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Chairman Bingaman, Senator Murkowski and members of the Committee, thank you for asking me to testify today. My name is Mark Zoback, I am a Professor of Geophysics at Stanford University. For your general information, I last spoke to this committee in October as a member of the Secretary of Energy's Advisory Board Shale Gas Subcommittee. I also served on the National Academy of Engineering committee that investigated the Deepwater Horizon accident. My field of expertise is in quantifying geologic processes in the earth that control earthquakes and hydraulic fracture propagation. I have been doing research in these fields for over 30 years ago. My PhD students and I have been carrying out a number of collaborative research projects seeking to better understand these processes in the context of carbon capture and storage and production from shale gas reservoirs.

While I was not a member of the NRC committee chaired by Professor Hitzman, I did have the opportunity to speak with the committee about the issues I'll comment upon today. Let me say at the outset that I am in full agreement with the principal findings their report.

Today, I will limit my comments to discussing earthquakes and energy technologies in two specific contexts. First, will be earthquakes triggered by injection of wastewater. While wastewater can come from many sources, of particular interest in the past few years has been the injection of the flow-back water coming out of shale gas wells following hydraulic fracturing. Second, I want to comment briefly about the potential for triggered seismicity associated large-scale carbon capture and storage, or CCS, as it is widely known.

In most cases, if earthquakes are triggered by fluid injection it is because injecting fluid increases the pore pressure at depth. The increase in pore pressure reduces the frictional resistance to slip on pre-existing faults, allowing elastic energy already stored in the rock to be released in earthquakes. For the cases I will speak about today, the earthquakes in question would have occurred someday as a natural geologic process — injection could simply advance their time of occurrence.

I have provided the committee staff with recently published papers I've written on these topics to provide more details.

Earthquakes associated with wastewater injection

In 2011 the relatively stable interior of the U.S. was struck by a surprising number of small-to-moderate, but widely felt earthquakes. Most of these were natural events, the types of earthquakes that occur from time to time in all intraplate regions. The magnitude 5.8 that occurred in northern Virginia on Aug. 23, 2011 that was felt throughout the northeast and damaged the Washington Monument was one of these natural events. While the magnitude of this event was unusual for this part of the world, the Aug. 23rd earthquake occurred in the Central Virginia seismic zone, an area known for many decades to produce relatively frequent small earthquakes.

This said, a number of the small-to-moderate earthquakes that occurred in the interior of the U.S. in 2011 appear to be associated with the disposal of wastewater, at least in part related to shale gas production.

Following hydraulic fracturing of shale gas wells, the water that was injected during hydraulic fracturing is flowed back out of the well. The amount of water that flows back after fracturing varies from region to region. It's typical for 25-50% of injected water to flow back. While the chemicals that comprise the fracturing fluid are relatively benign, the flow-back water can be contaminated with brine, metals and potentially dangerous chemicals picked up from the shale and must be disposed of properly.

Seismic events associated with injection of wastewater in 2011 include the earthquakes near Guy, Ark., where the largest earthquake was a magnitude-4.7 event on Feb. 27th and the earthquakes that occurred on Christmas Eve and New Year's Eve near Youngstown, Ohio. The largest Youngstown event was magnitude 4.0. It is understandable that the occurrence of injection-related earthquakes is of concern to the public, government officials and industry alike.

I believe that with proper planning, monitoring and response, the occurrence of small-to-moderate earthquakes associated with fluid injection can be reduced and the risks associated with such events effectively managed. No earthquake triggered by fluid injection has ever caused serious injury or significant damage. Moreover, approximately 140,000 Class II wastewater disposal wells have been operating safely and without incident in the U.S. for many decades.

