the ultimate reason for addressing and attempting to manage climate change is to preserve the earth's ecological functions. Any forestry sequestration strategy must ensure we get the right outcome:

- Single focus sequestration strategies can negatively impact ecosystem diversity.
- Strategies to provide incentives for sequestration *and* maintaining co-benefits should be rewarded.
- A national policy for forest sequestration should reward for all carbon sequestered in a forest and clarify that within appropriate management prescriptions

[1] Information about this software program can be found at *http://www.forestbiometrics.com/*

harvesting forests for renewable fuel and wood products is within the sequestration objectives.

Southeast Alaska's forests generate a broad spectrum of ecosystem goods and services (both carbon and other ecological co-benefits). Forest management practices directed to sequester carbon can provide a wide array of economic opportunities important to the public, especially to American Indians and Alaska Natives. Sequestering activities can create new commerce and job opportunities in some of the poorest rural, predominately Native areas of S.E. Alaska, while enhancing the forest's ecological functions.

By creating a regulatory framework that expands the economic opportunity to sequester carbon in these forests, the American public will benefit by managed landscapes that promote enhanced biodiversity and contribute in a positive way to greenhouse gas climate control. For these benefits to occur public policy must allow accounting of the entire forest carbon budget and related co-ecological benefits so purchasers get what they are paying for and sellers receive fair compensation for what they are providing with appropriate carbon sequestration verification systems and protocols.

Comments on S. 2191—America's Climate Security Act

Mr. Chairman, the Subcommittee on Private Sector and Consumer Solutions to Global Warming and Wildlife Protection of the Committee on Environment and Public Works has just reported S. 2191, the America's Climate Security Act. Since it appears that S. 2191 is a likely vehicle for Senate consideration of a climate change regulatory program, we would like to take this opportunity to provide our views on the legislation.

Sealaska strongly supports the provisions of S. 2191 that create two opportunities for forestry landowners to participate and earn revenue through sequestration—

- the set aside of 5 percent of the annual emission allowance budget for agricultural and forestry projects under section 3701; and
- the opportunity to generate and sell offset allowances under section 2402.

Both of these programs could provide significant contribution to the ultimate success of the U.S. efforts to control and reduce greenhouse gas emissions as well as provide substantial economic benefits to Sealaska and similarly situated land owners if the rules are right.

It is critical that the rules for what projects are eligible for emission allowances or offset allowances be consistent with our above testimony and focus on the credibility of each project. The rules should not limit the universe of projects that may qualify.

If the offsets from a project meet the legislation's test of representing "real, verifiable, additional, permanent, and enforceable reductions in greenhouse gas emissions or increases in biological sequestration" then that ought to be sufficient to receive allowances. There should not be any other artificial constraints on the ability of a particular project to earn such allowances.

To ensure maximum benefit from these two opportunities and maximum participation from forestry and agriculture land owners, the outreach program called for in Section 2401 and the research and development program called for in Section 3702 are essential. They need to be comprehensive, robust and well-funded.

Conclusion

Sealaska appreciates the opportunity to testify on this very important subject. Forest conservation and management needs to be a critical component of any cap and trade system designed to mitigate global green house emissions based on the voluntary participation of landowners. This business and regulatory framework must provide economic incentives that exceed the opportunity costs of other resource uses or land conversion for landowners to be successful. Managing organizations with a fiduciary responsibility must adhere to a higher standard of economic decision-making and carefully weigh future land uses and opportunities to generate sustainable sources of revenue. A properly designed national climate change regulatory program can be a "win/win" situation for the Nation and Sealaska. We stand ready to do our part to benefit the global climate, mankind and our shareholders and look forward to working with the Congress in that endeavor.

I am happy to address any questions the Subcommittee may have, Mr. Chairman. Thank you.

Senator STEVENS [presiding]. Thank you very much.

Amy, you came in late, do you want to have—do you have an opening statement?

Senator KLOBUCHAR. I can do it with my questions, go ahead.

Senator STEVENS. All right, thanks.

Mr. Wolfe, I know you have a real background in terms of serving the Alaska community, and in particularly the Native communities—I wonder if, you know, through your history you could tell us—this carbon sequestration must be a diversified effort, utilizing a variety of technologies, such as forest management. How, really, tell us how this forest management will, in terms of the percentage of overall carbon sequestration, how will it increase the goals of sequestration?

Mr. WOLFE. Senator Stevens, I'll be happy to provide more information on that for the record.

I believe that the ability of forests to sequester and store carbon is a part of an overall strategy——

Senator STEVENS. Let me interrupt you—is it just a standing forest? Or new timber? Or old timber? How does it—does it vary with age, in terms of its ability to sequester carbon?

Mr. WOLFE. Senator Stevens, actually, younger forests are better at taking up carbon and absorbing it, and in my testimony, I offer that for this to properly be accounted for, we need to look at the total carbon budget, and that includes not only the growing in the forest, but storing of carbon in the form of standing trees, but also in the products in which we produce and the, viewing the substitutes, alternative products in lieu of wood products.

Senator STEVENS. Dr. Benson, our State has half of the coal in the United States, most people don't realize that. Is it possible to have sequestration take place in terms of the functions we're looking at now, of coal gasification and coal liquefaction?

Dr. BENSON. Yes, it certainly is, and it's also possible to sequester carbon dioxide in deep un-mineable coal beds, as well. And there are very significant, in Alaska and actually in many places in this country, where carbon dioxide could be stored in deep unmineable coal beds, as well, and it's also possible to increase methane recovery in the course of those operations.

Senator STEVENS. When I recently had a briefing from the University of Alaska about the increased methane that's seeping out from the permafrost as it's more and more exposed in Russia and in Alaska, is there a concept of methane sequestration, is that possible?

Dr. BENSON. Thus far, I'm not familiar with a methane sequestration strategy. The issue you bring up is really very significant, having to do with the melting of the permafrost, and large methane emission into the atmosphere, which are much more potent greenhouse gases than are carbon dioxide.

I'm not familiar with a strategy to manage those emissions.

Senator STEVENS. Well, I was told each unit of methane contains 22 units, 21—22 units of carbon monoxide, is that right?

Dr. BENSON. They have the power of greenhouse gas, a global warming power about 22 times higher than carbon dioxide does.

Senator STEVENS. So, and I'm happy to join Senator Kerry in his bill about these demonstration projects, but should we have demonstration projects on other substances such as methane?

Dr. BENSON. I think you bring up a very interesting point, and remedial strategies to avoid those methane emissions would be a very useful element of a way to manage greenhouse gas emissions. So, yes, I think it's a good idea.

Senator STEVENS. I was told it might be possible to capture them, and to use them in the form of natural gas and when that was burned it would emit less, fewer units of carbon monoxide, is that correct?

Dr. BENSON. If you burn methane, it emits less carbon dioxide than does coal. So, yes, it's very beneficial. It could be quite difficult to capture, though, these emissions which are occurring over, you know, many thousands of acres, and a whole new strategy to capture those emissions from the land surface into the atmosphere would be needed, with regard to those methane emissions.

Senator STEVENS. Well, I've got to get, there's a young scientist at the University of Alaska that, she has briefed us on what might be possible to capture a substantial portion of those emissions, those leakages, I call them, of methane, as the permafrost warms.

Are we still following the early bird rule?

Dr. HANNEGAN. Senator Stevens? If I might add, if we're successful at developing these CO_2 capture technologies for coal plants, those are also applicable to natural gas units, as well. So, if you're successful at harnessing the natural gas from the permafrost, that is of concern to you, and you use that to generate electricity, number one, they generate fewer CO_2 emissions per kilowatt hour of electricity, but number two, you can also benefit from this research in terms of capturing the CO_2 from those plants, as well.

Senator STEVENS. I have to—I think it's very interesting that the amount of this methane that was projected to be coming out of the Arctic, compared to the history of methane seepages is just overwhelming. And, I think we ought to do something about trying to capture as much as we can.

Senator Ensign?

Senator ENSIGN. Thank you, I found your testimony fascinating, and I think that we're dealing with an exciting area, but also it sounds like a very technologically challenging area, dealing with the environment and energy production.

What I didn't hear was—there was mention, I forget which one of you mentioned that we should at least study three of the geologic formations that should have potential for carbon capture sequestration—what are the three types, I mean, the one that was mentioned—but what are the other types? Does anybody want to take a—Mr. Herzog?

Mr. HERZOG. I mentioned that we should do at least three demonstrations to get a representative geology. But, what you need to understand is, say we say saline formations——

Senator ENSIGN. Right.

Mr. HERZOG. They're very—what we call—heterogeneous. So, one saline formation may look very different than the others. Some may have low permeability, some may have high permeability. There's lots of different characteristics. So, there's different cuts you can make, so one thing one has to do when you look at these demonstrations is say, what's the type of, you know, when you look at these formations, what's the main type of characteristics they

have, and sample representative ones to do these demonstrations in. I think some of my colleagues here know a little more about the geology than me.

Senator ENSIGN. And also in that, have you identified, you know, potential sites where these things could occur in the United States, could you give me a few examples?

Mr. HERZOG. There's a large set of aquifers under the Midwest, there's a whole set of aquifers in the Gulf Coast and the Southeast U.S., there's some out in the Western U.S., and we haven't sat down and specifically said which ones should be done, and there's probably a lot more than three if you want to do, but we think three could cover a large majority of traits of those aquifers.

Senator ENSIGN. Dr. Benson?

Dr. BENSON. Could I provide a remark? So, there—a National Sequestration Atlas has been developed now, so there's quite a lot of information on the distribution of sequestration options, both in terms of saline aquifers, oil and gas reservoirs and coal formations.

And, so basically if you look at the United States, with the exception of parts of the Northeast, and parts of the Southeast, in particular the coastal plain, there are a wide variety of resources that are available, and many attractive targets for sequestration.

Senator ENSIGN. Just, because, obviously, being a layperson, just to give us some idea of volume. When you're—how much, let's say we have a coal-fired power plant, let's say it's a 400-megawatt coal-fired power plant. The amount of CO_2 that that produces in a year, how much physical volume would that take up? Yes?

Dr. BURRUSS. I'd like to address that, Senator.

A power plant on the order of 500 megawatts, or 400–500 megawatts, would produce on the order of 300 million tons of carbon dioxide each year. And if you envision taking that and injecting it into the subsurface, and convert that into volume of the fluid in the subsurface, over a 20 to 50 year lifetime, envisioning an actual working project, that kind of project would use the equivalent of about a 1 to 2 billion barrel oil field. If you, sort of, think in terms of those of you who are from oil-producing states—that's a fairly large oil field. There are not a lot of them, but we do know that they have the capability of storing CO_2, but I think that gives you some scale to envision a storage operation for a single project.

Dr. HANNEGAN. And to put that in perspective, the largest existing post-combustion pulverized coal equivalent, or excuse me, yes, post-combustion unit in current operation is about 800 tons per day, or about 50,000 tons per year. So, you're talking about a scale up to 50,000 to 300 million—there's a lot of research work that needs to be done. And not only just in a variety of geologies, but also with a variety of coals—how you handle bituminous versus lignite, versus subituminous will vary, just as the geologies will vary, as well.

Senator ENSIGN. One of the reasons that I wanted to have an idea of the volume is that if we are talking about trying to do even more coal plants into the future, do we have that volume available? I mean, it sounds like that the, you know, that size of an oil field, and if there aren't that many of those types of oil fields, at least in the United States, that those other types of aquifers that we're

talking about would have to be used. And, is there that volume out there, I guess?

Dr. BENSON. So, I'll address that, and answer two contexts. But, I want to answer your first question—4,000 Olympic-sized swimming pools is one coal plant for 1 year, so just as a, sort of, back of the pocket number.

So, the question about worldwide capacity and U.S. capacity. So, estimates worldwide are that we have anywhere between 2,000 and 10,000 billion tons worth of storage capacity. That's at the low-end of the range, that's enough for about 100 years of the maximum amount of carbon dioxide that we can imagine sequestering.

If we look in the U.S., the current estimates are that there are about 3,000 million tons worth of sequestration capacity—3,000 billion tons—again, in the range of hundreds of years of capacity.

However, though, the global numbers, or the U.S. numbers are quite impressive, regionally it can be quite different, and there may be smaller resources, and that's why these detailed capacity—regional capacity assessments are important.

But, the bottom line is the number is big. Hundreds of years worth of capacity.

Senator ENSIGN. Just—and I don't know, my time's up, but it would seem to me that if we can make at least a difference into the future, and maybe with new plants that come online, you know, we might not need every coal plant to have its carbon captured. But if we can make a difference, and like, Dr. Hannegan, I think you talked about, combining that with nuclear, combining that with other alternative energies into the future, that the greenhouse-type gases that are released into the atmosphere, you can make a serious dent in it through technology, and I think that that's really the underlying purpose of the hearing.

