

THE COST EFFECTIVENESS OF FRACTURE STIMULATION IN INCREASING THE FLOW FROM GEOTHERMAL WELLS*

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ABSTRACT

The cost effectiveness of fracture stimulation at The Geysers, the Imperial Valley, and other geothermal resource areas in the United States was studied using GEOCOM, a computer code for analyzing the impact of completion activities on the life-cycle costs of geothermal wells. Technologies for fracturing the reservoir near the wellbore involve the creation of a pressure pulse in the wellbore by means of either hydraulic or explosive force. The cost of a single fracture stimulation job can vary from \$50,000 to over \$500,000, with a typical cost of around \$300,000. The code shows that additional flow achieved by fracture stimulation must exceed 10,000 pounds per hour for each \$100,000 invested in stimulation in order for a fracture treatment to be cost effective. In some reservoirs, this additional flow must be as great as 30,000 pounds per hour. The cost effectiveness of fracturing has not yet been demonstrated in the field. The Geothermal Well Stimulation Program achieved an overall average of about 10,000 pounds per hour for each \$100,000 invested.

INTRODUCTION

In many geothermal reservoirs the majority of the wells that are drilled produce sufficient flow of high temperature fluids to be economic, but this is not always the case. Even in the best fields, it is common to drill production wells in which there is inadequate flow of fluids even though the wellbore itself is free of problems that would impede flow. Techniques that are commonly used to increase or "stimulate" flow from such wells include:

- (1) Redrilling the well (e.g., to deepen or underream it, or to drill a new leg)
- (2) Pumping the well
- (3) Treating the producing formation with chemicals (e.g., acid washing)
- (4) Fracturing the producing formation.

A sometimes viable alternative is to abandon the existing well (perhaps using it as an injector) and to drill a new production well.

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In determining which technique to use, it is important to estimate both the cost and the effectiveness of each option.

The stimulation procedure considered in this paper is fracturing the formation. This is achieved by increasing the pressure inside a wellbore to the point that the formation surrounding the wellbore fails in tension and parts (either at the site of a pre-existing crack or via a new fracture). Fracturing is intended to increase the flow into the well by increasing its surface area in the producing formation or by connecting it to existing fractures that will supply reservoir fluids.

Although stimulation, in general, and fracturing, in particular, are common completion practices in petroleum drilling, they have not been widely used in geothermal extraction. Accordingly, a U.S. DOE program was undertaken to investigate and develop stimulation techniques for geothermal wells.² Several different stimulation techniques were investigated in this program and tested at different geothermal fields. Most of the fracture stimulation tests that were run succeeded in producing new fractures, and some of the experiments resulted in additional flow into the wellbore. However, in spite of these technical successes, none of the experiments increased flow enough to be economically successful.

The results presented in this paper are part of those arising from a study investigating the additional flow is necessary for fracturing to be economically attractive.¹ The study was done using an existing economic model, GEOCOM^{4,5}, to analyze the cost-benefit ratio for stimulation operations. The analysis was performed to help establish priorities for tasks under consideration for Sandia National Laboratories' Geothermal Technology Development Program. Though derived for internal use, many of the conclusions are of general interest.

THE GEOCOM MODEL

The GEOCOM computer model was developed as an internal management tool to answer questions concerning the cost effectiveness of geothermal completion practices.³ The model facil-

itates comparison of the potential cost effectiveness of various technology development options and aids in project selection. In particular, it considers the cost and revenue streams associated with a well and can be used to determine rates of return or life-cycle effectiveness. The GEOCOM model is implemented in ANSI FORTRAN.

The specific GEOCOM output utilized in this study is the ratio of life cycle cost to benefit (expressed in dollars per million Btus of energy produced) for a geothermal well. Life cycle costs include capital, operating, maintenance, workover and abandonment costs. The modeling of the energy produced includes the quality of the fluid (temperature, steam content, etc.) and the end use for it, and accounts for the time when the production takes place (considering reservoir decline rates, well shut-in periods, etc.). The model inflates and discounts both costs and benefits over the life of the well.

One aspect of the model that makes it particularly useful in evaluating and comparing completion alternatives is its default data base that summarizes well and reservoir performance, cost factors, and production histories for several U.S. geothermal areas. Due to the default data, analysis of the cost effectiveness of fracture stimulation required only the independent computation of representative stimulation costs in order to conduct parametric studies. Some of the default data for six U.S. geothermal areas are presented in Table 1. The bottom row of Table 1 presents the GEOCOM estimate of the cost benefit ratio for producing fluid from the "default well" at each area.

