Testimony of

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and

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Chairman Bingaman, Ranking Member Murkowski, and members of the Committee, I would like to thank you for the invitation to address you on the subject of induced seismicity potential in energy technologies. My name is Murray Hitzman. I am a professor of geology at the Colorado School of Mines in Golden, Colorado and served as the chair of the National Research Council Committee on Induced Seismicity Potential in Energy Technologies. The Research Council is the operating arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine of the National Academies, chartered by Congress in 1863 to advise the government on matters of science and technology. I would like to thank the Committee for the invitation to address it on the subject of induced seismicity potential in energy technologies.

Although the vast majority of earthquakes that occur in the world each year have natural causes, some of these earthquakes and a number of lesser magnitude seismic events are related to human activities and are called "induced seismic events" or "induced earthquakes."

Induced seismic activity has been attributed to a range of human activities including the impoundment of large reservoirs behind dams, controlled explosions related to mining or construction, and underground nuclear tests. Energy technologies that involve injection or withdrawal of fluids from the subsurface can also create induced seismic events that can be measured and felt.

Since the 1920s we have recognized that pumping fluids into or out of the Earth has the potential to cause seismic events that can be felt. Only a very small fraction of injection and extraction activities at hundreds of thousands of energy development sites in the United States have induced seismicity at levels that are noticeable to the public. However, seismic events caused by or likely related to energy development have been measured and felt in Alabama, Arkansas, California, Colorado, Illinois, Louisiana, Mississippi, Nebraska, Nevada, New Mexico, Ohio, Oklahoma, and Texas. Although none of these events resulted in loss of life or significant structural damage, their effects were felt by local residents, some of whom also experienced minor property damage. Particularly in areas where natural seismic activity is uncommon and energy development is ongoing, these induced seismic events, though small in scale, can be disturbing to the public and raise concern about increased seismic activity and its potential consequences.

Anticipating public concern about the potential for induced seismicity related to energy development, the Chairman of this Committee, Senator Bingaman, requested that the Department of Energy conduct a study of this issue through the National Research Council. The Chairman requested that this study examine the scale, scope, and consequences of seismicity induced during the injection of fluids related to energy production. The energy technologies to be considered included geothermal energy development, oil and gas production, including enhanced oil recovery and shale gas, and carbon capture and storage or CCS. The study was also to identify gaps in knowledge and research needed to advance the understanding of induced seismicity; to identify gaps in induced seismic hazard assessment

methodologies and the research needed to close those gaps; and to assess options for interim steps toward best practices with regard to energy development and induced seismicity potential. The National Research Council (NRC) released the report *Induced Seismicity Potential in Energy Technologies* on June 15.

The committee that wrote this NRC report consisted of eleven experts in various aspects of seismicity and energy technologies from academia and industry. The committee examined peer-reviewed literature, documents produced by federal and state agencies, online databases and resources, and information requested from and submitted by external sources. We heard from government and industry representatives. We also talked with members of the public familiar with the world's largest geothermal operation at The Geysers at a public meeting in Berkeley, California. We also spoke to people familiar with shale gas development, enhanced oil recovery, waste water disposal from energy development, and CCS at meetings in Dallas, Texas and Irvine, California. Meetings were also held in Washington, D.C. and Denver, Colorado to explore induced seismicity in theory and in practice.

This study took place during a period in which a number of small, felt seismic events occurred that were likely related to fluid injection for energy development. Because of their recent occurrence, peer-reviewed publications about most of these events were generally not available. However, knowing that these events and information about them would be anticipated in this report, the committee attempted to identify and seek information from as many sources as possible to gain a sense of the common factual points involved in each instance, as well as the remaining, unanswered questions about these cases. Through this process, the

committee has engaged scientists and engineers from academia, industry, and government because each has credible information to add to better understanding of induced seismicity.

The committee found that induced seismicity associated with fluid injection or withdrawal associated with energy development is caused in most cases by change in pore fluid pressure and/or change in stress in the subsurface in the presence of faults with specific properties and orientations and a critical state of stress in the rocks. The factor that appears to have the most direct consequence in regard to induced seismicity is the net fluid balance or put more simply, the total balance of fluid introduced into or removed from the subsurface. Additional factors may also influence the way fluids affect the subsurface. The committee concluded that while the general mechanisms that create induced seismic events are well understood, we are currently unable to accurately predict the magnitude or occurrence of such events due to the lack of comprehensive data on complex natural rock systems and the lack of validated predictive models.

