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Geothermal Energy from Fractured Reservoirs
- Dealing with Induced Seismicity -

by
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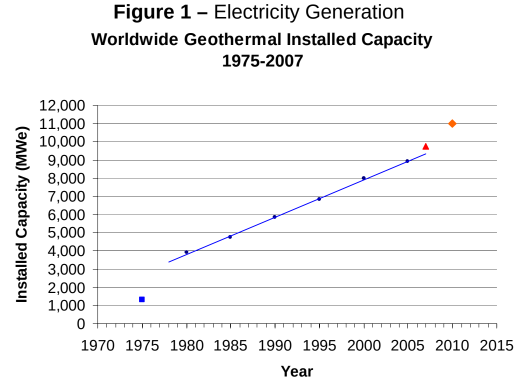
This article provides updates on the outlook for exploiting geothermal energy around the world. Drawing on collaborative research undertaken by the IEA Geothermal Implementing Agreement[4] (IEA-GIA), it reports on recent developments with one of today's major research topics, induced seismicity and enhanced (or engineered) geothermal systems (EGS) involving artificially fractured geothermal reservoirs.

Mike Mongillo (left) and
Chris Bromley (right), IEA GIA

Geothermal has an extremely bright future. Its potential for power generation and direct heat applications (including geothermal heat pumps) is vast, both for conventional geothermal systems and for today's emerging enhanced (or engineered) geothermal systems (EGS), which extend geothermal applications well beyond geological plate boundary regions and to most places in the world. Not surprisingly, investment in geothermal energy technology development world wide has increased significantly. Hundreds of millions of dollars have been spent in countries like Australia, New Zealand and the United States over recent years; and the trend looks set to continue into the coming decades, as energy companies and policy makers recognise the huge global potential of geothermal energy as a renewable resource.

A number of characteristics make geothermal energy an attractive option. It is a renewable resource (recharged by crustal and sub-crustal sources). It is widely available around the globe. It is suitable for diversified and distributed power generation. It is an indigenous energy resource and, when appropriately managed, it is environmentally friendly. It can be used in a sustainable manner and provides base-load electricity and heat supply whatever the season or weather conditions. Clearly, geothermal energy can make a significant contribution to meeting fast growing global demand for renewable energy.

Figure 1 – Electricity Generation



Red triangle = 2007. Orange diamond = forecast for 2010
Graph from Mongillo (2007). Data from Bertani (2007)

As Figure 1 shows, development of geothermal energy for electricity generation, which is the chief focus of this article, has entered a new, rapid growth phase world wide. One of geothermal energy's advantages over other renewable resources is its very high availability factor (typically >90%), hence its suitability for base-load electricity generation. Taking contribution efficiency – GWh produced for each MW_e

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[4] This research culminated in three international workshops, a published paper (Majer *et al*., 2007), and a suggested protocol (IEA-GIA, 2007) – see also the website recording detailed results of the research (http://esd.lbl.gov/EGS/).

of installed capacity – we see that, on average, geothermal out-performs hydro generation by a factor of 2, wind by a factor of about 3.5, and solar PV by a factor of some 20 (IEA, 2007).

A major pathway to more widespread use of geothermal lies in development of EGS. As we shall see, EGS induced micro-seismicity is a common consequence of reservoir stimulation to create, or extend, fractures in order to enhance heat extraction. But EGS-seismicity need not pose a threat for future development of global geothermal resources if projects are conceived and managed in a sensible and pragmatic manner.

Geothermal basics

To understand this argument, we have to look first at how geothermal energy is exploited. The geothermal resource consists of thermal energy, or heat, stored beneath the earth's surface (99% of the earth's volume is at temperatures >1000^{o}C) and discharging continually from the earth's surface, as in hot springs. Within the earth's crust, the heat is transferred slowly towards the surface by conduction and transmitted convectively by fluid (water or steam) through fractures and pores. The principal sources of geothermal energy are the heat flow from the earth's core and mantle (~40%), and heat generated by the decay of radioactive isotopes in the earth's continental crust (~60%).