Dr. HANNEGAN. Just as a further point to that, the challenge with retrofitting today's existing coal units with CO_2 capture and storage really can't be understated. You're talking about putting a small chemical facility alongside an existing plant, which probably has space constraints, which probably would need significant re-engineering, and so we're primarily looking at new units as the first place in which these technologies would be deployed.

Senator STEVENS. Senator Klobuchar?

STATEMENT OF HON. AMY KLOBUCHAR, U.S. SENATOR FROM MINNESOTA

Senator KLOBUCHAR. Thank you very much, and I'd like to thank my Senate colleagues for holding this hearing. I'm fortunate to not only serve on this Committee, but also the Environment and Public Works Committee. And as you know, we're working hard on comprehensive legislation on climate change, and in fact, have a bipartisan bill, the Lieberman-Warner bill, I'm a co-sponsor of it, and we are working very hard to get that through the Committee in the next few weeks.

One of the many provisions of the bill establishes a framework for the geological sequestration and storage of carbon dioxide, Title VII of the bill initiates a series of rulemakings in geological surveys and scientific studies designed to pave the way toward a national

infrastructure for carbon capture, transportation and storage. So, I was very interested in what you were talking about today.

My first questions were just to follow up a little bit, I know Senator Ensign was getting at this with you, Mr. Herzog, but how this would work with these demonstration projects, or some projects going on right now, but they're in Texas, is that right? Or other places? That aren't a full-scale demonstration that you're talking about?

Mr. HERZOG. There are some, what I would call pilot projects that inject maybe a couple of thousand tons, maybe up to 10,000 tons of CO_2. What we're interested in are demonstrations on the scale of about a million tons a year, you know——

Senator KLOBUCHAR. Exactly.

Mr. HERZOG. Not exactly a million, but that type of scale.

Because, what you need to do is put enough in a reservoir so that you see what happens to the features at, sort of, this commercial scale. So, you get feedback from the pressure, seeing those that get sent in, and you start seeing what happens on these scales. The small tests you can learn some things, but you can never learn——

Senator KLOBUCHAR. Exactly.

Mr. HERZOG.—the big scale.

Senator KLOBUCHAR. And what's the timeline, do you think, that you could have for this, in terms of getting this done?

Mr. HERZOG. Well, we think you could have a series of these things, and they have to go in parallel, not one after another, but I think you're looking at an 8 to 10 year period, partially because you want to have several years of injection with each of these projects, it would take 2 or 3 years to get them started——

Senator KLOBUCHAR. And you think they'd be commercially viable at that time?

Mr. HERZOG. I think what we would say that the technology will be commercially ready, whether it's totally commercial depends partly on the cost, what type of climate regulations there are in the marketplace.

Senator KLOBUCHAR. Do you agree with Dr. Hannegan's assessment that it's better to go forward with new projects, rather than retrofitting?

Mr. HERZOG. I think it's going to be less expensive with new projects than with retrofitting. I think that as we learn, I think hopefully we have the technology to be able to retrofit at least some of the plants, and——

Senator KLOBUCHAR. So, it would be possible?

Mr. HERZOG.—over time you may have, whether it's a retrofit, or a plant gets shut down and a new plant gets built on that same site, eventually over time, that could happen, too. So, I think——

Senator KLOBUCHAR. So, you think that maybe working on these demonstration projects could help with the retrofitting technology as well?

Mr. HERZOG. Well, I think the same technology that you would use for new plants would also be for retrofits. At least for some. I mean, if you're looking, say, the pathway with gasification, most of our current plants are combustion, so they may not work well with that, but we recommend in our report they should work on both gasification and combustion pathways as you go forward.

Senator KLOBUCHAR. And, Mr. Fox, you talked about how the most economical way to transport large volumes of CO_2 would be by pipeline, and if carbon capture and sequestration becomes a commercial reality, what increases in the pipeline infrastructure would be needed, if any? Are there any other ways to transport this?

Mr. FOX. There are other ways to transport it, but they are very expensive. You can put it in a truck, but it's only small volumes, it's about three times as expensive. You could put it into railcars, again, it's very expensive, so—what we're talking about here with such a pervasive problem, you'll either put it into pipelines, or if possible, you could put it into ships, if you were going to take it offshore.

Senator KLOBUCHAR. So, do you think we'd need more infrastructure if we really——

Mr. FOX. We would definitely need more infrastructure—it's taken about 20 years to build a fair sized infrastructure in the Permian Basin, to replicate something like that would be about $3 billion today, and there was a Professor, Dr. Sokolow, who said that—broke down this whole carbon capture, carbon problem into 7 wedges, one of which was carbon sequestration. Worldwide, by 2050 you'd have to build 150 Permian Basins, about 40 of those would have to be in the United States. So, it would be——

Senator KLOBUCHAR. Because I would think—what is it, China is constructing the equivalent of two 500-megawatt coal-fired plants a week? Is that right?

Mr. FOX. Yes.

Senator KLOBUCHAR. And is this when you, Dr. Benson, were going through these projections, you figured that into it as well? With your Olympic swimming pools?

Dr. BENSON. Right, well, certainly, yes. We need thousands of these projects.

Senator KLOBUCHAR. OK. And, so, Mr. Fox I should have let you finish.

Mr. FOX. I think that we certainly know how to pipeline the CO_2 safely. One of the issues that is going to come up is, I think that the coal plants are not going to want to, may not want to clean up the CO_2 to what is now pipeline specs, and if you put impurities in there like hydrogen sulfide, or SO_X and NO_X, it makes it a little more difficult, a little bit more dangerous to transport. Certainly not something you couldn't do in a rural area, but if you're doing it in a city, an urban area, it raises some issues that we really haven't addressed, there hasn't been anybody, bothered to look at how to do that safely.

Senator KLOBUCHAR. Dr. Burruss?

Dr. BURRUSS. Yes, Senator, I'd like to make a comment that one issue that you've raised with pipelines and the issue with retrofitting where they interact is the fact that the largest coal-fired power plants in the country today are basically along the Ohio and Mississippi River Valleys. They're basically in the Midwest, and also in the East. But the storage that we know the most about, the large oil fields of the kind that Mr. Fox has worked on for enhanced oil recovery, are in West Texas, and along the Texas Gulf Coast, so there's actually at present day, a mismatch between the

largest existing sources of power plants, and the places we know the most about storage today. So, that would basically imply, if we're going to connect the two, we clearly have to build more pipeline infrastructure. Otherwise, we have to go forward with new plants that might be co-located with the best storage, and decrease the amount of pipeline necessary to connect those.

So, there's some important tradeoffs to consider in infrastructure between new technologies, retrofit, and pipelines.

Senator KLOBUCHAR. Just one last question before I turn it over to Senator Stevens, just to follow up on the retrofitting and the cost you foresee for this and the future of this, if anyone else wanted to comment on that——

Dr. HANNEGAN. Sure. Senator, I'm happy to do that, and clarify, a bit, my earlier comments.

Retrofit is, from an engineering standpoint, more difficult, with existing units primarily because of the space requirements, and because of the fact that these plants were not engineered to capture and store the CO_2 in the first place. That doesn't mean it can't be done, it certainly can be done, and one of the ways in which we foster that possibility is to do work, not only on gasification, but on post-combustion capture as well, from pulverized coal units, since they make up the majority of what's in the fleet right now. So, that underscores the need to do research on this, across the wide range of coal technologies.

Our work has shown that the energy penalty, and thus, the economic cost associated with capturing CO_2 from a pulverized coal unit, is presently around 30 percent, and that with advances in technology of the kind that we envision in our road map, you can bring that down to a 10 or a 15 percent increment, and in so doing coal—even with CO_2 capture—becomes part of the—you know, it stays the backbone of the electric system, even under a carbon constraint.

Senator KLOBUCHAR. All right. Thank you very much.

Senator Stevens?

Senator STEVENS. Dr. Hannegan, you have given us a description of your UltraGen project, and you had the option there of capturing 25 percent of the CO_2 from the plant. Why 25 percent? Why not 10? Why not 50? Is this cost-related?

Dr. HANNEGAN. Thank you for asking that question, Senator Stevens. The UltraGen project that we've proposed and put before a number of folks in the industry to consider, is a new large, 800-megawatt clean and efficient pulverized coal plant. So, 25 percent of the CO_2 from that 800-megawatt plant is effectively a 200-megawatt, fully captured, activity. Which is larger than what's currently being done out there, at a pilot stage, and it's frankly, the maximum level to which we think we can pilot existing developmental technologies for post-combustion capture with some reasonable certainty that this will actually work. We could scale it up, but the risk involved in scaling that project up even further to 50 or 80 or 90 percent, technologically we're not ready to support that, given the research that we've done so far, and the basis for the pilot projects that we've done to date.

Senator STEVENS. On that same project, would the demonstration proposed there for UltraGen I qualify for Federal funding under existing law? That's the Energy Act of 2007?

Dr. HANNEGAN. As it presently reads, Section 304 of H.R. 6 requires an 85 percent of the produced carbon dioxide at the facility to be captured in order to qualify for funding under that section. It also requires it to be half a million short tons per years.

In the case of UltraGen I, the first of the two that we would foresee going forward at 25 percent, it would not qualify for that funding. But the second, the follow-on, UltraGen II, we would treat at least 50 percent of the flue gas, with a 90 percent removal process. And then the Ultimate Plant, sometime into the future beyond UltraGen II there, would be a full-scale 90 percent capture and deployment that it would, clearly satisfy the requirements in the Senate language.

Senator STEVENS. Let me ask this for the panel, this will be my next to last question. There are sizable areas of production of coal, or gas, and the consumers, the plants where that energy is used are fairly far from the place of production. Has anyone looked into the question of, can we sequester this carbon before it's transported to a plant in, you know, somewhere in Texas, to Ohio, and then it's burned there, and then you want to transport the CO_2 back to Texas? It does seem to me that one of the answers might be to try to find some way to sequester this carbon at the point of production of the energy itself, am I off base?

Dr. Benson, am I off base?

Dr. BENSON. No, and I think as we look to the future energy system, co-location of generating capability with storage capability will become a very desirable attribute. The situation we're in right now——

Senator KERRY [presiding]. Doctor, I think the Senator's asking about extraction, production——

Senator STEVENS. But she's talking about at the point of extraction, right?

Dr. BENSON. Right.

Senator KERRY. You're talking about production of the energy.

Dr. BENSON. Right, so it would be desirable to locate the, our plant where you can store the CO_2.

Senator STEVENS. That's what we were experimenting with 20 years ago, but we ran into the problem of the line loss. It's my understanding now that the line loss of high voltage is miniscule to what it was 20 years ago. Why aren't we pursuing the sequestration at the point of production?

Dr. Burruss, you started to answer that.

Dr. BURRUSS. Well, I don't, I think the question—you've raised an excellent question, the only way we can answer that is to basically decide to go forward with these large demonstration plants and make a decision—should we locate them where the best storage is, and then if there are electrical generating plants, move the electricity, versus the question of capturing CO_2 where it may be present, generated at present, and then move the CO_2 to a storage site. We simply—those questions have been considered in economic models, but there's no final decision about which one would be the best choice.

Senator STEVENS. My last question, and thank you, Senator, when it comes right down to it, is this finally going to be a question of cost? We know the problem, and we have to move forward. Is anyone analyzing what is the best use of the investment now? I know we're going to go with these demonstration projects, and I support that bill as I said, but has anyone looked at the overall national program of how to do this job of sequestration and do so the most efficiently, and effectively from the point of view of the use of investment?

Dr. HANNEGAN. Yes, Senator, we—as I mentioned in my testimony if you would look at the slide number 2 in our submittal, we've actually done some very detailed economic analysis of what an efficient pathway to de-carbonizing the U.S. economy would look like, and it involves making some significant investments in research and development today that put us in better stead to efficiently and economically de-carbonize the economy over the next several decades, and the data that we show here out to 2050.

What we've done is we've contrasted an approach on the left-hand side, which waits until the carbon constraint arrives, and then begins the research, versus one which does the research in advance of the carbon constraint, and actually develops more tools in your toolbox.

Senator STEVENS. Respectfully, that doesn't deal with my mind, I'm an appropriator, looking at money.

Dr. HANNEGAN. Yes, sir, I understand.

Senator STEVENS. How are we going to use the money we have available now most effectively to achieve our goals in the future?

Dr. HANNEGAN. The underlying work behind this analysis, Senator, contains very detailed timetables and research road maps and actual expenditure amounts that we believe are necessary to achieve the R&D goals outlined in our work, and I'm happy to put that into the record if you're interested.

Senator STEVENS. I would.

Senator KERRY. We would like that.

Senator STEVENS. I said last question, but Dr. Benson wants to answer. What do you have?

