Appendix B:
BLM Induced Seismicity Screening Worksheet Guidance Document

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Disclaimer:

The induced seismicity screening worksheet ("ISS Worksheet") presented in this document is for informational and guidance purposes for the Bureau of Land Management (BLM) only, for the limited purpose of identifying certain low-risk projects that may be approvable without the need for a formal probabilistic seismic hazard analysis conducted by a seismologist. The worksheet is not intended to provide an analysis of the seismic risk or seismic hazard of a geothermal hydraulic stimulation or Enhanced Geothermal System (EGS) project; nor does successful completion of the screening factors guarantee approval of a permit. It takes good judgment on when and how to implement an induced seismicity protocol. To try to boil it down to a few pages of guidance may be unrealistic. The IS expert team highly recommends that the BLM hire internal expertise (a seismologist or structural geologist) and involve that person as early in the process as possible.

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Executive Summary

An Induced Seismicity Screening Worksheet (ISS Worksheet) and accompanying guidance document have been prepared by the National Renewable Energy Laboratory (NREL) for the BLM in collaboration with an induced seismicity expert team (IS Expert Team). The ISS Worksheet and guidance document assist BLM field office staff with conducting a preliminary screening on seismic risk of a geothermal hydraulic stimulation or Enhanced Geothermal System (EGS) project. The ISS worksheet guides the user through eleven questions related to the operator performance, geothermal project technical details, historical local seismicity, and proximity to faults and population centers. Successful completion of the screening worksheet does not provide or indicate permit approval, but is intended only to inform the BLM of whether it has sufficient information related to the potential for induced seismicity, and resource specialists with an appropriate level of expertise on staff, to proceed in considering the permit. Based on the answers to these questions, the worksheet has four possible outcomes:

1. Resolve issues with operator: Unsatisfactory communication or mitigation plan or unresolved past negligence or non-compliance issues should be resolved before screening can continue
2. Low level concern: Initial screening passed; proceed with next steps in processing the application
3. Medium level concern: The BLM field office can proceed with evaluation of the application after involving the State Office Geothermal Program Lead. He / she may recommend consulting with industry or academic seismic experts and potentially apply the DOE Induced Seismicity Protocol.
4. High level concern: The BLM field office should not proceed further with processing the application without first contacting the State Office Geothermal Program Lead. The Geothermal Program Lead will perform in-depth review (likely in consultation with industry or academic seismic experts) and require the applicant to implement the full Induced Seismicity Protocol.

The ISS Worksheet is included in Appendix A. This guidance document (Appendix B) explains the reasoning for each question and where to find relevant data to answer these questions. Four examples are included in Appendix C to illustrate how to apply the ISS Worksheet.

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1 Introduction

In 2012, DOE released a Protocol for Addressing Induced Seismicity with Enhanced Geothermal Systems (EGS). The Protocol identified 7 steps (as shown in Figure 1) for addressing induced seismicity issues as they relate to the whole project. This induced seismicity screening worksheet is to be used by BLM staff as a preliminary screening evaluation as suggested by Step 1 of the Protocol. See the Protocol (Majer et al., 2012) and best practices document (Majer et al., 2016) for detailed information on Steps 2 through 7.

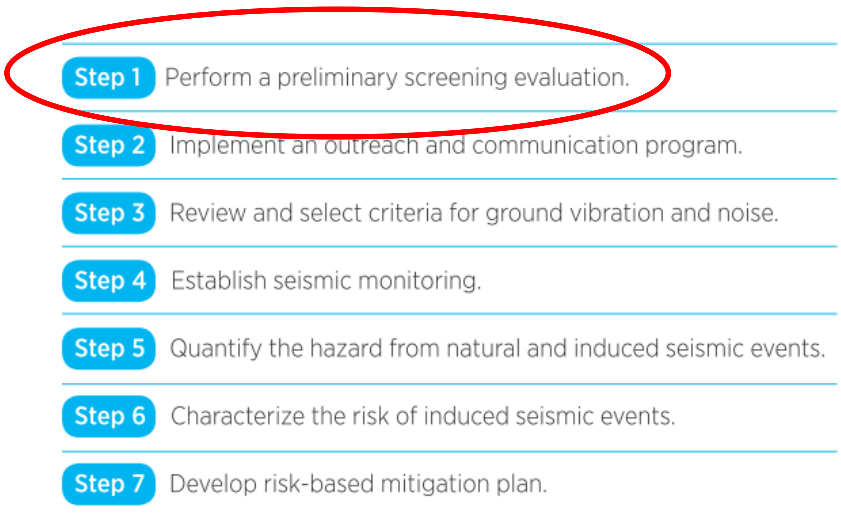

Figure 1. **Screenshot of the steps in addressing induced seismicity as taken from Majer et al. (2012).** The BLM induced seismicity screening worksheet is to be used by BLM staff as a preliminary screening evaluation as suggested by Step 1 (red oval) of the Protocol. See the Protocol (Majer et al., 2012) and best practices document (Majer et al., 2016) for detailed information on Steps 2 through 7.