The earth's total heat content is estimated to be about 10^{13} EJ. At today's average global terrestrial heat flow rate of 44 million MW_t (1,400 EJ/yr) – that is, almost three times the world's primary energy consumption rate (479 EJ/yr in 2005) – it would take over a billion years to exhaust that heat content. The key to tapping this huge quantity of renewable stored heat efficiently and economically is to locate or create fractures in high-temperature rock so that water and steam circulating through them can transfer heat rapidly to the surface. Where fractures are not naturally abundant, it is technically feasible to create new fractures, or re-activate existing ones, through high-pressure water injection, a practice developed for EGS (previously known as hot dry rock [HDR] application).

The earth's surface heat flow is not uniform. It is concentrated in regions of tectonic plate boundaries and volcanic hot spots, which account for about 15% of global land surface and are home to some 15% of the world's population. Earthquakes of natural origin are relatively common in these areas of elevated seismic and volcanic activity. The past 100 years has seen steady development of the high-temperature hydrothermal resources in these regions for electricity production.

Today's worldwide installed geothermal capacity of ~10 GW_e (mid-2007, Figure 1) is mainly hydrothermal-based and distributed among 24 countries, though largely in Central America, Iceland, Indonesia, Italy, Japan, Kenya, Mexico, New Zealand, the Philippines and the United States. Almost 50% of installed capacity (~4.5 GW_e) has been operating for more than 25 years. This provides a sound basis for long-term assessments of sustainable resource utilisation strategies and operational costs. But today's installed capacity exploits only 4% of an estimated 240 GW_e worldwide potential of identified, technically feasible hydrothermal resources, or ~0.5% of global geothermal resources if we include estimates of resources as yet undiscovered. So potential exists in the tectonically or volcanically active regions for much more conventional geothermal development.

IEA Geothermal Implementing Agreement (IEA GIA)

The International Energy Agency (IEA) Implementing Agreement for a Cooperative Programme on Geothermal Energy Research and Technology provides an important framework for wide-ranging international co-operation in geothermal R&D. Its activities presently cover four different task areas: Environmental Impacts of Geothermal Development, Enhanced Geothermal Systems, Advanced Geothermal Drilling Techniques and Direct Use of Geothermal Energy. The programme's participants are listed on the IEA GIA Web site.

Induced seismicity and public reactions

The presence of natural tectonic forces can cause a build-up of stress in geothermal reservoir rocks over geological time scales. This stress is usually relieved naturally through rock fracturing, resulting in earthquakes. But stress changes can also be triggered in advance by relatively small perturbations in pressure, or by redistribution of thermal and mechanical stresses through contraction or expansion resulting from the production and injection of fluid. These man-generated seismic events, arising from sudden movement along fracture planes of naturally-stressed reservoir rocks, are termed "induced seismicity", and have been observed in several geothermal reservoirs around the world.

Induced seismic events are generally small in magnitude compared with natural earthquakes. But, because of their shallow origin, they can sometimes be felt at the surface. In some instances (notably in Basel, Switzerland, in late 2006), induced seismic events have generated public concern resulting from the notion that larger, potentially damaging events could result from future geothermal activities.

On the whole, however, public concern is usually minimal regarding the possibility of increased ground-shaking caused by induced seismicity in conventional geothermal developments. This is because the induced seismicity is seldom felt and because there have been no instances of significant damage from induced events. Indeed, local communities in tectonically active areas are usually quite familiar with feeling small, natural earthquakes. It is therefore rare to see constraints on conventional geothermal developments imposed by publicly perceived risks associated with large induced seismic events. Of the hundreds of developed conventional geothermal reservoirs world wide, few have produced induced seismic events of a magnitude felt by people during normal operations (usually fluid extraction and low pressure injection). Examples like events at The Geysers in California (up to 4.6 on the Richter[5] magnitude scale) and Palinpinon in the Philippines have caused neither significant damage nor curtailment of reservoir operations.