Dr. BENSON. I just want to add something—I think that the demonstration projects are incredibly important, but at the same time we need to be sure that we're building the fundamental research base. And there's a high amount of leverage for a tiny fraction of the amount that you're putting into these very large-scale demonstration, you can have a tremendous amount of learning that's occurring. In addition, you'll be developing the capacity for students, and the future workforce will be able to do this.

So, I think that fundamental research is an important component, and I also believe that these small-scale pilot tests are also very important, because in reality, we're going to have, you know, maybe 5 demonstration projects, while in reality, we probably have 40 or 50 places where we would like to sequester CO_2. The very small-scale pilots are complementary to the big demonstration projects, so that there's a readiness that's being developed, both in terms of the regulatory community and detailed geologic knowledge. So, all three, I think, are very, very important now.

Senator STEVENS. Thank you very much.

Senator KERRY. Just before Senator Stevens leaves, a quick—what shape should that research funding take? I mean, how do you structure that?

Dr. BENSON. I mean, I think that there are certainly very good models for the fundamental research that takes place, for example, through the Department of Energy's Office of Science that, you know, funds graduate student research, and so forth——

Senator KERRY. Should it be targeted to a specific set of disciplined questions?

Dr. BENSON. Yes, absolutely.

Senator KERRY. You want to help shape that, give some ideas?

Dr. BENSON. It's basically use-inspired fundamental research. We have to know what we're trying to achieve, we're going to know the questions we're trying to answer, and then get the best minds working on those problems.

Senator KERRY. And the second question just in terms of the appropriator role Senator Stevens plays, which is pretty critical, how urgent is that kind of commitment here?

Dr. BENSON. Well, my view we need to do it now, we needed to do it yesterday. I think this is urgent. I think that we need to move ahead now.

Senator STEVENS. Do we need a Los Alamos-type project on this? Do we need to get the scientific community together to get them into an agreement before we go forward?

Dr. HANNEGAN. Excuse me, much of the scientific community, much of the technical community which is here on this panel, is in agreement on many of the steps that we need to take to develop carbon capture and storage as a tool that we can use to address climate change. The sooner we do that——

Senator STEVENS. But there's not an agreement on the technology.

Dr. HANNEGAN. Well, you need a portfolio of technologies, in our view, because you're going to be dealing with different coals, you're going to be dealing with different resources and requirements, you need both pulverized coal, IGCC, oxy-fuel—these are things that we can develop a very specific road map, in fact, we have—with targets and timetables, and these are the kinds of things that if we do it, then we can accelerate the rate at which we can then de-carbonize the broader economy.

Senator KERRY. Mr. Herzog, I was wondering, I know Senator Stevens has to go, but did MIT work through any of those best practices, best routes with respect to the fuel, *i.e.,* different kinds of coal?

Mr. HERZOG. In our report we gave some breakdowns of general categories and general ways you can go on there. Subsequent to the report, I've been in meetings with EPRI, people like the Coal Utilization Research Council, several other, I guess, Edison Electric—and while there's some subtle differences in the approaches, I think the basic thrust of what everybody's saying is fairly similar. And when you look at, say, in the underground, in the sequestration, we all know we need to work on the geochemistry, the geomechanics, the biology down there, we have to look at the modeling at the basin scale. So I think there's a pretty good agreement throughout

the community of the major directions and what the gaps are in our knowledge to move forward.

Senator KERRY. Now, some people have raised the question occasionally and said, "Well, we don't know how to do this." And I've heard this argued by some Senators. The fact is, we do know how to do it, do we not?

Mr. HERZOG. Yes.

Senator KERRY. Literally in the Finance Committee, we had a struggle over whether or not we have the technology to do this. We had some people arguing, well we don't know how to do it, we can't do it, so we couldn't create an incentive. It's my understanding not only do we know how to do it, but there are several countries, three of them, specifically, that are already doing it, is that correct?

Mr. FOX. Yes, Senator. We operate plants that capture CO_2 right now, and we've been—people have been capturing CO_2 for over 60 years. We have—there's, in the United States, the Dakota Gasification Company is capturing CO_2 from a gasification plant. That works. We've been injecting CO_2 in the ground for 35 years and tracking it. This—much of this is just an extension of technology we're already——

Senator KERRY. We've been injecting it, we've been injecting it for the purpose of forcing oil—out of pockets where it's hard to get it.

Mr. FOX. Yes.

Senator KERRY. Without regard to whether or not it stays where we forced it.

Mr. FOX. That's correct, although we have no—we do not believe it's going anywhere else.

Senator KERRY. But that's because the effective sealing that you talked about earlier, if it seals the oil in, or the natural gas, it's going to seal the CO_2, likewise.

Mr. FOX. Correct. This is something we know how to do, it's a question of doing it the least expensively, and having the smallest effect on the economy.

Dr. HANNEGAN. Mr. Chairman, with all due respect to the contributions of my colleague, the examples that he's cited are from chemical plants and other sorts of activities which are not electric power plants. And when you look at coal-fired electric power plants, we are at a much smaller scale of CO_2 capture and storage than you would like to have in order to make an investment at commercial scale today. And so, you need a set of steps that will scale you up to that.

Senator KERRY. That's because of the post-combustion, pre-combustion——

Dr. HANNEGAN. That's correct.

Senator KERRY.—issue that you raised earlier.

Dr. HANNEGAN. The difficulty is in capturing the CO_2 from a conventional pulverized coal unit, and from operating the IGCC unit, at scale, which we have not yet done in the United States.

Senator KERRY. But, we do know that we have the technical capacity to capture, either in post- or pre-combustion.

Dr. HANNEGAN. That is correct.

Senator KERRY. The real issue here is the efficiency and cost of a commercial-scale operation.

Dr. HANNEGAN. And, I would add, scale. The question of——

Senator KERRY. Fair enough.

Dr. HANNEGAN.—what do you do with all that CO_2.

Senator KERRY. Which is precisely why there's an urgency to doing it. Get it out there, correct?

Dr. HANNEGAN. Correct.

Senator KERRY. Now, some private entities are moving to do this, isn't that correct? AEP, I think, is doing an IGCC in West Virginia or in Ohio.

Dr. HANNEGAN. At a 20-megawatt scale, on a much, much larger unit, yes.

Senator KERRY. Now, someone might ask the question, well, if the private sector is going to start to move toward this, and electricity rates ought to reflect the investment, why should the government be involved? I think I have an answer, but I want to hear from you, what your take is on that.

Dr. Burruss?

Dr. BURRUSS. Mr. Chairman, I would say that you raised the basic issue in your opening statement. The issue is urgency, the rate at which this technology has to be deployed, in order to ultimately impact climate change. Because, if we're not going to do that, there's not a lot of point to the technology. So, the fact is that——

Senator KERRY. Well, I would assume, also, that we have a much better ability to deal with both the eminent domain and the liability issue, which is going to be critical to moving rapidly.

Dr. BURRUSS. That's true, and I think there's also a separation that we have to be aware of. I think those of us on the geological side know that we can, in fact, store CO_2. There's some scale issues, and some questions we need to answer.

Senator KERRY. Can you answer the question whether or not we have the capacity in the U.S. to sequester the amount of CO_2 necessary to get a 60 to 80 percent reduction?

Dr. BURRUSS. I believe——

Senator KERRY. Let's kill the 60. An 80 to 90 percent reduction?

Dr. BURRUSS. An 80 to 90 percent reduction in total CO_2 emissions in the United States? Boy, that's a tough question, Senator.

Senator KERRY. What is the capacity?

Dr. BURRUSS. And——

Senator KERRY. What is the known current capacity?

Dr. BURRUSS. We have an estimate, based on the DOE——

Senator KERRY. Without saline, correct?

Dr. BURRUSS. Excuse me?

Senator KERRY. That's without the saline pocket, correct?

Dr. BURRUSS. The estimate that we know about, in oil and gas reservoirs——

Senator KERRY. Is that based on oil and gas reservoirs?

Dr. BURRUSS. That's correct, and that——

Senator KERRY. And how much do we get out of the current estimate on oil and gas that we believe is sealable?

Dr. BURRUSS. I'd say that's still a subject of additional evaluation to understand which part of those oil and gas reservoirs, which fraction of them, are the best storage sites. We, I think, we can make a reasonable estimate that, that is on the same order that,

you know, DOE has published, because these are based on things we know a lot about, it's about 100 billion tons, maybe 100 billion tons of CO_2 in known oil and gas reservoirs.

But that doesn't get the job done if you tell me that we need to capture 90 percent of the CO_2 emitted by all industrial processes in the United States.

Senator KERRY. Well, I'm not telling you, the scientists are telling us that it is going to take, in order to avoid the tipping point, if you accept the science, does anybody here argue with the science? Anybody on the panel argue with the science?

Dr. BURRUSS. No.

Senator KERRY. So, if you don't argue with the science, if you accept the science you can't be half-pregnant on this thing. You accept the science, you've got to accept the predictions of the consequence that the science, not only the science is telling us is going to happen, but the science is showing is happening to a greater degree and faster than the science previously predicted.

So, that said, it seems to me that when they tell you, you've got about 10 years to get it right, and you now have to reduce your goal from 550 to 450 and from 3 degrees to 2 degrees, we're operating with a very small cushion, here. If you're already at 370, and you can only go to 450, and we already know that at the rate China and the U.S. are currently building pulverized coal-fired power plants, we're going to be at 600 to 900 parts per million very quickly here.

What do we do? How do we grab this fast?

Dr. BENSON. Could I answer your—so, the DOE Atlas does include saline aquifers.

Senator KERRY. It does?

Dr. BENSON. Yes, it does include saline aquifers, and——

Senator KERRY. Is that a percentage that they give you, as well as a metric—?

Dr. BENSON. It's a quantitative number, it's about 3,000 billion tons of carbon dioxide.

Senator KERRY. Where does that fall on the percentage that we have to get?

Dr. BENSON. In terms—so what that—if you took all of the stationary sources over 100,000 tons per year, you could sequester hundreds of years of those CO_2 emissions, from the stationary sources. It doesn't include the transportation sector. So, yes, it's a big chunk, and so what's that—about 40 percent or so of U.S. emissions for hundreds of years.

Senator KERRY. Well, at the meeting I was just at, we were talking about the Energy bill, and how we're going to try to do the transportation sector piece, and hopefully get some of that done in December.

Dr. HANNEGAN. Senator, if I might add a point to the previous discussion? When you think about 60, 80, 90 percent reductions across the broader economy, we're not going to be relying just on carbon capture and storage to meet that.

Senator KERRY. Absolutely correct.

Dr. HANNEGAN. And so, some of the pressure that might have been implied on the reservoir space——

Senator KERRY. That why I'm trying to get a handle on what the estimate is of the percentage that we get out of the carbon capture? Reliably.

Dr. HANNEGAN. Well, our work, looking at just the electric sector, showed that a considerable amount of the future emissions reductions from that sector would come in the form of carbon capture and storage and advanced coal technologies.

As far as the transportation sector goes, one of the more promising options that we see is, if you're able to de-carbonize the electric supply, early, through a technology like CCS, then that provides a low-carbon and affordable source of fuel for other sectors of the economy, including transport.

Senator KERRY. So, what are the three most important steps that we ought to take to get moving on this? Fund the demonstration project? Is that number one? What's number two and three? Research, liability?

Mr. FOX. I think, Senator, I would echo what Dr. Benson said earlier, was that, or it was Mr. Herzog—that we need to fund the larger demonstration projects to find out what happens when you put a lot of CO_2 into the ground, but we also need to do some of the smaller projects. When I think about trying to invest money to develop a carbon, or a storage facility, and invest hundreds of millions of dollars into that—we would have, you'd have to have more than just three places to go. You'd really want to have, you know, have a few things that you can know a lot about, and a lot of them where you might know a little bit about it, and then you could extrapolate to that. So, I think it's important to have both of that. And——

Senator KERRY. Anybody want to add a third?

Dr. HANNEGAN. Yes, Mr. Chairman, I'll take a crack. The first is, obviously as you pointed out, the need for demonstrations, a variety of technologies, variety of geologies, variety of scales. The second is getting the regulatory regime in place that gives investors confidence to move forward, and it gives the opportunity for folks like those seated at the table to participate, and the third, one that we——

Senator KERRY. What's the, before you—go ahead.

Dr. HANNEGAN. Sure. The third that we haven't really talked a whole lot about is, I think environmental aspects are important—measuring, monitoring, verifying the storage of the CO_2, the fact that there are not adverse, unanticipated environmental consequences—really, using our demonstration projects as a basis to get that right is going to be key to also getting public acceptance.

Senator KERRY. And the key regulatory issues, in your judgment?

