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Lessons learned from the pioneering hot dry rock project at Fenton Hill, USA

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ABSTRACT

Interest in geothermal energy production has grown rapidly in recent years due to the increasing demand for clean, renewable, domestic energy. Recent publications have suggested that geothermal energy from Enhanced Geothermal Systems could satisfy a large portion of the energy needs in the U.S. if the technology were implemented on a large scale. Pertinent to this goal are many of the lessons learned from the pioneering Hot Dry Rock project aimed at producing usable energy form the heat of the earth, conducted from 1970 to 1995 at Fenton Hill, New Mexico, USA. During this project, the Los Alamos National Laboratory created and tested two reservoirs at depths in the range of 2.8–3.5 km in crystalline rock formations underlying the Fenton Hill site. Thermal energies in the range of 3–10 MWt were produced demonstrating the technical feasibility of the concept. Many important lessons were learned regarding the creation, engineering and operation of such subsurface systems—these lessons will prove valuable as the geothermal community moves towards the goal of realizing the immense potential of this ubiquitous renewable energy resource. The purpose of this paper is to provide a brief, easy to read overview of this pioneering project.

1. Introduction

The abundant heat of the Earth's interior, known as geothermal energy, is manifested ubiquitously throughout the world. At a few tectonically and volcanologically active locations around the globe, such as The Geysers in California, U.S., naturally occurring hydrothermal fluids have been produced to operate commercially viable electric power plants. However, the co-occurrence of geothermal heat and ground water with sufficient formation permeability is relatively rare; much more common and abundant is the occurrence of deep geothermal formations that are hot but lack the ability to produce sufficient quantities of hot water at the surface of the Earth (Tester et al., 2006; Williams and DeAngelo, 2008). Enhanced (or Engineered) Geothermal Systems (EGS) aim to exploit such renewable energy resources by enhancing formation permeability using engineering techniques and supplying heat exchange fluids (DOE, 2009). Hot Dry Rock (HDR) reservoirs are EGS reservoirs with sufficient heat content but very low permeability and water content. Historically, the HDR concept (Potter et al., 1974) was first developed during the experimental Fenton Hill project at the Los Alamos National Laboratory (LANL); subsequently leading to the more general concept of EGS reservoirs.

Interest in EGS has grown rapidly in the recent years due to the increasing demand for clean, renewable, domestic energy resources. Geothermal resources are ubiquitous within the U.S. and have the potential of contributing to baseload as well as peak demands for electricity. Recent publications (Williams and DeAngelo, 2008) suggest that geothermal energy could satisfy a large portion of energy demands in the U.S. if EGS technology were implemented on a large scale. While electricity has been generated from hydrothermal systems by producing naturally occurring hot water or steam for many decades, the Enhanced Geothermal Systems (EGS) have the potential of supplying at least ten times more electrical energy than all existing or likely future hydrothermal power generation systems (DOE, 2009). The Geothermal Technologies Office (GTO) of the U.S. Department of Energy (DOE) is actively funding a number of projects with the goal of realizing this renewable energy potential. These and future EGS projects stand to benefit from the lessons learned during the development of the world's first HDR demonstration project conducted at LANL. This project successfully demonstrated many aspects of the feasibility of

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EGS concept in low permeability basement rock. The goal of achieving power generation capacity on a commercial scale still remains a research objective for the world-wide EGS community. The utility of the data gathered by this HDR project for future work has been recognized (Robertson-Tait et al., 2000), and a project is currently under way to archive existing manuscripts from the project (Kelkar, 2015). Further, the Geothermal Code Comparison project funded by GTO has selected the Fenton Hill HDR project as the basis for challenge problems in 2015.

The purpose of this short paper is to bring the major lessons learned from the Fenton Hill HDR project to the attention of the readers who may be unfamiliar with the work, and to provide a concise summary of the work including a selection of relevant references. We believe that the readers familiar with the work will also find value in this brief, easy to read article. A detailed technical description of the project along with an extensive bibliography is provided by Brown et al. (2012), and a chronological description along with numerous references is provided by Kelkar et al., (2015). Another good summary of the technical work accomplished by the project up to 1985 is presented by Armstead and Tester (1987). The progress of the project was documented in annual reports from 1976 through 1995, which are listed in Kelkar et al., (2015). The world's first successful demonstration of an EGS system, the HDR project for extracting underground geothermal energy was conducted at Fenton Hill, New Mexico, USA. The HDR concept was developed in 1970 at Los Alamos National Laboratory (LANL) (Brown et al., 2012). The concept originated as an outgrowth of the Subterrene project in the late 1960s (Smith, 1995). The project at Fenton Hill began in 1972. The project terminated at the end of 1995, and in 1996 the project wells were plugged and the site was decommissioned.

