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Geothermal Induced Seismicity National Environmental Policy Act Review

Aaron Levine, Jeff Cook, Koenraad Beckers, and Katherine R. Young

National Renewable Energy Laboratory

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ABSTRACT

In 2016, the U.S. Bureau of Land Management (BLM) contracted with the National Renewable Energy Laboratory (NREL) to assist the BLM in developing and building upon tools to better understand and evaluate induced seismicity caused by geothermal projects. This review of NEPA documents for four geothermal injection or EGS projects reveals the variety of approaches to analyzing and mitigating induced seismicity. With the exception of the Geysers, where induced seismicity has been observed and monitored for an extended period of time due to large volumes of water being piped in to recharge the hydrothermal reservoir, induced seismicity caused by geothermal projects is a relative new area of study. As this review highlights, determining the level of mitigation required for induced seismic events has varied based on project location, when the review took place, whether the project utilized the International Energy Agency or DOE IS protocols, and the federal agency conducting the review. While the NEPA reviews were relatively consistent for seismic monitoring and historical evaluation of seismic events near the project location, the requirements for public outreach and mitigation for induced seismic events once stimulation has begun varied considerably between the four projects. Not all of the projects were required to notify specific community groups or local government entities before beginning the project, and only one of the reviews specifically stated the project proponent would hold meetings with the public to answer questions or address concerns.

1. Introduction

In 2016, the U.S. Bureau of Land Management (BLM) contracted with the National Renewable Energy Laboratory (NREL) to assist the BLM in developing and building upon tools to better understand and evaluate induced seismicity caused by geothermal projects. In the geothermal context, induced seismicity refers to small earthquakes (typically between a magnitude of 1.0 and 3.5 on the Richter scale) that may occur as a result of human activity (i.e. stimulating the geothermal reservoir or injecting fluid to replenish the geothermal reservoir).

The most infamous hydraulic stimulation event for creating an enhanced geothermal system (EGS) reservoir is likely the 2006 Basel 1 project in Switzerland. The project site was located in downtown Basel with known historic seismicity and presence of nearby active faults. An estimated M 6.0 to 6.9 earthquake in 1356 destroyed downtown Basel and is considered the most significant seismological event to have occurred in Central Europe in recorded history (RMS, 2012). In December 2006, a 21-day hydraulic stimulation job was planned for the Basel 1 well. Increased seismic activity (with a maximum event of M_L 3.4) resulted in structural damage of nearby buildings and 2,700 damage claims by local residents, triggered halting of fluid injection prematurely (within 6 days of start of injection), and eventually terminated the entire project (GPB, 2007; Häring et al. 2008).

The seismic event at the Basel 1 EGS project resulted in the development of the "Induced Seismicity protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems" by the U.S. Department of Energy (DOE) in 2008 (Majer et al., 2008) and an updated protocol in 2012 (Majer et al., 2012). This IS protocol was developed to guide geothermal developers for managing induced seismicity and applying EGS technology safely. It consists of seven steps an operator must follow when given permission to perform activities that may cause induced seismicity.

In this paper, we analyze existing National Environmental Policy Act of 1969 (NEPA) environmental review documents and summarize a selection of geothermal projects that had induced seismicity concerns. This paper focuses on:

- The NEPA process and how it relates to geothermal resource development;
- The DOE's Geothermal Induced Seismicity Protocol; and
- NREL's findings as they relate to how previous EGS and geothermal injection projects have analyzed and mitigated concerns around human-induced seismic events.

2. Background

This section provides a brief overview of NEPA and its relation to the BLM and/or DOE geothermal funding or permitting process, the DOE Geothermal Induced Seismicity Protocol, and the geothermal projects reviewed for this analysis.

2.1 NEPA and Geothermal Funding and Permitting on Federal Land

NEPA requires federal agencies or departments to consider the environmental impacts of all major federal actions significantly affecting the quality of the human environment ("major federal action") (NEPA, Sec. 102). The NEPA review is a procedural tool used to consider the environmental impacts of the proposed action as well as alternatives to the proposed action before a federal agency approves or rejects it.

A geothermal project on BLM-managed federal land must complete an environmental review under NEPA for any project that includes a major federal action, such as activities that require permit approval from the BLM, including a Notice of Intent to Conduct Geothermal Resource Exploration (where the project includes new surface disturbance or extraordinary circumstances), a Geothermal Drilling Permit (GDP), and a Site License and Facility Construction Permit (43 CFR 3200 et seq.). Often the environmental review under NEPA is in the form of an Environmental Assessment (EA), but a more comprehensive review termed an Environmental Impact Statement (EIS) may be required for projects with significant environmental impacts

(NEPA, Sec. 201 (C)). In many instances, the BLM may require mitigation measures in the EA for the project to reduce the environmental impact caused by the project. For this analysis we reviewed BLM geothermal NEPA documents that addressed induced seismicity to better understand these concerns, how these concerns are evaluated, and how the BLM has previously addressed these concerns through mitigation measures.

In addition, geothermal activities funded by the DOE also constitute a major federal action and require NEPA review. We have included a DOE NEPA environmental review for a DOE-funded EGS project that occurred on private land for additional comparison.

2.2 DOE Induced Seismicity Protocol

Due to concerns surrounding the potential for seismic events caused by EGS projects and to gain public acceptance for EGS projects, the DOE commissioned experts in induced seismicity, geothermal power development, and risk assessment to revise and write a "Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems" ("DOE IS Protocol") building upon the 2009 International Energy Agency (IEA) protocol. *(See* Majer et al. 2012). The objective of the DOE IS Protocol is to promote safety and help gain acceptance for geothermal activities, particularly EGS projects (Majer et al. 2012). The Protocol provides a set of guidelines detailing steps to evaluate and manage the effects of induced seismicity related to EGS projects and is commonly used and/or referred to in DOE and BLM NEPA documents.