Recently, however, much attention has been focused on the substantial heat resources available at depths of 3-10 km almost anywhere on earth, and their potential for electricity production and direct use applications. EGS techniques can provide access to this heat by enhancing fracture permeability (*i.e.* opening/widening existing fractures and creating new fractures) and/or by providing water to convey the heat. The process of creating permeability involves high-pressure pumping of water to fracture the rock, *i.e*. hydraulic fracturing, or hydro-fracing, causing (inducing) micro-seismic events. Because naturally occurring earthquakes are less common in these settings far from plate boundaries, public perception of the risk of large induced seismic events can be a much bigger issue.

EGS resource potential

EGS investigations have been conducted in the past at several sites around the world, including: Fenton Hill (Los Alamos, United States); Rosemanowes (Cornwall, United Kingdom); and Hijiori and Ogachi (Japan). Projects (>1 MWe) are currently at an advanced stage of development at Soultz-sous-Forêts (France), Landau and Unterhaching (Germany), Basel (Switzerland) and Cooper Basin (Australia).

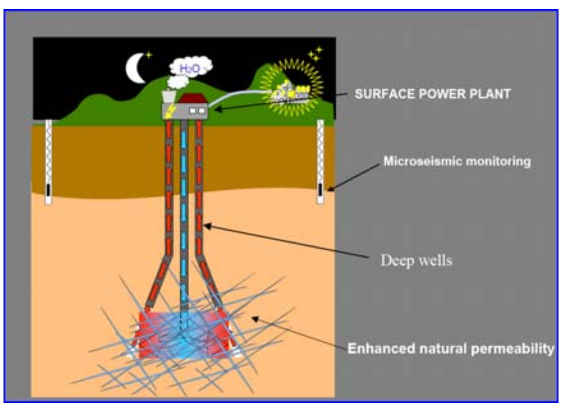

Figure 2 - Basic EGS Concepts
(Courtesy of R. Baria, E. Majer and D. Teza)

In the United States, EGS investigations were recently conducted at Coso, Glass Mountain and Desert Peak. In Australia, 33 companies hold licenses for different EGS developments. The first EGS power plant was installed at Landau (>1 MW_e) in late 2007 and others are expected to follow in 2008.

Recent assessments of deep heat resources for EGS development have been performed for the United States (MIT, 2006), Germany, India and China. They indicate a huge potential, ≥100,000 MW_e in the United States, with similar potentials estimated for parts of China and India.

Most EGS projects in continental settings require drilling to depths of 4-5 km to reach adequate temperatures for economical electricity generation. Some sectors of conventional hydrothermal reservoirs have poor local permeability, despite high temperatures, and these could benefit from EGS techniques at shallower depths. Reservoir stimulation techniques are used to enhance permeability, and thus increase circulating flow rates and energy extraction rates. Heat recharge is supplied through conduction, so a large network of interconnecting fractures is required for an economically sustainable operation. If the full global potential of

[5] The Richter scale for measuring the source magnitude (M) of an earthquake is a logarithmic scale, so an M=5 event is ten times stronger than a M=4 event. Also, statistically, there are about ten times more M=4 events than M= 5 events. Actual intensity of shaking is site-specific and depends on other factors such as distance from the earthquake source and type of sub-soil. All magnitudes mentioned in this article are Richter magnitudes.

EGS is to be realised, one of the challenges is to understand and control larger-magnitude induced seismicity associated with fracture stimulation or hydro-fracing.

Induced seismicity and fracture stimulation

The enhancement of reservoir permeability by stimulating fractures through hydro-fracing involves pumping water down wells at high pressure to fracture the hot rock hydraulically. Fracture stimulation and creation induces micro-seismic events, which can sometimes be felt at the surface. Typically, these are not sufficiently large, nor of the right vibration frequency, to cause structural damage.

