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March 10th, 2009

Regarding
The Future of Coal under Climate Legislation

Carbon Sequestration Risks, Opportunities, and Learning from the CO2-EOR Industry

Submitted to
The U.S. House
Committee on Energy and Commerce
Subcommittee on Energy and the Environment

My name is Ian Duncan. I have a PhD in Geological Sciences and I am an Associate Director of the Bureau of Economic Geology (BEG) at the University of Texas at Austin. The University of Texas has arguably the largest group of researchers in the country focused on CO2 sequestration in deep brine reservoirs. The BEG is engaged in research in a broad range of energy related and environmental issues including CO2 sequestration. The BEG's Gulf Coast Carbon Center (GCCC) is an industry-academic-NGO collaboration working on geologic CO2 sequestration including Enhanced Oil Recovery CO2 EOR.

The GCCC's Frio Pilot Injection Project, led by the BEG's Dr Susan Hovorka and funded by the DOE's National Energy Technology Laboratory, was the first highly instrumented CO2 injection experiments in the world. The GCCC currently has a significant field-test of CO2 sequestration in brine reservoirs underway in Mississippi (Denbury resources Cranfield CO2-EOR site) part of the South East Carbon Sequestration Partnership led by the Southern States Energy Board (Dr Gerald Hill, Principle Investigator). This field test seeks to show the effectiveness of CO2 sequestration, and how we can best predict and document the long term retention of CO2 through modeling and monitoring. This study involves monitoring a multi-well injection of CO2 at a rate of a million tons of CO2 a year (equivalent to rates likely for full scale CO2 sequestration projects. The deep brine reservoir being injected into is the Tuscaloosa-Woodbine Formation one of the top few sequestration targets in the Gulf Coast. These studies are funded by on the order of $50 million in Department of Energy funds and corporate matching funds (over 10 years). Preliminary results increase our confidence in our ability to monitor CO2 injections and to detect future possible leakage from the containment zone.

For the past nearly four years I have been doing research on the role that CO2 sequestration in deep brine reservoirs and associated with CO2 enhanced oil recovery (CO2-EOR) can play in mitigating greenhouse gases in the atmosphere and in increasing domestic oil production in the US. Recently I have been working on research to quantify the risks associated with carbon capture and storage (CCS) in general and CO2 sequestration in particular.

The key points that I would like to make are:

(1) Based on all the available information I believe that large scale CO2 sequestration in deep brine reservoirs can be done safely and effectively without endangering the nation's underground sources of drinking water (USDW).

(2) Based on the safe transportation of over 600 million metric tons of CO2 in the US over the last 37 years and the safe injection of over 1,200 million tons of CO2, it is clear that we have the ability to carry out the operational phase of CO2 sequestration in deep brine reservoirs safely and effectively.

(3) The long term risks of CO2 sequestration in deep brine reservoirs is strongly site dependant. The likelihood of leakage, the likely leakage rate, and the consequences of leakage in terms of possible damages to drinking water vary greatly between sites.

(4) Although the EPA has done a commendable job in developing their draft rules for class six UIC injection permitting, there rule making does not encompass any mechanism to encourage or require selection of the optimal sites for sequestration. Their approach (as is the case for all permitting procedures that I am aware of) is the equivalent to a pass/fail exam. In my previous testimony to the Energy and Commerce Committee last year I suggested that EPA may well not have a legislative mandate for encouraging the identification and use the optimal sites (those with the lowest risk of long term leakage). I also suggested some mechanisms that could be used to solve this problem.

(5) In the near term, CO2-EOR combined with appropriate monitoring, mitigation, and verification, (MMV) can make a significant contribution to mitigating increases in CO2 emissions by putting man-made CO2 (CO2-A) into permanent storage in depleted oil reservoirs.

(6) Congress should appropriate funds for the DOE to support university research into CO2 sequestration associated with CO2 EOR and for individual investigator research outside of the Sequestration Partnership program. Such funding would help produce young engineers and geologists trained in CO2 related technologies and alleviate a shortage that is critical now and will grow more so in the near future.

