# HYDRAULIC FRACTURING TEST AND PRESSURE BEHAVIOUR ANALYSIS FOR FRACTURE EVALUATION

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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. The hydraulic fracturing technique of well stimulation can provide a useful method for improving well productivity in geothermal reservoirs. To evaluate the created fracture geometry by hydraulic stimulation in geothermal well, we apply the real-data, three-dimensional hydraulic fracturing simulator. The fracture simulator provided realistic modeling of the mechanics of fracture propagation as well as allowing the approximate modeling of the simultaneous propagation of the multiple hydraulic fractures.

This paper presents the results from performing hydraulic fracturing treatments in three geothermal reservoirs (two 'HDR', one 'wet'). The net pressure matching indicated that multiple hydraulic fractures were created during the stimulation. AE measurements and PTS log results also support the evaluated geometry by the simulation. As a conclusion, the Multi-fracture analysis technique will be useful for the evaluation and design of hydraulic fracturing treatments through case studies.

## 1. 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 or fractures. 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. The retained hydraulic conductivity of the generated fractures (which are often held open by pumping in particulates known as 'proppant') increases the cross-sectional area over which a wellbore contacts the 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 natura! fracture systems. Significant productivity enhancement can often be achieved by establishing the necessary communication with nearby natural fracture systems through hydraulic fracture stimulation.

Hydraulic fracture stimulation plays an indispensable role in the extraction of heat from Hot Dry Rock (HDR) reservoirs. Efficient energy production depends not only on achieving effective hydraulic fracture stimulation of a large volume of reservoir rock, but also on possessing the modelling and diagnostic capability required to optimally design hydraulic fracture stimulations and to reliably estimate the geometry and dimensions of the induced hydraulic fracture systems.

This paper outlines some of the basic concepts behind hydraulic fracturing and briefly overviews the current modeling approaches. 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 three separate field sites. The fracture simulator provides realistic modelling of the mechanics of fracture propagation, as well as allowing the approximate modelling of the simultaneous propagation of the multiple hydraulic fractures which were generated on these stimulations. Finally, three case studies of hydraulic fracturing applications -- two in an HDR reservoir and the other in a (nominally) hydrothermal reservoir -- are presented with detailed analysis of collected treatment data. Results from an extensive Acoustic Emission (AE) and Pressure/Temperature/Spinner (PTS) logging surveys for fracture diagnostics are also presented as independent measures of the actual created hydraulic fracture geometry. The final section presents a summary of conclusions.

## 2. MODELING OF HYDRAULIC FRACTURES

Early fracture models, which are still in 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 ten 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 modelling 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 modelling approaches.

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. The initial effort focused on comparing carefully collected field data sets from dozens of actual hydraulic fracture stimulations to the predictions from existing 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 behaviour 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.

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 model can therefore run much faster than real time, as required for on-site pressure history-matching. 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 behaviour, 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 modelling 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 do not '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 modelling 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 microcracks, 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 complementary, 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 modelling. The goal of FRACPRO is to determine the areal 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).

## 3. REAL-TIME FRACTURE ANALYSIS

The achievement of 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 matches 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.

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 propertics 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.

## 4. CASE STUDY 1: HDR-1 WELL, JAPAN

The HDR-1 well is located at the Hijiori Japanese Hot Dry Rock Test Site. As with typical HDR reservoirs, the pre-existing natural fracture system at the Hijiori site does not 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 hydraulically fractured openhole wellbore section is at a measured depth of 2,151m - 2,200m).

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 (23.8 MPa) and the value of the reservoir leak-off coefficient (approximately 6.1 x $10^{-5}$ m/√min) for the Hijiori deep reservoir, and to evaluate the effectiveness of the main hydraulic fracture treatment. The main fracture treatment consisted of 2,100 $m^3$ of fresh water pumped at an average rate of 3,600 l/min (60 l/sec). The total treatment schedule was approximatelv 12 hours. The collected treatment data were analyzed by matching the net pressures using the FRACPRO system. Core-derived reservoir mechanical properties and log-derived natural fracture descriptions were used in the analysis. Figure 1 illustrates the observed net pressure to simulated net pressure match.

