

REAL-TIME AND POST-FRAC' 3-D ANALYSIS OF HYDRAULIC FRACTURE TREATMENTS IN GEOTHERMAL RESERVOIRS

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ABSTRACT

Economic power production from Hot Dry Rock (HDR) requires the establishment of an efficient circulation system between wellbores in reservoir rock with extremely low matrix permeability. Hydraulic fracturing is employed to establish the necessary circulation system. Hydraulic fracturing has also been performed to increase production from hydrothermal reservoirs by enhancing the communication with the reservoir's natural fracture system. Optimal implementation of these hydraulic fracturing applications, as with any engineering application, requires the use of credible physical models and the reconciliation of the physical models with treatment data gathered in the field. Analysis of the collected data has shown that 2-D models and 'conventional' 3-D models of the hydraulic fracturing process apply very poorly to hydraulic fracturing in geothermal reservoirs. Engineering decisions based on these more 'conventional' fracture modeling techniques lead to serious errors in predicting the performance of hydraulic fracture treatments. These errors can lead to inappropriate fracture treatment design as well as grave errors in well placement for hydrothermal reservoirs or HDR reservoirs.

This paper outlines the reasons why conventional modeling approaches fall short, and what types of physical models are needed to credibly estimate created hydraulic fracture geometry. The methodology of analyzing actual measured fracture treatment data and matching the observed net fracturing pressure (in real-time as well as after the treatment) is demonstrated at two separate field sites. Results from an extensive Acoustic Emission (AE) fracture diagnostic survey are also presented for the first case study as an independent measure of the actual created hydraulic fracture geometry.

INTRODUCTION

Hydraulic fracture stimulation has been extensively employed for nearly fifty years by the petroleum industry as a technique to increase an individual wellbore's contact, or communication, with reservoir rocks. Hydraulic fracture stimulation is achieved by injecting fluid into reservoir rocks at rates and pressures

(above in-situ reservoir confining stress) sufficient to part and hydraulically propagate fractures in the reservoir rock. A schematic of the process and equipment necessary for a hydraulic fracture stimulation is shown in Figure 1 (from Ref. 1). The retained hydraulic conductivity of the generated fractures (which are often held open by pumping particulates known as 'proppant') increases the cross-sectional area over which a wellbore contacts reservoir rock, therefore, allowing significantly enhanced fluid production rates compared to those achievable with an unstimulated wellbore.

Hydrothermal reservoirs offer the same opportunity as oil and gas reservoirs to enhance production from a wellbore by employing hydraulic fracture stimulation. In contrast, however, to conventional oil and gas reservoirs where production rates are (predominantly) controlled by the reservoir (matrix) permeability, hydrothermal reservoir fluid production rates are typically controlled by the conductivity of the natural fracture system intersected by the wellbore. Prolific wells usually intersect highly conductive and interconnected natural fracture networks. Often, adjacent wells may be far less prolific producers simply because they lack the connection at the wellbore to the nearby natural fracture systems. Significant productivity enhancement can often be achieved by establishing the necessary communication with nearby natural fracture systems through hydraulic fracture stimulation (Refs. 2 - 3).

Hydraulic fracture stimulation plays an indispensable role in the extraction of heat from Hot Dry Rock (HDR) reservoirs (Refs 4 - 7). The tremendous resource base of HDR reservoirs versus conventional hydrothermal reservoirs makes efficient HDR production technology of global importance. Heat extraction from HDR reservoirs is the result of circulating water from an injection wellbore through an artificially created fracture system and out a production wellbore(s). Efficient energy production depends not only on achieving effective hydraulic fracture stimulation of a large volume of reservoir rock, but also on possessing the modeling and diagnostic capability required to optimally design hydraulic fracture stimulations and to reliably estimate the created geometry and dimensions of the induced hydraulic fracture systems.

