

## JASON Review of Enhanced Geothermal Systems

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### ABSTRACT

At the request of the U.S. Department of Energy, the JASON group that provides independent technical advice to the U.S. Government studied Enhanced Geothermal Systems (EGS) with a focus on i) assessment of technologies and approaches for subsurface imaging and characterization; and ii) assessment of approaches toward creating sites for EGS, including science and engineering to enhance permeability and increase the energy recovery factor. The group developed simple but effective analyses of tracer experiments and of heat-extraction strategies, and identified several promising directions of research, including: sub-surface imaging using ambient-field and non-linear seismic techniques; combined electromagnetic and tracer monitoring; field experiments at smaller-than-production length scales; and the potential for developing engineered heat exchangers at depth.

### 1. INTRODUCTION

Geothermal resources currently provide peak capacity of 3.4 GWe baseload non-carbon power in the U.S. (average 2.5 GWe based on capacity factors above 70%), which corresponds roughly to 0.5 percent of domestic electrical energy generation at present. Given the contribution geothermal energy is now making to U.S. energy production, and the potential EGS offers for the future, the Department of Energy requested through the Geothermal Technologies Office that JASON study Enhanced Geothermal Systems (EGS), with a focus on: i) assessment of technologies and approaches for subsurface imaging and characterization, so as to be able to validate EGS opportunities; and ii) assessment of approaches toward creating sites for EGS, including science and engineering to enhance permeability and increase the energy recovery factor (i.e., the fraction of heat present in the ground that is extracted as useable energy). For the purposes of the study EGS is considered to incorporate a range of activities, from stimulation and expansion of existing hydrothermal fields to developing methods for mining Earth's heat to depths of 1-5 km (e.g., hot dry rock).

This paper briefly summarizes the findings, recommendations and underlying approaches of the study, with all details – including, analyses, assumptions and references – being provided in the report (JASON, 2013).

### 2. FINDINGS

1. Near-term (perhaps 5-10 year) geothermal potential, including from sites developed through enhanced geothermal systems, can contribute an additional 5-10 GWe for the U.S., with a larger potential once this success is achieved.
2. Major challenges for EGS include: *i*) the cost of drilling, with a near-exponential increase in the cost  $C$  of drilling to depth  $z$ ,  $C \sim \exp(z/d)$  with  $d = 0.5$ -3 km; *ii*) the small heat-recovery factors found in practice (about 1-5% of the heat in the reservoir at depth is typically recovered at the wellhead); and *iii*) uncertain and potentially limited lifetimes of EGS well pairs.
3. The nature of the subsurface flow network, including its variation in space and time, presents a major technical uncertainty for EGS, affecting heat-recovery factors, production rates and well lifetimes.
4. Thermal drawdown reduces both thermal power and Carnot efficiency of EGS over time, with mitigation strategies including tailored production schedules.
5. Water availability can be a significant factor in operating geothermal plants in areas of water scarcity, and could become a limiting constraint for EGS at scale.
6. Induced seismicity *i*) is associated directly with geothermal operations; *ii*) is a partially understood hazard; and *iii*) offers benefits for subsurface characterization.

### 3. PHYSICAL AND MATHEMATICAL MODELS

As there is a vast literature on geothermal processes, and on enhanced geothermal systems more explicitly, simple models were developed to inform the study and provide insights into scaling and trade-offs among factors to be considered.

#### 3.1 Drilling

Micro-drilling and other subsurface technologies need to be further developed and fielded – at least for exploration and field-monitoring, and for production to the degree possible – in order to mitigate the rapid increase of drilling costs with depth. Proving technologies that can increase the depth scale for drilling costs to  $d > 5$  km, or achieve more-nearly linear depth-cost relations, is therefore at a premium.

### 3.2 Tracer Dispersion

A one-dimensional convective-dispersion analysis provides a means of understanding breakthrough curves for tracers placed in fluids at depth. For example, consider a typical breakthrough curve that reports the concentration versus time at the location of a production well. Concentrations at  $1/2$  ( $C_{1/2}$ ) and at 4 times ( $C_4$ ) the time ( $t_m$ ) of maximum concentration ( $C_m$ ) are determined from observations, as illustrated in Figure 1. The mean speed  $v$  of the flow can be estimated as  $\ell/t_m$ , for travel distance  $\ell$ , but this estimate can be improved using the shape of the dispersion curve. In particular, the relative concentrations are used to form non-dimensional ratios  $c_4 = C_4/C_m$  and  $c_{1/2} = C_{1/2}/C_m$  that are then combined to obtain a characteristic time scale,  $\tau_m$ , through solution of:

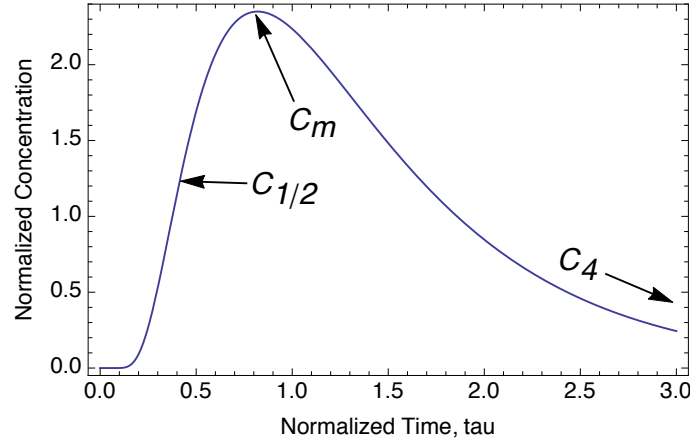
$$\frac{3(4\tau_m^2 - 1)}{2(2 + 3\tau_m - \tau_m^2)} = \frac{\ln(2c_4)}{\ln(c_{1/2}/\sqrt{2})} \quad (1)$$

Once  $\tau_m$  is determined, numerically or graphically from (1), the subsurface transport velocity ( $v$ ) and longitudinal dispersivity ( $\mathcal{D}$ ) are calculated from the observed time  $t_m$  to the maximum concentration measured at distance  $\ell$ :

$$v = \frac{\tau_m \ell}{t_m} \quad (2)$$

$$D = \left[ \frac{v\ell}{-\frac{16\tau_m}{3(4\tau_m^2 - 1)} \ln(2c_4)} \right] \quad (3)$$

The simplified model was shown to agree well with measurements available for the Soda Lake and Steamboat geothermal sites. Consequently, for the simplest cases, three measurements from a dispersion curve suffice to estimate the average flow speed and the dispersion coefficient.



**Figure 1: Concentration of a chemical tracer as a function of time in normalized units, indicating time and concentration at the maximum concentration ( $C_m$ ), and then concentrations at half ( $C_{1/2}$ ) and 4 times ( $C_4$ ) this maximum time ( $C_4$  is at approximately time  $\tau = 3.2$  in this case). These parameters can be used to identify a characteristic time scale  $\tau_m$  through (1), from which dispersion properties of the subsurface flow are derived from (2) and (3).**

### 3.3 Thermal Evolution of a Reservoir

Flow velocity plays a key role in optimizing the extraction of heat from the subsurface. Two important parameters are the longitudinal and transverse time scales associated with the cooling front propagating into the rock from each channel of flowing water (Figure 2). In particular, the former is proportional to (flow velocity)<sup>-2</sup>

$$t_{longitudinal} \text{ (years)} = 3 \times 10^{-3} \left[ \frac{\ell / 1 \text{ km}}{(v / 1 \text{ m/s})(b / 1 \text{ mm})} \right]^2 \frac{\kappa_r}{10^{-6} \text{ m}^2/\text{s}} \quad (4)$$

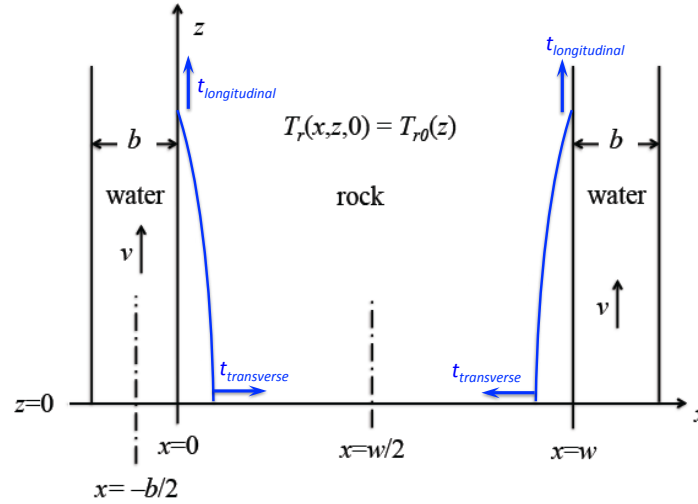
and defines the characteristic time over which energy extraction is optimal ( $\ell \approx z_{extraction}$  and  $\kappa_r$  are the vertical length-scale and thermal diffusivity of rock, respectively). That is, for typical values of vertical extent ( $\ell = 1$  km), flow rate ( $v = 1$  m/s), crack width ( $b = 1$  mm) and rock thermal diffusivity ( $\kappa_r = 10^{-6}$  m<sup>2</sup>/s), the longitudinal time-scale is  $t_{longitudinal} = 3 \times 10^{-3}$  years (26 hours) and Equation (4) describes the scaling with changes in parameter values.