The DOE IS Protocol consists of seven steps for addressing induced seismicity issues:

1. Perform a preliminary screening evaluation.
2. Implement an outreach and communication program.
3. Review and select criteria for ground vibration and noise.
4. Establish seismic monitoring.
5. Quantify the hazard from natural and induced seismic events.
6. Characterize the risk of the induced seismic events.
7. Develop risk-based mitigation plan.

2.3 Geothermal NEPA Documents Analyzed

For this memorandum, NREL staff analyzed four NEPA documents presented in Table 1:

- Newberry Volcano EGS Demonstration Project EA
- Bottle Rock Power Steam Project Environmental Impact Report (EIR)/EA
- Brady Hot Springs Well 15-12 Hydro-Stimulation EA
- Calpine Enhanced Geothermal Systems Project EA.

Table 1: List of Projects Reviewed

Project	Location	Review Type	Lead Agency	Participating Agencies	Review Completion
Newberry Volcano EGS Demonstration Project	Deschutes National Forest Lands in Oregon	EA	BLM	USFS DOE	December 2011
Bottle Rock Power Steam Project	Lake County, CA	EA/EIR	BLM/Lake County	None	December 2010
Brady Hot Springs Well 15-12 Hydro-Stimulation	Churchill, NV	EA	BLM	DOE	January 2013
Calpine Enhanced Geothermal Systems Project	Sonoma County, CA	EA	DOE	None	June 2010

In the following section, we discuss the findings from environmental review documents for these four geothermal projects that included potential induced seismicity issues.

3. Induced Seismicity NEPA Review by Project

This section provides detailed findings for four geothermal projects that included induced seismicity concerns on a case-by-case basis. For each geothermal project we highlight:

- The lead and participating agencies
- The action triggering NEPA review
- Noted seismic concerns with the project
- The seismicity evaluation conducted for the project
- Utilization of the DOE IS Protocol
- The level and type of seismic monitoring
- Pre-stimulation mitigation measures and planning
- Stimulation and post-stimulation mitigation measures and planning
- Actual events measured during project.[1]

3.1 Newberry Volcano EGS Demonstration Project

Date of completed EA: December 2011

The Newberry Volcano EGS Demonstration Project is located on BLM leases in the Deschutes National Forest lands in Oregon and completed an EA under NEPA in 2011. The BLM acted as lead agency for the EA, with the U.S. Forest Service (USFS) and DOE signing onto the document as cooperating agencies. The Newberry project utilized a deep geothermal well on an

[1] Seismic data for this study were accessed through the Induced Seismicity Data Website (EGS Earthquake Maps) at the Lawrence Berkeley National Laboratory, which is supported by the U.S. DOE Office of Geothermal Technology.

existing well pad to stimulate the reservoir using hydroshearing.[2] During this operation, developers injected high-pressure water estimated in the range of 1,160 to 2,500 psig at depths of 6,500 to 10,000 feet. After creating the EGS reservoir, the proponent proposed to drill two additional deep production wells that would be directionally drilled from the same well pad to bring the heated water up to the surface.

Noted seismic concerns with the project included induced seismicity at the Newberry National Volcanic Monument, damage to structures and resorts, the potential for property damage, and avalanche risk.

3.1.1 Mitigation Plan

Based on induced-seismicity concerns, the project proponent completed an induced seismicity/seismic hazards and risk evaluation conducted by an independent third party. The evaluation considered the potential magnitude and seismic rate that could result due to hydroshearing. The evaluation stated that the probable upper bound of an induced seismic event at Newberry was estimated in the 3.5 to 4.0-magnitude range and that other seismic events of less than a magnitude of 2.0 are largely not of concern.

In completing the NEPA review, the BLM (and third party consultants) used the IEA protocol from 2008 and later incorporated components of the draft DOE IS protocol. The EA called for the installation of two additional seismic monitoring stations at Newberry and utilization of one existing seismic monitoring station. In addition, 20 seismic monitoring devices (10 borehole, 10 surface) were to be installed at wells, boreholes, and surface stations to constantly monitor seismic activity. The continuous monitoring of microseismic events through these devices results in a daily seismic reports.

The EA stated that before the project begins, the developers must:

- Provide notice in local newspapers, which includes contact information for citizens to request additional information or report concerns
- Hold monthly public meetings
- Install rock fall hazard ahead signs that include information on reporting damage
- Install new avalanche warning signs
- Purchase general and umbrella liability insurance with an aggregate limit of $2,000,000 and $1,000,000 per occurrence
- Conduct structural engineering analysis to determine the vulnerability of 52 key assets near the site
- Install crack monitors on a bridge and monitor cracking at a nearby dam.

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[2] Hydroshearing is a process in which pressurized (often cold, clean) water opens up natural fractures in the rock and causes them to slip and create underground storage units. This differs from the hydrofracking done in the oil and gas industry, which uses a mixture of chemicals and significantly higher pressures to actually shatter the rock and create new fractures.

Once stimulation (hydroshearing) of the reservoir begins, the EA requires a series of mitigation measures based on the level of seismic event that occurs. Table 2 highlights the required mitigation based on magnitude of seismic event or ground shaking.