As Figure 1 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 modelled 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 and a maximum total hydraulic fracture width of 40 mm was achieved. Modelling 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 modelled fracture geometry is radial in nature. The radial shape of the hydraulic fracture was verified by the Acoustic Emission (AE) fracture diagnostics that were performed. Figure 2 shows three map views of the locations of the recorded high-quality AE events which were observed by tri-axis downhole AE measurement at the SKG-2 well located near the HDR-1 well. The PTS logging during injection of water shows five locations of zones within the openhole section that are taking the injected fluid.

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 two other 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 to account for complex hydraulic fracture mechanisms results in an estimated fracture size and geometry that roughly match the observed AE results.

## 5. CASE STUDY 2: TG-2 WELL, JAPAN

The TG-2 well, located at the Iwate Prefecture Japan, was drilled within 300 meters of the Matsukawa Geothermal Reservoir. A series of injection tests were performed in January and September of 1992, prior to the November 1992 massive fracture treatment. The goal of the massive stimulation was to create a hydraulic fracture extending from the TG-2's open hole wellbore section (710m - 1,298m measure depth) to the existing Matsukawa reservoir. In this way, the hydraulic fracture would

communicate with the hydrothermal reservoir and produce its steam and hot water.

FRACPRO was utilized to collect data and analyze all injections in both real-time and after the stimulation. The massive hydraulic fracture consisted of 4.352 $m^3$ of fresh water pumped at approximately 4,000 l/min (66.7 l/sec). The total treatment schedule was approximately 24 hours. A series of four 30 minute shut-ins were scheduled throughout the treatment to monitor the 'permeability' of the reservoir contacted by the created hydraulic fractures. The reservoir 'permeability' was interpreted by matching the successive pressure decline data. Since the Matsukawa reservoir has a permeability $10^1$-$10^3$ times greater than the rock immediately surrounding TG-2, a dramatically higher leak-off would result if the fracture extended into the Matsukawa reservoir.

Figure 3 shows the match of modelled net pressure to observed net pressure. This net pressure match implied that a fracture radius of 94 meters and a maximum total hydraulic fracture width of 58 mm was achieved. In addition, the net pressure matching also concluded that multiple (19 'equivalent') hydraulic fractures were created during the stimulation. PTS logging, which was carried out after the massive hydraulic fracture stimulation, showed that six zones in the openhole section were taking the injected fluid.

The AE measurements diagnostic indicated a fracture propagation radius of 100m - 200m.

## 6. CASE STUDY 3: RH-15 WELL, U.K.

The RH-15 well is located at the Cornwall Hot Dry Rock Test Site in south-west England. This well was drilled in 1985 as a part of Phase 2B of the Camborne School of Mines (CSM), United Kingdom, Hot Dry Rock Project. Phase 2A of the CSM HDR project involved the drilling of *two* deep wells, RH-11 and RH-12, and establishing a disappointing recovery efficiency (30%) and a very high total system impedance (1.8 MPa/l/sec). The purpose of RH-15 was to utilize hydraulic fracturing (without proppant) to increase communication between two existing wells drilled during the first phase of the HDR project. RH-15 was drilled to a measured depth of 2,800 meters and has a bottom hole temperature of 96 degrees Celsius.

The fracture treatment for the RH-15 well consisted of 5,730 $m^3$ of viscous (SO cp) fluid. Pumping, lasting for roughly 480 minutes at an injection rate of 12,000 l/min (200 l/sec), with a brief period of injection at 15,000 l/min (250 l/sec) towards the end of the treatment. The surface and bottomhole pressure data, together with the injection rate data were gathered during the stimulation. The bottomhole pressure was around 33 5 MPa within one hour of the start of injection and rose very gradually, to roughly 34.5 MPa, by the end of injection.

Both the microseismic data and the spinner log data in RH-15 indicated that almost all of the fluid was leaving the wellbore very near the bottom of the openhole interval (2,240m - 2,390m measured depth).

After the determination of formation closure stress and removing friction pressure from the measured data, the total leak-off coefficient, fracture dimensions and number of 'equivalent' fractures were determined by matching the observed net pressures measured during the job with FRACPRO's model-calculated net pressures. As Figure 4 illustrates, a very good match was achieved in this simulation. The quality of the pressure match is attributable to the high quality of data existing for the RH-15 reservoir and stimulation treatment. Matching of the observed net pressure required a gradually increasing number of 'equivalent' fractures, with approximately 3 'equivalent' fractures at the end of pumping. This pressure match results in an estimated fracture radius of 158 m and a maximum total hydraulic width of 15.8 mm at the end of pumping.