1.1 Data necessary for applying Induced Seismicity Screening Worksheet

When an operator submits a project with the potential for induced seismicity, make sure to gather the following information necessary to apply the ISS Worksheet:

❑	Operator’s communication and mitigation plan	from Applicant
❑	Operator’s compliance track record	from PET/GET at State Office
❑	Fluid injection plan (injection pressure, flow rate, total volume of injected fluid)	from Applicant
❑	Location of wellbore	from Applicant
❑	Regional historical seismicity (M2.0+ seismic events within 20 km radius)	from Applicant and/or USGS (See Section 2.2)
❑	Closest population center, and sensitive/critical infrastructure	from Applicant and/or Google Earth/Maps (see Sections 2.3.3a through 2.3.3d)
❑	Fault map of the area	from Applicant and/or USGS (see Section 2.3.3e)

1.2 Scope of BLM's Induced Seismicity Screening Worksheet

With guidance from a multi-agency Induced Seismicity (IS) Expert Team, the National Renewable Energy Laboratory (NREL) has prepared an Induced Seismicity Screening Worksheet (ISS Worksheet, Appendix A) and this accompanying guidance document for the BLM. The ISS Worksheet was designed to assist BLM field staff with evaluating the risk of induced seismicity caused by fluid injection for hydraulic stimulation to create an Enhanced Geothermal Systems (EGS) reservoir.[1] EGS reservoirs are man-made reservoirs in rock formations where temperatures are high but permeability is poor and often little to no water is present.

The potential for induced seismicity at an EGS site is different for each site, and the assessment of the impact of induced seismicity must be done on a case-by-case basis. Each site will have uncertainties in its properties and the unknowns will be different for each site. Therefore, the overall assessment of induced seismicity must be done as a sum of all the impacts, rather than each different potential parameter on the impact of induced seismicity.

The experts have suggested that the most reliable means for successfully dealing with induced seismicity is to follow the process in the Induced Seismicity Protocol, which starts with screening community outreach and ends with mitigation (i.e., a mix of sociology, engineering, hypothesis-driven science, risk analysis, and, if all else fails, politics, and insurance). Hence, one size does not fit all. Skipping one of the steps, or not using the right amount of each element at the right time, may lead to high costs or even failure.

Section 2 provides step-by-step guidelines for providing input data to the ISS Worksheet, as well as technical background information for each question. Section 3 discusses how to interpret and respond to the ISS Worksheet output. Appendix C provides four examples of EGS project sites and their concern of induced seismicity assessed with the ISS Worksheet. Appendix A includes the ISS Worksheet.

1.3 Hydraulic Stimulation and Induced Seismicity

In EGS, geothermal reservoirs are hydraulically stimulated to increase the reservoir rock permeability and connectivity and thereby enhance the overall performance of the reservoir. Hydraulic stimulation—or hydro-shearing—is one technique among others (e.g., acid and thermal stimulation) applied to treat hydrologically poorly performing wells. Hydraulic stimulation is performed by injecting high volumes of water (often cold and clean) into the reservoir at high pressures and high flow rates. This fluid raises the pore pressure, which will promote slip across *pre-existing* fractures (hydro-shearing), resulting in increased permeability. This stimulation differs from the hydrofracking done in the oil and gas industry, which uses a mixture of chemicals to actually shatter the rock. The process breaks the rock and creates new cracks or fractures in the rock, often propping them open with sand or other proppant material. Hydraulic stimulation for EGS typically uses lower injection fluid pressures and but larger injection fluid volumes, and does not require proppants.[2]

[1] Geothermal projects regularly inject fluids (geothermal or otherwise) into the geothermal reservoir to maintain reservoir pressure. The corresponding injection rates and pressures are typically significantly smaller than those used for hydraulic stimulation and usually do not cause a *net* increase of fluid volume in the reservoir (an equal amount of fluid is extracted from the reservoir by the production wells during regular operation). As a result, these activities typically are not of concern for causing significant seismic events (which may cause damage at the surface).

[2] Elevated pressure during EGS stimulation may cause creation of new fractures (hydrofracking).

Opening up pre-existing fractures and creating new fractures causes microseismic events also known as induced seismicity. Hydraulic stimulation often creates only small microseismic events that are not felt at the surface and that are a useful reservoir management tool (e.g., for mapping the extent of an EGS reservoir). It does not often lead to medium- or high-magnitude events, but the possibility increases with more aggressive stimulation, especially near large faults that are close to shear failure. Even if earthquakes large enough to be felt occur, they do not pose a risk unless a population center or critical infrastructures are nearby. Induced seismicity causes concern if the associated ground motions are felt or are damaging (Majer et al. 2007). Induced seismicity may become a legal nuisance, causing ceasing or modification of operations, even in the absence of actual damage.