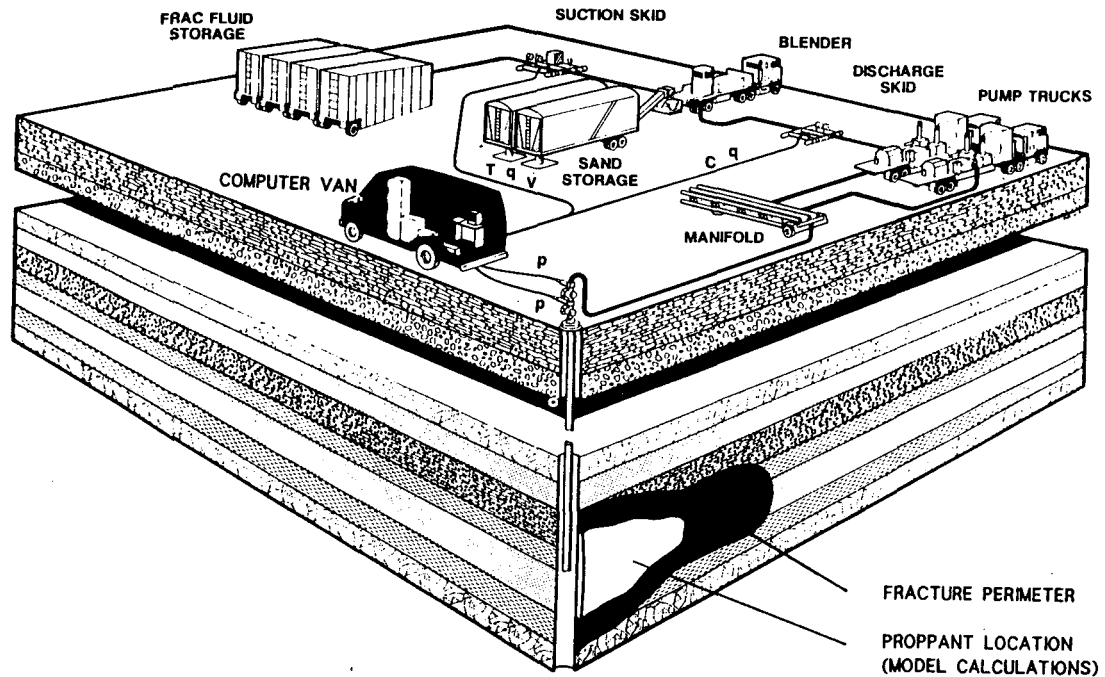


Figure 1: Isometric View of the Hydraulic Fracturing Process Including Surface Equipment and Generalized Created Hydraulic Fracture

This paper outlines some of the basic concepts behind hydraulic fracturing and briefly overviews the current modeling approaches. Detailed analysis of measured field data has shown that industry two-dimensional models and 'conventional' three-dimensional models of the hydraulic fracturing process apply very poorly to hydraulic fracturing in geothermal reservoirs. However, an enhanced three-dimensional fracture modeling system is described which contains real-time data acquisition and complex fracture modeling capabilities that more realistically represent fracturing in geothermal reservoirs. Finally, two case studies of hydraulic fracturing applications -- one in an HDR reservoir and the other in a (nominally) hydrothermal reservoir -- are presented with detailed analysis of collected treatment data and comparison with independent fracture diagnostic data. The final section presents a summary of conclusions.

MODELING OF HYDRAULIC FRACTURES

Early fracture models (Refs 8, 9), which are still in all-too-common use today, simply assumed that the height of the fracture was known and that only the length and width needed to be calculated. Various height assumptions were made, with those of the reservoir 'pay-zone' height and perforated (or open-hole) interval being the most common. Despite their lack of physical realism, two-dimensional models, due to their physical simplicity, are still by far the most widely used tools today for designing and evaluating hydraulic fracture