TECHNIQUES AND COSTS OF FRACTURE STIMULATION

Fracture stimulation requires the creation of a large pressure pulse within the wellbore that can be effectively coupled to the producing formation. The two most common methods of creating such a pulse are hydraulic pressure and chemical explosives. Both methods were developed for use in oil and gas wells and were tested in the Geothermal Stimulation Program.

Figure 1 schematically represents the physical setup for a hydraulic fracture stimulation. The zone to be fractured is sealed above and below by packers, hydraulic tubing is stabbed through the top packer, and proppants and gel (to suspend the proppants) are pumped through the tubing at high rates and pressures. The cost of hydraulic fracturing can be dominated by the costs of these materials (fluids and proppants). A typical stimulation would require 5000 barrels of fluid and 100,000 pounds of proppant for a total material cost of \$100,000. Pumping and related services comprise the second largest component of cost in hydraulic fracturing. It might typically cost \$70,000 to pump at the high rates (a

barrel a second) and high pressures (3000 psi) necessary. Rig costs, for setting the packers and running tubing might add roughly \$40,000; and other costs would bring the total to about \$250,000 of direct costs for hydraulic fracturing.^{4,7}

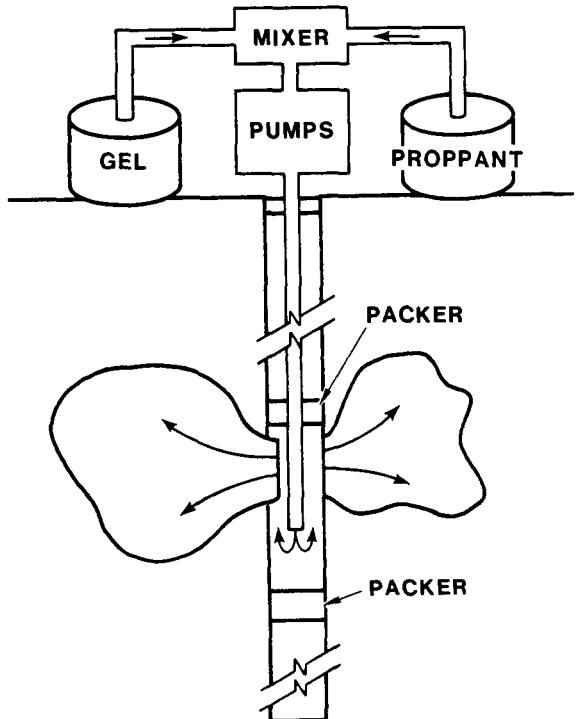


Figure 1. Schematic Representation of Hydraulic Fracturing

Explosive stimulation involves lowering explosives into the well and detonating them in the interval to be fractured. The direct costs for explosive fracturing are generally considerably less than for hydraulic fracturing. The major cost is the cost of expendable hardware which is likely to be in the neighborhood of \$200 per linear foot of well to be stimulated⁴. An average stimulation (200-foot treatment interval) would require \$40,000 in expendable hardware, including 1600 pounds of propellant, 30 sections of casing, and a detonator system. The costs of the services needed to support the stimulation would bring total direct costs to about \$60,000. Though considerably less expensive than hydraulic fracturing, there are many situations in which explosive stimulation is impractical or ineffective.

The indirect costs of fracturing can sometimes exceed the direct costs. The major contributor to indirect cost is often the requirement for a compatible well completion. In general, neither hydraulic nor explosive stimulation can be accomplished from inside a production liner. Typically, an uncemented liner can be removed and replaced for approximately \$100,000⁴. Similarly, stimulation may re-

quire a higher density of perforations in a cemented liner. A remedial perforation of a 200-foot interval would cost approximately \$50,000⁴. In summary, the indirect costs of fracturing are scenario dependent and can add significantly to stimulation costs.

Table 2 presents the hydraulic fracturing costs that were experienced in the Geothermal Well Stimulation Program^{7,8,9}. The table indicates a typical cost of about \$300,000. The large indirect costs for the Raft River experiments reflect the fact that the wells had to be recompleted before they could be fractured.

Location	Cost \$ (1000s)	
	Direct	Indirect
Valles Caldera	360	40
Raft River	64	240
Raft River	129	281
East Mesa*	420	34
The Geysers	300	34

*Sum of costs for two experiments in the same well.

Table 2. Hydraulic Fracturing Costs from the Geothermal Well Stimulation Program

COST EFFECTIVENESS

The basic measure used to evaluate the effectiveness of fracture stimulation is its effect on the well's cost-benefit ratio in dollars per Btu of fluid produced over the life of the well. There are several ways that this ratio could be used to evaluate stimulation operations.