Different magnitude scales have been developed for earthquakes. Historically, the Richter magnitude scale, developed in the 1930s, was widely used and is calculated as the base-10 logarithm of the ratio of the seismic wave amplitude with respect to a reference amplitude at a standard distance. Because the Richter magnitude scale tends to saturate at large magnitudes and is unreliable for measurements at large distances from the epicenter, the standard in seismological communities since the 1970s is the **moment magnitude scale**. The moment magnitude is based on the seismic moment of an earthquake, which is calculated as the product of the average slip, the fault area, and the modulus of rigidity. Unfortunately, this type of magnitude scale is not always included in reports and news articles. Both magnitude scales, however, follow a similar logarithmic trend and usually result in similar magnitude values for the same event. Throughout this document, the seismic moment magnitude scale is labeled as M whereas a magnitude expressed using the Richter magnitude scale is labeled as M_L (with L referring to “local”), following seismological community practices.

Earthquake magnitudes quantify the size of an earthquake on a logarithmic scale to account for the vast spectrum of seismic event size. The magnitude of an earthquake depends on the area of a fault rupture, the amount of slip on that area, and associated rock properties. The fault rupture excites seismic waves, which, in turn, are dependent on various rock properties as they travel from the earthquake location to locations where these waves may excite ground motions that can be felt or cause damage.

Magnitude does not vary as a function of distance from an event, but ground motion does. It is the ground motion at sensitive sites that governs the hazard posed by earthquakes.

1.4 Identifying Risk

The most infamous EGS case history is likely the 2006 Basel 1 EGS project in Switzerland. The project site was located in downtown Basel with known historic seismicity and the presence of nearby active faults. A naturally occurring M 6.0 to 6.9 earthquake in the year 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 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, which triggered a premature halting of fluid injection (within 6 days of the start of injection), and eventually it terminated the whole project (GPB, 2007; Häring et al., 2008). More information on the Basel 1 EGS project is provided in Example 1 of Appendix C.

The 2006 Basel 1 EGS project is one of the few EGS projects known, among about a dozen EGS projects developed so far worldwide, to have seen damage at the surface caused by induced seismicity. Examples of EGS Projects without surface damage are Fenton Hill, Newberry, Brady Hot Springs, and Desert Peak in the United States, Soultz-sous-Forest and Rittershoffen in France, Rosemanowes in the United Kingdom, Cooper Basin in Australia, and Ogachi and Hijiori in Japan. All of these EGS projects were in locations more remote than the Basel project, and most of these projects saw seismic events of lower magnitude than in Basel. The Basel, Newberry, Brady Hot Springs, and Desert Peak EGS projects are discussed in more detail in Appendix C.

The earthquake activity induced by the Basel 1 EGS project resulted in the development of the "IS Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems" by the 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 in managing induced seismicity and applying EGS technology safely. It suggests seven steps for an operator to follow when given permission to perform activities that may cause induced seismicity:

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 local seismic monitoring.
5. Quantify the hazard from natural and induced seismic events.
6. Characterize the risk of an induced seismic event.
7. Develop a risk-based mitigation plan.

Follow-on work included developing a "decision tree towards permitting" for the BLM and DOE by Majer (2014). The decision tree is an example of a preliminary screening evaluation (Step 1 of the IS Protocol) and provided some of the basis for the ISS Worksheet. The decision tree proposed by Majer (2014) has not been implemented at BLM because of the level of seismologic expertise required.

In 2016, Majer et al. developed a guidebook, "Best Practices for Addressing Induced Seismicity with Enhanced Geothermal Systems (EGS)," for the DOE that builds on the IS Protocol and provides additional detail for each of the seven steps, including guidance for evaluating ground vibration and noise criteria and conducting a seismic hazard analysis.

In 2017, the ISS Worksheet (Appendix A) and this supporting guidance document have been developed after literature review and in collaboration with the IS Expert Team. The ISS Worksheet is designed to be applied by non-seismologists at local BLM field offices at the initial stage of permit review when an application is submitted by a geothermal developer. It fulfills Step 1 of the IS Protocol, and it evaluates Steps 2 and 7. The ISS Worksheet guides the user through 17 questions related to operator performance, geothermal project technical details, historical local seismicity, and proximity to faults and population centers. This guidance document is intended to help BLM staff use the ISS Worksheet to assess if any aspect of geothermal hydraulic stimulation project submitted by an operator is of concern which would trigger the need for an expert being involved to carefully asses the seismic risk.

A **seismic hazard** is the probability that an earthquake will occur in a given geographic area, within a given window of time, and with ground motion intensity exceeding a given threshold.

Seismic risk is defined as the probability of loss or damage due to seismicity (Majer et al., 2016). In other words, seismic risk is not the probability of induced seismic events happening, but goes further to consider the probability of damage or loss at the surface caused by induced earthquakes.

