Technology Strategy Roadmap for Geothermal Induced Seismicity

Jay Nathwani[1], Ernie Majer[2], and John Ziagos[3]

[1]U.S. DOE GTP
[2]LBL
[3]LLNL

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ABSTRACT

The Induced Seismicity Technology Strategy Roadmap presents a strategic action plan for the Enhanced (or Engineered) Geothermal Systems (EGS) Subprogram to address issues surrounding induced seismicity. This draft document, soon to be released to stakeholders and the public for comment, falls under the Department of Energy's (DOE) Geothermal Technology Program (GTP) that sponsored an EGS Induced Seismicity Workshop on October 28, 2010 in Sacramento, California to script the necessary material for the first draft Induced Seismicity Technology Strategy Roadmap. Heretofore, several other workshops were held on induced seismicity but this particular workshop brought together a diverse group of experts from industry, academia, and government to initiate the roadmap. Draft induced seismicity vision and mission statements developed at the workshop for the roadmap and a strategic framework were built along with focus areas, program elements, and needed science and technology R&D themes.

In most cases induced seismicity (IS) is an inevitable consequence of geothermal energy production and EGS technology implementation; it is not a matter of whether or not IS will occur, it is a matter of at what magnitude will it express itself. EGS applies advanced tools and techniques to produce energy from reservoir systems with hot rock and tectonic stress but low permeability (i.e. "sealed fractures"). Normally, these reservoirs would produce little or no useful geothermal fluids. EGS technology boosts geothermal energy production by vastly increasing the number of potential geothermal sites as well as extending the life of existing reservoirs.

A strategic framework is presented to guide GTP's efforts to understand, manage, and make effective use of IS in the development of EGS resources. This IS strategic framework includes a Vision and Mission; three critical "leverage points" called Focus Areas, through which program actions tie to program goals; and then a detailed mapping of Program Elements and high-priority projects (or Project Themes) upon which concrete action can be taken.

The IS initiative's strategic framework begins with a vision of the ideal future where IS is a well-managed and well-accepted practice and useful tool. The IS initiative, in collaboration with geothermal developers and the R&D community, established the following Vision: A future where induced seismicity associated with EGS, and its associated risks, are thoroughly understood, modeled and managed by geothermal developers and accepted by communities, regulators, policy makers and other stakeholders, who judge the benefits of the geothermal production technique to outweigh the risks.

Next, the EGS subprogram along with expert elicitation collected at several workshops developed a mission statement that describes its plan to achieve the vision. The IS initiative's mission with respect to geothermal induced seismicity is: To enable developers, the R&D community and other industry stakeholders to achieve the above vision by initiating programs that support efforts towards improved prediction and management of induced seismicity and generating public trust in IS through communication, outreach and risk mitigation.

Three Focus Areas add further detail, both to the components of IS and actions to best address them. These three distinct but related focus areas represent three ways in which the Vision and Mission are strategically addressed by the program's activities. IS's Focus Areas are Enhanced Scientific Knowledge and Technology Solutions, Improved Developer Practices and Expertise, and Widespread Public Acceptance and Trust.

Given that interest in expanding geothermal energy production to previously infeasible geologic settings is relatively recent, the technical challenges of developing enhanced geothermal systems stem mainly from a lack of knowledge and experience. In addition to the lack of knowledge and experience with EGS, geothermal developers need better tools to measure, model and validate IS phenomenology.

A third set of challenges centers around the ability to accurately predict, mitigate, and control risks associated with IS. A fourth set

of technical challenges concerns the management of the injection, stimulation, and production of an enhanced geothermal system to optimize power.

Market challenges, unlike technical challenges, are not directly related to the feasibly of utilizing a geothermal resource. Public perception, public relations, education, and acceptance challenges often surround communication with the community who will be affected by the utilization of a resource, either by receiving the energy generated or by living and working in close proximity to the geothermal site. Market challenges for project investors and operators stem from the lack of knowledge and experience in geothermal energy compared to more common energy sources.