If the well being stimulated is subeconomic before stimulation, the true measure of effectiveness of the stimulation is whether it converted the well into an economic producer. This would require sufficient additional flow to significantly reduce the well's cost benefit ratio. Along this line, an indication is given in the "Results" section of the flow required for a relatively small reduction in the ratio. However, this standard is highly well-specific and cannot be applied in general analyses.

A second way to evaluate stimulation effectiveness is to compare the cost-benefit ratio for stimulation to the ratio for a good "default" producing well in the same field (as in Table 1). This would appear to indicate whether money is better spent in stimulating an existing well or in drilling a new one; although it ignores the probabilities of success for each.

A third, related way to evaluate effectiveness is to determine whether the stimulation improves the cost-benefit ratio of the well being stimulated. This is the standard used to evaluate effectiveness in this discussion and in the "Results" section below. This cri-

terion can be expressed in a simplified form as

$$\frac{\text{well cost without stimulation}}{\text{energy produced without stimulation}} >$$

$$\frac{\text{well cost with stimulation}}{\text{total energy produced}}$$

Since this criterion uses well cost and flow, it appears to be well specific. However, as shown below, in the cost and flow regions of interest, it is not. The major drawback to this criterion is that it ignores the well-specific questions of resulting total flow and overall well efficiency.

METHODOLOGY

The extensive GEOCOM data base allows the analysis of fracture stimulation to be done fairly easily. Building on the default values for each location, only the data on stimulation costs and additional flows are necessary as inputs. A parametric analysis of the cost effectiveness of fracture stimulation was carried out for the six geothermal sites included in Table 1.

Using its default data, GEOCOM was used to produce representative cost and revenue streams for different levels of initial flow for a well and to compute the appropriate cost-benefit ratios. Following this, numerous model runs were made in which stimulation cost and initial well flow were varied throughout their ranges of interest. These results were then used to develop iso-cost curves that connect values for which the cost-benefit ratio is constant. Since these curves (presented below) are roughly linear and parallel throughout the domain of interest, their common slope is important. Its value indicates the ratio between incremental additional stimulation cost and incremental additional flow for which the cost-benefit ratio for the well remains constant. That is, this slope represents the additional flow per stimulation dollar which must be exceeded by a fracture stimulation operation if it is to reduce the cost-benefit ratio of the well.

MODEL RESULTS

Wells were analyzed for several different geothermal fields. Typical results are shown for four areas in Figure 2.

For wells in the Imperial Valley, increases in initial flow of 25,000 to 30,000 pounds per hour are required per \$100,000 invested in stimulation in order for the stimulation to maintain the same overall cost of energy from the well. On the other hand, at The Geysers only 6000 to 8000 pounds per hour of additional flow are needed for each \$100,000. An intermediate value of 15,000 to 20,000 pounds per hour is required at Roosevelt Hot Springs. These differences arise from the varying qualities of the fluids produced and from the different well costs, well performances, and well lifetimes for the different areas.

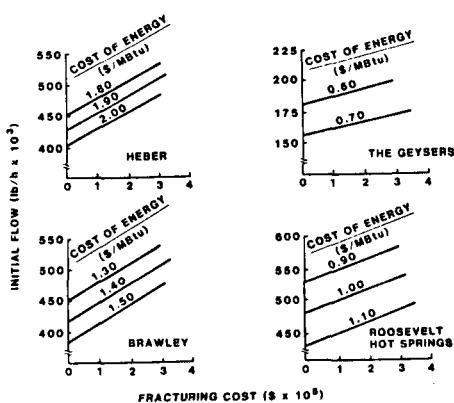


Figure 2. GEOCOM Results for Four Areas. The curves are iso-cost curves for different unit costs of energy.

The determination of the break-even values cited above for the various geothermal areas is illustrated in Figure 3. The common slope of the parametric iso-cost curves, denoted "a" in the figure, is the criterion value. The model was not used to determine energy costs outside the indicated ranges, and so there is no reason to assume that the linearity extends over greater ranges of either cost or flow. In addition, these results ignore reservoir-specific factors that drive cost and affect resulting flow. Nonetheless, the threshold values are important.

