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LA-6017-MS

Informal Report

UC-13

Reporting Date: June 1975

Issued: July 1975

Hydrologic Testing Geothermal Test Hole No. 2

by

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CONTRACT W-7405-ENG. 36

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HYDROLOGIC TESTING GEOTHERMAL TEST HOLE NO. 2

by

F. G. West, P. R. Kintzinger, and W. D. Purtymun

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ABSTRACT

Analyses of drill-stem tests performed in Geothermal Test Hole No. 2 (GT-2) indicate that the jointed, but competent, rock tested can for geothermal project purposes be considered "dry." The intervals tested were selected by the use of geophysical logs so as to exclude occasional zones of intense fracturing.

I. INTRODUCTION

Geothermal exploratory hole GT-2 was drilled under contract to the Los Alamos Scientific Laboratory (LASL) as a part of the field evaluation of the "dry hot rock" concept. The geohydrologic data presented in this report were obtained from the crystalline basement rock section of the hole, specifically from a depth of 732 m (2404 ft) to the interim total depth of 1937 m (6356 ft). Data for the sedimentary section of the hole (0 to 732 m) and data derived during the drilling phase were given by Purtymun et al.¹

The project hole is located on Fenton Hill 3.2 km (2 miles) northwest of La Cueva, Sandoval County, New Mexico. The site location is as follows: NE 1/4, Sec 13, T19N, R2E NMPM. The land surface elevation is 2648.7 m (8690 ft). The elevation of 2652 m (8701 ft) for the top of the drill-rig Kelly bushing will be used as the datum level for depths in the hole.

The project site is 3 km (2 miles) west of the ring fault zone which formed as a result of the collapse of the Valles Caldera. Faults associated with the Rio Grande rift valley are thought to be the locus of former volcanic activity.² One of these faults, the Jemez Springs fault zone, is some 5.1 km (3.2 miles) southeast of the site. The Jemez-Nacimiento Mountains area has been a structurally active area to varying degrees since Precambrian

time. Evidence of structural activity after the last eruption of the Valles Caldera is seen along the Jemez Springs fault zone, the closest being the Virgin Canyon fault.³ Some post-volcanism uplift may have taken place west of the Rio de Las Vacas in the Nacimiento Mountains. Fracture zones with unknown displacement were encountered in GT-2 as interpreted from drilling information and geophysical logs.

The hole penetrated some 137 m (449 ft) of volcanics, 238 m (780 ft) of Permian red beds, and 355 m (1165 ft) of Pennsylvanian-Mississippian shales and limestones before encountering granite at 732 m (2404 ft). The crystalline Precambrian rocks include granites, granodiorites, monzonites and some amphibolite. The textures have ranged from fine to coarse grained and the colors from pink to black. Appendix A contains a summary of drilling and geologic data by Pettitt.⁴

II. INFLUENCE OF FRACTURES ON HYDROLOGY

Knowledge of the hydrology of crystalline basement rocks has been limited for a combination of reasons. Most of the available knowledge is derived from mining operations with some small part coming from oil ventures. The relatively low permeability often found while mining in crystalline rocks has prompted the storage of oil and gas in old mines as well as in new excavations for this purpose.⁵ However, when crystalline rocks are sufficiently fractured

they are capable of transmitting oil.^{6,7} The water produced in mines is generally associated with fracture zones or patterns.^{8,9} It is not uncommon for mines, even deep mines, to be "dry."¹⁰ In regions where the water supply is derived from crystalline rocks, the ground water reservoir is usually contained in faults or joint systems.¹¹ The relative specific production capacity ($m^3/s/m$ of drawdown) of most water wells drilled into crystalline rocks is low and decreases appreciably with increased depth.^{12,13} Studies connected with the Rocky Mountain Arsenal disposal well indicated a logarithmic decrease in permeability with depth.¹⁴ Sedimentary rocks exhibit a decrease of permeability with depth as a result of the compaction and consolidation caused by the increased lithostatic load.¹⁵ The same processes contribute to the decrease of permeability of crystalline rocks; however, the principal decrease may be associated with a decrease in fracture frequency with depth.¹⁶