Dr. HANNEGAN. The first is probably the ownership of the CO_2, in terms of, at what point, when you put a CO_2 molecule into the ground, and you expect it to stay there for a century or more, who owns that CO_2? Who owns the porous space between the rocks? I think as one of my colleagues mentioned, and they may add some additional issues. When it comes to the transfer of liability when it moves into one of Mr. Fox's pipelines, for example. These are all issues that I think we can work collaboratively on.

Senator KERRY. It seems to me, that if we're going to get this done, and get it done at the scale and speed we need to, you can't

ask a company to take the risk of assuming that liability. You're going to have to provide something, as we did with nuclear, with the Anderson Act, where you give some kind of immunity there for at least the initial thing, until you figure it out, what those consequences and other things may be. I just don't know how you do it, otherwise. Because, I think a lot of people are going to be very reluctant from an investor point of view, let alone, Board of Directors, director of exposure, all of those other things, to get involved.

Dr. HANNEGAN. Yes. There's also the economic risk, given that many of these coal plants that we're thinking about are now billion dollar investments. And that, when we're talking about having them add carbon capture on the end of it, we're talking about a significant increase in the capital outlay up front, and that's where Federal assistance can be of great value.

Senator KERRY. Are any of you aware of any other technologies or alternatives currently being explored? Not dissimilar to what Senator Dorgan mentioned in terms of, until this moment unheralded, or un-focused on by-products and alternatives to how one may deal with CO_2, beyond the capture and sequestration?

Dr. BENSON. I think something at this level of maturity and the potential for very large-scale reductions, I think at this point, capture with geological storage is the primary option available. And that was certainly the conclusion of the IPCC Special Report on Carbon Capture and Storage that was done about 2 years ago.

Dr. HANNEGAN. There are, however, Senator, I think, some enterprising folks out there, like the algae folks that were discussed in Senator Dorgan's comments.

I'm also aware that there are some, there's an activity in Texas to get to a point Senator Stevens made before he departed about a plant that's generating electricity at the mine mouth, and actually capturing the CO_2 and turning it into a carbonate material. Now, they haven't figured out what to do with all of that carbonate yet, but one could imagine if there is a market for that as a commercializable product, then that would be a very useful thing to pursue, as well. And these are things we're looking at, at EPRI as part of our program.

Senator KERRY. Dr. Burruss, why doesn't the USGS have a role in assessing the capacity? What's going on here?

Dr. BURRUSS. Senator, that's a—I guess I'm rather sensitive to that. I—I mean, the simple truth is we're not funded to do the work. We have no project to pursue that, and no authorization to do so.

Senator KERRY. So, it's really just a budget issue, lack of priority?

Dr. BURRUSS. It's—yes. There was a——

Senator KERRY. Don't you have the best expertise, frankly?

Dr. BURRUSS. We believe that we have the best expertise for doing storage assessments and treating them as a natural resource, and using our methodologies for oil and gas and mineral resources and applying them to storage capacity. But, you know, until we have the authorization to move forward, we, you know, we literally cannot do so.

Senator KERRY. This year the DOE published the Carbon Sequestration Atlas, which I am told, while it's useful to some degree,

it does not have the kind of resolution necessary to really help identify, select, and manage injection projects, is that a fair statement? Who's qualified to answer that?

Dr. Burruss?

Dr. BURRUSS. That's a fair statement, Senator, but I also think that if you were to turn the question around and say, could we as the USGS do that, to identify sites that could be utilized for storage, we would have to say no, because we do not identify commercial projects. We assess resources and their distribution and——

Senator KERRY. But a capacity assessment, it seems to me would be a fairly generic and important assessment.

Dr. BURRUSS. Absolutely. And that——

Senator KERRY. So, wouldn't that be part of the study and funding analysis that we do?

Dr. BURRUSS. Absolutely. It has to be.

Senator KERRY. It's my sense that it would be.

Dr. BURRUSS. And, as part of that, there is the very basic question about the storage capacity of saline aquifers. We know the number is very large. But we really don't know where the most effective storage is, and what fraction we could actually use.

Senator KERRY. What are the known, if any, risks associated with CCS?

Mr. HERZOG. One of the biggest is leakage, but it's a fairly minimal risk to health and environment, because, in general, a leak would probably be fairly dilute. There's CO_2 all around us, and we put it up in the air so, only if it gets concentrated could it be a risk. Like radon, it seeps out of the subsurface, collects in things like basements, but that is easily mitigated if that's the case. But that's one of the worst cases you could see.

I think the biggest risk is it leaks out, and we spent all of this money to put it into the ground, we would not get the benefit from it.

Senator KERRY. Is there any risk with respect to beyond, perhaps, acidification, if it moves down into a water supply channel?

Mr. HERZOG. It would have to—we're going to inject below all of the potable water, so it would be moving up and getting into drinking aquifers. I don't think acidification is such a big risk, what some people think is, if it leaches out other materials and brings them up with it, it is a risk. But, at this point that's, people are researching that, at this point it's hard to really quantify it as a major risk or not.

Dr. BENSON. So, I think there's another risk, and that is——

Senator KERRY. Could I just, before you mention the other risk, could I just close off on that? I thought the increased CO_2, to the degree the oceans have acted as a sink, that increase of CO_2 storage has raised the acidity of the oceans by some 35 percent?

Mr. HERZOG. The surface layer of the ocean has changed by about .1 ph unit. I'm not sure what percent that is. But, I think what will happen in the ground water, it's like CO_2 that doesn't stay in the soda pop bottle once you have the thing open, it diffuses out into the atmosphere. The ocean, it gets down into the deep ocean. The surface ocean has equilibrium with the atmosphere, and that controls the pH. But the surface level of the ocean is actually basic, not acidic.

Senator KERRY. So we'd maybe turn all drinking water into San Pellegrino or something?

Mr. HERZOG. Well, theoretically, but unlikely.

Senator KERRY. Are there any areas of this that we ought to be aware of that have not been asked about by any of my colleagues or any of us, at this point? Is there something relevant to the Committee? We're going to leave the record open for a couple of weeks, just to get any other colleagues who may have some questions.

Mr. Wolfe, you—?

Mr. WOLFE. Yes, Mr. Chairman, as a representative of a forest landowner, it's a little bit of a different audience then the rest of my esteemed colleagues on this panel, but Sealaska Corporation, with the Department of Energy has investigated a variety of technologies to convert cellulosic, lignocellulosic material which is woody bark and material and stuff like that, into ethanol. The technologies are available, but we have not been able to move this from the laboratory into production scale. So, we think that this creates some opportunities.

There are us—the other incentives that need to happen for things such as taking wood waste material and turning it into pellet fuel technologies, now what these do is basically offer a savings over alternate fossil fuels. So, from the wood sector and from the forest sector, we think that there are such opportunities that need to be, need to have assistance, not only in the development of the technologies, but incentives to be able to get people to invest in this type of technology and deliver it to the marketplace.

Just one last thing, too—I think this is really quite important for our rural villages in Alaska. Rural village costs are like $4 and $5 a gallon for diesel, and this is a tremendous burden for our rural villages, in terms of simply heating their homes.

Senator KERRY. Sure.

Mr. WOLFE. So, alternate fuels and these sorts of things might be quite helpful.

Senator KERRY. Absolutely. And I might add, one of our top venture capitalists who has been involved in U.S. capture and sequestration, and with others as we're discussing these issues, is investing heavily in a wood chip-based cellulosic ethanol plant down in Georgia right now. Partly to prove that you don't have to be corn-based, grain-based, and you can do it almost anywhere, so there are a lot of options there.

The other thing I might mention, as I was reading recently, is in an analysis of tropical forests versus Northeast forests, obviously all forests act as a sink, and they are important, but it turns out that the Northeast forest is less important than we thought, whereas tropical is far more important. I think the deforestation that has taken place, just in the last year or so, has added the equivalent of 20 percent of our CO_2 creation today. And if we continue down that road, in deforestation of the tropical forest, we're in serious trouble, it's going to be a big add-on, a very serious add-on.

Dr. HANNEGAN. Mr. Chairman, if I could add one point to my colleagues' discussion of biomass—the promise of biomass and CCS coming together is rather an intriguing one, because biomass takes up CO_2 from the atmosphere as it grows, and if you were to combust that, or gasify that biomass to create power, and then capture

the resulting CO_2, the end result is actually, you're removing CO_2 from the atmosphere and putting it in these deep reservoirs, you're effectively lowering the burden. And as a long-term objective, there's an opportunity for some synergy here that's worth pursuing.

Senator KERRY. Absolutely. Well, it's a very, very interesting topic, and this has been a very important foundation being laid for our ability to do some important investing, the Federal Government, and try to move this forward. So, I'm very grateful to all of you. And I hope you'll keep pushing in your individual bailiwicks and jointly, because we really need to get some folks moving on this, in a very, very serious way.

Senator Thune, you haven't had a shot yet, and I apologize.

STATEMENT OF HON. JOHN THUNE,
U.S. SENATOR FROM SOUTH DAKOTA

Senator THUNE. All right, that's all right, Mr. Chairman.

I want to thank you for holding this hearing on what is a very important topic and that's the critical role that clean coal and carbon capture and sequestration will play in securing our energy independence, and I appreciate the panel's input. I apologize for not being able to get here a little bit earlier, but I wanted to just make it, I guess, maybe one observation and maybe ask one question, I realize you're probably getting ready to wrap this up, Mr. Chairman.

But I know the focus of the hearing today has been on geological carbon storage, but I would like to highlight with the Committee, also, that there's another very potent tool out there for carbon sequestration, in our Nation's heartland, and that's biological carbon sequestration, which uses land management to enhance natural carbon storage in plants and soil.

Altering crop planning practices, preventing soil erosion, changing grazing practices are all things that have a measurable impact on carbon sequestration, and according to the CBO, biological sequestration has the technological potential to sequester about 40 billion to 60 billion tons of carbon dioxide over the next 50 years. And while that potential is considerably smaller than the potential for geological sequestration, it's an important component of managing carbon dioxide concentration in the atmosphere, and I look forward to further discussing this issue with the Committee in the future.

It is going to require leadership from the private and public sectors in order to overcome some of the technological and market barriers of developing and applying carbon capture and sequestration technologies, and so I appreciate the insights the panel has shared today, and we'll review the record and some of the testimony and look at how we can find a way forward.

Just one question, I guess, I'd pose for the panel, and whoever would like to can answer this. But, the carbon offset issue right now, the range is between $5 and $20 a ton. According to Mr. Fox's testimony, the cost of carbon capture and sequestration ranges between $11 and $57 per metric ton. Do you expect future advances in technology to make CCS more competitive with other ways of limiting carbon emissions, and how long is it going to take for that to happen?

Mr. HERZOG. I would say in the type of cuts that we're talking about, whether it's 80 or 90 percent, that Senator Kerry mentioned or even more modest cuts of 50 or 60 percent, when you're talking those type of cuts, the technology at its current level is going to be competitive with other types of mitigation options.

The, I think initially you actually see costs a little on the higher side, because you have to go through new technology, you always have first of a kind costs. Any time you try new technology it's going to be more expensive until you start to do a few of them and learn how to do it.

I think there's a lot of technology in the pipeline that has a chance to significantly reduce the cost of this, maybe even 50 percent. But those technologies need to be nurtured through the R&D program, and that, I think should be something that's done in parallel with some of the demonstration programs that we talked about here.

Dr. HANNEGAN. And our work, Senator, has shown similar cost estimates to the MIT work around $40 to $50 to $60 per ton CO_2, with the current technologies that are out there. We've identified R&D that will bring those costs down by a considerable amount.

It's also important to recognize that, in general, investing in technology before you apply a carbon constraint, our economic analysis has shown that that's a far preferable economic outcome to applying the constraint first, and then expecting the technologies to come along behind. And that's work that we've detailed in our testimony.

Mr. WOLFE. Senator, if I may, from a different perspective, at $20 a ton, that starts to be a number that private landowners can get quite motivated in terms of management regimes to sequester carbon in forests or through annual agricultural crop productions such as the heartland that you've referred to. The analysis that we've done indicates that that could be a very attractive management regime for a forest land owner.

Mr. FOX. And I would like to note on those costs, the $11 a ton is on the very low end, and those were costs at which we could, as a company who is trying to acquire CO_2, could get it from an emitter, as opposed to what it would cost a power plant that would build something and then they would have to incur a lot more costs up to that point that they'd have to eat. So, those were on the low end, but it's, I think, very important that we have some research to drop those costs, because on a widespread basis throughout the economy, it is—it's very expensive.

Senator THUNE. Thank you, Mr. Chairman.

Thank you all very much.

Senator KERRY. Thank you, Senator.

And thank you very much. We have a roll call vote on now, so it's a good moment, notwithstanding I think we've sort of reached the end.

Thank you all very much. Enormously helpful, very, very important and I'm confident that, together with Senator Stevens' efforts and others, we can get going on this. So, we appreciate it.

We stand adjourned.