treatments. Constant height fracture models invariably overestimate the predicted fracture lengths, by as much as a factor of 10 or more. A more physically realistic (for most applications) two-dimensional fracture model is provided by the assumption of radial fracture geometry, where the two independent fracture dimensions become fracture radius and width. While the geometric assumption of a radial fracture may approximate reality for most hydraulic fracture stimulations of geothermal reservoirs which typically lack the necessary 'barriers' for fracture height containment, the typical fracture dimensions predicted by simple radial fracture models vastly overestimate the actual created fracture radius (the reasons for this are discussed below). 'Conventional' three-dimensional fracture modeling allows the incorporation of variations in reservoir stress, modulus, and (sometimes) permeability into the fracture modeling process. While this three-dimensional enhancement is necessary, the 'conventional' three-dimensional modeling assumptions of (1) the applicability of Linear-Elastic Fracture Mechanics (LEFM) and (2) the generation of a single planar fracture, prevent credible results from being obtained using such modeling approaches (Refs 10, 11).

Over the last decade a focused research effort, primarily sponsored by the U.S. Gas Research Institute, has striven to acquire the field and laboratory data necessary for the development of more realistic three-dimensional hydraulic fracture models. This research resulted in a commercially available hydraulic fracture modeling system called FRACPRO (Refs 12-13). The initial

effort focused on comparing carefully collected field data-sets from dozens of actual hydraulic fracture stimulations to the predictions from then state-of-the-art 'conventional' three-dimensional fracturing simulators. Model agreement with field data-sets was found to be very poor. A host of mechanisms, which were not previously accounted for, were found to often play dominant roles in hydraulic fracture growth, including; non-linear rock behavior near the fracture tip; fracture containment due to permeability barriers; proppant convection; near-wellbore fracture tortuosity; and the simultaneous propagation of multiple hydraulic fractures. The FRACPRO models are generalized and modular 'lumped' parameter three-dimensional models. This type of model formulation allows for the (approximate) handling of the complex fracture mechanisms mentioned above and, therefore, allows more realistic estimates of created fracture geometry (Ref 14).

The specific models contained in FRACPRO are three-dimensional, in that spatial variations in reservoir stress, permeability, modulus, pressure, and flow distribution are taken into account. However, the models are 'lumped parameter' and do not calculate the variations at specific points within the fracture: instead, the effects are integrated into (functional) coefficients of the governing differential equations, greatly simplifying the calculation of the fracture dimensions. The system can therefore run much faster than real time, as required for pressure history-matching on-site. The (functional) coefficients necessary to calculate the spatial variations are calculated from a full three-dimensional model and checked against experimental laboratory and field test data. It is through these (functional) coefficients that the complex fracture mechanisms (e.g. near-tip non-linear rock behavior, permeability barriers, etc.) are handled in the FRACPRO models.

When modeling hydraulic fracture stimulations in geothermal reservoirs, or any other reservoir which has significant natural fracturing, it is essential to consider the role natural fractures play in the evolution of induced hydraulic fractures. Fracture initiation from an open hole interval (or perforation) always takes place at points of pre-existing cracks with the greatest hydraulic conductivity. Wellbores which intersect swarms of natural fractures tend to initiate swarms of hydraulic fractures upon stimulation. The combined generality and relative simplicity of the FRACPRO models allows, at least to first order, the modeling of multiple hydraulic fractures growing simultaneously. Input assumptions must be made on the number of fractures growing (this can vary with time) and whether the individual fractures are competing for opening space, and/or access to the reservoir for fluid leak-off, or whether the fractures are growing independently and don't "feel" the effects of the other fractures. A time-history of the number of the fractures taking fluid, competing for opening space, and

leaking fluid is entered into the model and a simulation is run modeling the mechanical effects of the multiple fractures and the resulting fracture dimensions, pressures, etc. are calculated. As with any history-matching process, iteration is required to find which assumptions best match the observed fracturing pressure response. Care must be taken to justify the assumption of the simultaneous propagation of multiple fractures over the mechanically simpler assumption of the propagation of a single hydraulic fracture.