Coring performed in GT-2 indicates that considerable jointing exists at depth, but that most of the fissures are filled by minerals such as calcite or sericite, a condition noted by others.¹⁷

Unfortunately, as little is known about the occurrence of fractures or joints at depth as is known of the occurrence of fluids at appreciable depth. Miners and quarrymen have always been acutely aware of the nature of joints since their work, not to mention their very lives, is influenced by them. Little field work has been done to quantify the belief of miners that jointing tends to die away with depth.¹⁸ The relationship of joints with structural deformation is well recognized and defined.¹⁹ Less well defined is the belief that joints on a regional and even a global basis appear to occur in a systematic fashion with preferred orientations.²⁰⁻²³ Joint studies in oil and gas fields indicate that often a close correlation exists between the orientation of joints at depth and that of joints mapped at the surface.^{24,25} Most intrusive igneous rocks have a more or less regular fracture system that is related to the emplacement flow structure.²⁶ It has been found that even sets of microjoints often have preferred orientations.²⁷

Geophysical data such as the increase of resistivity encountered with increased depth of penetration of electric soundings^{28,29} imply a decrease

in water with depth and, as a possible corollary, a decrease in open fracture frequency. Laboratory studies suggest that the in situ seismic velocity should increase with loading, since the aperture of joints decreases, but this has not been confirmed by data obtained from two deep holes.³⁰ The nature and occurrence of fractures, hence water at depth, will in all likelihood be determined only by deep drilling in crystalline basement rocks.

III. HYDROLOGIC TESTING

Diagnostic hydrology testing in GT-2 was performed by drill-stem testing techniques typically used in oil field work. In general the procedure consists of sealing off a section of the borehole from external pressure, opening the zone to near-atmospheric pressure, allowing the formation to react to the reduced hydraulic head and then "shutting in" the zone, allowing the formation to recover toward the original pressure or fluid level.

The zone of interest is sealed off by the use of an arrangement of rubber packer elements and surface-actuated valves which are placed in the string of drill pipe. The packers are "set" when a part of the drill string weight is used to expand the packers out against the borehole wall. Pairs of packer elements are used on each side of the zone "straddled," except for tests at the bottom section of a hole where the lower pair of packers is unnecessary. The pressure history of the test is scribed on a metal foil on a downhole recording Bourdon gauge. The accuracy of the pressure gauges used is 0.25% of the total recording range.

Interpretation of geophysical logs provided the basis for the selection of zones in GT-2 to be tested. In general, the full-wave sonic log and the electrical resistivity logs were the most used logs. Zones that appeared to be competent rock with high resistivity, although jointed, were selected to the exclusion of rock with low resistivity and questionable competence, on the assumption that they would be most representative of crystalline rocks at the depths expected for "dry hot rock" operations. Due to project programmatic constraints, occasional zones of apparent intense fracturing, with one exception, were not tested at this time. Suitable packer seats were picked by a utilization of the caliper (borehole diameter) log. The geophysical logs will be discussed in a separate

report; however, copies of the logs used are included in Appendix B so that some feeling for the nature of the rock tested may be imparted.

A. Methods of Analysis

Methods for the analysis of flow of fluids in a porous fractured medium are currently being developed by various investigators.^{31,32} The work of Witherspoon³³ is quite useful in understanding the differences one may expect between flow in fractured and unfractured media, especially along a fracture zone. The data from hydrologic tests in GT-2 were analyzed initially by the equation governing unfractured isotropic media, that being the Theis recovery equation, or as it is known in oil field work the "Horner" plot. In this method, pressure is plotted against the logarithm of the ratio of the time that a hydraulic transient pressure was applied to the time since the transient was removed. The slope of the straight-line part of this semilog plot is a measure of the permeability. Extrapolation of this slope to infinite time provides an estimate of original reservoir pressure.