Conventional Geothermal Project-Related Induced Seismicity Experiences

The Geysers (United States) – Induced seismicity, well documented at this steam-dominated system since 1975, appears to correlate with increasing injection rates of cool water, initially consisting of steam condensates. In 1997 and 2003 significant injection increases of supplementary waste water collected and piped from nearby towns have arguably qualified this as an EGS project. As Figure 3 shows, of the thousand or so seismic events detected per year (M>1.5), less than 1/yr on average has been of M>4 (maximum 4.6). A diverse set of triggering mechanisms is thought to be responsible, including pore pressure changes, cooling contraction, volumetric decline from fluid loss and associated stress changes in this tectonically stressed environment. One small community (Anderson Springs) is close enough to the borefield for residents to be theoretically able to detect vibrations from induced events on average 1.5 times per day (Majer *et al*., 2007).

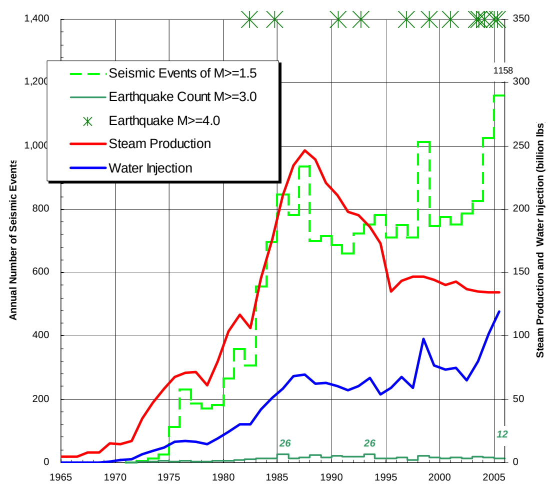

Figure 3
History of The Geysers geothermal field steam production, water injection and induced seismicity rates for various magnitude ranges. (From Majer *et al*., 2007)

Berlin (El Salvador) - In 2003, a trial EGS operation was carried out at the developed Berlin Geothermal Field, located in a tectonically active area. It used pressurized injection in a 'tight' injection well at 1-2 km depth to improve fracture permeability in a hot part of the resource (Bommer *et al*., 2006). A calibrated real-time 'traffic-light' control system was put in place to reduce or stop injection operations if the levels of vibration (peak ground velocity) from injection-induced seismicity exceeded acceptable levels (normal background = 'green', significant felt events = 'orange', and damaging events = 'red'). The stability of local housing and shallow ground conditions were taken into account. What eventuated were low levels of seismicity induced around the injection well by three episodes of pumping, totalling 54 days. The 'traffic light' thresholds were not exceeded, and the project was not adversely affected. The largest event recorded was of magnitude 4.4, occurring two weeks after injection shut-in, and located about 3 km south of the injection well (in the production sector). It is unlikely to have been directly related to the EGS pressurized injection activities, but some peripheral, time-delayed, stress-relief triggering mechanism for this larger event is still plausible.

Palinpinon (Philippines) - During the first few years of production and injection for the Palinpinon 1 project (1983-86), there was a significant increase in the level of induced micro-seismicity (0<M<2.5) (Bromley *et al.*, 1987). Some high-frequency events were felt within the project due to their shallow depth (1-4 km) and proximity. There was a correlation in space and time between swarms of micro-seismic events (up to 100/day) and changes in injection and production rates. Event hypocentres were distributed on fractures throughout the pressure-affected parts of the reservoir, and were not concentrated on major permeable fault planes. After 1986, the level of locally induced seismicity declined to natural background levels. 0n 13 July 2007, a magnitude-5 earthquake occurred at shallow depth within the borefield, but was apparently triggered by a 70 km deep earthquake beneath the same area a minute earlier. These events were judged to be of natural tectonic origin, rather than induced by geothermal activities. The magnitude-5 event briefly tripped some of the generating turbines because of vibration sensor control, but caused no damage to the geothermal field infrastructure or nearby domestic dwellings.

Other forms of permeability enhancement are also possible, such as chemical stimulation (which leaches parts of the rock matrix), explosive fracturing and local thermal stress cracking, usually using colder water. These latter options are most useful in stimulating formations close to the wells. Hydraulic pressure decreases radially away from the well bore and dissipates with time, depending on the permeability (both natural and induced). An increasing volume (termed a 'cloud') of induced seismic events therefore typically forms progressively around the injection point. The degree and extent of hydro-fracturing can depend on both pumping pressure and total volume of fluid injected.