Based on the available information from over 37 plus years of CO2 injection into geologic reservoirs in the Permian basin of Texas and on scientific knowledge from natural CO2 reservoirs, I believe that large scale CO2 sequestration can be done safely and effectively without endangering the nation's underground sources of drinking water (USDW). The CO2-EOR industry has more than 37 years of experience in successfully transporting and injecting CO2. In the US alone the industry operates over 13,000 CO2 EOR wells, over 3,500 miles of high pressure CO2 pipelines, has injected approximately 1,200 million tons of CO2 (22 trillion standard cubic feet) and produces about 245,000 barrels of oil a day from CO2 EOR projects. This testimony leverages the CO2-EOR experience and information from natural gas storage, oil and gas exploration and published risk studies to conclude that large scale CO2 sequestration in deep brine reservoirs can be technically accomplished without incurring risks larger than those currently existing in oil and gas production and similar industrial activities. Early entry projects may require public incentives to overcome perceived risks in the absence of an established track record.

EVALUATING THE RISKS ASSOCIATED WITH GEOLOGICAL CO2 SEQUESTRATION

The Union of Concerned Scientists has suggested that "the potential environmental consequences and risks to public safety are generally acknowledged but frequently dismissed as minor" they further suggest that these concerns are "insufficiently studied through systematic research to date". They suggest that the three main "direct risks to humans" are:

1. "the potential for environmental risks to humans, such as catastrophic venting of CO2, i.e., the rapid re-release of stored gas in toxic concentrations from underground storage sites
2. the potential for potable aquifer contamination
3. the possible risk of induced seismicity (earthquakes) due to underground movement of displaced fluids".

Risk can be measured by a number of different metrics such as: the risk to society as a whole (the risk of climate change for example); the risk to an individual; the average individual risk of an exposed population, the average individual risk of the total population and the overall average death rate. The individual risk is the probability of death at point in space and time as a result of any hazardous event. It is typically expressed as a probability of death per year. If multiple fatalities are possible from a single hazardous event then the societal risk is typically defined in terms of a relationship between the likelihood of a particular type of incident and the resultant number of victims.

A risk assessment of a geologic CO2 sequestration project would attempt to address the following four questions:

- What can go wrong (what are the possible adverse outcomes)?
- What is the probability or likelihood of these outcomes?
- What would the consequences (or damages) be of each of the possible outcomes at this site?
- In view of the uncertainty in the data used, how confident are we about the answers to these first three questions?

Adequate answers to these questions can be an important step towards gaining public acceptance of geologic CO_2 sequestration. Risk management is concerned with implementing processes and policies to both prevent and control risks. This is an approach widely used to manage hazards in oil and natural gas fields, refineries, and chemical plants. Risk is composed of two elements, the likelihood (probability) of an adverse outcome (hazardous event) and the magnitude of its consequences that is:

$$\text{Risk} = \text{Likelihood} \times \text{Consequences}$$

This approach can address issues of public health and safety, employee safety, threat to USDW and other environmental damage. Geologic sequestration of CO_2 in deep brine reservoirs is an appropriate application of this approach it is a process-driven system that will exist for long times. The risks resulting from events that have significant consequences but small probabilities of occurrence are difficult to estimate in the absence of large datasets.

Before discussing the nature and magnitude of risks that will be encountered in the geologic sequestration of CO2 it is useful to have some understanding of risks in other industrial projects and common activities for comparison. For example in the case of North Sea offshore oil and gas production the upper limit of tolerance for risk to personnel is 1 in 1000 or 1×10^{-3} per year. This level of risk is industry practice and is consistence with the policy of the UK government. This is equivalent to a rate of just above 30 fatal accidents per 10^8 exposure hours. Mountain climbing has about the same level of individual risk as working on an offshore oil platform. In comparison driving an automobile has a risk of 1×10^{-4} per year and flying on commercial flights has a risk on the order of 5×10^{-5} per year.

An acceptable risk can be defined by: $P < (10{-}5/N^2)$ where P is the cumulative frequency per year and N the number of fatalities. Two zones (A and B) of tolerable risk can be defined as: A $(10{-}5/N^2) < P < (10{-}4/N^2)$ and B $(10{-}4/N^2) < P < (10{-}3/N^2)$. If the cost of risk reduction exceeds the benefits gained then the risk in region A is tolerable. The risks in region B can be regarded as tolerable only if risk reduction is impracticable or if it has a cost that is grossly disproportionate to any gain in safety. An unacceptable risk (one that cannot be justified under any circumstances) can be defined as $P > (10{-}3/N^2)$.

Geologic sequestration lacks a large historical data base that would enable computation of long term risks. The absence of such actuarial data for large scale CO2 sequestration projects and a still not settled regulatory framework, creates major obstacles to project financing, and ultimately wide-scale deployment. In the language of risk analysis such systems are “ambiguous”. In essence the term ambiguity refers to imprecisely specified probabilities. Decision makers are more adverse to ambiguous situations than they are to risky ones. For example insurers are known to seek higher premiums for projects that are perceived as ambiguous, than for those known to be risk prone.