Beyond the three Focus Areas that concentrate certain stakeholders on to the mission and vision another different set of stakeholders, the research community, needs emphasis. To this end, the Program Elements translate the previously described goals into more specific categories of research, development, application, and communication. The Program Elements represent types of program activity in which concrete science and technology actions service the vision: Source Physics, Monitoring and Characterization, Risk Analysis and Management, and Public Engagement.

The above vision, mission, focus areas, project elements and project themes, and their relationships to each other, together represent the strategic framework for action of this roadmap. It is the intention of this framework to support the EGS subprogram mission and to guide future subprogram and industry efforts to expand and promote IS as a safe and well-managed practice used in EGS. This framework ultimately represents a "line of sight," or a clear connection between actions and goals, for the stakeholders implementing the projects towards the ultimate future vision for IS as it is used in EGS.

The path forward to implement the roadmap starts with identifying key program element stakeholders, and then following the strategic action plan's development through activity implementation, increased deployment of IS technologies, and achievement of the vision. Information from performance evaluation and changes in the industry landscape are likely to feed back into specific pathway plans and the overall strategic roadmap.

Introduction

Geothermal energy has significant potential to supply stable, renewable, and domestic energy. Latest estimates of geothermal energy's potential for electrical energy production are enormous–the U.S. Department of Energy's Geothermal Technologies Program estimates that identified hydrothermal energy holds 6.4 GWe of potential resources (figure 1). In addition, undiscovered hydrothermal holds 30 GWe, near-hydrothermal field enhanced geothermal systems (EGS) holds 7 GWe, and deep EGS holds 15,900 GWe[1].

This vast potential of EGS, however, is not without risk. Enhancement of geothermal reservoirs will introduce pressure and temperature changes into the subsurface with commensurate strain energy release and earthquakes. This outcome, called induced seismicity, is defined as earthquakes that are the result of human activity causing a rate of energy release, or seismicity, beyond the normal level of natural seismic activity in a given area[3]. Induced

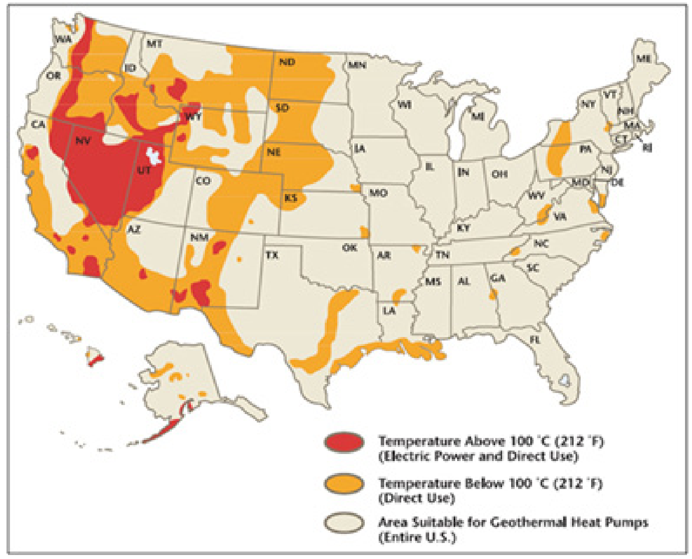

Figure 1. National Geothermal Data System's map of potential geothermal locations across the U.S.[2]

seismicity is not new and has been observed with fluid impoundment (dams), energy production, mining, and waste disposal, among many other human activities. It could, however, become an increasingly important issue for geothermal, CO_2 sequestration, stimulation of oil and gas reservoirs, etc., as energy production in a climate constrained earth advances. Although induced seismicity has been observed for many years and associated with a variety of causes, recent attention has been focused on oil and gas and geothermal sites.