Input assumptions are often influenced from direct knowledge of a wellbore's reservoir contact from observed zones of lost circulation during drilling; core data; or borehole imaging log data. Since FRACPRO does not know the orientation of the in-situ stress field or the orientation of the existing natural fractures and micro-cracks, it simply assumes that fractures are created in the plane perpendicular to the least principle stress direction. FRACPRO's generated fracture profiles and opening (width) profiles are *approximations of the overall* created hydraulic fractures. Borehole imaging and other logs, in contrast, can be used to attempt to get a more detailed view of the fracture(s) at the *point of intersection with the wellbore*. These are very different, but complimentary, views of the same phenomenon.

The actual complexity of the created fracture(s) is certainly greater than that captured in FRACPRO, as is the case in all engineering modeling. The goal of FRACPRO is to determine the aerial penetration (radius or length); the geometry (i.e. is the fracture roughly radial or do stress or permeability barriers significantly contain or elongate the fracture(s)?); the complexity (i.e. are there likely to be multiple created hydraulic fractures?); and the opening width(s) of the created hydraulic fracture(s).

REAL-TIME FRACTURE ANALYSIS

Real-time analysis requires an on-site PC (80386/486) with appropriate data acquisition and modeling software (FRACPRO, in this case) and measured treatment data (injection rates, pressures, fluid properties, etc.) in digital format. Digital treatment data can usually be acquired directly from the pumping service company or from on-site data acquisition hardware. A schematic of this set-up is shown in Figure 2.

To achieve confidence in the predictions of any hydraulic fracture simulator requires that the net fracturing pressure (fracturing fluid pressure above formation closure stress) predicted by the model match the observed net fracturing pressure of the treatment. In fact, the two-dimensional and 'conventional' three-dimensional fracturing models discussed earlier can often be dismissed based on their complete inability to match observed net fracturing pressures. The

determination of observed net fracturing pressure requires accurate knowledge of the bottomhole pressure, $P_{bottomhole}$, during the pumping of the fracturing treatment. Bottomhole pressure, when not measured directly, can be calculated using the following formula:

$$P_{bottomhole} = P_{surface} + P_{head} - P_{friction} \quad (1)$$

$P_{surface}$ is the treating pressure measured at the surface; P_{head} is the hydrostatic head, or weight, of the fluid in the wellbore; and $P_{friction}$ is the head-loss due to friction in the pipe. Once bottomhole pressure is known, the net fracturing pressure can be calculated by subtracting the closure stress and any pressure loss due to perf and/or near-wellbore friction, $P_{perf/near-wellbore}$, from the bottomhole pressure:

$$P_{net} = P_{bottomhole} - P_{closure} - P_{perf/near-wellbore} \quad (2)$$

Frictional losses in the wellbore and/or the perf/near-wellbore region, the major unknowns in the equations above, are very difficult to predict, but they are relatively simple to measure using abrupt flow-rate changes and shut-ins.

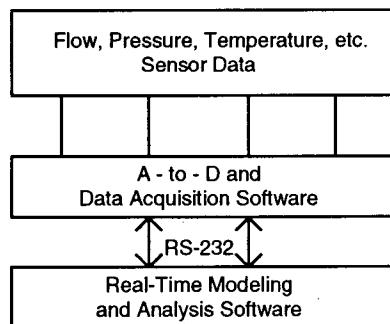


Figure 2: Schematic of Real-time Data Acquisition and Fracturing Analysis

FRACPRO uses the measured flow rate, fluid rheology, proppant concentration and reservoir description to predict the net fracture pressure. This predicted net pressure can be compared, in a history-matching process, to the 'observed' value of net pressure described in Equation (2). Unknown or uncertain reservoir properties upon which the pressure response (and therefore, fracture growth) depends can be changed and the simulator re-run until the observed and predicted net pressures match. A good match of net pressures will result in a good estimation of fracture extent and proppant placement. Obviously, the more accurately bottomhole pressure and closure stress are known, the more precisely the true net pressure in the fracture can be calculated, and the more precise will be the fracture-geometry predictions.