The committee found that the largest induced seismic events associated with energy projects reported in the technical literature are associated with projects that did not balance the large volumes of fluids injected into, or extracted from, the Earth. We emphasize that this is a statistical observation. It suggests, however, that the net volume of fluid that is injected and/or extracted may serve as a proxy for changes in subsurface stress conditions and pore pressure. The committee recognizes that coupled thermo-mechanical and chemo-mechanical effects may also play a role in changing subsurface stress conditions.

I will briefly discuss the potential for induced seismicity with each of the energy technologies that the committee considered, beginning with geothermal energy.

Geothermal Energy

The three different types of geothermal energy resources are: (1) "vapor-dominated", where primarily steam is contained in the pores or fractures of hot rock, (2) "liquid-dominated", where primarily hot water is contained in the rock, and (3) "Enhanced Geothermal Systems" (EGS), where the resource is hot, dry rock that requires engineered stimulation to allow fluid movement for commercial development. Although felt induced seismicity has been documented with all three types of geothermal resources, geothermal development usually attempts to keep a mass balance between fluid volumes produced and fluids replaced by injection to extend the longevity of the energy resource. This fluid balance helps to maintain fairly constant reservoir pressure—close to the initial, pre-production value—and aids in reducing the potential for induced seismicity.

Seismic monitoring at liquid-dominated geothermal fields in the western United States has demonstrated relatively few occurrences of felt induced seismicity. However, in vapor or steam dominated geothermal system at The Geysers in northern California, the large temperature difference between the injected fluid and the geothermal reservoir results in significant cooling of the hot subsurface reservoir rocks. This has resulted in a significant amount of observed induced seismicity. EGS technology is in the early stages of development. Many

countries including the United States have pilot projects to test the potential for commercial production. In each case of active EGS development, at least some, generally minor levels of felt induced seismicity have been recorded.

Conventional Oil & Gas

Oil and gas extraction from a reservoir may cause induced seismic events. These events are rare relative to the large number of oil and gas fields around the world and appear to be related to decrease in pore pressure as fluid is withdrawn.

Oil or gas reservoirs often reach a point when insufficient pressure exists to allow sufficient hydrocarbon recovery. Various technologies, including secondary recovery and tertiary recovery - also called enhanced oil recovery or EOR - can be used to extract some of the remaining oil and gas. Secondary recovery and EOR technologies both involve injection of fluids into the subsurface to push more of the trapped hydrocarbons out of the pore spaces in the reservoir and to maintain reservoir pore pressure. Secondary recovery often uses water injection or "waterflooding" and EOR technologies often inject carbon dioxide. Approximately 151,000 injection wells are currently permitted in the United States for a combination secondary recovery, EOR, and waste water disposal with only very few documented incidents where the injection caused or was likely related to felt seismic events. Secondary recovery—through waterflooding—has been associated with very few felt induced seismic events. Among the tens of thousands of wells used for EOR in the United States, the committee did not find any documentation in the published literature of felt induced seismicity.

Shale Gas

Shale formations can also contain hydrocarbons—gas and/or oil. The extremely low permeability of these rocks has trapped the hydrocarbons and largely prevented them from migrating out of the rock. The low permeability also prevents the hydrocarbons from easily flowing into a well bore without production stimulation by the operator. These types of "unconventional" reservoirs are developed by drilling wells horizontally through the reservoir rock and using hydraulic fracturing techniques to create new fractures in the reservoir to allow the hydrocarbons to migrate up the well bore. This process is now commonly referred to as "fracking." About 35,000 hydraulically fractured shale gas wells exist in the United States. Only one case of felt seismicity in the United States has been described in which hydraulic fracturing for shale gas development is suspected, but not confirmed. Globally only one case of felt induced seismicity at Blackpool, England has been confirmed as being caused by hydraulic fracturing for shale gas development. The very low number of felt events relative to the large number of hydraulically fractured wells for shale gas is likely due to the short duration of injection of fluids and the limited fluid volumes used in a small spatial area.