Scientists and engineers have a good understanding of the risks associated with CO2 sequestration in brine reservoirs in terms of the spectrum of risk elements. However, a consensus is lacking in the published literature as to the relative (and absolute) probabilities of adverse outcomes. There is a particular concern for the long-term risk in the post closure period of injection projects. The risk during the operational phase of CO2 sequestration projects is arguably relatively well understood can be adequately addressed through and existing financial risk management frameworks or straight forward modifications thereof.

The transportation of CO2 by pipelines for the CO2-EOR industry has an excellent safety record. No deaths or serious injuries have been associated with CO2 pipelines. The IPCC Report (that included both industry and academic authors) suggested that “If CO2 is transported for significant distances in densely populated regions; the number of people potentially exposed to risks from CO2 transportation facilities may be greater than the number exposed to potential risks from CO2 capture and storage facilities” and that “Public concerns about CO2 transportation may form a significant barrier to large-scale use of CCS”. A recent report prepared by the Australian

Government suggests that although transport of carbon dioxide by pipeline is a potential safety hazard that this risk is "less that natural gas". The differences are that natural gas is highly flammable (and potentially explosive). Serious accidents associated with natural gas pipelines typically involve explosion or jet fire. Natural gas released by a pipeline rupture forms a buoyant vapor plume that typically will not in a persistent ground level vapor cloud. In contrast CO2 is non-flammable, heavier than air (producing ground hugging clouds when released in quantity) and causes death at high concentrations. CO2 leaking from a pipeline will not have the same dispersion as would natural gas. CO2 will have a tendency to pond in pits and topographic depressions. Recent modeling of the dispersion of CO2 clouds by scientists at Lawrence Livermore and Lawrence Berkeley National Labs suggests that dangerous CO2 levels generated from plausible releases from pipelines (or well blowouts) are highly unlikely to exist for "a very long time" and under most wind conditions disperse rapidly.

It must be noted that the sample size for CO2 pipelines is small compared to those for natural gas and hazardous-liquids transmission. Although CO2 pipelines have a near perfect safety record it is reasonable to conclude that in a statistical sense, the frequency of pipeline incidents involving CO2 should be similar to those for natural gas pipelines. The risk analysis group DNV, estimated the likelihood of small (3-10 mm) breaches in CO2 pipelines as 1.1×10^{-5} and for large (50-150 mm) breaches as 3.3×10^{-7} per meter of pipe length per year. A similar calculation based on US CO2 pipeline statistics was made as part of the FutureGen EIS which estimated puncture failure frequencies as 1.9×10^{-5}/miles-year (1.18×10^{-4}/[kilometer-year]) and rupture frequencies as 9.55×10^{-5}/miles-year (5.92×10^{-5}/[kilometer-year]). Computation of risk from these probabilities requires knowledge of the consequences which is typically done on a site specific basis. Developing a quantitative understanding of the risks associated with large scale pipeline transport of CO2 for a future CCS industry will probably require generalizing the results from a significant number of site specific risk assessments similar to those done for the FutureGen sites.

It has been suggested in the literature that the incident rate CO2 pipelines can be estimated from that for natural gas pipelines. USDOT statistics recorded ten incidents of CO2 pipelines failures. The DOT data suggest that these incidents were caused by: relief valve failure (four incidents); weld, gasket, valve packing failure (three); corrosion (two); and outside force (one). Similar DOT statistics for a very large data set of natural gas pipelines in the US showed the reasons for failure as: outside force, including damage by contractors, farmers and utility workers (35%); corrosion (32%); other, such as vandalism, train derailment and improper operation of manual valves (17%); weld and pipe failures (13%); and operator error (3%). There is good reason to believe that the rate of incidents (rupture, puncture etc) for CO2 and natural gas pipelines should be the same if CO2 sequestration is implemented on a large scale. It is important to note that even if the rates of incidents for CO2 and natural gas pipelines begin to look the same in the future. my judgment is that the risk will still be lower for CO2 pipelines (a conclusion that appears to be increasingly supported by governmental reports and academic studies). I also believe that the risk from rupture of CO2 pipelines is the largest risk facing a future CO2 sequestration industry. If this conclusion proves correct then this places strong bounds on the risks of geologic CO2 sequestration. Ultimately the risk from pipelines depends on: siting of the pipelines (risks are site specific); operation of the pipelines to minimize possible corrosion (particularly the current industry focus on keeping the water levels in the CO2 below saturation); and implementation of effective risk management and mitigation plans.