The ISS Worksheet does not intend to calculate seismic risk. Rather, it flags if something is of concern (e.g. nearby population center or massive injection rates) which would trigger a review by the State Geothermal Program Lead likely in consultation with a seismologist who would estimate the seismic risk. Based on the answers to the ISS Worksheet questions, there are four possible outcomes:

1. Issues to be resolved with the operator before screening can continue
2. Low level of concern project
3. Medium level of concern project
4. High level of concern project.

Low-level concern projects can proceed with the next steps in the approval process. Projects with higher levels of concern are flagged and need additional review by the BLM State Office and/or a seismologist, which may include an induced seismicity mitigation plan and a probabilistic seismic hazard analysis (PSHA). In some cases, the seismologist may believe that the risks cannot be sufficiently mitigated and may recommend that the BLM deny the permit.

Even when the screening indicates a medium or higher level of concern, indicating a need for analysis by a qualified seismologist or structural geologist before further processing can proceed, there is value to both the BLM and the operator. Denying a permit at the preliminary screening phase would be exceedingly rare, but may save the operator millions of dollars by (1) not developing a project that may be halted prematurely due to seismic activity, and (2) preventing earthquakes that could cause structural damage, resulting in damage claims by local residents. Operators may choose to redesign their project for re-evaluation.

The Basel 1 EGS project is a prime example illustrating the importance of performing a preliminary IS screening. Example 4 in Appendix C illustrates that the Basel 1 EGS project would not have passed the preliminary screening and the project would not have moved forward.

Final approval or rejection is not intended to be based solely on the outcome of this ISS Worksheet. Even when all questions are answered "yes," a second review by a State Office geologist or subject-matter expert before proceeding with the project can be useful for lowering the possibility of human error in the first review. The ISS Worksheet is not intended for evaluating oil and gas operations, wastewater injection, acid stimulation, or geothermal heat pumps.

2 Induced Seismicity Screening Worksheet Questions and Input Data

The ISS Worksheet contains 17 questions grouped into four categories:

1. Screening Worksheet Applicability (questions 1a to 1e)
2. Operator and Project Details (questions 2a to 2e)
3. Seismicity (question 3a)
4. Proximity (questions 4a to 4e).

This section provides guidance on how to evaluate the information derived from the 17 questions, where to find the input data, relevant technical background information, and the reason for including these questions in the ISS Worksheet. Four examples are included in Appendix C to illustrate how to answer the questions when applying the ISS Worksheet to an EGS project.

2.1 Screening Worksheet Applicability

The Induced Seismicity Worksheet is only to be used by the designated (trained) Field Office employee to conduct a broad preliminary assessment of the seismic risk of fluid injection for hydraulic stimulation for a geothermal project. Therefore, the following 6 questions are asked upfront to the screening worksheet is correctly applied:

- 1a. User of this screening worksheet is designated field office employee?
- 1b. All necessary data has been collected to apply this screening worksheet (ref. data checklist in Section 1.1 of this guidance document)?
- 1c. Project concerns geothermal project (i.e. no oil & gas project)?
- 1d. Project concerns geothermal wells deeper than 400 m (i.e. no geothermal heat pumps)?
- 1e. Project does not concern acid stimulation, tracer test, or clean-out?
- 1f. Project does not concern regular fluid injection during normal power plant operation (ref. UIC)?

Only if the answers to these six questions is “yes”, the user can continue applying the worksheet.

2.2 Operator and Project Details Questions

2a. Operator has communication and mitigation plan?

As identified by the U.S. DOE Induced Seismicity Protocol (Majer et al 2012) and the Best Practices Guidebook (Majer et al. 2016), an operator should have a communication and mitigation plan in place. These plans typically are part of the application package submitted by the developer to the BLM to conduct a geothermal hydraulic stimulation job.

A communication plan is necessary to establish a positive relationship with and gain acceptance from the community. Establishing this relationship early may result in the community being more favorably inclined toward the project. In addition, different communities have different risk acceptance levels and socio-economic needs. Engaging the community allows one to assess the risk acceptance level and identify the public concerns.

The communication plan shall explain how the local community will be informed and engaged. Specifically, it is recommended that the communication plan address the following five items, as identified in the U.S. DOE Induced Seismicity Protocol (Majer et al. 2012):

1. Identify the outreach needs
2. Develop a plan to approach community, stakeholders, regulators, and public safety officials
3. Develop a public relations plan to generate interest in the project from local media
4. Set up a local office in the community, ideally including technical displays for visitors
5. Hold an initial public meeting and site visit that covers both technical and non-technical issues.