B. Testing in GT-2

The first zone to be tested was the bottom part of the hole, since it had been least disturbed hydrologically. This test was over the bottom 122 m (400 ft) of the hole, which included a definite fracture zone from 1829 to 1844 m (6000 to 6050 ft) having moderate permeability. The permeability of the zone apparently decreased with depth, as interpreted from the microcontact electric resistivity log--which essentially looks at near-surface borehole effects such as mud-cake buildup resulting from fluid losses. Approximately 246 m (807 ft) of water was placed in the drill pipe to prevent boiling during the flow period. During the 4-h flow period some 2.9 m³ (766 gal) of water flowed into the drill pipe, increasing the head by 146 m (479 ft) of water. The tools used for the hydraulic test automatically capture a sample of the fluid flowing through the tool, when the downhole valve is closed to start the shut-in part of the test. Although some flow occurred during this test, the sample obtained was thought to be mostly drilling fluid rather than natural formation fluid. Analysis of this sample will appear in a separate report considering the geochemistry. The 4-h shut-in-pressure recovery-period semilog data plot indicated an average permeability

of 1.6×10^{-10} m/s (0.16 microdarcy) for the 122-m (400-ft) zone. The graph did not give indications of wellbore damage or boundary effects. Extrapolation of the pressure recovery indicated a maximum initial reservoir level at a depth of 519 m (1703 ft). Assuming that for practical purposes the pressure response came principally from the 15-m (50-ft) long fracture zone, the permeability would be 1.3×10^{-8} m²/s (1.3 millidarcy). The other fracture zones encountered in the hole probably have permeabilities within an order of magnitude of that found for this zone.

Several of the succeeding tests were unsuccessful due to an "exotic" tool malfunction. The design of the tool precluded operational checks at the surface.

The next successful test was over the interval from 856 to 883 m (2808 to 2897 ft). Formation flow was allowed for a period of 2 h. The pressure chart indicated that essentially no flow had taken place; actually a slight negative pressure was recorded. The 4-h shut-in pressure curve showed a pressure step at about 2 h 30 min. This step may have been caused by a temporary unseating of the packer causing a minor positive increase in pressure, but since the basic hydrologic environment was little changed, the slope of the recovery plot was essentially the same. The permeability indicated by this test was 3.3×10^{-12} m/s (0.33 microdarcy). The initial reservoir level given by extrapolation of the semilog pressure plot is a depth of 419 m (1375 ft). During the shut-in period the drill pipe was filled to the surface for an injection test. The pressure response indicated a partial blockage in the downhole valve system. The packer assembly was then moved up the hole to test the interval from 796 to 823 m (2612 to 2700 ft). The tool system again pointed to a partial hydraulic blockage. Analysis of this pressure history, although of very doubtful quality, indicated a permeability slightly greater than that shown by the previous test, 2.4×10^{-11} m/s (2.4 microdarcys).

Two tests were again performed on one trip into the hole, the first being over the interval from 1679 to 1804 m (5509 to 5918 ft). The 2-h flow period was again marked by essentially no inflow of water. The semilog plot of the 8-h shut-in pressure-recovery curve indicated a permeability of 4.0×10^{-12} m²/s (0.4 microdarcy). The initial pressure value

extrapolated for this interval was at a depth of 255 m (837 ft).

The packers for the straddle test were unseated and moved uphole to test the interval from 1549 to 1674 m (5082 to 5492 ft). During the 2-h flow interval a slight inflow of $0.06 \text{ m}^3/\text{s}$ (15.9 gpm) was estimated from the pressure history. The shut-in pressure-recovery plot had a slight negative curvature, which might be suggestive of the response expected from a fractured medium.³⁴ While the recovery test was in progress, water was placed in the drill pipe to a depth of 203 m (666 ft) so that an injection test could be performed. The pressure-recovery curve of the shut in and the decay curve of the injection test both indicated an initial formation level of 379-m (1243-ft) depth. The permeability indicated by the standard shut-in test was $9.2 \times 10^{-11} \text{ m}^2/\text{s}$ (9.2 microdarcys). The permeability of $3.8 \times 10^{-10} \text{ m}^2/\text{s}$ (0.38 microdarcy) determined from the injection test was slightly inflated by the residual hydraulic effects of the preceding shut-in test.