Stress redistribution over a larger volume of rock surrounding the well may also result from near-well hydraulic or thermal stress fracturing, and could trigger events at more distant faults or fractures that are naturally pre-stressed to near-failure conditions. Diffusion of pressure and redistribution of stress can take weeks or months. Monitoring of induced seismicity at several geothermal sites has shown that many of the larger felt events (magnitudes 3 to 4) tend to be located at or beyond the edges of the seismic 'cloud' of small events, occurring significantly later than the changes in the injection rate.

It may thus be difficult to determine whether a particular seismic event was caused by a particular stimulation process. Importantly, however, the triggering of such events can be regarded as a desirable premature stress release mechanism allowing movement on larger faults. As with the explosive triggering of avalanches, the catalysing of early rock failure may help prevent much larger natural earthquakes. All these factors make it difficult to recommend a universally applicable procedure for managing fluid injection that both minimises risks and maximises benefits.

EGS Project-Related Induced Seismicity Experiences

Basel (Switzerland) - Deep drilling (to 5 km) and reservoir stimulation (pumping) for a trial EGS project within the city was conducted in 2006. A number of perceptible events (magnitudes up to 3.4) occurred that were clearly caused by the high pressure pumping. As a consequence, the project has been halted, pending findings of a detailed seismic risk study. A thorough seismic risk assessment was not conducted before the project commenced, even though Basel experienced an historic large earthquake (magnitude 6.5) that destroyed most of the city in 1356. Better public education in the potential effects of induced seismicity could have been helpful.

Soultz-sous-Forêts (France) - Development at ~5 km depth, and at temperatures of >200°C, is expected to produce flows of 35-50 litres per second (l/s) from each of the two production wells, with injection into a third well, to operate a pilot 1.5 MW_e organic rankine cycle (ORC) binary power plant. During reservoir stimulation at high pressure and flow rate, induced seismicity was observed; the largest event reached a magnitude of 2.9. Although no structural damage was caused, public complaints led to restrictions on subsequent stimulation options. As a result, the second production well has not yet made good hydraulic connection with the other wells. As in Basel, the risk issue is one of perceived risk. Better public education about the project might have been beneficial (Baria, 2007).

Landau (Germany) - Commissioned in late 2007, this installation generates electricity using an ORC binary plant and provides heat to a district heating scheme. Total project funding of €15.5 million was used to drill two wells to about 3.3 km, stimulate one of them, and construct the plant to produce 1.5 MW_e power and 5.1 MW_t heat using re-circulated ~150°C fluid, at flow rates of ~70-80 l/s . There have been no detected micro-seismic events from the stimulation.

Cooper Basin (Australia) - A "proof of concept" project has drilled two wells to ~4.4 km (temperature of ~250°C) and successfully fracture-stimulated and flow-tested them (25 l/s at 210°C). A third well was completed on 22 January 2008, and demonstration of economic heat extraction using a pilot plant is expected by the end of 2008. This is to be followed by production of 40 MW_e by 2012 and 250 MW_e by 2015. Large numbers of micro-seismic events occurred during pumped stimulation in December 2003, with magnitudes up to 3.7. But this site is located in a remote area so there is little or no community concern (Majer, *et al.*, 2007).

Rosemanowes (UK) - Although seismic events were felt around the Rosemanowes area during reservoir stimulation, there were no complaints, possibly as a result of early "rock and roll" public education initiatives (Baria, 2007). The maximum observed magnitude was 3.1, although events of maximum 3.5 magnitude had been predicted through a seismic risk assessment on the basis of a maximum affected fault length of 100 m.

Induced seismicity as a community issue

The IEA-GIA identified induced seismicity as an important issue for EGS development in 2004, subsequently bringing together scientists and engineers at three international workshops between February 2005 and February 2006. Important outputs from these gatherings were a *Protocol for Induced Seismicity Associated with Enhanced Geothermal Systems* (IEA-GIA, 2007), along with a published paper *Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer, *et al*., 2007). This paper presents an up-to-date review of the knowledge on seismicity-induced by EGS creation and operation. It identifies issues which, once addressed, will generate better understanding of the event-generating mechanisms.