In the geothermal industry, production and injection in geothermal fields can and does produce induced microseismicity, however, more recently the possibility for IS in reservoir development practices (such as hydrofracturing and hydroshearing) to create or improve the permeability of reservoirs, in particular with EGS, has increasingly become a public concern. A greater understanding of induced seismicity is necessary because (1) it is an essential tool for developing, operating and optimizing an EGS reservoir, and (2) it's perceived hazard to the broader community in close proximity to EGS sites must be understood, and the risks calculated, communicated and effectively managed.

Background

Technical Challenges

Although IS can and does occur in conventional hydrothermal projects, it is an inevitable consequence of Enhanced Geothermal Systems (EGS) technology implementation[4]. This is because the main mechanism of permeability enhancement in such systems is a combination of hydraulic, thermal, and chemical processes, which when successful would develop an expansive network of fractures that form a large underground heat exchanger. During reservoir stimulation and operation, IS data are evaluated both spatially and temporally to understand how rock permeability is improving and evolving. As such, IS events are an important indicator of reservoir growth as well as an important reservoir evaluation and management tool.

Several mechanisms have been hypothesized to explain the occurrence of IS when fluids are injected into the reservoir[5]. All of these mechanisms change either the state of stress on and/or the frictional resistance of individual fractures, leading to slip, which can result in IS. Rock stresses and frictional resistance tend to keep a fracture closed, therefore, reservoir enhancement techniques focus on overcoming those forces. Fracture slip is caused by four main mechanisms:

- Pore-Pressure Increase: The effective stress on a fracture is reduced as pore pressure increases, facilitating slip.
- Temperature Changes: A process known as "thermoelastic strain" causes contraction of fracture surfaces when cool fluid is injected into hot rock.
- Volume Change Due to Fluid Withdrawal/Injection: As water is withdrawn or injected into a geothermal reservoir, contraction or expansion in or around the affected rock volume may lead to failure along certain fractures
- Chemical Alteration of Fracture Surfaces: Chemical stimulation agents may dissolve minerals deposited within fractures, weakening them by reducing the frictional resistance to slip.

An improved understanding of permeability-related issues gained through IS research will assist researchers and engineers in the creation and development of more efficient and cost-effective EGS reservoirs. In addition, research and empirically derived data will assist public and private stakeholders in supporting the development of EGS resources, building public understanding, and acceptance of EGS as a major energy source. The ultimate technical goal is to be able to manage IS in ways that meet stakeholder approval while optimizing power production.

Vision and Mission

The IS initiative's strategic framework begins with a vision of the ideal future where induced seismicity is a well-managed and well-accepted practice and useful tool. The IS initiative, in collaboration with geothermal developers and the R&D community established the following vision:

> *A future where induced seismicity resulting from EGS, and its associated risks, are thoroughly understood, modeled and managed by geothermal developers and accepted by communities, regulators, policy makers and other stakeholders, who judge that the benefits of the geothermal production technique to outweigh the risks.*

Following the vision, the EGS subprogram along with expert elicitation collected at several workshops developed a mission statement that describes its plan to achieve the vision. The IS initiative's mission with respect to geothermal induced seismicity is:

> *To enable developers, the R&D community and other industry stakeholders to achieve the above vision by initiating programs that support efforts towards improved prediction and management of induced seismicity and generating public trust in IS through communication, outreach and risk mitigation.*

IS Focus Areas

To plan and direct program actions, three Focus Areas were created to add further detail, both to the components of IS and actions to best address them. These focus areas represent ways in which the Vision and Mission may be strategically addressed by the program's activities. IS's Focus Areas are:

- Enhanced Scientific Knowledge and Technology Solutions that will help stakeholders better understand the impacts of induced seismicity so as to minimize risks and unintended impacts of this EGS practice.
- Improved Developer Practices and Expertise involves detailed characterization of risk and the mitigation of regulatory and siting concerns related to EGS projects that cause induced seismicity.
- Widespread Public Acceptance and Trust is partially achieved by success in the other two focus areas, but also involves successful public outreach programs that educate the public on the real risks of induced seismicity and communicate the efforts industry and government are making to address them.