To evaluate the propriety of the results of FRACPROs multiple fracture model, the RH-15 fracture treatment was also analyzed using two more traditional fracture models -- the two-dimensional PKN fracture model (Figure 5) and a 'conventional' three-dimensional fracture model which can handle only a single hydraulic fracture (Figure 6). Both of these Figures show that the traditional models do not match the observed net pressure and, therefore, cast serious doubt on the fracture dimensions/geometry predicted by these models. FRACPRO's ability to match the observed net pressure response and account for more complex hydraulic fracture mechanisms results in an estimated fracture size and geometry that roughly match the observed AE results.

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.

## 7. CONCLUSIONS

Effective hydraulic fracture stimulation is essential to the technology of producing power from Hot Dry Rock reservoirs. Hydraulic fracture stimulation can also be applied to hydrothermal reservoirs to increase production/injection (and improve the economics) by enhancing the communication with the reservoir's natural fracture system. From these studies, we can conclude the following:

(1) 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.
(2) Expanded (from conventional) physical modelling capabilities are required for realistic hydraulic fracture modelling, particularly in geothermal reservoirs.
(3) Real-time analysis provides critical information on-site arid in time to make necessary design changes during fracturing operations.
(4) Modelling of the simultaneous growth of multiple hydraulic fractures is one of very useful method for estimating the created fracture dimensions and geometry in geothermal reservoirs which contain natural fractures.
(5) Through case studies, the Multi-fracture analysis technique and evaluation method will be useful for the design of hydraulic fracturing treatments.

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## REFERENCES

Camborne School of Mines (1988). *Camborne Geothermal Energy Project Viscous Stimulation of Hot Dry Rock Reservoir.* Report for the Department of Energy U.K.

Cleary, M.P. (1988). Engineering of hydraulic fractures – state of the art and technology of the future. *Journal of Petroleum Technology,* pp. 13–21.

Cleary, M.P., Wright, C.A. and Wright T.B. (1991). Experimental and modeling evidence for major changes in hydraulic fracturing design and field procedures. *Society of Petroleum Engineers Gas Technology Symposium,* Houston, Texas, pp. 131–146.

Crockett, A.R., Okusu, N.M. and Cleary, M.P. (1986). A complete integrated model for design and real–time analysis of hydraulic fracturing operations. *Paper SPE* 15069*presented at the 56th California Regional Meeting of the Society of Petroleum Engineers,* Oakland, CA, April 2–4, 1986.

Hyodo, M., Inoue, K. and Takasugi, **S.** (1993). Hydraulic fracturing test and pressure behavior analysis at the HDR–1 well. *The 2nd International Hot Dry Rock Geothermal Energy Forum 1993,* Section C–6.

Hyodo, M., Shinohara, N. and Takasugi, **S.** (1993). Hydraulic fracturing test and pressure behavior analysis at the TG–2 well. *Proceedings* of *the 88th SEGJ Conference,* pp. 349–354.

Perkins, T.K. and Kern, L.R. (1961). Widths of hydraulic fractures. *Journal of Petroleum Technology,* pp. 937–949.

Wright, C.A., Tanigawa, J.J., Hyodo, M. and Takasugi **S.** (1994). Real–time and post–frac 3–D analysis of hydraulic fracture treatments in geothermal reservoirs. *29th Annual Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program.*

**Table 1. Comparison of three fracture simulators to actual acoustic emission data.**

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

Note: (1) Fracture length assuming height equal to open hole interval (55 m).
(2) Based on acoustic emission result.