Five straightforward steps can be taken to reduce the probability of triggering seismicity whenever we inject fluid into the subsurface. First, it is important to avoid injection into faults in brittle rock. While this may seem a “no-brainer”, there is not always sufficient site characterization prior to approval of a injection site. Second, formations should be selected for injection (and injection rates limited) so as to minimize pore pressure changes. Third, local seismic monitoring arrays should be installed when there is a potential for injection to trigger seismicity. Fourth, protocols should be established in advance to define how operations would be modified if seismicity were to be triggered. And fifth, operators need to be prepared to reduce injection rates or abandon injection wells if triggered seismicity poses any hazard. These five steps provide regulators and operating companies with a framework for reducing the risk associated with triggered earthquakes.

In addition, the re-cycling of flow-back water (for use in subsequent hydraulic fracturing operations) is becoming increasingly common (especially in the northeastern U.S.). This is a very welcome development. Re-use of flow-back water avoids potential problems associated with transport and injection flow-back water or the expense and difficulty of extensive water treatment operations.

It is important to note that the extremely small microseismic events occur during hydraulic fracturing operations. These microseismic events affect a very small volume of rock and release, on average, about the same amount of energy as a gallon of milk falling off a kitchen counter. The reason these events are so small is that pressurization during hydraulic fracturing affects only limited volumes of rock (typically several hundred meters in extent) and pressurization typically lasts only a few hours. A few very small earthquakes have occurred during hydraulic fracturing (such as a magnitude-2.3 earthquake near Blackpool, England, in April 2011), but such events are extremely rare.

It is important for the public to recognize that the risks posed by injection of wastewater are extremely low. In addition, the risks can be minimized further through proper study and planning prior to injection, careful monitoring in areas where there is a possibility that seismicity might be triggered, and operators and regulators taking a proactive response if triggered seismicity was to occur.

Earthquake potential and large-scale carbon storage

I would now like to comment briefly about the potential for triggered seismicity associated large-scale carbon capture and storage. My colleague Steve Gorelick and I have recently pointed out that not only would large-scale CCS be an extremely costly endeavor, there is a high probability that earthquakes will be triggered by injection of the enormous volumes CO_2 associated with large-scale CCS.

There are two issues I wish to emphasize in particular this morning. First, our principal concern is not the probability of triggering large earthquakes. Large faults are required to produce large earthquakes. We assume that such faults would be detected, and thus avoided, by careful site characterization studies. Our concern is that even small-to-moderate size earthquakes would threaten the seal integrity of the formations being used to store CO_2 for long periods without leakage. Studies by other scientists have shown that a leak rate from underground CO_2 storage reservoirs of less than 1% per thousand years is required for CCS to achieve the same climate benefits as switching to renewable energy sources.

Second, it is important to emphasize that we recognize that CCS can be a valuable and useful tool for reducing greenhouse gas emissions in specific situations. Our concern is whether CCS can be a viable strategy for achieving appreciable global greenhouse gas reductions. From a global perspective, if large-scale CCS is to significantly contribute to reducing the accumulation of greenhouse gases, it must operate at a massive scale, on the order of 3.5 billion tonnes of CO_2 per year. This corresponds to a volume roughly equivalent to the ~27 billion barrels of oil currently produced annually around the world.

Multiple lines of evidence indicate that pre-existing faults found in brittle rocks almost everywhere in the earth's crust are close to frictional failure, often in response to small increases in pore pressure. In fact, over time-periods of just a few decades, modern seismic networks have shown that earthquakes occur nearly everywhere in continental interiors. In light of the risk posed to a CO_2 repository by even small-to-moderate size earthquakes, formations suitable for large-scale injection of CO_2 must be well-sealed by impermeable overlaying strata, weakly cemented (so as not to fail through brittle faulting) and porous, permeable, and laterally extensive to accommodate large volumes of CO_2 with minimal pressure increases.

Thus, the issue is not whether CO_2 can be safely stored at a given site, the issue is whether the capacity exists for sufficient volumes of CO_2 to be stored in geologic formations for it to have a beneficial affect on climate change. In this context, it must be recognized that large scale CCS will be an extremely expensive and risky strategy for achieving significant reductions in greenhouse gas emissions.

Mr. Chairman, Senator Murkowski and members of the Committee, thank you for the opportunity to speak to you today.