Table 2: Newberry EGS Project Seismic Event Mitigation Measures

Seismic Event within 3 KM *(in Magnitude)*	Required Mitigation
Less than M2.0	Only a concern if a seismic event greater than M1.0 is detected by at least 6 monitors located shallower than 6,000 feet. This would trigger a diversion mitigation strategy, resulting in the use of a diverter to shift stimulation to another zone. No increase in flow rate would be allowed until after the diverter is applied.
M2.0 to M2.7	Triggers diversion mitigation strategy (see *less than M2.0*). No increases in flow rate until after the diverter is applied.
M2.7 to M3.5 **Or** **Peak Ground Acceleration (PGA) greater than 0.014 g on the SMS**	Reduction of flow rate. Injection rate decreased so that downhole pressure is reduced by 250 psi. Additional pressure reduction by 250 psi if M2.0 or greater continue to occur. May gradually increase flow rate back to normal if no M2.0 or greater occurs for 24 hours. Project website will be updated after such events to provide instructions for how to report damage. Written trigger reports and phone calls will be made to inform key personnel. Notification to park visitors and owners of nearby homes.
Greater than M3.5 **Or** **PGA greater than 0.028 g on the SMS**	Halt all injection. Flow well to surface test equipment to relieve reservoir pressure. Do not resume stimulation until after consultation and agreement between developer, DOE, BLM, and USFS. Project website will be updated after such events to provide instructions for how to report damage. Written trigger reports and phone calls will be made to inform key personnel. Notification to park visitors and owners of nearby homes.

3.1.2 Seismic Results Associated with Well Stimulation

The Newberry Volcano EGS Demonstration project began the first phase of stimulation (hydroshearing) using an existing well in October 2012 and completed this phase in December 2012 (Cladouhos et al., 2013). Seismicity occurred throughout the two-month stimulation period, with seismic monitors recording a total of 174 seismic events, 114 of which occurred during the stimulation period of 10/29/12 to 12/7/12 (Cladouhos et al., 2013). The largest magnitude event to occur during the first phase of stimulation registered M2.39 and a total of three events greater than M2.0 occurred. The M2.39 event triggered a mitigation action per the mitigation plan to wait 24 hours before increasing well head pressure or flow rate, however the event occurred on the last day of planned stimulation and the well was shut-in later that day (Cladouhos et al., 2013). No PGA greater than 0.014 occurred during the first phase of stimulation (Cladouhos et al., 2013).

The second phase of stimulation (hydroshearing) began at an existing well in September 2014 and was completed in November of 2014 (Cladouhus et al., 2016). The stimulation occurred from September to October 2014 and again in November 2014. Seismicity occurred throughout the stimulation periods, with the rate of seismicity being the highest in early October 2014 when wellhead pressure exceeded 2800 psi. In total, 398 seismic events occurred, however only two of those events were larger than M2.0 (a M2.1 in early October 2014 and a M2.3 during the November stimulation period) (Cladouhus et al., 2016). A timeline of seismic events for both phases of stimulation was developed (see Figure 1) using discrete event data pulled from Lawrence Berkeley National Laboratory's (LBNL) EGS earthquake maps (LBNL, 2017).

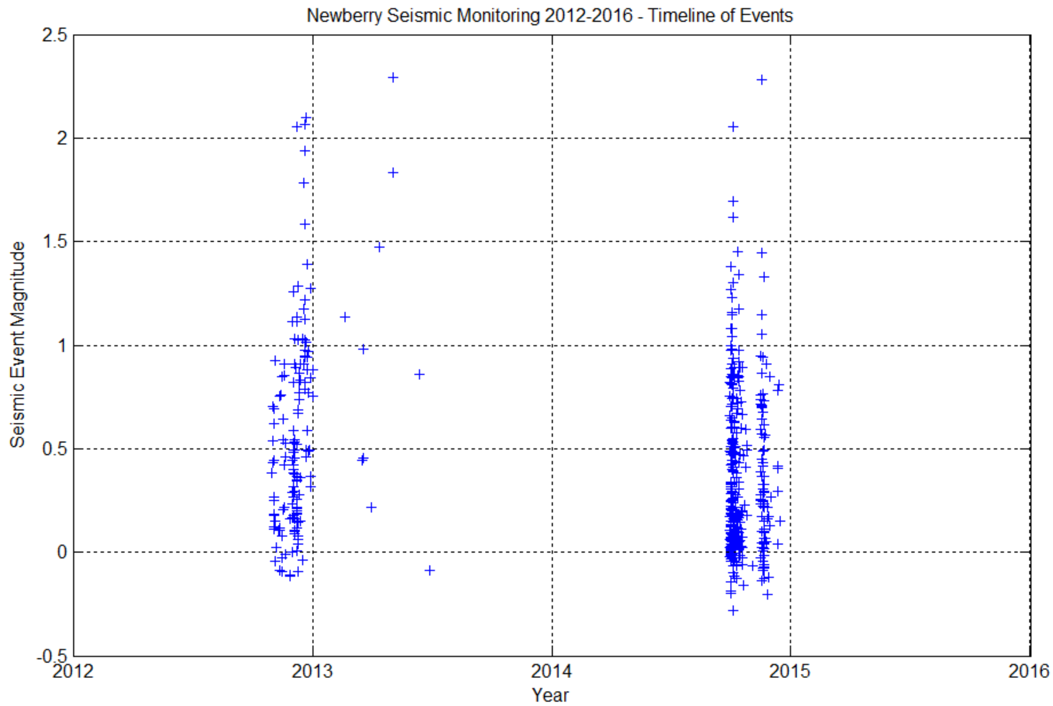

Figure 1. Newberry Volcano EGS Demonstration Project Seismic Monitoring Data from LBNL's EGS Earthquake Maps