[Whereupon, at 4:20 p.m., the hearing was adjourned.]

A P P E N D I X

PREPARED STATEMENT OF ALSTOM POWER, INC.

Alstom Power Inc. welcomes this opportunity to submit its views on the role of technology innovation and the need for Federal support of research, development, and deployment (RD&D) for CO_2 capture and storage technology in coal-fired power generation. America's long-term energy and economic security depends on the availability of a strong portfolio of clean, reliable, and economic technologies for power generation including renewables, nuclear, and clean use of fossil fuels. Alstom strongly believes that CO_2 capture and storage is critical to a sustainable long-term energy supply. As such, our company is a global leader in innovative R&D to meet the technological and economic challenges of capturing CO_2. *A policy framework that includes adequate Federal funding for technology demonstrations, coupled with incentives for early deployment, can help to accelerate commercialization of these and other crucial technologies that help utilities address CO_2 restrictions*.

Alstom has a 100+ year history of providing power generation and environmental control technologies to the global electric industry. Alstom is a global specialist in energy and transportation infrastructure with annual sales of over $21 billion. In the U.S., Alstom has 65 locations in 22 states, including its U.S. corporate headquarters in Windsor, CT. The company serves the energy market through its activities in power generation, power transmission and distribution, and power conversion. Alstom offers a comprehensive range of power generation solutions from turnkey plants to all types of turbine (gas, steam, hydro) generators, boilers, environmental control products and control systems, as well as a full range of services including plant modernization, maintenance and long-term operation.

Clean Coal Technology—Moving Toward Low Carbon Emissions

While our corporate interests and technical capabilities span all forms of energy resources and applications for power generation, we recognize that *the Nation faces a particular challenge in ensuring environmentally sustainable options to continue use of coal while moving toward restrictions on CO_2 emissions.* Coal is an abundant, low cost, and secure domestic energy resource that has steadily and reliably provided over 50 percent of our Nation's electricity over the past two decades. In recent years, coal's stable performance has helped moderate price volatility from rapidly rising gas prices.

Because Alstom is active in global power markets, many of our international clients already face restrictions on CO_2. As a result, we have been working for over a decade on the development of advanced coal combustion technologies focused on reducing CO_2 and enabling CO_2 capture and storage. Some of these technologies, such as high efficiency supercritical steam cycles, are now being placed in commercial operation. Other technologies, such as ultrasupercritical, are in laboratory and proven at bench scale. Still others, including our post-combustion CO_2 capture processes are moving into initial demonstration and deployment with utility partners. These technology options are discussed in the testimony below.

Efficiency—the First Step to Lower Emissions, Including Carbon

For coal based power, plant efficiency improvement is by far the most predictable lowest cost, and nearest term, method to reduce all emissions, including CO_2. Higher efficiency in conversion means less coal (*i.e.,* carbon) is used per megawatt hour of electricity produced, resulting in less emissions to reduce/capture, as well as less coal mined and transported. *Therefore, it is prudent to first minimize CO_2 emissions by higher plant efficiency before incorporating more expensive carbon capture and sequestration.*

Upgrades to the operating fleet can produce modest, but very real and near term, reductions in CO_2 emissions. A recent study by the National Coal Council, in which Alstom participated, concluded that:

> *Any framework for managing CO_2 emissions must take into account the realities of the existing infrastructure of energy production and use in our nations. Imme-*

diate opportunities focus on efficiency improvements within the current fleet of plants. These gains can be made at several points withing the system and included turbine blade upgrades, condenser system and boiler feed water system improvements, washing and cleaning the coal that is used and improving the milling systems used to grind the coal. The development of regulatory incentives would dramatically speed up achievement of these efficiencies. (National Coal Council, "Technologies to Reduce or Capture and Store Carbon Dioxide Emissions", June 2007)

However, improvements produced through upgrades are modest due to the limitations of the installed technology. Further significant efficiency increases will be possible only with deployment of new technology. These technologies include supercritical pulverized coal (SCPC) and circulating fluidised bed (CFB) and integrated gasification combined cycles (IGCC).

Increasing the temperature and pressure of the steam cycle for PC/CFB technology from that of older subcritical designs to today's supercritical cycles can reduce CO_2 (and other) emissions per megawatt hour by as much as 5–15 percent. Today, U.S. utilities and independent power producers are ordering and installing these high efficiency SCPC cycles, tailored to U.S. coals and site requirements. A few are taking the next step to ultrasupercritical PC (USCPC), incurring first of kind risk, but realizing additional efficiency gains, with potential benefits of 2–5 percent additional emissions reductions.

Further increases in steam cycle efficiency are technically feasible, with the potential to reduce CO_2 emissions by as much as 25 percent from the existing fleet average. *These technologies will require investment in advanced materials research and system design to allow operation at even higher temperatures.* The Committee has previously received testimony from both the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE) describing their ongoing programs in materials development for advanced USCPC power plants, including EPRI's proposed UltraGen program to bring these technologies to first of kind demonstration. Alstom is an active participant in these programs.

Systematic replacement of the oldest portion of the existing fleet by new high efficiency USCPC and IGCC power plants over the next two decades can be a basic building block for a CO_2 strategy. *Support of demonstration/deployment in the U.S., for example, provides a platform for proving high efficiency USCPC technology for future export, thus contributing to global CO_2 emissions reductions in the rapidly growing markets in India, China, and Asia.*

Beyond Efficiency to Carbon Capture and Storage (CCS)

Beyond the potential 25 percent reduction that could be achieved via improved efficiencies, technologies are needed to capture remaining CO_2 from the gas streams and to effectively store/sequester the CO_2 long term if more extensive carbon reduction goals are to be met. There are three main CO_2 capture technologies: post-combustion processes, oxy-firing/chemical looping, and pre-combustion capture. CO_2 can be removed from the gas stream of all coal-based technologies, both combustion and gasification based. After capture and compression, the nature of the CO_2 from both gasification and combustion is identical and the costs to transport and store this CO_2 would be the same. (Figure 1 presents Alstom's view on the timeline for demonstration of first of kind demonstrations and commercial deployment of these technologies. A full description of the technologies is included in the attached Appendix.)

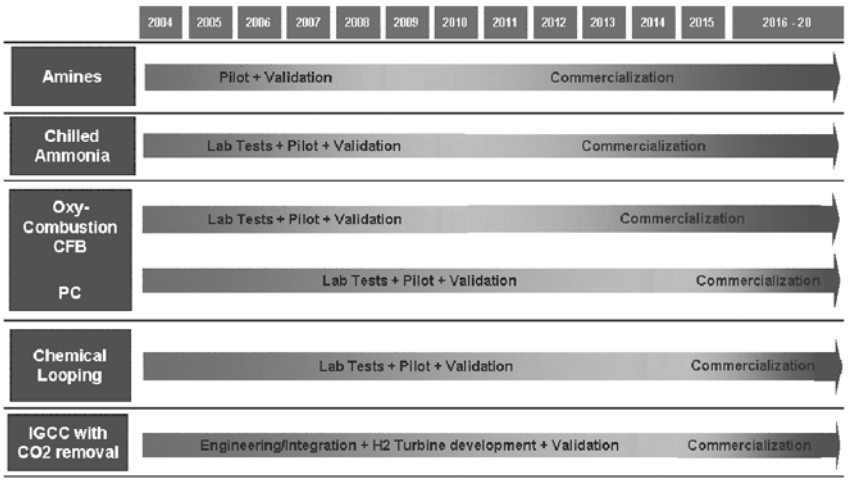


Figure 1: CO_2 CAPTURE SOLUTIONS Time-line of CO_2 Capture Processes

However, there are differences in the current cost of capture technologies, their stage of development and scale-up, and the forecasts of future costs and performance. If implemented today, capture costs from oxygen-fired IGCC may be somewhat lower than from a PC/CFB using existing older commercial amine processes. However, today's costs of IGCC are high and future cost reductions for IGCC are uncertain. More importantly, the cost for CO_2 capture would be excessively high for both combustion and gasification technologies. Better technologies are needed for carbon capture and storage to minimize the potential impact on energy costs. Alstom's own corporate interests are focused on demonstration and commercialization of technology options for cost competitive CO_2 capture from combustion technologies. *Nevertheless, as technologies to capture CO_2 from both combustion and gasification are still under development and continue to evolve, Alstom believes strongly that Federal policy should encourage development of the full range of options, rather than bias selection or predict technology winners related to only one technology*.

Incentives and Models for Early Deployment

As a technology innovator, Alstom firmly believes that carbon reduction, capture and sequestration technologies at competitive costs are a critical and achievable goal for coal-based power. However, realizing this goal will not be easy, it will require the combined skills and knowledge of the public and private sector, working in close cooperation over, at a minimum, the next decade. Due to the large investment required to support R&D and commercial demonstration/deployment of new technologies, *Alstom* believes that both Congressional and Administrative support will be critical to the successful deployment of new these technologies. The U.S. Government must play a leadership role to support this critical effort through legislation and appropriation of funds to support research, development and deployment of the next generation of clean coal technologies.

Alstom believes that the models of development and deployment successfully utilized for currently regulated emissions could be applied to achieve deployment of technologies to meet the next challenge of lowering carbon emissions.

Two aspects of this model are important to recognize. First, development and deployment of new large capital intensive technologies for power generation is risky and complex, requiring major R&D expenditures and a long term commitment by all industry stakeholders. Second, successful deployment requires strong cooperative efforts between generators, technology suppliers and government to manage risk and to ultimately provide the most effective, reliable, and cost effective solutions. It is also critical that legislative and regulatory initiatives reflect realistic, achievable timelines for technology development and deployment.

A solid example of successful innovation and deployment in environmental controls for coal-based power was the development of flue gas desulfurization (FGD) for sulfur dioxide (SO_2) emissions control.

Alstom and other companies began laboratory bench scale testing of post-combustion FGD systems in the 1960s, followed by pilot scale demonstrations in the early 1970s. The first generation of commercial units followed these demonstrations. These first of kind units achieved SO_2 emissions reductions of approximately 70 percent, but they were relatively expensive, requiring redundant systems to ensure reliability. As technology suppliers and utilities installed more FGD units, lessons learned from this initial operating fleet resulted in improved designs with better emissions performance. Collaborative learning, supported by strong government technology programs such as the DOE's Clean Coal Power Initiative, produced capital and operating cost reductions as a range of system designs were explored and optimized. Over time, the most reliable, effective and cost efficient processes became evident and FGD technologies moved from first and second generation 'proof of concept' to solid commercial offerings. Concurrent with this technology development, Federal and state regulators implemented a series of flexible, stepwise and increasingly stringent emissions regulations which drove technology advancements while recognizing the time required to achieve each incremental reduction goal. A combination of cap and trade and national ambient air quality goals gave generators the ability to implement emissions reductions in an efficient manner across their fleet.

Today, with 25 years of experience and deployment, FGD systems routinely achieve 95–99 percent reductions of SO_2 at capital costs approximately 50 percent of early FGD systems. The competitive marketplace has effectively replaced the initially vital government and industry funding support.

Equally important, many of the FGD technologies developed and proven on U.S. power plants are now being deployed globally as developing nations, most notably China, begin to address environmental issues. Thus, U.S. technology FGD technology expertise is being exported to improve the global environment.

Conclusions

Alstom Power applauds the directions set forth in S. 2323 to provide Federal support for demonstration of capture technologies on coal-fired power plants, accompanied by sequestration. We urge the Committee to ensure that such programs will support a portfolio of coal generation technologies, with adequate focus given to advanced combustion processes, as well as gasification. There is a very strong case for pursuing all technology options to significantly increase the probability of achieving the complex goals of environmental performance, reliability and reasonable costs for all applications. In addition, support for CO_2 capture processes applicable to SCPC plants has major implications for future technology exports to address the large supercritical fleet being built today in China and India.

We ask that the Committee recognize the importance of supporting adequate funding for key programs such as DOE's Advanced Materials Research, which provides fundamental advances to support CCS technology development.

Alstom participates in groups such as EPRI and the Coal Utilization Research Council (CURC) who have both outlined recommendations for incentives to support initial demonstration/deployment at large scale and rapid early deployment. We highlight the following recommendations for the Committee's consideration to better achieve objectives for technology deployment.

- Support appropriate scale-up for first of kind demonstrations, but do not burden these projects with excessive requirements of scale.

  Post combustion capture processes can readily be evaluated and demonstrated on slip streams of exhaust gases from new or existing PC or CFB plants. Levels of capture (such as 50 percent removal, 70 percent removal, etc.) can be demonstrated on this partial gas flow and are readily translated to full plant scale-up. However, the most efficient method of initial deployment is to build first of kind at a scale sufficient to: (1) utilize commercial size modules/components, and (2) provide sufficient CO_2 to support viable integrated storage/EOR testing. There is no technical rationale for first of kind demonstrations to be larger than necessary for initial proof of technology. In fact, this would result in unnecessary cost, as it is very likely that initial capture systems designs will be improved and modified as operational experience accrues. Improved systems designs can be added to the same plant as additional modules of the advanced designs, after the learning takes place.