A mitigation plan is necessary because some level of mitigation might be needed during the project.[3]

The developer should have a plan prepared that explains where IS monitoring stations will be placed, how long the monitoring will take place prior to the project to establish baseline seismicity, the threshold levels of induced seismicity that trigger mitigation, the type of mitigation associated with each threshold level, and a description of how the operator plans to address nuisance and damage associated with these operations. The mitigation plan should specify what type of direct and indirect mitigation measures will be taken if mitigation becomes necessary during the fluid-injection activity (Majer et al. 2012). The most common direct mitigation measure is the traffic light system to control pumping operations based on measured seismicity activity. Indirect mitigation measures can be compensation, community support (e.g., support for local schools and libraries), increased outreach, and continuous seismic monitoring.

[3] An example mitigation plan will be included in the final documentation for this BLM/NREL IS Task.

2b. Operator has excellent track record of compliance?

This question was not explicitly identified as a criterion in the preliminary 2014 IS screening decision tree (Majer 2014) or in the U.S. DOE Induced Seismicity protocol (Majer et al. 2012). However, the IS Expert Team felt that an operator with a poor performance track record (e.g., issued Incidents of Non-Compliance, caught on negligence) should demonstrate that their historical poor performance has been addressed and prove that improvements in operation procedures and compliance with standards/rules have been applied before the project can continue.

The information to answer this question is available from the BLM petroleum/geothermal engineering technician (PET/GET) who inspects the site or applicant and by reviewing previous communication between the BLM and applicant. The answer to this question is no if <u>any</u> of the following is true:

1. The operator has been issued Incidents of Non-Compliance (INC) forms that have been unaddressed
2. The operator has failed to respond satisfactorily to BLM inquiries regarding negligence
3. The operator has a habit of not informing the BLM satisfactorily and on time of any subsurface activity.

2c, 2d, and 2e. Volume, Rate, and Pressure of Injection

In a general sense, the volume (question 2c), rate (question 2d), and pressure (question 2e) of injected fluid will all affect the potential for induced seismicity. Also, factors such as the local subsurface stress values, proximity to faults, and size and extent of existing faults will all affect the potential for induced seismicity. Below is some general guidance that was based on observed induced seismicity examples. Exceeding or limiting the values for any one factor is not a reason for stopping or proceeding with the project, since all factors must be considered together for any specific site. Instead, it is important in these cases to involve a seismologist on the evaluation.

2c. Anticipated net total volume of injection fluid for the project is less than 13 million gallons?

This question is incorporated in the ISS Worksheet due to the relationship between the total injection-fluid volume (for the stimulation project) and the maximum magnitude of an induced earthquake (McGarr 2014, Majer 2014). In theory, a volume of 13 million gallons (5×10^4 m^3) can cause an M3.9 event if all energy is released at once (for granite with shear modulus of 27 GPa) and with $K = 0.5$ (Majer 2014). To incur major structural damage,[4] at least an M5.0 event would be needed within a few km distance (Majer et al. 2012). A list of induced seismic events is shown in Table 1. Only the first two rows apply to EGS, with Basel the only known EGS project to have seen surface damage due to induced seismicity.

[4] Major structural damage is defined as damage to buildings, bridges, or other infrastructure so severe they become unsafe to occupy or access.

Table 1. Select "Maximum Observed Events" Related to Subsurface Fluid Injection
Only the Basel and Cooper Basin examples are EGS-related and would be appropriate activities for the application of the IS Worksheet.

Maximum Observed Event	Location	Size	Year	Injection Volume (million gallon)	Maximum Injection Rate (gpm)	Maximum Injection Pressure (psi)	Activity	Impact	Source
Damage caused by EGS-related event	Basel, Switzerland	M_L 3.4	2006	3	925	4,300	hydraulic stimulation	minor cosmetic damage (e.g. cracks in walls), which resulted in 2,700 damage claims	Majer et al., 2007; 2012
EGS-related event	Cooper Basin, Australia	M 3.7	2003	5	760	11,000	hydraulic stimulation	no damage because project site was in remote desert location	Majer et al., 2007, 2012
Geothermal-related event	Geysers Field, CA	M 5.0	2016	350,000 (for 75 injection wells over 45 years)	14,000 (for 75 injection wells)	Unknown	combination of massive production and injection rates in a tectonically-active region	event was felt by people in several nearby towns but no damage reported	USGS, 2016
Fluid injection-related event	Prague, OK	M 5.7	2011	42	9	525	wastewater injection from oil and gas operations	injured two people, destroyed 14 homes, damaged many other buildings, and buckled pavement	Keranen, 2013

The anticipated volume of injection fluid should be provided by the operator in their Plan of Operations as part of the application package. Unit conversions are necessary if the volume is expressed in different units.[5] If a hydraulic stimulation job includes different fluid injection phases, the total volume is calculated as the sum of the injection volumes planned in each phase. If the operator provides injection data in terms of injection rates and injection time, the total volume (or the volume in each phase) is calculated as the injection rate multiplied by the injection time (for that phase).

2d. Anticipated rate of injection fluid less than 650 GPM?