3.2 Bottle Rock Power Steam Project EIR/EA

Date of completed EA: December 2010

The Bottle Rock Power (BRP) Steam Project is located on BLM leases near the Geysers in Northern California. The BLM served as the lead agency under NEPA for completion of an EA, while Lake County served as the lead agency under the California Environmental Quality Act (CEQA) for completion of an EIR in 2010. GeothermEx evaluated geothermal resource data under contract to AECOM, which was hired by BRP as the environmental consultant. This NEPA review was related to BRP GeoResource LLC's (BRP) application for a GDP and Commercial Use Permit to support expanded electricity production at the existing BRP Plant. The proposal was termed the "BRP Steam Project" and included two new well pads with a total of 22 geothermal production wells. Initially 12 to 14 production wells would be drilled, while the remaining 8 to 10 wells would serve as replacements over the life of the project. BRP proposed constructing two additional injection wells (one on each pad) to return condensate from the power plant to the geothermal reservoir. BRP planned to construct about 4 miles of steam and injection pipelines to transport the geothermal resource to and from the power plant. The construction of the well pads along with the access roads would disturb 22.51 acres.

Geothermal activities and injection in particular, have been associated with increased seismicity at the nearby Geysers geothermal operations. This induced seismicity has been felt by residents in communities such as Cobb and Anderson Springs. Residents have been concerned with these impacts, and the aforementioned two injection wells included in the BRP Steam Project could cause additional seismic activity. Thus, the BLM and Lake County (hereinafter referred to as BLM) analyzed the potential impacts of induced seismicity from the BRP Steam Project. The BLM did not leverage the IEA protocol in their study of induced seismicity (the DOE IS Protocol did not exist at the time).

GeothermEx analyzed the existing faults where natural earthquakes could occur and identified no active faults in or near the project site. As a result, the BLM concluded that geothermal operations were not likely to trigger earthquakes at existing faults. However, the site could be impacted by earthquakes at regional faults (i.e. the San Andreas Fault system located 37 miles west) that could result in injury and damage at the site. The BLM included a range of mitigation efforts to address natural earthquake risks including constructing project components in compliance with the applicable International Building Code.

3.2.1 Induced Seismicity Associated with Historical Geothermal Operations in the Area

To evaluate the potential effects of geothermal operations on induced seismicity, GeothermEx evaluated historical geothermal injection data at the Francisco Geothermal Lease (nearby to the proposed project) and potential correlation with seismicity. Over the spatial-temporal distribution study period from 1970 – 2009, GeothermEx identified that fluid injection at the Francisco Lease was associated with increased seismic activity typically below M2.0. GeothermEx identified approximately six seismic events per month below M2.0, which can be felt as far as eight kilometers from the epicenter. Seismic events of $2.0 \leq M \leq 3.0$, were limited to one event every seven months and GeothermEx determined that seismicity at smaller M levels ($M < 3.0$) may be associated with reservoir operations, while those at higher magnitudes ($M > 3.0$) may be associated with another cause such as natural earthquake activity. GeothermEx could not effectively evaluate ground peak acceleration because of the ground shaking effects of local operations causing these measurements to significantly vary across the Geysers.

GeothermEx identified that seismic activity was not consistently correlated with injection at the wells stating "seismicity rates are unrelated to injection periods and volume at some locations and correlated to the same properties at other locations." As a result, GeothermEx could not make a prediction relating to potential seismic rates at the BRP Steam Project. Nevertheless, GeothermEx assumed that the close proximity of the Francisco Lease to that of the BRP Steam Project provided a useful case study for the expected results of the project. On this basis, Geothermex concluded that the project might expect between one to four events per month of $M > 2.0$ and one to two events per month at $M > 2.5$. Given induced seismicity would likely not correlate with large-magnitude earthquakes that can be felt on the surface ($M > 3.0$), the BLM concluded that potential induced seismicity from the BRP Steam Project was a less than significant impact that did not require mitigation.

3.2.2 Mitigation Plan

Despite this finding, the BLM did require BRP to install a seismometer at a location deemed appropriate by the BLM and Lake County[3] to monitor seismic activity. Once installed, all the collected seismic activity would be submitted to the BLM, Lake County, and the Lake County Seismic Monitoring Advisory Committee.

Prior to stimulation, the BLM required the developer to submit a complete operations plan including a production and injection plan along with the locations of the wells for review. With the plan, the BLM would determine whether the BRP Steam Project operations would be similar to those in the Francisco Geothermal Lease or require additional mitigation measures.

During stimulation, if the seismic activity correlated with injection varied substantially from the conclusions presented in the EA (generally $M < 3.0$), BRP would be required to take corrective actions such as adjusting injection volumes and location of injection wells among other measures. These corrective actions would be developed via consultation between the developer, the BLM, and Lake County.

3.2.3 Seismic Results Associated with Well Stimulation

The Bottle Rock Steam Project stimulation initially began in March 2011 with a series of stimulation activities occurring through April 2011. The Geysers geothermal area has extensive seismicity, making it difficult to identify the total number of seismic events associated with stimulation based on LBNL's EGS Earthquake Maps (LBNL, 2017).[4] The project operator (and hired consultant) could not find any conclusive evidence in the maps or the consultant's earthquake processing system for an increase in earthquake activity as a result of the stimulation (Foulger Consulting, 2011). The operator's consultant identified five seismic events in a cluster near one of the stimulated wells that may have resulted from the stimulation, but results were not conclusive (Foulger Consulting, 2011).