IS Program Elements and Project Themes

Whereas the three Focus Areas concentrate on certain stakeholders' issues as consequences of engaging the mission to reach the vision, but the requirements of the Program Elements translate the previously—described vision and mission into more specific categories of research, development, application, and communication. Program Elements describe the concrete science and technology activities that will service the vision:

- Source Physics
- Monitoring and Characterization
- Risk Analysis and Management
- Stakeholder Engagement

Each of these Program Elements relates to one or more of the Focus Areas. Additionally, within each program element lies a further level of detail: Project Themes, defined as the high-priority science and technology advancements that are needed to achieve success in the initiative's three Focus Areas. They are intended to initiate specific activities that will be carried out and/or supported by the IS subprogram.

Program Element: Source Physics

Background

Improved understanding of the fundamental physics of induced seismicity mechanisms is critical to the development of EGS. Basic research on the subsurface phenomena at work during the application of EGS technologies has the potential to result in better design optimization, overall system management, and reduced IS. A better understanding of induced seismicity will lead to further developments in geomechanical modeling, while also strengthening the basis for hazard analysis.

Key Barriers

Effective source physics based IS mechanism models will require as yet undeveloped coupled-physics, chemistry and mechanics algorithms and rock properties computer codes, as well as an understanding of the intial subsurface state of stress in the region surrounding the EGS target volume, which is, usually, unknown. In addition, the location and character of faults and fractures within the volume of interest is crucial to any estimate of IS potential and largely unknown. Source Physics themes are defined as high-priority science and technology knowledge advancements necessary to make progress in IS. Each theme suggests one or more research, development, partnership, or communication projects that will advance the Source Physics program area.

Key Themes

1. Geomechanical modeling, including hydraulic, thermal, and chemical issues
2. Specific methods to determine subsurface stress state
3. Lab experimentation of fracture nucleation and dynamic rupture
4. Inference of source processes from different kinds of field observations
5. Empirical evaluations to address the scaling problem
6. Models that serve to scale lab experiments to earthquakes or acoustic emissions

Program Element: Monitoring and Characterization

Background

Data gathered through IS monitoring both before, during and after EGS subsurface modifications and initial and ongoing characterization are needed to validate source physics models, to characterize and estimate stress conditions, and as input to hazard and risk assessments. Currently, there is a paucity of fundamental data on rock properties from geothermal reservoirs. To overcome this problem, an accurate physical understanding of rocks from geothermal reservoirs must be established as a prerequisite to geophysical interpretation. Monitoring and characterization enables a better reservoir model and associated operational management by enhancing the effectiveness of the injection process and the stress evolution of a reservoir. It also provides valuable input for the initial probabilistic IS hazard assessment.

Key Barriers

Specific challenges include undersampling of rock properties, inadequate and incomplete stress field data, a practical characterization of the heterogeneity and complexity of the geological environment, and environmental and permitting restrictions hindering and limiting spatial, azmuthal and temporal coverage. The following Monitoring and Characterization Project themes are defined as high-priority science and technology knowledge advancements necessary to make progress in IS. Each theme suggests one or more research, development, partnership, or communication projects that will address the Monitoring and Characterization program area.

Key Themes

1. Better collection, modeling and understanding of rock properties
2. Improved methods to determine local in situ stresses and fault locations before stimulation
3. Innovative signal processing and analysis techniques (especially, but not exclusively, for large data sets)
4. Advanced data acquisition techniques, particularly those that enable accurate imaging of the seismic source and overcome environmental/permitting barriers
5. Innovative data storage and management (integration and fusion of data sets)
6. Data sharing, openness, and transparency

At the workshop and subsequent to the workshop, R&D challenges and strategies to address those challenges, as well as how the program element will be advanced including potential value and consequences if not addressed were developed for each theme.