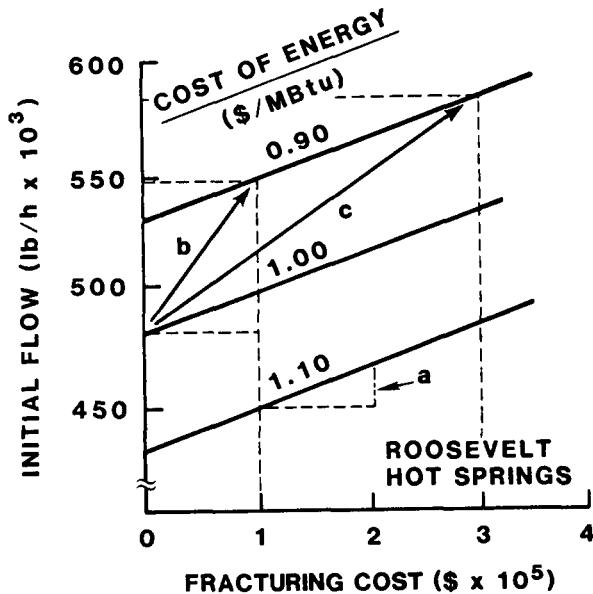


Figure 3. Sample Calculations

Even greater amounts of initial flow are required to significantly reduce the cost of producing energy. For example, lowering the cost of one MBtu from the Heber well by ten cents (5%) would require approximately 50,000

pounds per hour of additional flow for a \$100,000 fracture stimulation. At Roosevelt Hot Springs approximately 70,000 pounds per hour of additional initial flow for a \$100,000 expenditure would result in a 10% decrease in energy costs ("b" in Figure 3). However, these results are not proportional. Roughly 100,000 pounds per hour for a \$300,000 expenditure at Roosevelt would have the same effect. These calculations are shown by "c" in Figure 3. Similar estimates can be made for other wells from the data shown in Figure 2.

Although these parametric results derived from the model are interesting, they represent only one way to evaluate cost effectiveness. They do not consider the reservoir parameters that affect whether or not stimulating the reservoir is possible or if it makes sense. The results also ignore the effect of the fluid temperature after stimulation. Higher temperature flow can be as valuable as greater quantities of flow. The GEOCOM model was used to study this and several other parameters, but the results are not discussed in this paper.¹

EXPERIMENTAL RESULTS

The GEOCOM modeling results place in perspective the limited results of the geothermal fracture stimulation experiments. The field tests that have been conducted have averaged an increase of 8000 to 15,000 pounds of fluid in initial flow per \$100,000 invested. This appears to be close to the breakeven point for some of the reservoirs; but for most reservoirs, it is considerably below the level necessary to significantly reduce the costs of producing fluid from a marginal well.

CONCLUSIONS

Fracture stimulation is an expensive operation with insufficient geothermal experience to allow high-confidence estimates of its cost effectiveness. Based on modeling and limited experimental results, it appears that for the most favorable geothermal fields, a successful fracture stimulation can be nearly a breakeven operation (in terms of its effect on total energy costs). However, analysis and experience indicate that the effectiveness of fracture stimulation must be greatly improved before it can be used with confidence to salvage nonproductive wells (by significantly reducing the total energy costs). Fracture stimulation has been used for years in oil and gas wells; and because of the maturity of this technology, the costs of fracture stimulation are not likely to fall. Instead, the most promising areas for work relative to geothermal wells would be in improving effectiveness (as measured by increased flow) and in increasing the probability of success. A key element in this work will be developing an understanding of the fractures that can be produced by different stimulation techniques and how they interact with geothermal reservoirs.

Table 1.
Default GEOCOM Data for Six U.S. Geothermal Areas

Parameter	1	2	3	4	5	6
Location	Brawley	Heber	E. Mesa	The Geysers	V. Caldera	Roosevelt H.S.
Temperature (°F)	344	360	340	365	358	344
Well Depth (ft.)	6000	8000	7600	8000	6000	7500
Well Life (mo.)	120	120	120	330	360	200
Flow (lbs./hr.)	500,000	500,000	500,000	200,000	200,000	580,000
Steam Fraction	.058	0	0	1.	.30	.20
Dissolved Solids (PPM)	80,000	14,000	2,200	0	6,100	6,500
Well Cost (\$)	612,600	771,300	723,600	1,131,600	1,075,300	1,129,300
Workover Inter- val (yrs.)	1	2	5	5	5	5
Workover Delay (mo.)	.25	.25	.25	.25	.25	.25
Flow Decline- Reservoir (frac./mo.)	.004	.005	.005	.00195	.00308	.004
Flow Decline- Correctable (frac./mo.)	.03	.01	.005	0.0	.01	.01
Cost/Benefit of Fluid (\$/MBTU)	1.17	1.60	1.71	0.54	1.58	0.87

Table 1. Default GEOCOM Data for Six U.S. Geothermal Areas

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