- First of kind demonstrations for post combustion capture can be installed on either new units or as retrofits. Each has benefits. Installation on existing units has a shorter timeline and moves the technology to demonstration earlier. However, retrofits are limited in the ability to optimize the integrated power plant design with the capture technology; application to new units will likely yield the

highest performance in terms of reduced energy penalty for capture. Both types of projects should be pursued, with incentives to move first of kind into operation.

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APPENDIX

Description of Key Carbon Capture Technologies for Electric Power Plants

Provided by Alstom Power, Inc.

Post-Combustion Capture

Alstom is developing post-combustion capture technologies, which have the advantage of being applicable to new USCPC and CFB plants, as well as potentially retrofittable to a portion of the global installed base of coal and gas units. In post-combustion capture, CO_2 is selectively removed from the flue gas, typically via a regenerable solvent which is recycled within the capture process. The concentrated CO_2 stream thus produced is compressed to a liquid for either on-site storage or transported via pipeline to off-site storage or to use in enhanced oil recovery (EOR).

Post-combustion CO_2 capture based on amines currently is in use in other industries. These systems, which use MEA as the capture solvent, are not at the scale required for large power plants and are expensive due to the high parasitic energy load to run the capture system. Alstom is an active participant in the European CASTOR program that aims to develop advanced amine capture systems which will significantly reduce the cost and high energy requirements. A new state-of-the art advanced amine capture pilot plant was recently launched at Esbjerg Power Station in Denmark.

Alstom also is aggressively pursuing a very promising new post-combustion process utilizing chilled ammonia as the capture solvent. This technology has the potential for significantly lower energy requirements, thus reducing the impact on plant output and efficiency, which would in turn significantly reduce the cost of CO_2 capture. Key projects underway to evaluate and demonstrate the chilled ammonia process include:

- 5 MW_t pilot plant in association with EPRI for We Energies at their coal-fired Pleasant Prairie plant in Wisconsin.
- 5 MW_t demonstration plant for E.ON in Sweden (oil and gas).
- 30 MW_t product validation unit for American Electric Power (AEP) at their Mountaineer coal power plant in West Virginia, followed by the design, construction and commissioning of a commercial scale CO_2 capture system of up to 200 MW.
- 40 MW_t test and product validation facility for a natural gas combined cycle for Statoil in Norway.

Alstom has garnered significant interest from potential utility customers in this ambitious technology development and deployment program. Its success will depend not only on utility participation, but also appropriate funding and incentives to mitigate technical and financial risks for these early innovators.

Oxy-Firing/Chemical Looping

In addition to post combustion capture, Alstom is developing combustion-based technologies that incorporate direct CO_2 capture: oxygen-firing (oxy-firing) and chemical looping. Oxy-firing burns solid fuel with pure oxygen rather than air. The flue gas thus obtained mainly is composed of water and CO_2, the latter being easily removed from the flue gas by water separation. Oxy-firing applies to new units but may suit some selected retrofits as well.

The main challenge of oxy-firing technology lies in the current cost of producing oxygen on a large scale through air separation units (ASU). Energy required for air separation results in a 20–25 percent drop in net plant output compared to an air-fired plant. This issue is currently being addressed by major gas specialists, who are working on improving ASU technology and exploring new oxygen-production techniques. DOE is also actively supporting advancements in air separation, as oxygen is also used for many IGCC technologies.

Alstom is playing a key role in developing oxy-firing PC and CFB techniques and has been selected to set up the first pilot scale power plant using oxygen combustion of brown coal for the power producer Vattenfall at a power plant in Germany. We are also in studies to evaluate the retrofit of small plants to oxy-firing in France and Canada. With the potential for breakthrough in reducing costs of air separation, oxy-firing warrants support to move to demonstration.

Based on its CFB know-how, Alstom is also investigating breakthrough technologies such as chemical looping. This unique system replaces the traditional boiler with a two stage chemical conversion process, using an oxygen "carrier" to transfer oxygen to the fuel. The exhaust gas is similar to oxy-firing, enabling easy CO_2 capture. Preliminary tests at the 10 kW Chalmers unit (under the EU ENCAP programme) and on-going research on the Chemical Looping process development unit of Alstom in Windsor, CT, supported in part by DOE funding, are very promising.

Pre-Combustion Capture from Gasification/IGCC

The integrated gasification combined cycle (IGCC) process transforms a carbon-rich fuel such as coal, through a chemical reaction, into a syngas (carbon monoxide (CO) and hydrogen (H_2)), which can then be burned in a combined cycle plant. The level of carbon emissions from an IGCC plant is similar to that of a SCPC plant due to comparable efficiency levels. Carbon capture with IGCC is considered "pre-combustion" because the carbon is separated right after the gasification phase, prior to burning the syngas in a gas turbine. (In fact, the gasification phase is actually partial combustion to CO, rather than full combustion to CO_2 as occurs in a PC or CFB plant.) IGCC technology, with or without carbon capture, is used in new plant construction, since repowering of PC or CFB into an IGCC plant is very complex.

To capture carbon from an IGCC unit, additional processing steps are added, including a shift reaction from the original syngas blend to a mixture of CO_2 and hydrogen, followed by separation of the CO_2 using a physical solvent. The pre-combustion capture process is in itself cheaper than currently available post-combustion capture systems and has been validated in other industries. Alstom is not aware of any existing commercial applications of CO_2 removal technologies installed on coal-fired IGCC facilities.

For IGCC, the challenge lies not so much in the capture itself, but in the fact that syngas—after CO_2 removal—essentially contains only hydrogen. Burning a hydrogen-rich syngas raises significant issues for gas turbines and is a technological hurdle to be overcome. Alstom and other gas turbine suppliers are working to generate fundamental knowledge on the combustion of H_2-rich fuels, and to direct this knowledge to the development of gas turbine combustors. The burners must be compatible with established industrial standards governing emissions, safety, operability, fuel flexibility, reliability and durability.

In addition to longer-term CO_2 challenges, IGCC faces two major issues—its: (1) reliability (operating IGCC availability is currently several percentage points below that of SCPC plants), and (2) cost (currently around 20–30 percent more expensive than SCPC technology).

Alstom is participating in IGCC developments for the future and has put in place in-house programs to develop its GT fuel flexibility for syngas and H_2 combustion. We already participate in the gasification market as a supplier of components, including synthesis gas cooling equipment and low calorific value fuel gas turbines.

PREPARED STATEMENT OF DR. S. JULIO FRIEDMANN, LEADER, CARBON MANAGEMENT PROGRAM, LAWRENCE LIVERMORE NATIONAL LABORATORY

Mr. Chairman, and Members of the Committee: Thank you for inviting me to testify today on the technical aspects of carbon capture and sequestration, specifically on the current status of technology, on readiness for deployment, what current standards and protocols exist, and on what the Federal Government can do to narrow these gaps. I am pleased to be here in my capacity as leader of the Carbon Management Program at the Lawrence Livermore National Laboratory and report on this important technology pathway, which could help America continue to meet its domestic energy needs while dramatically reducing the emission of greenhouse gases. Carbon capture and sequestration can be a vital element of a comprehensive energy strategy that includes efficiency gains, conservation, and carbon free energy supplies such as renewable or nuclear power. It can also support environmentally sound domestic development of transportation fuels including biofuels, coal-to-liquids, and hydrogen, and a smooth transition to a carbon-free energy infrastructure.

Over the past 2 years, much has been written on the subject of carbon capture and sequestration (CCS). The Intergovernmental Panel on Climate Change (IPCC)

2005 special report includes a 135-page chapter on geological carbon sequestration (GCS). The MIT Report on the *Future of Coal in a Carbon Constrained World,* released in March, discusses geological sequestration in detail. The National Petroleum Council report "Facing Hard Truths" includes a chapter on capture and sequestration. The state of California has recently assembled a document for the legislature that covers many CCS topics including GCS, and the Interstate Oil and Gas Compact Commission recently published a set of draft guidelines for commercial deployment. These documents and others listed at the end of this testimony provide more technical details about matters that underlie my testimony.

I was specifically asked to comment on what we do and do not know about CCS as an option for addressing climate change. My testimony starts with an overview of what is known about GCS. I will then discuss the prospects for GCS on a commercial scale together with estimates of cost and impact on reducing global carbon emissions. My presentation concludes with a discussion of three particular immediate needs to resolve unknowns: an assessment of geological resources within the U.S., the pursuit of some large-scale CCS projects, and improved hazards assessment and management to reduce risks.

Overview of Geological Carbon Sequestration

Carbon capture and sequestration has two components. The first is the separation and concentration of CO_2 from point source flue gases, which are produced at power plants, refineries, ethanol plants, fertilizer plants, and other sources like cement factories. This step is needed to bring CO_2 concentrations up to 95 percent before the second step, sequestration. Geological carbon sequestration (GCS) or carbon storage, involves injection of CO_2 into porous rock formations deep below the surface. The goal is to keep CO_2 out of the atmosphere so as to avoid atmospheric warming and the consequences of climate change while allowing the continued use of fossil fuels for power generation and industrial purposes. This hearing and my remarks will focus on GCS.

GCS involves compressing CO_2 and injecting it into geological formations at great depth (from 3,000 to 20,000 feet). The most promising reservoirs are *porous and permeable rock bodies,* generally at 1 km depth or more and pressures and temperatures where CO_2 would be in a supercritical phase in which it behaves like a very dense, liquid-like gas. These potential reservoirs include:

- *Saline formations,* which contain brine in their pore volumes, commonly of salinities greater than 10,000 ppm.
- *Depleted oil and gas fields* that have some combination of water and hydrocarbons in their pore volumes and a demonstrated seal. Injection of CO_2 into these reservoirs can stimulate enhanced oil recovery (EOR) or enhanced gas recovery and increase domestic fuel supply; substantial CO_2 EOR already occurs in the U.S. with both natural and anthropogenic CO_2.
- *Deep coal seams,* often called unmineable coal seams, which comprise organic minerals with brines and gases in their pore and fracture volumes.

Once the CO_2 is injected into the subsurface, it will flow throughout the storage formation where it will remain trapped. This trapping will keep those greenhouse gases out of the atmosphere indefinitely. The IPCC issued a special report in 2005 on the topic of carbon sequestration, stating that if a site is chosen well and operated well, then it is highly likely (>90 percent) to store 99.9 percent of injected CO_2 in place for 100s of years, and likely to store 99 percent for 1,000s of years.

The Earth's shallow crust is well suited to the indefinite trapping and storage of CO_2 because of its physical and chemical properties. To begin, CO_2 sequestration targets will be selected that have *physical barriers* to CO_2 migration out of the crust to the surface. These barriers will commonly take the form of impermeable layers (*e.g.,* shales, evaporites) overlying the reservoir target and act immediately to limit CO_2 flow. Four different mechanisms serve to trap CO_2 in the subsurface. At the pore scale, *capillary forces* will immobilize a substantial fraction of CO_2 as tiny, isolated bubbles trapped as a residual phase. Over a period of tens to hundreds of years, CO_2 in the formation will *dissolve* into other pore fluids, including hydrocarbon species (oil and gas) or brines, where the CO_2 cannot be released without active intervention. Over longer time scales (hundreds to thousands of years) the dissolved CO_2 may react with minerals in the rock volume to *precipitate* the CO_2 as new carbonate minerals. Finally, in the case of organic mineral frameworks such as coals, the CO_2 will physically *adsorb* onto the rock surface, sometimes displacing other gases (*e.g.,* methane, nitrogen). These trapping mechanisms have been documented and observed in natural analogs (*e.g.,* the natural CO_2 domes in Colorado) and laboratory experiments, and they have been simulated in integrated geological models. Although substantial work remains to characterize and quantify these

mechanisms, they are sufficiently well understood today to trust estimates of the percentage of CO_2 stored over the timeframes discussed by the IPCC.

Because of their large storage potential and broad distribution, saline formations are likely sites for most geological sequestration. However, initial projects probably will undertaken in depleted oil and gas fields, accompanying EOR, due to the density and quality of existing subsurface data and the potential for economic return; the Weyburn EOR and storage project in Saskatchewan is one example. Availability of pore volumes in suitable formations for sequestration may be considered a natural resource. Areas that have this resource in abundance have a competitive advantage in a carbon constrained world compared to those that lack storage capacity.