This question is included in the ISS Worksheet because the injection rate is identified as one as the factors that have an impact on induced seismicity (Majer et al. 2016). Majer et al. (2016) suggest that during a fluid-injection operation, if sufficiently high magnitudes are detected, then rate limitations based on a traffic light protocol should be imposed. Generally, if a magnitude threshold is exceeded, then the traffic light switches to orange, which imposes a reduction in injection rate. Higher magnitudes may trigger a red light, in which case injection is stopped until further notice.

For the purposes of this ISS Worksheet, the IS Expert Team calculated an injection rate of 650 GPM (41 L/s) as the screening threshold, (corresponding to 13 million gallons of fluid injection in 2 weeks for Question 2c).

[5] 1 m^3 = 1000 L = 264 gallon = 8.4 barrels

The anticipated rate of injection fluid should be provided by the operator in their Plan of Operations as part of the application package. Unit conversions are necessary if the volume rate is expressed in different units.[6] If a hydraulic stimulation job includes different fluid injection phases, the volume rate considered is the maximum across the different phases. If the operator provides injection data in terms of total volume and injection time, then the injection rate is calculated as the injection volume divided by the injection time (potentially calculated for each phase).

2e. Anticipated wellhead injection pressure less than or equal to 1000 psi?

This question is included in the ISS Worksheet because the injection pressure is identified as one of the factors that have an impact on induced seismicity (Majer 2016). For induced seismicity to occur, the pressure at the depth of injection must exceed the forces holding any faults in the injection volume from slipping.[7] One of these forces preventing the fault from slipping is the pressure acting perpendicular to the fault (normal stress). Any pressure (injection pressure) added to the water pressure in the borehole will add to the pressure acting against the "normal" forces that are holding the fault from slipping. If the fault if close to slipping, it may take very little added pressure (injection pressure) to induce the fault to slip. If the forces holding the fault from slipping are large, or the natural forces promoting fault slip are small, then it may take a great deal of injection pressure to generate induced seismicity.

The value of 1000 psi injection at the wellhead was chosen because this wellhead pressure would translate in a downhole pressure large enough to overcome natural forces holding the fault from slipping. However, much lower injection pressures can cause induced seismicity, depending on subsurface stress, proximity to faults, and the rates and volumes of injected fluid.

The anticipated **wellhead injection pressure** and **depth of the stimulation target zone** should be provided by the operator in the Plan of Operations as part of the application package. If a hydraulic stimulation job includes different fluid-injection phases, then the wellhead injection pressure considered is the maximum pressure across the different phases.

2.3 Seismicity Question

3a. Historical seismicity within 20 km less than M2.0?

This question is included in the ISS Worksheet because "being in an active earthquake zone" was one of the questions included in the 2014 preliminary IS decision tree (Majer 2014). An "active earthquake zone" was defined as an area that experienced seismicity (naturally or induced) > M1.5 in the last 5 years within 10 km (Majer 2014) or within 30 km (Majer et al. 2013). Based on this information, the IS Expert Team:

1. Set an average value of 20 km as the distance threshold for the ISS Worksheet; and
2. Changed the time period from "5 years" to "recent history" because some scientists within the earthquake community state that an active earthquake zone should have a time scale of hundreds or thousands of years instead of 5 or 10 years. For example, an active fault in California is defined as fault that has moved in the past 35,000 years (Majer et al. 2016).

The operator should have identified the historical seismicity in the area to characterize the background seismicity as part of the mitigation plan. Historical seismicity includes both natural and induced

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[6] 1 m^3/day = 0.0116 L/s = 0.184 GPM = 8.4 U.S. barrels/day

[7] At almost any site, there are natural subsurface forces acting to make faults slip; however, friction on the fault surfaces, rock strength, and other forces are preventing the faults from slipping.

seismicity. A map is likely included showing historical seismicity, and a ruler can be used to measure distance to the project site. In addition, it is recommended to consult the USGS earthquake database (http://earthquake.usgs.gov/earthquakes/search/) as well as news articles to identify any other seismic events of M2.0 or larger not listed by the operator. The project site location corresponds to the coordinates (longitude/latitude) of the wellhead of the well considered for fluid injection.

2.4 Proximity Questions

3a. Closest significant population center more than 10 km away?

This question is included in the ISS Worksheet because seismic activity can only be of high risk if it is close enough to a population center that it may cause significant annoyance or disturbance to the local population, or close enough to critical infrastructure that it may pose a risk to existing (or future) structures (Majer et al. 2007). Some sites are very remote, and thus, there is little public concern regarding induced seismicity. The 2014 preliminary IS screening decision tree (Majer 2014) did not specify a distance-to-population-center criterion, only a distance-to-sensitive-site criterion (see Questions 3c & 3d). As recommended by the IS Expert Team, a population-center-proximity criterion is included in the ISS Worksheet. The same distance threshold (10 km) is used for population centers as was used for a sensitive facility (see Question 4e); but in this case, it does not result in immediate consultation with the State Office when answering “no” (as is the case for Question 4e).