A second phase of stimulation occurred in April 2014. The frequency of seismic events increased during the stimulation, but a 2014 stimulation analysis concluded there was "little evidence" to support this was a direct result of the stimulation activities (AltaRock, 2014).

3.3 Brady Hot Springs Well 15-12 Hydro-Stimulation EA

Date of completed EA: January 2013

The Brady Hot Springs Well 15-12 Hydro-Stimulation Project is located on BLM leases at an existing geothermal well pad at the Brady Hot Springs Federal Lease located nearest to Fernley, Nevada. The BLM was designated as the lead agency for the NEPA process, while DOE agreed

[3] Administered by the Lake County Special Districts department, the Lake County Seismic Monitoring Advisory Committee was formed in 1998 and meets bi-annually to provide the local community with regular updates and information on seismicity issues within the Geysers. For more information *see* http://www.geysers.com/smac.aspx.

[4] Additionally, the LBNL EGS Earthquake Database Map website appears to be missing data during the 2011-2013

to be a cooperating agency due to project funding provided through a 2008 DOE Funding Opportunity Announcement (FOA).

In 2013, the BLM completed the EA in response to Ormat's application to allow the developer to test EGS technologies at Well 15-12 to increase geothermal reservoir production at the field. The well was originally constructed as a production well, but it was unsuccessful because it did not have "sufficient hydraulic connections with the geothermal reservoir." The developer proposed to inject relatively cool geothermal water (90 – 140 °F) into Well 15-12 at wellhead pressures less than 1,400 psi at depths between 4,245 and 5,096 feet below the surface to hydroshear the reservoir (i.e., stimulate or further open existing fissures or connections within the geothermal reservoir). The developer would stimulate the reservoir at varying pressures over a period of three weeks and add tracer compounds to the injected water to assess geothermal fluid movement and increased steam pressure at other production wells. The expectation was that the injection of cool geothermal water would allow for increased production from the reservoir thereby increasing power generation at the nearby Brady Power Plant.

Because injecting the cool geothermal water into the reservoir could cause induced seismicity, there was a concern that these events might have adverse impacts above and below ground. Before the development of the EA, Ormat (in cooperation with DOE) began evaluating these impacts with the aid of the IEA protocol and (once finalized) the DOE IS Protocol. BLM leveraged the results of this analysis in completing their NEPA review.

3.3.1 Induced Seismicity Associated with Historical Geothermal Operations in the Area

Ormat identified that historical geothermal operations at the Brady Hot Springs field are associated with microseismic events (M>2.0), while at the same time, noting there has been some natural earthquake activity in the area (M<4.0). To quantify potential seismic hazards, Ormat leveraged the results of a nearby geothermal project that employed well stimulation that showed low seismicity between M0.11 – M0.77. Based upon these results and geological and geophysical surveys, Ormat concluded that there was a low probability that an induced seismic event over M2.0 would occur within 500 meters of Well 15-12. Outside of this area, the probability of such an event was significantly lower to nonexistent.

3.3.2 Mitigation Plan

Given these results, in completing the NEPA review, the BLM required the project to install 15 microseismic monitoring stations to detect and map induced seismic events. Six of the microseismometers would be installed a few feet below ground, while nine would be installed at existing boreholes up to 300 feet below ground. The stations would be installed in an array around the stimulation well to increase monitoring effectiveness. Once installed, the developer must publish this real-time seismicity data for public consumption via an online website during injection.

Prior to stimulation, the developer must also notify the Churchill County Local Emergency Planning Committee of its intention and install a ground motion sensor in Fernley, Nevada, the only community within 30 miles of the well.

During well stimulation, the developer must submit daily project reports that outline on-site activities, seismic events, and other information to the BLM and DOE. Table 3 highlights the required mitigation based on magnitude of seismic event or ground shaking.

Table 3: Brady Hot Springs Seismic Event Mitigation Measures

Seismic Event within 3 KM *(in Magnitude)*	**Required Mitigation**
M2.5 or greater	Project must halt injection. Developer must submit a Trigger report to the BLM and DOE and notify key personnel at the BLM, DOE, and Churchill County immediately.
Single reading over 0.02 g or more than 10 readings per day over 0.002 g peak ground acceleration measured at the Fernley ground motion sensor	Project must halt injection. Developer must submit a Trigger report to the BLM and DOE and notify key personnel at the BLM, DOE, and Churchill County immediately.

3.3.3 Seismic Results Associated with Well Stimulation

The Brady Hot Springs Well 15-12 stimulation initially began in late 2010 with a series of stimulation activities occurring through March 2015. Seismic monitors recorded a total of 403 seismic events, none of which reached M2.5 or greater (the required mitigation threshold) and only one event reached a magnitude of M2.0. A timeline of seismic events for both phases of stimulation based on LBNL's EGS Earthquake Maps (LBNL, 2017) is provided below in Figure 2.