Waste Water Disposal

In addition to fluid injection directly related to energy development, injection wells drilled to dispose of waste water generated during oil and gas production, including during hydraulic fracturing, are very common in the United States. Tens of thousands of waste water disposal wells are currently active throughout the

country. Although only a few induced seismic events have been linked to these disposal wells, the occurrence of these events has generated considerable public concern. Examination of these cases suggests causal links between the injection zones and previously unrecognized faults in the subsurface.

In contrast to wells for EOR which are sited and drilled for precise injection into well-characterized oil and gas reservoirs, injection wells used only for the purpose of waste water disposal normally do not have a detailed geologic review performed prior to injection and the data are often not available to make such a detailed review. Thus, the location of possible nearby faults is often not a standard part of siting and drilling these disposal wells. In addition, the presence of a fault does not necessarily imply an increased potential for induced seismicity. This creates challenges for the evaluation of potential sites for disposal injection wells that will minimize the possibility for induced seismic activity.

Most waste water disposal wells typically involve injection at relatively low pressures into large porous aquifers that have high natural permeability, and are specifically targeted to accommodate large volumes of fluid. Of the well-documented cases of induced seismicity related to waste water fluid injection, many are associated with operations involving large amounts of fluid injection over significant periods of time. Thus, although a few occurrences of induced seismic activity associated with waste water injection have been documented, the majority of the hazardous and nonhazardous waste water disposal wells do not pose a hazard for induced seismicity. However, the long-term effects of any significant increases in the number of waste water disposal wells in particular areas on induced seismicity

are unknown.

Carbon capture and sequestration

Carbon capture and sequestration – or CCS - is also a means of disposing of fluid in the subsurface. The committee found that the risk of induced seismicity from CCS is currently difficult to accurately assess. With only a few small-scale commercial projects overseas and several small-scale demonstration projects underway in the United States, there are few data available to evaluate the induced seismicity potential of this technology. The existing projects have involved very small injection volumes. CCS differs from other energy technologies in that it involves continuous injection of carbon dioxide fluid at high rates under pressure for long periods of time. It is purposely intended for permanent storage – meaning that there is no fluid withdrawal. Given that the potential magnitude of an induced seismic event correlates strongly with the fault rupture area, which in turn relates to the magnitude of pore pressure change and the rock volume in which it exists, the committee determined that large-scale CCS may have the potential for causing significant induced seismicity.

The committee's findings suggest that energy projects with large net volumes of injected or extracted fluids over long periods of time, such as long-term waste water disposal wells and CCS, appear to have a higher potential for larger induced seismic events. The magnitude and intensity of possible induced events would be dependent upon the physical conditions in the subsurface—state of stress in the rocks, presence of existing faults, fault properties, and pore pressure.

The committee also investigated governmental responses to induced seismic events. Responses have been undertaken by a number of federal and state agencies in a variety of ways. Four federal agencies—the Environmental Protection Agency (EPA) the Bureau of Land Management (BLM), the U.S. Department of Agriculture Forest Service (USFS), and the U.S. Geological Survey (USGS)—and different state agencies have regulatory oversight, research roles and/or responsibilities related to different aspects of the underground injection activities that are associated with energy technologies. Currently EPA has primary regulatory responsibility for fluid injection under the Safe Drinking Water Act. It is important to note that the Safe Drinking Water Act does not explicitly address induced seismicity.

To date, federal and state agencies have dealt with induced seismic events with different and localized actions. These actions have been successful but have been ad hoc in nature. With the potential for increased numbers of induced seismic events due to expanding energy development, government agencies and research institutions may not have sufficient resources to address unexpected events. The committee concluded that forward-looking interagency cooperation to address potential induced seismicity is warranted.

Methodologies can be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. The committee determined that such assessments should be undertaken before operations begin in areas with a known history of felt seismicity and updated in response to observed, potentially induced seismicity. The committee suggested that practices that consider induced seismicity both before and during the actual operation of an energy project should be

employed to develop a “best practices” protocol specific to each energy technology and site location. The committee’s meetings with individuals from Anderson Springs and Cobb, California, who live with induced seismicity continuously generated by geothermal energy production at The Geysers were invaluable in understanding how such a best practices protocol works.

Although induced seismic events have not resulted in loss of life or major damage in the United States, their effects have been felt locally, and they raise some concern about additional seismic activity and its consequences in areas where energy development is ongoing or planned. Further research is required to better understand and address the potential risks associated with induced seismicity.

I would like to thank the Committee for its time and interest in this subject and I look forward to questions.