A significant population center is defined as a community with at least 100 people. The operator should identify the well that will be used for fluid injection in the operations plan as part of the application package. The coordinates of the injection zone[8] should be used as project location, which becomes the center of a circle with 10-km radius drawn in Google Earth. If infrastructure in a significant population center is within the circle, the answer to Question 3a is “no.”

4b. Closest population center with historical opposition more than 15 km away?

A specific question concerning population centers with historical opposition is included in the ISS Worksheet because Majer et al. (2012) identified that *“… different communities may have different acceptance levels of risk, and/or possibly different socioeconomic circumstances*.” Majer (2014) listed a “hostile public” as a factor that could automatically disqualify a site. A hostile public may become less hostile with an effective communication plan (see Question 2a). Therefore, immediate disqualification is not applied in this ISS Worksheet; instead, an additional screening by seismic experts is triggered if a population center with historical opposition is within 15 km of the project site.

The same tools and data used for answering Question 4a can be applied for addressing this question—with the threshold now at 15 km instead of 10 km. Whether or not a population center has had historical opposition is subjective. It is recommended to first consult with the operator, who should have obtained a feeling for this after developing the communication plan. Also, review of news articles and knowledge within the BLM on past projects in the area can provide a sense of where the community stands with respect to induced seismicity, hydraulic stimulation, and development of energy projects (in particular, geothermal and oil and gas projects). For this question, communities with a population less

[8] Deviated wells are very common in geothermal reservoirs. Wellhead locations can differ by up to a km from the injection zone, depending on the deviation of the well and depth of the well.

than 100 people should be considered because one individual can take legal actions potentially resulting in the project being halted in court for years.

4c. Proximity to closest sensitive or critical site/facility is more than 20 km away?

Note: A sensitive site/facility is any of the following: archeological or historic sites: national park, state park, or national natural landmark deemed vulnerable to felt ground motion (such as dams); research laboratory; chemistry laboratory; hospital; semiconductor manufacturing facility; or facility with sensitive electronics (electron microscope, photolithography machines, electron deposition machines, laser interferometers, laser metrology systems, or machining equipment, etc.)

This question is similar to the 15-km proximity criterion to a sensitive/site facility in the 2014 preliminary IS screening decision tree (Majer 2014) and results in requiring additional expertise review at the Field Office level, potentially in collaboration with the State Office, instead of immediate elevation to the State Office level (as in Question 4e). As recommended by the IS Expert Team, the distance threshold is set to a more conservative value of 20 km instead of 15 km.

The same tools and data used for answering Question 4a can be applied for addressing this question.

4d. Closest fault with length larger than 0.5 km more than 10 km away?

This question is included in the worksheet because nearby active faults are reasons for concern for induced seismicity as stated by several references:

- "*The maximum event will depend upon the size of the fault available for slippage*" (Majer et al. 2007)
- "*Large or damaging earthquakes tend to occur on developed or active fault systems. In other words, large earthquakes rarely occur where no fault exists, and the small ones that do occur do not last long enough to release substantial energy*" (Majer et al. 2012)
- "*As a general rule, EGS projects should be careful with any operation that includes direct physical contact or hydrologic communication with large active faults*" (Majer et al. 2012)
- "*Near large faults (ones that may generate events larger than acceptable levels)*" is identified as a factor that may automatically disqualify site (Majer, 2014).

The 2014 preliminary IS decision tree (Majer 2014) explicitly includes a criterion: "Is the expected diameter of pressured influence less than 3 times distance to any critically stressed faults greater than area of 500 meters by 500 meters?" This area can maximally cause a M3.5 earthquake, using the Kanamori and Anderson equation:

$$\text{Log } A = 1.21M - 5.05 \qquad \textit{Eq. 1}$$

where M = Magnitude and A = fault area in km^2. (Majer 2014)

This criterion is quite technical and cannot always be answered by BLM field office personnel. Therefore, the criterion was conservatively simplified by the IS Expert Team to "within 10 km of fault with length larger than 0.5 km." Note, however, that nearly all faults that have been associated with induced seismicity have been discovered by the earthquake locations due to the induced seismicity. They are buried faults that were not accessible to geologists in the field for mapping.

Known faults in the EGS area should have been identified by the operator's seismic expert and included in the Plan of Operations as part of the application package. A map is likely provided with known faults, well location, and scale. In addition, it is recommended to consult the USGS Quaternary faults website (http://earthquake.usgs.gov/hazards/qfaults/map/#qfaults) to identify any other faults with length longer than 0.5 km within 10 km of the project site. This faults database, which includes the lengths of the faults, can be downloaded as a shapefile to use in geospatial software for easy measurement of distance from project site to faults. The project site location corresponds to the coordinates (longitude/latitude) of the wellhead and bottom-hole location (if different) of the well considered for fluid injection.