Status of Geological Carbon Sequestration (GCS)

GCS is very analogous to the injection of CO_2 for enhanced oil recovery, which has been done in the U.S. for over 30 years. Sequestration also has similarities with natural gas storage, hazardous waste disposal, and acid gas management as well as other aspects of oil and gas production in addition to EOR. These activities use the same technologies as GCS, and their technical basis provides confidence in the viability of commercial GCS deployment. Furthermore, natural accumulations of CO_2 have demonstrably retained large CO_2 volumes for 10s to 100s of millions of years. This provides confidence in the possibility of long-term storage of CO_2 in suitable rock formations.

Commercial projects in carbon storage are underway in the U.S. and elsewhere in the world. In the U.S., the DOE's Regional Carbon Sequestration Partnership program has announced three large-scale projects last month, which are slated to begin injection within 4 years. These projects anticipate commercial programs. BP has announced a project in Carson California that will inject 4 million tons of CO_2 each year while producing 500 megawatts (MW) of zero-emission power. Xcel Energy, Duke Energy, and American Electric Power have all announced projects to generate zero-emission power from coal power using CCS. Other countries (Sleipner in Norway, In Salah in Algeria, and Weyburn in Canada) have projects that have been on-going for 10 years and annually inject over 1 million tons of CO_2 from anthropogenic sources. Several more projects will come online in 2008 in Norway and Australia, and nearly a dozen are on track worldwide for completion and injection before 2012. Finally, the DOE's FutureGen project is in the final stage of selection among four outstanding sites. This project will provide insight into the design, engineering, and likely unit economics of combined generation and sequestration efforts. A few of these examples are enhanced oil recovery projects, which will produce additional liquid fuels. Most of these projects will inject into saline formations, which represent the largest potential CO_2 sinks in the U.S. and the world. These activities demonstrate tremendous technical readiness in the U.S. and the world for commercial deployment.

A key difference between GCS and applications mentioned above (*e.g.,* EOR, natural gas storage) is that the GCS goal is to keep the CO_2 in the target reservoir indefinitely. There are many technologies used in industry today that can monitor CO_2 in the subsurface and the surface, including time-lapse reflection seismic surveying, use of tracers, and electrical soundings. Some of these approaches have been tested in commercial and experimental projects, including DOE sponsored efforts like the Frio Brine Pilot and current efforts in the Regional Partnerships program. However, to date there has not been a concerted effort to apply these technologies in a comprehensive or integrated manner to monitor CO_2.

This new application will have new requirements, such as a monitoring and verification (M&V) program. A site M&V program to support GCS should provide these services:

- identify any early concerns or problems (as mentioned below) and protect public health and safety;
- assign credits or offsets for commercial GCS, especially under a cap-and-trade regime;
- validate simulations and current understanding of sequestration science; and
- guide any necessary mitigation efforts.

Several hazards could affect CCS operations at a site. These hazards, such as well failure or CO_2 seepage along faults, could lead to problems such as atmospheric release of CO_2 or groundwater contamination. Pre-existing wells present the largest risks as potential leakage paths, but leakage through wells is the simplest to detect and mitigate. Preliminary analyses through analog studies and simulation, which have been performed by industry, academia and national laboratories, suggest that the risks posed by these hazards are both very small and manageable. As such, the

technical community has considerable confidence that carbon capture and sequestration can be safely and effectively deployed widely within the U.S.. Key steps to avoiding hazards are careful site characterization before injection and appropriate M&V programs during injection. If good sites are selected and effectively monitored, there is little chance of site failure or CO_2 leakage.

In short, there is enough knowledge and experience available today to safely and effectively choose a site, characterize it, operate it, monitor it, and close it. On a project basis, then, sequestration is technically ready, but it is rarely commercially deployed since potential operators have few mechanisms to recover their costs. In contrast, there is not enough information to proceed with regulations and legal structures to enable sequestration on a regional or national basis. This lack of technically founded regulation is important to bring sequestration into commercial operation, and the government has a role both in supporting projects that provide this technical information and in integrating these results rapidly into guidelines, statutes, standards, and ultimately regulations that provide market clarity and sureness.

The Potential for Commercial GCS

Today, the U.S. emits annually 2 billion tons CO_2 from large point sources, and 25 percent of U.S. CO_2 emissions come from coal power generation (~1.5 billion tons). To help you appreciate the scales involved, 1 billion tons is greater than the mass of all human beings on Earth. Alternatively, the volumes of CO_2 at depth represented by this mass exceed current annual U.S. oil and natural gas production combined. A single 1,000 MW coal power plant will emit from 5 to 8 million tons of CO_2 each year, roughly the same emissions as a 25,000 barrel/day coal-to-liquids plant. With sequestration in an appropriate geological formation, a 50 year injection program for one of these plants would accumulate in excess of 2 billion barrels of CO_2. It is the necessary scale of sequestration projects and enterprise that present challenges to deployment.

The good news is that it appears that the U.S. has more than enough capacity to deploy CCS at large scale. Conservative estimates (including some I've published) are that the U.S. has 2,200 billion tons capacity. The DOE Office of Fossil Energy has recently published a Carbon Sequestration Atlas for North America that estimates capacity between 1,000 billion and 3,700 billion tons. Large sequestration resources occur in the Midwest, Texas, and the intermountain West, and substantial opportunities also exist in California, the Dakotas, Michigan, and offshore of the eastern U.S. The largest of these resources lie in saline formations and depleted oil and gas fields. While these published estimates are uncertain, it is likely that they substantially underestimate total U.S. capacity. Said another way, we appear to have enough capacity to comfortably inject all of our current point source CO_2 emissions for more than 100 years, and are likely to be able to do so comfortably for more than 1,000 years.

Potential Climate Change Abatement and Cost

CCS has the potential to substantially reduce U.S. and global greenhouse gas emissions. From a technical basis, that potential is only limited by the characteristics of the geology. Three conditions are important, sometimes called the ICE characteristics:

- I: sufficient *injectivity* to receive large volumes of CO_2 rapidly (up to several million tons CO_2/year for each project).
- C: sufficient *capacity* to accept large volumes of CO_2 (for some projects, in excess of 300 million tons over the project lifetime).
- E: *effectiveness* in trapping CO_2 for long time spans (100s to 1,000s of years).

Based on these characteristics, it appears that CCS provides both the U.S. and world a potential to reduce global emissions between 15 and 55 percent by 2050. This abatement estimate is based on current understandings of global geological options and energy supply infrastructure. The high reductions can be achieved through advanced technology options which connect the transportation sector to a decarbonized electric power sector that includes CCS (*e.g.,* plug-in hybrid deployment, biofuels, or hydrogen). Importantly, this is a very attractive option for rapidly developing countries like China and India with large coal resources.

Most experts see CCS as a bridging technology providing time for new carbon free technologies, including renewables, advanced fission and fusion power, and other developing technologies, to grow in the marketplace. The technology is actionable immediately and could be sustained for many years, allowing us to dramatically reduce greenhouse gas emissions while maintaining the economic benefits of fossil fuel power generation and making use of the current infrastructure. CCS could be sus-

tained in the U.S. for a century serving as an affordable interim measure to buy time while an energy strategy and infrastructure is developed to support long-term needs.

Others testifying before this committee have discussed the costs of carbon capture and separation. By comparison, the costs of sequestration are much lower. For most U.S. targets, the estimated cost of storage injection projects ranges from $1 to $12 per ton CO_2, and average cases range from $5 to $8 per ton CO_2. This is roughly 10 percent the total cost of capture and separation. The cost of monitoring and verification is much lower, with estimates from $0.25 to $1.00 per ton CO_2. The costs of assessment and site characterization are even less, estimated to be much less than $0.001 per ton CO_2.

One important way to consider cost vs. benefit of carbon capture and sequestration is its potential role in managing global climate change. Recent reports published by the UK's Stern Review and Pacific Northwest National Laboratory suggest that if CCS were not available as an option, the costs of addressing climate change would be 50–80 percent higher than if CCS were a major contributor.

Technical Needs

I want to focus on three particular immediate technical needs: an assessment of geological resources within the U.S., the pursuit of large-scale sequestration projects, and improved hazard assessment and management to reduce risks.

Resource Assessment

To better bound the 15 to 55 percent estimate of potential greenhouse emission abatement through carbon sequestration, we need to increase the current understanding of global and national geological storage resources. Ultimately, GCS potential will depend on local geological conditions and energy infrastructure choices. Future energy infrastructure decisions (*e.g.,* plant type and location) should be informed by understandings of storage resources. Assessment of this resource can be accomplished through careful and detailed geological studies and validated by a handful of large-scale demonstrations in representative geology. Those demonstrations should both confirm the safe and effective storage of CO_2 in the key formations and should provide the technical basis for future regulatory framework and operation protocols.

A national capacity assessment would provide the same kinds of information that the national hydrocarbon assessments offer in mapping the natural resources of the country with respect to this purpose. In this context, available pore volume to store CO_2 is such a resource. An assessment of geological storage resources should provide several key pieces of technical information:

- A uniform, documented methodology that allows intercomparisons of geologic opportunities and accounts for the different trapping mechanisms.
- A capacity estimate for each region or state and for the Nation as a whole.
- A relative ranking of potential sites by storage effectiveness, and their associated capacities.
- Rate information indicating the likely maximum sustainable injection rates for formations and regions.
- Data needed to develop economic models for GCS projects.

As mentioned above, DOE's Office of Fossil Energy published the Carbon Sequestration Atlas, which provided preliminary estimates of capacity in saline formations, depleted oil and gas fields, and unmineable coal seams. This was an important initial step in understanding the U.S. sequestration resource. This work can continue to be refined and improved to provide greater understanding of the location and density of high quality sequestration resource. The DOE and the U.S. Geological Survey have only begun joint work on this effort, and should be funded to pursue development of methodology and maps.

Large-scale, Long-term Experiments

Large projects are crucial to confirming our understanding of how CO_2 is trapped and stored, refining deployment operations, and demonstrating success. Because of the enormous scale required for commercial CCS operation,. While smaller projects provide a partial learning platform; however, the key unresolved questions pertaining to commercial-scale injections can only be resolved at large scale. This is due to the hydrological, chemical, and mechanical response of the crust to changes in pressure and fluid composition from CO_2 injection. Many important responses only occur when thresholds are reached, and these will not be reached by small-scale injections. For example, the pressure build-up could cause mechanical failure of the caprock, faults, or wells only when their yield strength is exceeded. That cannot be

tested with small-scale injections. Similarly, the rock heterogeneities that control flow in target reservoirs do not become apparent until large volumes are injected for long periods of time.

These issues are critical for establishing long-term commercially viable operational and regulatory frameworks. Of equal importance, these technical issues should advise the formation of practices, protocols, and ultimately standards for CCS. We currently lack guidelines and protocols on minimal requirements for site characterization, operational safety, monitoring and verification, hazard management, and site closure. Implementing a select number of large-scale experimental projects (on the order of 1 million tons CO_2/year injection) in target reservoirs of different characteristics that are instrumented, monitored, and analyzed to verify the practical reliability and implementation of sequestration. With appropriate, integrated science and technology program to provide the needed analysis, large experiments will provide the critical segue way to commercial operation and significant abatement of CO_2 in our atmosphere. To help assure the delivery of the scientific information most crucial to success, a minimum project budget of $120 million would be prudent, with a minimum scientific budget of $40–$70 million.

The specifics of an individual large sequestration experimental project are detailed in MIT (2007), Friedmann (2006), and U.S. DOE (2007) studies.

Initial sets of projects could be most rapidly brought forward where low-cost, pure CO_2 streams are available. These include natural CO_2 supplies, hydrogen plants, ethanol plants, fertilizer plants, synthetic natural gas plants, and gas processing plants. This mix is well reflected in the current effort of the regional partnerships, such as the DOE Regional Carbon Sequestration Partnership previously mentioned, which is configured in a way to produce the necessary learnings. It must be stressed that the very first projects should be selected with the utmost care and due diligence both to help ensure project success and to guard against potential unanticipated hazards (the FutureGen selection process was constructed with this goal in mind). Most importantly, these projects must serve the urgent need to provide answers to key questions asked by potential operators, regulators, insurers, financiers, and public stakeholders. These questions involve questions of site selection, monitoring, hazard identification and management, and subsurface process. As such, they must be both appropriately funded and appropriately managed to achieve these goals. Finally, as the projects proceed, the learnings should be integrated in a staged way. For example, an operational protocol onsite characterization could be released after just 2–3 years of work, followed by other protocols and guidelines on infrastructure development, baseline monitoring, hazard assessment and evaluation, operations, and monitoring and verification.

Hazards Assessment and Management

As mentioned above, a number of potential hazards to long-term storage have been identified (such as wells and faults). While it is believed that these hazards can be readily avoided and managed, prudence suggests a more concerted and technically grounded effort to understand the risks posed by these hazards. Three issues are of greatest interest:

- Protocols and standards for hazard identification and characterization.
- Improved understanding of the potential failure modes of these hazards.
- Protocols and standards for avoiding hazard failure.