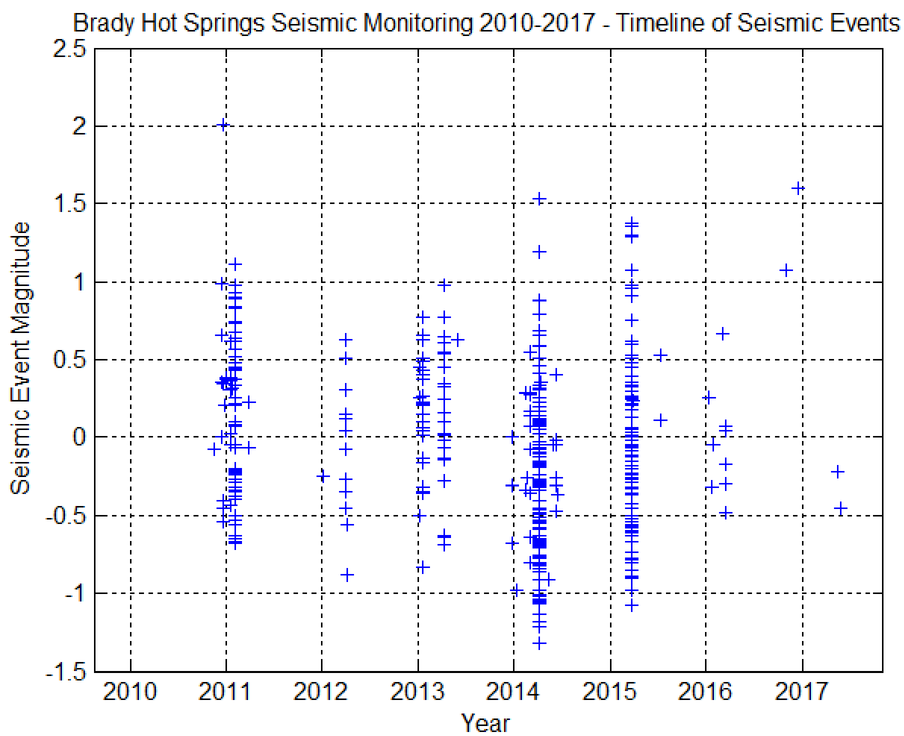

Figure 2. Brady Hot Springs Seismic Monitoring Data from LBNL's Earthquake Maps

3.4 Calpine Enhanced Geothermal Systems Project

Date of completed EA: June 2010

The Calpine Enhanced Geothermal Systems Project is located on private land within the Northwest Geysers in Sonoma County, California. DOE was the lead agency on the project as a result of providing the project funding through a 2008 FOA. The Calpine project sought to develop an EGS demonstration project to inject water ranging from 50 to 80 °F at increasing rates (100, 200, 400, and 800 gpm, depending on the ability of the fracture to accept the fluid) into abandoned exploratory wells converted to deep injection wells to enhance permeability of an existing high-temperature hydrothermal reservoir. The project utilized water obtained from other wells on site, with injection rates declining at those wells. The project, as proposed, consisted of three phases:

1. Pre-stimulation activities, including construction of a pipeline to deliver water for injection, preparation of the well pad and access roads, and re-opening/modification of two wells.
2. Stimulation activities, including implementation of the stimulation plan and monitoring the EGS system.
3. Long-term injection and monitoring the sustainability of the EGS project.

Noted seismic concerns included re-opening the formation, which may impact nearby communities and structures, as well as 25 historical (probable) Geysers-induced earthquakes of M4.0 and greater since 1972. Based on these induced seismicity concerns, the project conducted pre-stimulation modeling of the selected EGS wells, analyzed the historical induced seismicity in the Geysers, and conducted injectivity tests. The evaluation stated that seismic events were expected to be lower than M3.0, with a maximum predicted (but unlikely) event of M4.5 (based on events of this magnitude occurring over the last 40 years).

<u>3.4.1 Mitigation Plan</u>

In completing the NEPA review, DOE utilized and required adherence to the IEA protocol from 2008 based on a DOE decision to follow international protocols to address and mitigate potential impacts resulting from induced seismicity. (This environmental review was completed prior to the development of the DOE IS protocol.) The project planned to add four seismic monitoring stations to an existing network of twenty-nine seismic monitoring stations operated by the U.S. Geological Survey and LBNL. Additionally, two accelerograph stations are located in nearby communities that are used to determine the relationship between drilling and effects felt in the communities.

In addition to monitoring improvements, pre-stimulation efforts included informing community groups, seismological experts, regulatory agencies, and local government officials through the Seismic Monitoring Advisory Committee for the Geysers, which meets biannually to inform attendees of upcoming EGS projects. Further, software improvements were made to enable routine automated locating and mapping of nearby epicenters.

Mitigation during stimulation included analyzing well data to determine which wells are more susceptible to induced seismicity and a reduction of injection pressure at wells that produce higher levels of felt seismicity. During stimulation the success of the redistribution of water and any other modifications to reduce felt seismicity will be continually evaluated.

<u>3.4.2 Seismic Results Associated with Well Stimulation</u>

The Calpine Enhanced Geothermal Systems project initially began stimulation in October 2011 with a series of stimulation activities predominately occurring through March 2013 (Figure 3). The Geysers geothermal area has extensive seismicity, making it difficult to identify the total number of seismic events associated with stimulation based on LBNL's EGS Earthquake Maps (LBNL, 2017). However, Calpine used the LBNL seismic monitoring stations to identify a total of eight seismic events greater than M2.5 associated with stimulation (Garcia et al., 2016). The largest of these seismic events were an M3.74 in January of 2014 and an M2.87 in May of 2012 (Garcia et al., 2016). The timing of the events greater than M2.5 did not show a strong correlation with injection rate or injection rate variability (Garcia et al., 2016).