Unfortunately, public perception of the risks associated with geologic sequestration of CO_2 in deep brine reservoirs is strongly shaped by accounts of the effects of catastrophic releases of CO_2 (such as the Lake Nyos event), related to unique deep tropical lakes in equatorial volcanic terrains. Unfortunately many of the review papers on the topic of risk associated with CO2 sequestration have been written by researchers with little or no training in geology or the natural sciences. As a result a number of statements exist in the CO2 sequestration risk literature would lead a reasonable person to conclude that a “Lake Nyos” type incident could occur in the future associated with leakage from CO2 sequestration. I believe that these statements and other assertions of catastrophic results from leakage from deep brine reservoirs are not supported by the facts or any published analysis. It is important that these highly inflammatory misconceptions are corrected in published articles in refereed journals.

The risks of CO2 storage in a geological reservoir should be seen in the context of an engineered reservoir. The subsurface engineering technology that will form the basis of a new sequestration industry is in large based on equipment and approaches developed over the last 37 years for CO2-EOR. After consideration of possible ruptures of CO2 pipelines the next most plausible risk to public health and safety comes from the “blow out” or loss of control of a CO2 injection well. Injection wells are typically equipped with “blowout preventer” technology to stop such events. Blowouts do occur rarely in association with CO2-EOR injection activity and understanding the nature and consequences of these events can help us predict the risk of such events occurring in association with future CO2 sequestration. There are currently 4,700 injector wells operating in the Permian Basin amounting to 40% of the CO2 EOR wells currently operating, the other 60% of wells being production wells. The total CO2 injected into the Permian Basin amounts to approximately 1,200 million tons of CO2. Almost certainly the number of injection wells that will be used for CO2 sequestration in brine reservoirs to inject an equivalent amount of CO2 will be far fewer. This is important to consider this when attempting to use statistics for blowouts of CO2-EOR injection wells in predicting the operational risk of large scale CO2 sequestration projects.

The International Energy Agency (IEA) has documented frequency estimates for natural gas well blowouts from three different data sources: (1) 2.02×10^{-5} major incidents/well-year for natural gas storage wells (estimated from worldwide data from the 1970s onwards); (2) 2. 5.1×10^{-5} accidents/well-year for natural gas storage wells (estimated from European data); and (3) 3. 5.0×10^{-5} blow outs from oil and gas production/well-year (estimated using data from the Netherlands). They note that failure (blowout) rates reported for natural gas storage wells are remarkably similar to those reported in offshore oil and gas wells. A 1997 textbook on injection technology, recommends using a well blowout frequency of $5.0X10^{-5}$ blowouts per well year for wells in the operational phase (production and injection wells). This blowout frequency is likely to be larger than that actually experienced due to outdated well design (in the data set, new operating practices that have been implemented since the study, and the broad definition of blowout used in the study). A recent (2006) IEA study has suggested that the failure rate of a CO2 injection well during operation (blowout rate) can be estimated as 2.02 x 10^{-5} per well per year based on experience with natural gas injection wells from.

I am currently engaged in a research project that is examining the record of blowouts associated with the CO2 EOR industry. This study is in its initial phases. So far four blowouts associated with CO2 injection wells have been identified and another twelve are being evaluated. Although this study is incomplete the preliminary conclusions is that the incident rate is small. Significantly in considering the risk and consequences of blowouts during deep brine sequestration projects the differences between EOR and sequestration inject projects must be addressed. Typically CO2 sequestration injection wells will operate at a higher pressure than CO2-EOR injectors. Developing technologies for improved well integrity will be an ongoing focus in the design of future sequestration wells. Attention must also be paid to developing improved operational procedures.

The next most likely risk associated with CO2 sequestration is related to leakage into groundwater (USDW) from well bore failures (corrosion, cracked casing etc). From 20,271 cumulative site-years of underground natural gas storage experience, the IEA in 2006 identified eight leakage incidents that appeared to fit this category for a frequency of occurrence of 3.95 x 10^{-4} significant leaks/site-year. They found that the frequency of significant leakage from all underground mechanisms (sixteen incidents) was estimated at 7.89 x 10^{-4} significant leaks/site-year for all types of underground natural gas storage facilities. Because this estimate included salt caverns, and aquifers storage, this estimate probably significantly overestimates the likelihood of such phenomena associated with CO2 sequestration.