In addition, the induced-seismicity hazard from hydro-fracing at the Cooper Basin EGS project was recently assessed (Hunt and Morelli, 2006).

It was concluded that EGS-induced seismicity need pose no threat for development of geothermal resources if sites are selected judiciously, so long as community issues are handled effectively, and developers/operators and licensing authorities understand the mechanisms that cause the events. In fact, induced seismicity could be beneficial for the purposes of monitoring the effectiveness of EGS operations and providing information on reservoir processes, as well as relieving accumulated rock stresses with large numbers of relatively small events. Some of the results and conclusions from this work follow.

- When considering sites for EGS development, especially urban locations such as Basel, it is prudent to consult geological and seismological information to gauge suitability in relation to background natural seismicity, the state of stress and the existence of superficial deposits with potential for exaggerated ground shaking.

- With regard to vibration hazard, EGS is similar to other activities such as mining, hydrocarbon production, waste disposal or dam filling operations, where a possibility always exists of higher stress release when a load changes. In these cases, the frequencies generated are generally too high to cause significant structural damage. The defining criteria used for assessing the magnitude of induced seismicity should be ground acceleration and frequency content. For structural damage to occur, frequencies of less than about 10 Hz are normally required. Generally, frequencies associated with induced seismicity are much higher, between 100Hz and 300Hz, consequently less likely to cause structural damage, though occasionally larger events generate around 40Hz.

- Some recent investigations indicate that the smaller the strain energy placed in the formation, the smaller the possibility of generating larger seismic events. Pumping at lower pressures over longer periods, or more slowly building up pumping pressures, then slowly reducing pressures as the stimulation period ends, may be advantageous. However, more research is needed on this important topic.

- A "Traffic-Light" approach has also been suggested, whereby communities are assured that high-pressure pumping activities will be amended or suspended if certain levels of large-magnitude induced seismicity are exceeded. The level of acceptability depends on local ground conditions, proximity of buildings, and susceptibility of infrastructure to vibration damage. However, this approach is reactive. As shown at Basel, even though injection was halted after the first felt event, this did not prevent subsequent felt events. The ultimate need, therefore, is a procedure to prevent, or at least reduce, disturbing events (magnitude$\geq$ 3) related to EGS operations.

- It is important to note that, to date, there have been no known cases where any large induced seismic events associated with EGS projects have caused major damage or injury. However, many smaller damage claims associated with the Basel event have been paid out by the project developer's insurance company. Public perception is important and this should be dealt with correctly at the start of a project. Expectations and fears must be taken seriously. The public should be educated about the advantages and potential adverse effects of fracturing a reservoir and kept informed during the project's implementation.

Ongoing research

Meanwhile, it is important to pursue the R&D effort, notably in the following areas.

1. **How to discriminate between EGS-related and natural seismic events –** identifying and characterising attributes typical of induced events (duration, frequency content, dominant frequency).

2. **Investigating possible seismic effects during long-term EGS operation (production phase).** There is little experience regarding long-term thermo-elastic effects (cooling cracks). Will the level of seismicity due to hot fluid production be lower than that experienced during stimulation?

3. **Defining how far relevant stress field pertubations can extend from EGS operations.** What are the implications of this in terms of safe proximity of stimulated EGS reservoirs to major active faults?

4. **Further studies on post shut-in seismicity.** Why do micro-seismic events continue to occur after suspension of injection?

5. **Designing downhole EGS operations to minimise ground shaking.** The management scheme may involve adjusting volume, rate or temperature of fluid injection. Research should investigate the nature and degree of dependency of these factors on the local conditions at depth.

Exploring these and other other issues will remain high on the agenda of the IEA Geothermal Implementing Agreement in its drive to further expand the role of geothermal in the world's sustainable energy systems.

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