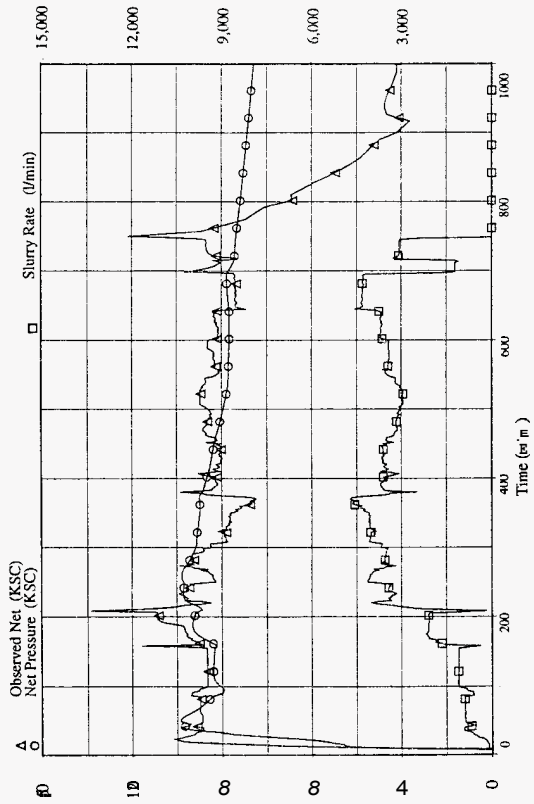


**Figure 1. Net pressure match for HDR–1 main fracture treatment.**

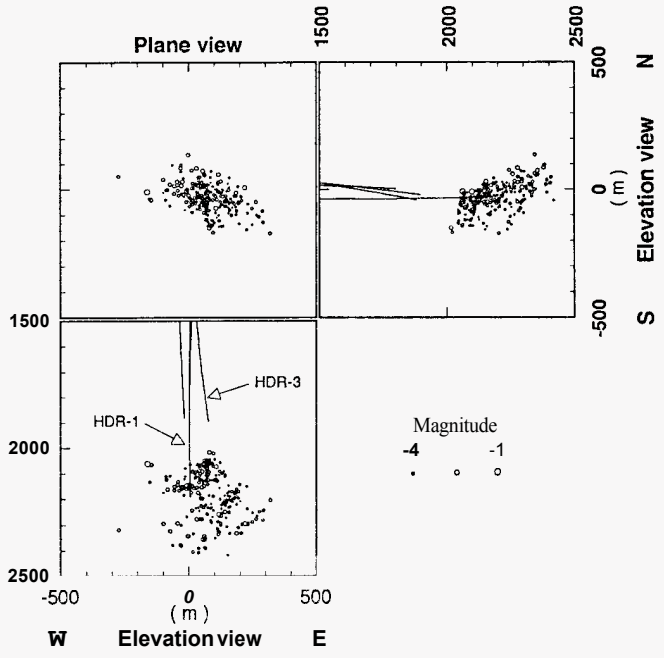


**Figure 2. Epicenter plot of AE results from HDR–1 main fracture treatment.**

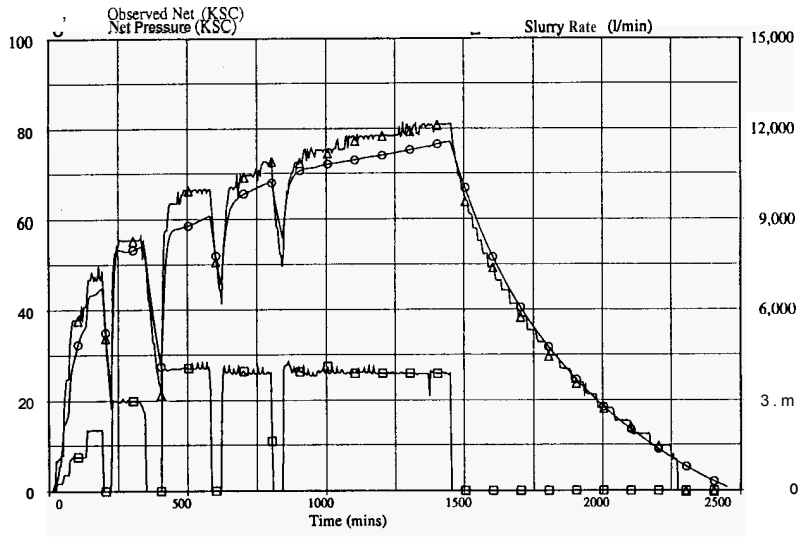


Figure 3. Net pressure match for TG–2 fracture treatment.