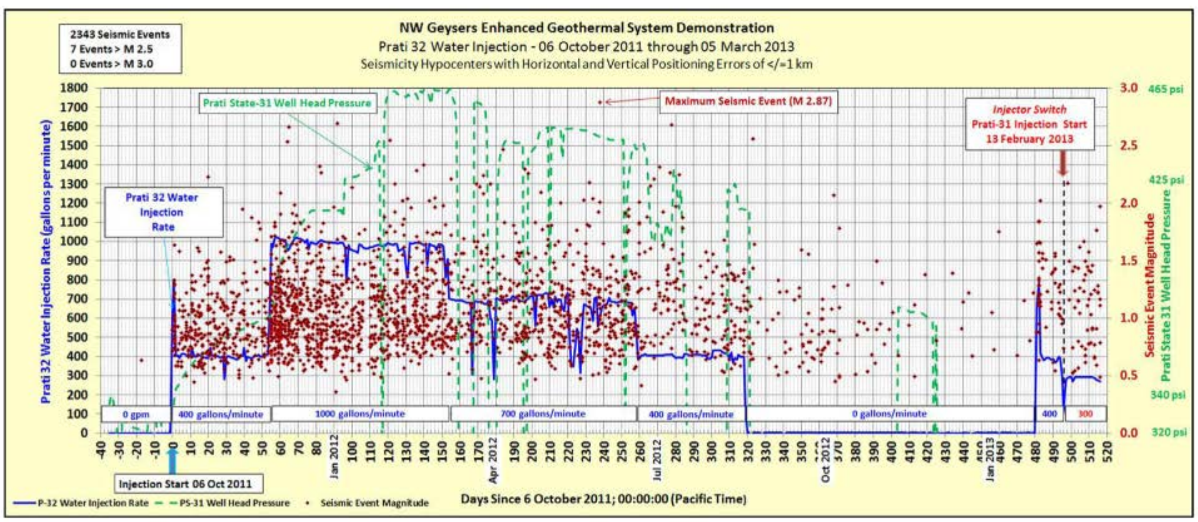

Figure 3. Calpine EGS Demonstration Project. Timelines shows fluid injection pressures (green curve), flow rates (blue curve) and seismic event magnitudes (red dots) highlighting maximum seismic event of M2.87 (Garcia et al., 2016).

4. Induced Seismicity NEPA Review Summary

This section summarizes the varying methods used to evaluate induced seismicity impacts across the projects and documents the key differences and similarities in the pre-stimulation, stimulation, and post-stimulation mitigation requirements.

4.1 Seismic Evaluations

To structure NEPA-related studies of seismic activity, three of the four projects (excluding BRP) used either the IEA protocol or iterations of the DOE IS Protocol. Calpine leveraged the IEA protocol, Newberry started with the IEA protocol and then incorporated components of the DOE IS protocol, and Brady Hot Springs used only the DOE IS Protocol. The use of the IEA protocol can likely be attributed to the environmental reviews taking place prior to the development of the DOE IS protocol.

All four projects conducted an evaluation of historical seismicity. These data were generated from existing seismometers and associated networks located near each project. From these data, an upper bound of plausible seismic events related to induced seismicity was established for each project and ranged from M3.0 $\leq$ M $\leq$ 4.5. BRP anticipated the lowest induced seismicity impact of M3.0. In comparison, Calpine anticipated the highest probable magnitude of 4.5.

In addition to this historical analysis, each project modeled the likely induced seismicity associated with stimulation activities. Here, each project took somewhat different approaches. In the Newberry case, the developer contracted with a third party to conduct an induced seismicity/seismic hazards and risk evaluation. In the Calpine case, the developer conducted pre-stimulation modeling of the selected EGS wells and evaluated the historical seismicity at the Geysers (where the project was located) and the results of injection tests. In the Brady Hot Springs case, the developer analyzed the induced-seismicity effects of a nearby project that employed well stimulation, along with geological and geophysical surveys of the area. Finally, in the BRP case, the BLM estimated the potential impacts of induced seismicity by evaluating the historical seismicity correlated with re-injection of geothermal fluid at a nearby project.

Despite this varied methodology, each document predicted that the induced seismic events of magnitudes less than 3.0 were the most probable. In the case of Brady Hot Springs and Newberry the expectation was that normal operations (re-injection) would result in induced seismic events of magnitude typically less than 2.0. Calpine and BRP expected 1-2 events per month (during normal operations) between 2.0 $\leq$ M $\leq$ 3.0.

4.2 Pre-stimulation Monitoring and Communication Activities

A range of pre-stimulation activities were required for each project, based in part upon the predicted induced seismicity effects. First, each project was required to conduct seismic monitoring during operations through the installation of 1-20 seismometers above and below ground. The BRP and Calpine projects represent the low end of the range with requirements to install one and four seismometers, respectively. In comparison, the Newberry project was required to install the most seismometers at 20, followed by Brady Hot Springs with 15. These seismometers were necessary to provide more accurate data linking stimulation activities with seismicity. Though Calpine only added four seismometers, they would be added to a much larger network of 29 seismometers already located at the Geysers. Though the BRP project was located near the Geysers, the EA does not specify that the larger network of seismometers would be used to monitor activities at the project site.

These seismometers offer continuous data of seismic activities, and each project was required to submit daily reports during stimulation to specified agencies such as the BLM, DOE, and local government entities. In the case of Brady Hot Springs, the developer was required to publish this seismicity data for public consumption via an online website. Calpine was required to update software to more effectively identify and map epicenters of seismic activity.

Three of the four projects were also required to install new, or monitor existing, ground acceleration detectors in certain populated areas, generally within 30 miles of the project. Brady

Hot Springs was required to install a detector in the nearby (20 miles away) populated area of Fernley, Nevada. Similarly, Calpine was required to monitor existing detectors at two nearby communities (Cobb and Anderson Springs), and Newberry was required to monitor activity at the Paulina Lake Visitors Center.