CASE STUDY 1: HDR-1 WELL, JAPAN

The HDR-1 well is located at the Hijiori Hot Dry Rock Test Site, in central Honshu Island, Japan. This well is a part of the New Energy and Industrial Technology Development Organization's (NEDO) and the Geothermal Energy Research and Development Company's (GERD) effort to develop fundamental technologies in Hot Dry Rock geothermal reservoirs (Ref 15). As with typical HDR reservoirs, the pre-existing natural fracture system at the Hijiori site does not nearly provide adequate reservoir communication and, therefore, must be fracture stimulated to achieve the necessary rates of heat extraction. In July 1992, HDR-1 was hydraulically fractured (without proppant) to create an artificial reservoir between injection and production wells in the Hijiori deep reservoir.

The treatment included a pre-frac' test, a massive main fracture stimulation, followed by two post-frac' tests. The purpose of the pre and post pump-in tests was to ascertain the value of reservoir closure stress (243 KSC) and the value of reservoir leak-off coefficient (approx. $2.0 \times 10^{-4} \text{ ft} / \sqrt{\text{min}}$) for the Hijiori deep reservoir, and to evaluate the effectiveness of the main hydraulic fracture treatment. The main fracture treatment consisted of 2,110 m³ of fresh water pumped at an average rate of 3,600 l/min. The collected treatment data was analyzed by matching the net fracturing pressures in real-time using the FRACPRO system. Core derived reservoir mechanical properties and log derived natural fracture descriptions were incorporated in the analysis. Figure 3 illustrates the observed net pressure to simulated net pressure match.

As Figure 3 illustrates, the character and the level of observed net pressure was matched during the injection period. Oscillations in the observed net pressure are the result of rapidly changing wellbore friction (not actual changes in net fracturing pressure) due to sporadic addition of friction reducer. The difference in the rate of pressure decline (between observed net pressure and modeled net pressure) after the end of pumping was due to flow-back of the injected fluid. The post-treatment flowback made the observed net pressure appear to fall much faster than it would have fallen if the well were shut-in after the stimulation. Therefore, the correct value for fluid leak-off coefficient was inferred from the pre- and post-frac' tests.

This net pressure match concluded that a fracture radius of 145 meters (476 ft) and a maximum total hydraulic fracture width of 40 mm (1.57 inches) was achieved (Ref 16). Modeling also deduced that the width was divided among roughly 18 'equivalent' multiple, near-parallel, fractures. Since no significant barriers to fracture growth were known to exist at the Hijiori test site, the modeled fracture geometry is radial in nature. The radial shape of the hydraulic fracture was verified