Program Element: Risk Analysis And Management

Background

Induced Seismicity is an integral part of EGS development but is also a source of perceived hazard since it is capable of causing detectable ground motions at the surface. Risk analysis provides the tools for assessing, managing and mitigating risks to the local environment and population, and the risk assessment forms the basis for decisions. Risk analysis also provides the framework for focusing source physics and monitoring and characterization research. Experience has shown that the risk of IS perceived by the community may severely restrict project development[6], even when the actual level of risk is often much less than that perceived. Educating the community on the risk and taking into consideration their concerns as part of the project planning is an important component of risk management. Therefore, early and frequent engagement of the community is imperative to building a positive public perception that the risks are known and are within acceptable limits.

Key Barriers

The development of an effective EGS IS risk analysis is hampered by the lack of availability and accuracy of the necessary data, and the proper probabilistic models for comparison and analysis. Inadequate empirical and physical models are also an issue, as well as high uncertainties in estimated probabilities. Specifically, there is no PSHA method that takes account of both natural (tectonic) and induced earthquakes. The lack of useful models and accurate data can also make it difficult to recognize imminent critical situations and to know how to react to them. Risk Analysis and Management Themes are defined as high-priority technology or knowledge advancements with each theme suggesting one or more research, development, partnership, or communication projects that will advance the Risk Analysis and Management program area.

Key Themes

1. Research into time-dependent models and more sophisticated statistical analyses
2. Geographic variation of risk
3. Adding physics-based models to the current set of empirical models
4. Adapting current risk assessment methods to induced seismicity
5. Surrogates for EQ data (strain rate, other)

Program Element: Stakeholder Engagement

Background

The overarching goal of the outreach and communication program is to engage the community in a positive and open manner, before activities begin on site, and continuing as operations proceed. The first step is to understand the needs and concerns of the community and then determine creative ways to inform the community, engage them in a dialogue, and demonstrate the benefits of the project, particularly at the local scale. In addition to being an information campaign and a public relations exercise, the outreach and communication program should be designed to engender long-term support for the project. To the extent that a project is distant from local population, the requirements of the outreach program would lessen.

Key Barriers

Effective EGS IS stakeholder engagement is hindered by public fear of earthquakes, large variations in priorities and challenges between sites and legal liability for operators. These key barriers can impede project progress:

- Must overcome major public acceptance hurdles:
  - The public is not well-informed of the hazards
  - There is a public fear of large earth quakes
  - Need to build public trust and acknowledge the risk and uncertainty associated with induced seismicity
  - Striking a balance between oversimplification and too much detail
  - Need to gain public acceptance in the face of uncertainty
  - Annoyance to public
  - Need to define the benefit to the public (which will be different for each community)
  - Need regulation to ensure public acceptance (balance this with the cost of regulation to industry)
- Legal liability is a fact for operators:
  - There is an existing legal definition of "nuisance" that can apply here
- Challenges and priorities can differ greatly between sites:
  - There is no uniform agreement on "acceptable" across sites
  - Different localities will accept different levels of risk
  - There is a separation of the risks and benefits within the industry

Key Themes

The outreach program should help the project achieve a level of transparency based on the following themes:

1. Before the project starts the developer should generate an outreach plan
2. The amount and type of outreach should be related to the specific project situation
3. The dialogue should be open, informative and multi-directional
4. Multiple meetings should be held as the project progresses and more information is obtained
5. Each stakeholder group should be approached in an appropriate way and technical level
6. A mechanism to respond to stakeholder concerns and questions should be put in place and maintained throughout the project

Going Forward

This draft Induced Seismicity Roadmap has been written with an acute understanding of the current draft *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems*, both intended to be living documents for the public, regulators, and geothermal operators. In addition, this document is intended to supplement the existing International Energy Agency Protocol[7] and as practically as possible, kept up-to-date with state-of-the-art knowledge and practices, both technical and non-technical. As methods, experience, knowledge, and regulations change, so should the IS Roadmap and Protocol. It also recognizes that "one size" does not fit every geothermal project, and not everything presented herein should be required for every EGS project. Local conditions at each site will call for different types of action. Variations in procedures will result from such factors as the population density around the project, past seismicity in the area, the size of the project, the depth and amount of injection and its relation to any faults, etc.

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