The thirty seven plus years of history of CO2 injection involved in CO2 based Enhanced Oil Recovery in the US represent the most tangible evidence available for understanding the risks of CO2 sequestration in deep brine reservoirs. In the case of both pipeline incidents and blowouts; component failure rather than corrosion or human errors have resulted in the leakage of CO2. The rarity of corrosion related incidents reflects the industries success in implementing anti-corrosion measures. In the case of blowouts, incidents related to CO2 production wells from natural reservoirs and those that occurred during work over of production wells, resulting from unexpectedly early CO2 breakthroughs are not directly relevant to understanding the risk of CO2 sequestration in deep brine reservoirs. Although safety and health issues are always of paramount concern, the excellent safety and health record of the CO2 industry in the Permian Basin of West Texas may suggest that these issues are not a major component of the operational risk faced by a putative carbon sequestration industry.

Unfortunately some authors of academic papers have been intemperate in their use of language when addressing risk issues. One paper in 2004 suggested that the “acute hazards” related to geologic CO2 sequestration are “wellhead failure [blowouts], seismic hazard during injection, accumulation and explosion in lakes, and massive efflux in soils”. This is rather odd language for a paper that in the numerical probability data presented apparently demonstrated that CO2 related incidents would be extremely rare. Another paper in 2003 suggested that the “most obvious local [associated with the surface release of CO2] risk” is related to “catastrophic leaks such as well blowouts or pipeline ruptures”. Similarly a 2005 paper suggests that “the most frightening scenario [related to risks associated with geologic CO2 sequestration] would be a large, sudden, catastrophic leak.

This kind of leak could be caused by a well blowout or pipeline rupture". Both these papers apparently ignored (or were unaware of) the excellent safety record off the CO2-EOR industry in transporting and injecting CO2.

The risk that science has the least factual basis to constrain likelihoods is that of leakage through the seal or containment zone of the sequestration reservoirs, ultimately leading to pollution of drinking water. Leakage may be diffuse but most likely would be focused by transmissive faults or fracture zones. These issues are the subject of considerable current research effort. Though much of this research is not yet complete and only a small portion has yet been published, a consistent picture is emerging. First numerical modeling results support the assertion that the chances of catastrophic leakage through the seal are extremely small. In well chosen sites I believe that such a risk is effectively non-existent. The main impact of leakage through the seal (should it occur) will be on groundwater quality. Research so far suggests that both the likelihood of such leakage and the consequences that would results from it are site specific. Some sites are more likely to leek that others. If the seal of a reservoir does leak the consequences also vary from site to site. At some sites there are negligible quantities of drinking water and therefore the consequences are limited. I would argue that careful site selection is the key to controlling risk from slow (long term leakage). This type of risk will dominate the long term (post-closure) risk.

Although safety and health issues are always of paramount concern, the excellent safety and health record of the CO2 industry in the Permian Basin of West Texas, and the absence of known negative impact on USDW suggest that these issues are not a major component of the business risk faced by a putative carbon sequestration industry. Having said this, it is very unfortunate that very little research funding is available to study and assess the wealth of potential information available from studying the results of the long term CO2 injections in the Permian Basin by CO2 EOR operators. Apart from a small DOE funded research project through the Southwest carbon Sequestration Partnership and led by the BEG, only very limited research is being done in this crucial area. I recommend that Congress should appropriate funds for the DOE to support university research into CO2 sequestration associated with CO2 EOR particularly in the Permian basin which has the longest history of CO2 injection in the world. An aggressive research program including pilot projects would help improve the performance of current EOR activity and enable the development of new more effective approaches that could increase oil recovery, reduce the geological and technical risks, and enhance sequestration rates incidental to CO2-EOR. Such funding would also help produce young engineers and geologists trained in CO2 related technologies and alleviate a shortage that is critical now and will grow more so in the near future.

It has recently been suggested that an effective system of regulation for geologic sequestration should share place the long-term risks of sequestration in public hands. I prefer to place the emphasis not on the government taking on the long term risk but rather on reducing risk of leakage by creating a regulatory framework that: (1) provides a mechanism to assure optimal site selection (2) minimizes risk by requiring adequate site characterization; (3) assures early detection of any leakage by insisting on deep monitoring; and (4) requires preventive action to lower the chance of leakage leading to adverse outcomes. Government resources should be deployed early in the project life cycle, focused on optimizing selection and evaluation of sites. Providing careful oversight of risk assessments and then requiring early and vigorous implementation of preventative action will be more valuable than reserving resources to remediate problems that could have been prevented. It is possible that assumption of some long term risk by the public may be necessary to enable early entry projects to get financing.