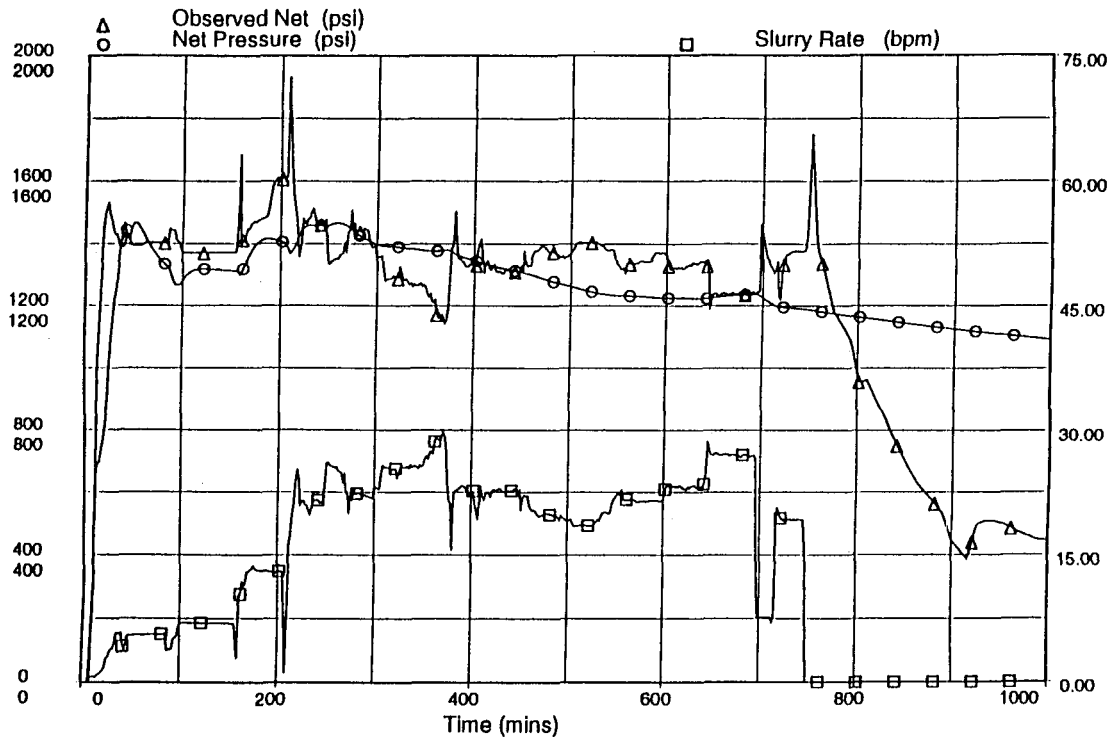


Figure 3: Net Pressure Match for HDR-1 Main Fracture Treatment

by the Acoustic Emission (AE) fracture diagnostics that were performed on the HDR-1 main fracture. Figure 4 shows three map views of the locations of the recorded high quality AE events.

The HDR-1 main fracture treatment was also analyzed using two more traditional fracture models -- the two-dimensional PKN fracture model and a 'conventional' three-dimensional fracture model. These results are shown in Table 1.

As Table 1 illustrates, the other two fracture models predict a far greater fracture radius than that predicted by the FRACPRO model (or observed by the AE diagnostics). In addition, the other models predict net fracture pressures that are more than an order of magnitude lower than the observed net fracture pressure, casting doubt on their predicted fracture dimensions even before the AE results were known. FRACPRO's ability to match the observed net pressure response and account for complex hydraulic fracture mechanisms results in an estimated fracture size and geometry that roughly match the observed AE results, but at a fraction of the cost of an AE survey.

Since the creation of an artificial reservoir is crucial to any HDR system, realistically modeling the created fracture's dimensions (i.e., reservoir size) is of paramount importance. If unrealistic fracture dimensions

are estimated, injectors and producers can be drilled too far apart yielding economically disastrous results.

CASE STUDY 2: TG-2 WELL, JAPAN

The TG-2 well, located in the Iwate Prefecture Japan, was drilled *within* 300 meters of the Matsukawa Hydrothermal Reservoir (the exact distance was not known) and was a part of NEDO's "Technology for Increasing Geothermal Energy Recovery Project". A

Table 1: Comparison of Three Fracture Simulators to Actual Acoustic Emission Data

SOURCE	FRACTURE RADIUS (METERS)	NET PRESSURE AT SHUT-IN (KSC) ¹
PKN Model	900 ²	7
Conventional 3-D	640	2
FRACPRO	145	90
AE Results	150-200	

NOTE: 1. Observed Net Pressure was 90 KSC
 2. Fracture Length assuming height equal to open hole interval (55 m)

series of injection tests were performed in January and September of 1992, prior to the November 1992