Prior to conducting stimulation activities, three of the four (excluding BRP) projects were required to notify certain community groups, agencies, and/or local governments such as advisory or emergency planning committees. In the case of Newberry, developers were also required to provide notice in local newspapers and hold monthly public meetings to allow citizens the ability to seek additional information or report concerns.

With Newberry's proximity to nearby structures, infrastructure, and geography it was required to adopt several other unique measures. The developer was required to install crack monitors on a nearby bridge, monitor cracking at a dam, evaluate the vulnerability of 52 assets around the project, purchase liability insurance, and install rock and avalanche hazard signs on specified roadways near the project.

Though BRP was not required to adopt many of these mitigation measures, the lead agency in the NEPA process, the BLM, did request that the developer submit a complete operation plan prior to construction to ensure that the project did not require further monitoring than the aforementioned seismometer.

4.3 Stimulation and post-stimulation mitigation activities

The level of mitigation required once stimulation of the wells begins varied significantly between the four projects reviewed as a part of this memorandum. The projects varied from specifying no specific mitigation measures for seismic events under M3.0 (BRP) to using diverters to shift stimulation to another zone if 6 monitors shallower than 6,000 feet measured an event greater than M1.0 (Newberry). The lack of consensus on stimulation mitigation activities was most significant for the *threshold* at which the project was required to halt injection completely. The Newberry EGS project required halting all injection into the well when stimulation produced an event greater than M3.5, or where ground shaking readings were at least 0.028 g PGA, while the Brady Hot Springs project required a halt to all injection for any event greater than M2.5 or where ground shaking readings were at least 0.02 g or 10 readings of 0.002 g. By comparison, BRP and Calpine did not require halting injection at all, with both projects' mitigation measures only discussing adjusting the volume of pressure or location for events that were M3.0 or greater (BRP) or where wells were determined more susceptible to induced seismicity through analyzing well data (Calpine). Further, neither the BRP nor Calpine projects included any mitigation measures based on PGA readings from ground shaking.

In addition, likely due to Newberry's proximity to Newberry National Volcanic Monument, this was the only project that specifically called for stimulation requirements to include a website for how to report damage as well as notification to nearby visitors and home owners after induced seismic events occur.

5. Conclusion

This review of NEPA documents for four geothermal injection or EGS projects (Table 4) reveals the variety of approaches to analyzing and mitigating induced seismicity. With the exception of the Geysers, where induced seismicity has been observed and monitored for an extended period of time due to large volumes of water being piped in to recharge the hydrothermal reservoir, induced seismicity caused by geothermal projects is a relative new area of study.

As this review highlights, determining the level of mitigation required for induced seismic events has varied based on project location, when the review took place, whether the project utilized the IEA or DOE IS protocols, and the federal agency conducting the review. While the NEPA reviews were relatively consistent for seismic monitoring and historical evaluation of seismic events near the project location, the requirements for public outreach and mitigation for induced seismic events once stimulation has begun varied considerably between the four projects. Not all of the projects were required to notify specific community groups or local government entities before beginning the project and only one of the reviews specifically stated the project proponent would hold meetings with the public to answer questions or address concerns.

Table 4: Project Summaries

Project	Action	Use of IS Protocol	Monitoring	Mitigation Trigger	Seismic Results
Newberry Volcano EGS Demonstration Project EA;	EGS test project using hydroshearing to stimulate the reservoir with injection pressure of 1,160 to 2,500 psig at 6,500 to 10,000 feet	IEA IS Protocol and components of the Draft DOE IS Protocol	Two new seismic monitoring stations; 20 pre-existing seismic monitoring devices installed at wells, boreholes, and surface stations	M1.0 shallower than 6,000 feet detected by at least 6 monitors or any seismic event greater than or equal to M2.0	174 total seismic events; Largest seismic event M2.39
Bottle Rock Power Steam Project EIR/EA	Drill new wells to expand existing hydrothermal power plant from 18 MW to 55 MW	No	Installation of new seismometer and utilization of existing system of seismometers	None stated. BLM and Lake County can re-evaluate if seismic events greater than M3.0 occur.	No conclusive evidence of increased seismicity
Brady Hot Springs Well 15-12 Hydro-Stimulation EA	EGS test project at existing production well and well pad; Hydraulic stimulation at 1,400 psig at 4,000 to 5,000 feet	DOE IS Protocol	Fifteen new microseismic monitoring stations (6 on surface, 9 in boreholes at depths up to 300 ft); Use of existing ground motion detector in nearest town	M2.5 or a single reading of 0.002g PGA ; 10 readings per day over 0.0002g PGA	403 total seismic events; No seismic event M2.5 or greater
Calpine Enhanced Geothermal Systems Project EA.	Injection of cool water at 100-800 gpm to enhance permeability of an existing high temperature reservoir through alteration of existing exploratory wells	IEA Protocol	Four new seismic monitoring stations; Use of 29 existing seismic monitoring station Use of two accelerograph stations in nearby communities	Analyze well data to see which wells are more susceptible to induced seismicity and decrease injection rate at wells with higher levels of felt seismicity	8 seismic events greater than M2.5; Largest seismic event M3.74

During the stimulation phase, while all of the projects required active monitoring and reporting of seismic events, multiple projects did not include specific requirements to halt injection if specific magnitude or groundshaking thresholds are met. In addition, these same projects failed to specify the exact mitigation measures that would be required for seismic events above a certain magnitude.

Moving forward, this NEPA review in combination with other activities completed under the induced seismicity task, including an induced seismicity check-list and associated guidance document, will enable the BLM to draft technical guidance on how to implement the DOE IS protocol within the BLM NEPA process to address concerns associated with geothermal induced seismicity.

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