By focusing on hazards management in addition to understanding risks, it is possible to provide potential operators, regulators, and investors the information they need to make key decisions swiftly. Such a program would help bring GCS projects to operational readiness more quickly.

A concerted program that combines field, laboratory, and numerical approaches could provide the technical basis for hazard assessment and management within 5 years. This work should include a focus on those hazards, failure modes, and consequences that present credible, substantial health, safety and environmental risks. Additional funding to rapidly begin and execute this effort is warranted.

Summary

Opportunities for rapid deployment of GCS exist in the U.S. There is enough technical knowledge to select a safe and effective storage site, plan a large-scale injection, monitor CO_2, and remediate and mitigate any problems that might arise (*e.g.,* well-bore leakage).

This knowledge derives from over 100 years of groundwater resource work, oil and gas exploration and production, studies of geological analogs, natural gas storage site selection and operation, and hazardous waste disposal. A careful operator could

begin work today at a commercial scale and confidently select and operate a site for 30 to 50 years.

National deployment of commercial CCS poses technical challenges and concerns due to the required operational scale to make a tangible impact on CO_2 emissions. In particular, there is an acute lack of standards and protocols to guide the decisions of potential operators, regulators, and investors. An aggressive research, development, and deployment program focused on large, sustained field experiments could answer the key technical questions and provide these protocols within 10 years and could advise the formation of a legal and regulatory framework to protect the public without undue burden to industry.

Key References

Benson S.M., Cook P., 2005, Chapter 5: Underground Geological Storage, IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Interlachen, Switzerland, *www.ipcc.ch*, pp. 5–1 to 5–134.

MIT, 2007, *Future of Coal in a Carbon Constrained World,* MIT Press.

U.S. DOE, 2007, Carbon Sequestration Technology Roadmap and Program Plan for 2007, Morgantown, W.V., 39 p.

Intergovernmental Panel on Climate Change, 2005, Summary for Policy Makers, IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Interlachen, Switzerland, *www.ipcc.ch.*

Jarrell P.M., Fox C.E., Stein M.H., Webb S.L., 2002, *Practical aspects of CO_2 flooding*. Monograph 22. Society of Petroleum Engineers, Richardson, TX, USA.

Pacala S., Socolow R., Stabilization Wedges: Solving the Climate Problem for the Next 50 Years Using Current Technologies, *Science,* 2004, v.305, pp. 986.

National Petroleum Council, 2007, *Facing the Hard Truths About Energy,* Washington, D.C., 442 p.

California Energy Commission, 2007, *Geological carbon sequestration strategies for California: The Assembly bill 1925 report to the California legislature,* Report # CEC–500–2007–100–SD, 161 p.

Interstate Oil and Gas Compact Commission, 2007, Storage of Carbon Dioxide in Geological Structures: A Legal and Regulatory Guideline for the States and Provinces, 49 p. *http://www.iogcc.state.ok.us/PDFS/CarbonCaptureandStorage ReportandSummary.pdf.*

Current Large Projects

Arts R., Eiken O., Chadwick A., Zweigel P., van der Meer L., Zinszner B., 2004, Monitoring of CO_2 injected at Sleipner using time-lapse seismic data, *Energy,* 29, pp. 1383–1392

Wilson M., Monea M.. (Eds.), IEA GHG *Weyburn CO_2 Monitoring & Storage Project Summary Report* 2000–2004, 2004, 273 p.

Riddiford F., Wright I., Espie T., Torqui A., 2004, Monitoring geological storage: In Salah Gas CO_2 Storage Project, GHGT–7, Vancouver.

Natural Analogs

Allis R., Chidsey T., Gwynn W., Morgan C., White S., Adams M., Moore J., 2001, Natural CO_2 reservoirs on the Colorado Plateau and southern Rocky Mountains: Candidates for CO_2 sequestration. Proceedings of the First National Conference on Carbon Sequestration, May 2001, DOE NETL, Washington, D.C.

Czernichoswki-Lauriol, I., *et al.,* 2002, The French carbogaseous province: an illustration of the natural processes of CO_2 generation, migration, accumulation, and leakage, Proc. of GHGT–6, Kyoto, E1–2.

IEA International Energy Agency (2006) Natural Emissions of Carbon Dioxide. International Energy Agency Greenhouse Gas Programme. *http://www.iea green.org.uk/*.

IEA International Energy Agency (2005) A review of natural CO_2 emissions and releases and their relevance to CO_2 storage. International Energy Agency Greenhouse Gas Programme, Report 2005/8. *http://www.ieagreen.org.uk/*.

Capacity Assessments

U.S. DOE, 2007, Carbon Sequestration Atlas of the United States and Canada, Office of Fossil Energy, National Energy Technology Laboratory, Morgantown, W.V., 90 p.

Gibson-Poole C.M., Lang S.C., Streit J.E., Kraishan G.M., Hillis R.R., Assessing a basin's potential for geological sequestration of carbon dioxide: an example from the Mesozoic of the Petrel Sub-basin, NW Australia; Keep, M. & Moss, S.J. (eds). *The Sedimentary Basins of Western Australia 3:* Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 2002, pp. 439.

Bradshaw J., Allison G., Bradshaw B.E., Nguyen V., Rigg A.J., Spencer L., Wilson, P., Australia's CO_2 Geological storage potential and matching of emission sources to potential sinks. In: Greenhouse gas control technologies: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1–4 October 2002, Kyoto, 2003.

Carbon Sequestration Leadership Forum, Discussion Paper on Capacity Estimation, Technical Working Group, Olveida, Spain, 2005. *http://www.cslforum.org/presentations.htm.*

Friedmann S.J., Dooley J.J., Held H., Edenhofer O., 2006, The low cost of geological assessment for underground CO_2 storage: Policy and economic implications, *Energy Conversion Management,* v47, pp. 1894–1901.

Dooley J.J., Friedmann S.J., A regionally disaggregated global accounting of CO_2 storage capacity: data and assumptions, Pacific Northwest National Laboratory, Report PNWD–3431, 2004.

Large Project Design and Policy Support

Friedmann S.J., 2006, The scientific case for large CO_2 storage projects worldwide: Where they should go, what they should look like, and how much they should cost, 8th Greenhouse Gas Technology Conference, Trondjheim, Norway, Poster session II.

Wilson E.J., Friedmann S.J., Pollak M.F., 2007, Research for Deployment: Incorporating Risk, Regulation and Liability for Carbon Capture and Sequestration, *Environment and Science Policy,* v41, 5945–5952.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN THUNE TO HOWARD HERZOG, CH.E.

Question 1. As is noted in some of your testimony, China and India also use coal to meet significant portions of their energy needs and are quickly becoming some of the world's largest polluters. What is the potential of these countries to use CCS to limit their emissions? Will technologies that we develop be of use to them, or do they face a different set of technical and non-technical limitations?

Answer. The biggest factor in determining a country's CCS potential is the availability of the appropriate geologic reservoirs. To my knowledge, no detailed studies have been conducted in China or India to determine their resource base. The general feeling is that their opportunities will be more limited than the U.S. (which has a very good resource base), but that significant opportunities should exist.

In general, the technologies developed in the U.S. should be transferable to India and China, but they may need to be adapted for local conditions. A key factor in determining the type of capture technology to use is the coal grade and quality.

Question 2. A number of you mention the necessity of large scale experiments on CCS. Is government funding for these projects necessary, or is it possible that there can be partnerships between various private entities that could conduct this research? In addition to funding, what role should the Federal Government play in these experiments?

Answer. Based on observing industry trying to address this issue, it is my strong feeling that significant government funding will be needed for the initial round of large-scale projects. Other government roles include (1) setting experimental objectives so these projects produce the data needed for wide-scale implementation and (2) helping deal with nontechnical issues such as permitting and liability.

Question 3. Mr. Herzog, The National Energy Technology Laboratory reports that the United States has the largest coal deposits in the world the most suitable geology for carbon sequestration. Moreover, the Department of Energy is about to embark on an $800M carbon dioxide sequestration program that will be conducted at seven sites in the U.S. If carbon dioxide sequestration is proven to work, is there any reason not to do it immediately so we can take advantage of our large coal deposits?

Answer. From a technical standpoint, there is no reason we will not be able to proceed immediately. The question on how fast to proceed will be mainly economic.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN THUNE TO CHARLES FOX

Question 1. You mention that there is a great amount of energy needed for post combustion capture of carbon. Could you compare the current lifecycle energy usage and emissions of post-combustion capture and pre-combustion capture? With reasonable advances in technology, how is this expected to change?

Answer. I cannot compare the total lifecycle energy usage of post-combustion capture and pre-combustion capture because I don't know how much carbon is emitted in the manufacture and construction of the facilities. I don't think that there would be much difference, but I have never seen a comparison.

I will base a partial response on the IPCC Special Report: Carbon Dioxide Capture and Storage. The increased fuel requirement for capture for a new pulverized coal (PC) plant (post-combustion) is 24–40 percent. The increased fuel requirement for an Integrated Coal Gasification and Combined Cycle power (IGCC) plant (pre-combustion) is 14–25 percent. The net plant energy efficiency for the new PC plants is estimated to be 41 to 45 percent while the estimated net plant energy efficiency of the IGCC plants is a similar value of 38–47 percent. Based on these numbers, the increased fuel requirement for CO_2 capture is about 64 percent greater for capture at a new PC plant vs. a new IGCC plant.

This information along with the information on CO_2 emissions is provided in the table below:

Power Plant with Capture	New PC Plant (Post-Combustion)	New IGCC Plant (Pre-Combustion)
Increased Fuel Requirement (%)	24–40	14–25
Net Plant Energy Efficiency (%)	41–45	38–47
CO_2 Emissions Rate after Capture (t/MWh)	0.09–0.15	0.07–0.15

I don't know how much new technology would change these values. I believe that one of the most valuable process improvements will be better integration of the capture technology into new plants. Mr. Herzog, who was on the panel, is an expert in this area.

Question 2. Currently, carbon offsets range between $5 and $20 per ton and according to your testimony, the cost of carbon capture and sequestration ranges between $11 and $57 per metric ton. Do you expect future advances in technology to make CCS more competitive with other ways of limiting carbon emissions? How long will this take to happen?

Answer. I believe that advances in technology will reduce the cost of CCS; however, I also expect that we will see new technology reduce the cost of limiting carbon emissions in other areas. Given the numerous other ways to limit carbon emissions, I believe that CCS will continue to be a relatively expensive method to combat climate change because it is energy intensive in itself. Nevertheless, society will continue to need electricity. I doubt that other sources such as nuclear, solar and wind energy will completely displace coal (and natural gas) during the next half century. In a world largely dependent on coal-fired electrical plants, we will need to develop a CCS program—at least as a bridging technology.

With respect to timing, I think that it would take approximately 5 years to field test a capture technology and advance to another level. Capture technology could improve in several areas: improved chemical solvents, better integration of the capture process into the power plant, higher efficiency compression and pumping technologies and perhaps usage of membranes to separate the CO_2. It may take several rounds to improve the process to the point where society chooses to pay for CCS rather than for other carbon mitigating techniques.

Unlike capture, transportation and storage will not drive the costs. Issues related to storage should be answered during the next 10 years. Injection into depleted oil and gas fields may be a first step toward injection into saline reservoirs because reservoir descriptions were completed for hydrocarbon recovery.

Question 3. I have been following the issue of carbon sequestration closely. This is an issue which is vital to our future energy needs and to our national security. As many of you know, the United States Air Force has been working with coal-to-liquids technology in order to provide a domestic source of fuel for their air fleet. They have also been a proponent of carbon dioxide reuse. Can you tell us what emerging technologies exist for commercial use of substantial volumes of carbon dioxide other than enhanced oil or coal bed methane recovery?

Answer. I am familiar with one emerging technology that could use substantial volumes of CO_2, enhanced gas recovery (EGR). This is a process somewhat similar to Enhanced Oil Recovery (EOR) and coal bed methane (CBM) recovery. In this process, (liquid or supercritical) CO_2 is injected in the bottom of a natural gas reservoir while the natural gas (methane) is produced in wells some distance away and at higher depths. The idea is to repressure the reservoir with a substance that fills up the bottom of the reservoir and does not diffuse rapidly into the methane.

This process is not yet in commercial use. It is being field tested in The Netherlands, perhaps elsewhere. Curtiss Oldenburg at the Lawrence Berkeley National Laboratory is a U.S. expert.

In the U.S. about 70 percent of CO_2 usage is for enhanced oil recovery. According to SRI Consulting (Chemical Economics Handbook—2007) in 2004, 31,900 short tons of CO_2 was produced for EOR vs. 14,900 short tons which were produced for other commercial sales. This split of underground usage vs. surface usage has been fairly consistent for over a decade. I believe that finding new large scale usages (other than EGR) is unlikely.

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