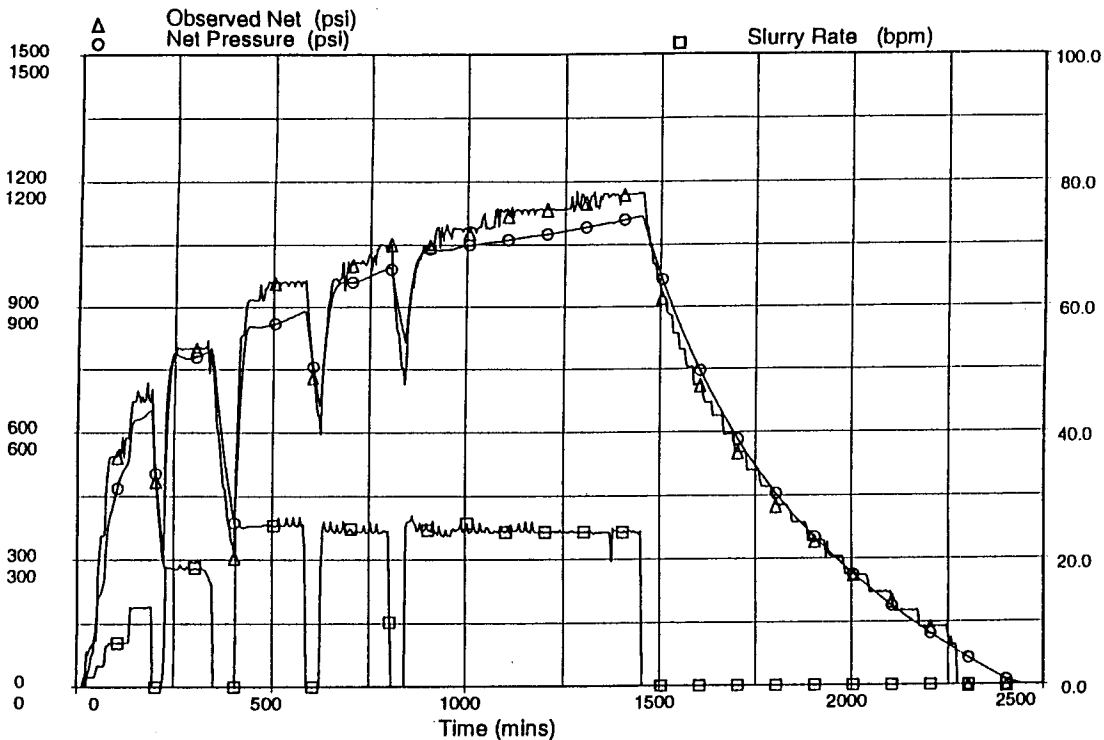


Figure 5: Net Pressure Match for TG-2 Massive Fracture Treatment

This net pressure match concluded that a fracture radius of 94 meters (310 ft) and a maximum total hydraulic fracture width of 58 mm (2.28 inches) was achieved. In addition, the net pressure matching also concluded that multiple (19 'equivalent') hydraulic fractures were created during the stimulation. As in the previous example, since no barriers to height growth were known to exist, the modeled fracture propagated radially from the wellbore.

While the massive frac of the TG-2 well failed to achieve the initial goal of establishing communication with the prolific Matsukawa reservoir, the series of tests performed did provide tremendous insight into the process of fracturing hydrothermal reservoirs and the range of achievable results. It was also the first time a real-time hydraulic fracture modeling technology had ever been employed in a geothermal reservoir.

CONCLUSIONS

- (1) Effective hydraulic fracture stimulation is essential to the technology of producing power from Hot Dry Rock reservoirs.
- (2) Hydraulic fracture stimulation can also be applied to hydrothermal reservoirs to increase production (and improve the economics) by enhancing the

communication with the reservoir's natural fracture system.

- (3) Careful analysis of observed data from hydraulic fracturing treatments has revealed the inadequacy of conventional fracture modeling approaches in predicting created hydraulic fracture dimensions and geometry.
- (4) Expanded (from conventional) physical modeling capabilities are required for realistic hydraulic fracturing modeling, particularly in geothermal reservoirs.
- (5) Real-time analysis provides critical information on-site and *in time* to make necessary design changes during fracturing operations.

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