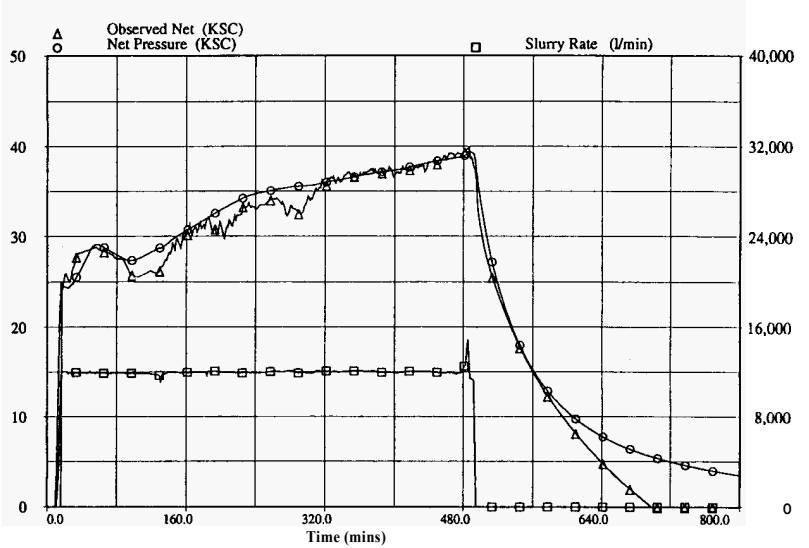


Figure 4. Net pressure match for RH–15 fracture treatment.

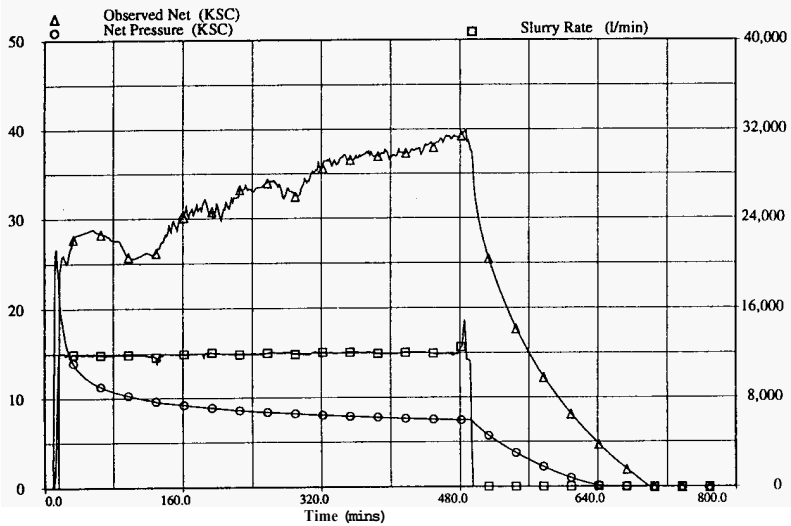


Figure 5. Net pressure match for RH–15 with single fracture.

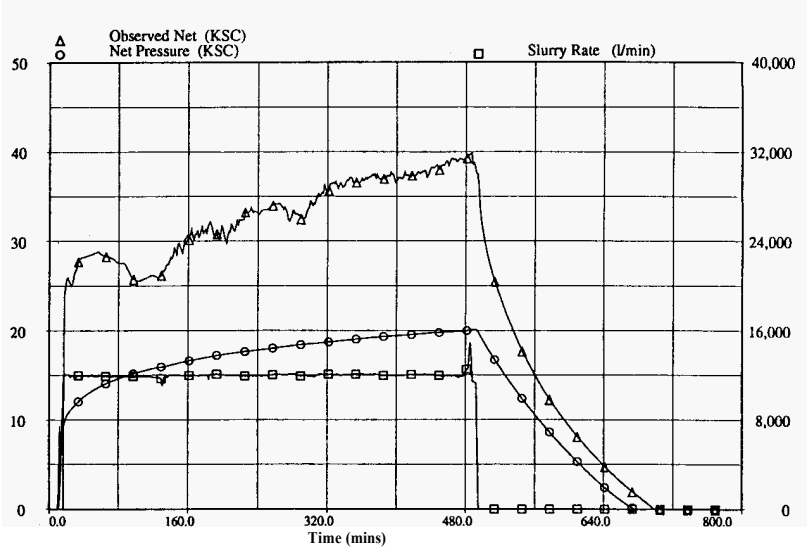


Figure 6. Net pressure match for RH–15 with PKN model.