4e. Closest sensitive or critical site/facility more than 10 km away?

This question is included in the ISS Worksheet because a project site close to a sensitive facility (e.g., historical artifacts, hospitals) was identified as a factor that may disqualify a site (Majer 2014). Sensitive sites have very low tolerance to ground motion (Majer et al. 2016). In contrast, a critical site (e.g., nuclear power plant) may have high tolerance for ground motion but because of the dire consequences if damage occurs, much lower probability ground motion must be accommodated. Acceptable induced seismicity ground motion could be much less than what most buildings and people can tolerate. The 2014 preliminary IS screening decision tree (Majer 2014) has a 15-km proximity criterion to a sensitive site/facility that triggers a seismic risk and hazard analysis by experts. It was recommended by the IS Expert Team to include in the ISS Worksheet a similar criterion that automatically elevates the project to the State Office level but with a smaller distance threshold at 10 km instead of 15 km. The State Office will conduct an in-depth review (likely in consultation with industry or academic experts) to assess the seismic risk of the project, taking into account the presence of a nearby sensitive or critical site/facility.

The same tools and data used for answering Question 4a can be applied for addressing this question. A sensitive site/facility is any of the following: archeological sites: national park, state park, or national natural landmark deemed vulnerable to ground motion; research laboratory; chemistry laboratory; hospital; semiconductor manufacturing facility; or facility with electron microscope, photolithography machines, electron deposition machines, laser interferometers, laser metrology systems, or machining equipment.

3 Interpreting and Responding to ISS Worksheet Output

The ISS Worksheet has four possible outcomes with different BLM actions for each outcome:

3.1 Resolve Issues with Operator

In case Questions 1a and/or 1b are answered “no,” an issue has arisen with the operator that needs to be resolved before screening or further processing of the permit can continue. BLM staff should reach out to the operator to explore if the operator can resubmit an acceptable communication or mitigation plan (Question 1a) and/or explain how past negligence or non-compliance has been addressed, resolved, and prevented from happening again in the future (Question 1b). If the issues are resolved, the screening can continue with Question 1c; otherwise, the screening is terminated and the IS Expert Team recommends that the BLM reject the project.

3.2 Initial Screening Passed

If all questions are answered “yes,” then the ISS Worksheet did not identify any reason for concern of induced seismicity, and the project is considered to have **low level of concern**. The IS Expert Team recommends that the BLM continues with the next steps in the approval process. The State Office should be informed of the outcome of the initial screening and may still require that the full DOE IS Protocol be implemented by the operator (e.g., install geophones network to detect seismicity, conduct educational workshops with local community if local community is present engage qualified expert to conduct analysis to forecast or calculate a qualitative seismic hazard and to characterize the probability or risk of damage or harm, should such an even occur).

3.3 Medium level concern: Proceed with evaluation and involve State Office Geothermal Program Lead

If the answer to any of the Questions in Section 2, 3 or 4 except Question 4e is "no," then the project is considered to have **medium level of concern**. The BLM Field Office level should involve the State Office Geothermal Program Lead who may obtain the services of a seismic expert and potentially apply the Induced Seismicity Protocol before a decision can be made. The risk would typically increase with more questions answered "no." It is recommended that the seismologist reviews these questions and answers and conducts a full seismic hazard and risk analysis to make a decision on the risk level of induced seismicity. If the **seismologist** concludes that the seismic risk is **low**, then the IS Expert Team recommends that the BLM approve the project to proceed under the condition that the DOE IS Protocol is implemented by the operator. If the **seismologist** concludes that the seismic risk is **medium** or **high**, then the IS Expert Team recommends that the BLM may reject the project.

3.4 Higher level concern: Do not proceed until first contacting State Office Geothermal Program Lead

If the answer to Question 4e is "no," then the project site is relatively close to a sensitive site/facility, and the project is considered to have **high level of concern**. A sensitive site/facility has low tolerance to nearby seismic events—even of relatively low ground motion from events that are very likely to occur by any hydraulic stimulation job. The IS Expert Team recommends that that the BLM Field Office immediately contacts the State Office Geothermal Program Lead who will conduct an in-depth review (likely in consultation with industry or academic seismic experts).

The seismologist should determine the maximum probable event from the EGS activity over its lifetime, then determine the maximum event that nearby facilities or people are likely to tolerate. If the design EGS seismicity is larger, the project is considered to have **high seismic risk**.

The operator could be given the chance to redesign the project or its mitigation approach. For example, the operator could reduce the design earthquake by mitigating through engineering methods or other method (such as insurance). If this is uneconomical, the IS Expert Team recommends that BLM reject the project.

By rejecting the project at this initial stage (if mitigation is impractical/uneconomical), BLM prevents the operator from implementing the DOE Induced Seismicity protocol (costly for small operators) on a project that would have had a relatively high chance of failure.

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