During the project, thermal energy production at a level of approximately 4 MWt was sustained for 115 days of continuous fluid circulation. The project made many important contributions to the state of the art in drilling and completion technology (Carden et al., 1983), downhole tools (e.g. Dennis et al., 1985), microseismic analysis (e.g. House, 1987), geochemical and tracer analysis (Robinson and Tester 1984), and numerical modeling (e.g. Zyvoloski, 1983; Swenson, 1995). One important development from the project was the conceptual model of a region hydraulically stimulated using water. The older models conceptualized this as a penny-shaped vertical fracture model This was replaced by a conceptual model of the HDR reservoir as a network of preexisting joints that are dilated and sheared (e.g. Smith et al., 1983; Pine and Batchelor, 1984) under high pressure stimulation. This conceptual model has had beneficial impacts on the currently used fracking technology for developing low permeability unconventional petroleum resources. Based on the data from the Fenton Hill project, Murphy et al. (1983) proposed a model with a discrete number of planar joints surrounded by existing joints. A conceptual model has emerged (Brown, 1989, 1995) of two sets of intersecting joints, one at an inclination to the least principal stress, inflated at pressures exceeding the joint opening pressure. A model consisting of fractures failed in shear with accompanying tensile cracks that join the fractures to form planar zones has been recently proposed by Jung (2013) to explain the results of EGS projects such as Soultz and Ogachi.

The HDR research and development project was conducted in collaboration with scientists and engineers from a number of agencies inside and outside the United States. The experiment was funded primarily by the U.S. Department of Energy with additional support from the New Energy and Industrial Technology Development Organization (NEDO) representing the Government of Japan, and Kernforschungsanlage-Julich GmbH, representing the Federal Republic of Germany.

The potential for extracting usable energy from the earth's heat has attracted researchers for several centuries (Smith, 1995). Lord Kelvin in a paper read at the Royal Society of Edinburgh drew attention to natural heat as a source of power in 1852 (Thomson, 1852). In 1931 Nikola Tesla in a popular article (Tesla, 1931) proposed a scheme to extract geothermal heat by circulating water to the bottom of a deep shaft. The use of nuclear explosives to fragment rock on a large scale so as to create a heat exchange system was discussed in the 1960s but not attempted. But all these suggestions did not reach the stage of practical implementation, until a group of scientists at LANL proposed the use of hydraulic stimulation for this purpose in 1970. They envisioned a system of two wellbores connected to a region of stimulated high temperature rock, injecting cold fluid into one and producing hot fluid out of the other (Potter et al., 1974). The early work in the HDR project (Cramer et al., 1980) envisioned two inclined wellbores connected to heat exchange surfaces created by stimulating multiple distinct zones would be needed to produce a total power in the neighborhood of 20–50 MWt for a duration of 10 years (Tester, 1980). This concept calls to mind the current practice of completing long horizontal holes with multiple hydraulic stimulations in shale and other tight unconventional hydrocarbon reservoirs.

2. Overview of the Fenton Hill project

2.1. Site selection process

In 1971, a search was initiated to identify a drilling site to test the HDR concept in the nearby Jemez volcanic field, approximately 15–40 km west of LANL (Smith, 1995). The volcanic and tectonic settings of the Jemez volcanic field provided the necessary conditions for the HDR experiment. This volcanic field has high heat flow associated with a shallow magma chamber and contains Middle to Late Pleistocene eruptive centers along the Valles caldera ring fracture, which is consistent with the occurrence of hot springs and steam vents within and outside the Valles-Toledo caldera complex, indicating the presence of abundant geothermal resources (e.g. Goff and Grigsby, 1982; Heiken and Goff, 1983). The discovery of high-temperature hydrothermal reservoirs within the caldera complex by an oil exploration well drilled in 1960 also confirmed the surface manifestations (Smith, 1995). Geothermal resources assessment drilling by Union Oil Company provided valuable information about the subsurface geology and structure and also indicated the existence of high-temperature hydrothermal resources within the Valles caldera complex. Thermal evolution modeling of the Valles Caldera supported the thermal measurements (Kolstad and McGetchin, 1978). The detailed geological map of the Jemez volcanic field published by the USGS provided additional information about the surface geology and distribution of faults (Smith et al., 1970).

A site within the Santa Fe National forest to the west of the volcanic field, a few kilometers from the Valles caldera margin, was selected. Considerations that factored into the decision included (Brown, 2015) permitting requirements, obtaining permission from US Forest Service, liability concerns, proximity to utilities, and site accessibility via paved highway, as well as heat flow measurements, depth to the top of the basement rocks, and the need to be outside the system of ring faults of the caldera while remaining sufficiently close to the magmatic heat source. Favorable geological elements for the HDR experiment were also noted in the stratigraphic succession near the proposed site where Precambrian crystalline rocks (the prime target formations) are thermally insulated by thick, fine-grained Paleozoic sedimentary deposits that are capped by lava and ash-flow tuffs of the Jemez Volcanic Field (Smith et al., 1970).