Taking Carnot efficiency into account (electrical and thermal power generation are proportional to  $(\Delta T)^2$  and  $\Delta T$ , respectively, with  $\Delta T = T(z_{\text{extraction}}) - T(z=0)$  in Figure 2), we find that electrical power generation decays as  $t^{-1/2}$  for early times ( $t < t_{\text{longitudinal}}$ ) and then switches to the more rapid decay of  $t^{-1}$  at later times ( $t > t_{\text{longitudinal}}$ ). This model suggests that a strategy for maximizing total electrical power generation would therefore involve slowing the flow rate as a function of time, so as to delay the transition at  $t_{\text{longitudinal}}$ .

The transverse time scale

$$t_{\text{transverse}} \text{ (years)} \approx 0.3 \frac{(w / 10 \text{ m})^2}{(\kappa_r / 10^{-6} \text{ m}^2/\text{s})} \quad (5)$$

determines the thermal lifetime for heat extraction from the fracture-pair, and there is again a tradeoff between rate of power production and total power extracted per well-pair because both depend on separation (e.g.,  $w$  in (5)).



**Figure 2: Schematic of two neighboring fractures (width  $b$ , separation  $w$ ) through which cold water is being injected at velocity  $v$  from bottom ( $z = 0$ ) to the extraction height ( $z_{\text{extraction}}$ ) above the figure. Cooling fronts (blue curves) propagate diffusively into the rock from each side of each fracture, and define two characteristic time scales: a longitudinal time,  $t_{\text{longitudinal}}$ , when the cooling front reaches  $z = z_{\text{extraction}}$ ; and a transverse time,  $t_{\text{transverse}}$ , when the cooling front reaches  $x = w/2$ .**

These models are intended to supplement – not supplant – the sophisticated analyses currently used by researchers, in that they provide quick scaling relations that can aid communication with broader, perhaps non-technical, communities interested in EGS.

#### 4. ENGINEERED SUBSURFACE HEAT EXCHANGER

Advances in drilling technology, such as hydraulic fracturing methods, horizontal drilling and micro drilling small-bore holes to depth, suggest the opportunity to engineer permeability in otherwise dry rock by drilling a channel continuously between injection and production wells. The placement of a heat exchanger directly in the subsurface would solve the problem of connectivity between the fluid injection and extraction sites, and also solve problems of leak-off of injected fluid into the reservoir. An additional potential advantage of this engineered configuration is that the cylindrical geometry of a drilled heat exchanger draws thermal energy from a larger volume of the surrounding hot rock than a flat crack of comparable dimension, so that draw-down time per well could be longer than in traditional systems.

To appreciate the possible energy production rates of this manner of engineered heat exchanger, we consider a reservoir with a temperature of  $250^\circ \text{C}$ , and assume that after 10 years of operation we still desire water temperatures of  $150^\circ \text{C}$  (where the inlet temperature is  $50^\circ \text{C}$ ). If micro drilling can produce a heat exchanger with a hole of diameter 1 inch ( $b = 1.3 \times 10^{-2} \text{ m}$ ), then in order to still be producing thermal power of 1 MW after 10 years the heat exchanger would need to have a length of about 2.5 km, which is of the order of magnitude suggested for advances in micro drilling. Furthermore, after 40 years of operation the thermal power produced would only have decreased by 10%, to 0.9 MW.

#### 5. CONCLUSIONS

The study produced the following recommendations based on these and other analyses:

1. To pursue EGS, an integrated program of laboratory and field studies, combining experiments with modeling, simulation and theory, should be undertaken to reduce i) uncertainties in the nature of the subsurface (permeability, stress, etc.), and consequent heat-recovery factors, thermal-drawdown losses and well lifetimes; and ii) the difficulty and cost of drilling to depth. Such a program for validating methods and ideas can benefit from developing and applying recent technical advances in subsurface

characterization, at field-scale as needed, such as: microdrilling with sensor deployment at depth; advanced seismic imaging; electromagnetic monitoring of fluids; and tracer tests.

2. The portfolio of EGS activities should at present emphasize enhancing conventional geothermal production. Combining better understanding of the subsurface with advances in well design, drilling and operational procedures provides opportunities for improved production of geothermal energy.
3. Water-use plans with realistic contingencies should be developed for EGS at scale.
4. A thorough technical evaluation of the hazards associated with induced seismicity includes continued monitoring of induced earthquakes along with targeted studies of their causes and possible mitigation.
5. Deleterious effects of corrosion and scaling of equipment and subsurface channels, by gases (e.g., HCl or H<sub>2</sub>S mixed with steam) or by carbonates dissolved in brine should be further assessed, with continued development of mitigation strategies.

## **REFERENCES**

JASON: *Enhanced Geothermal Systems*, JSR-13-320, 141 pp., MITRE Corporation, McLean, VA (2013).