The final test was over the interval of 1442 to 1564 m (4731 to 5131 ft). The 1-h flow period indicated no inflow of water. The semilog plot of the 8-h recovery curve exhibits a curvature which decreases with time. The curvature may indicate that the test zone included rocks of different permeabilities. During the last 2 h of the recovery, the plot showed appreciable leakage around the packers. The permeability determined was $1.0 \times 10^{-11} \text{ m}^2/\text{s}$ (1.0 microdarcy). The initial reservoir level was indicated at the depth of 99 m (325 ft).

It was not possible to analyze in the standard manner tests for which no inflow of water was measured, since a determination of flow volume is required. The flow was estimated by converting the pressure increase measured during the shut in to the volume of water represented by this pressure increase.

C. Additional Methods of Analysis

Several additional methods of data analysis were tried with varying degrees of success. The initial formation pressure levels estimated by the Theis recovery plot were in reasonably good agreement with those obtained by the method of Muskat.³⁵ The pressure data were also plotted on log-log paper and compared with the type curve of Theis³⁶ for

nonleaky artesian aquifers and with the type curves of Hantush³⁷ for leaky artesian aquifers. The tests appeared to have some small amount of aquifer leakage. Considering the low permeabilities observed, the effect observed was probably due to slight hydraulic end effects caused by the packers. This situation will tend to give inflated values of permeabilities. The assumption used in the Theis analysis is that of an infinite line source, whereas our packer situation is somewhere between the physical model of a semi-infinite line source and a point source. The type curves of Papadopoulos³⁸ were also tried, but little "fit" was found.

It should be pointed out that the "initial" formation fluid levels or the equivalent pressures estimated from the semilog recovery plots may only reflect a long-period transient caused by exposure to a fluid column extending upward to land surface. During the drilling of the sedimentary section, the water table was found at a depth of 536 m (1760 ft). The "initial" formation hydraulic levels estimated from the drill-stem tests were in all cases at lesser hole depths than the main level, which implies artesian conditions, geopressurization, aquathermal pressurization or a transient of over-pressurization. It is improbable that the crystalline basement rocks would have a hydraulic continuity with the lateral extent necessary for a connection to a recharge area of the appropriate elevation. Geopressurization is a compaction- and consolidation-related phenomenon of abnormally high fluid pressures occasionally found in sedimentary rocks, but not usually associated with crystalline basement rocks. Aquathermal pressures can result when rock in which the water is confined is subjected to an elevation in the isotherms. Over-pressurization and hence fluid injection probably occurs in most holes during the drilling phase as a result of the maintenance of drilling-mud levels to above land surface. Since the period of application of this pressure level in GT-2 was several orders of magnitude longer than the drill-stem tests, any determination of a true "initial" formation pressure is doubtful. The initial formation-fluid pressures estimated will be effective pressures experienced during hydrofracturing operations for a distance out from the borehole dependent on the permeability, injection pressure, and period of over-pressurization.

IV. CONCLUSIONS

The permeabilities measured in this series of tests are comparable with those reported in the literature.³⁹ Whether these values are representative of what one would find upon extensive drilling is problematic. The permeabilities measured are certainly considered "dry" by the standards of the irrigation farmer, the oil producer, or even the geothermal steam-well developer. The permeabilities measured would at this time seem to fit the current project objectives and needs for "dry" rock.

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SUMMARY OF DRILLING, CASING, CEMENTING AND GEOLOGIC DATA

LOS ALAMOS DRY GEOTHERMAL SOURCE DEMONSTRATION PROJECT
GEOTHERMAL TEST HOLE NO. 2
(GT-2)

SUMMARY OF DRILLING, CASING, CEMENTING AND GEOLOGIC DATA

Sheet 1 of 2

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LOS ALAMOS DRY GEOTHERMAL SOURCE DEMONSTRATION PROJECT
GEOTHERMAL TEST HOLE NO. 2 (CONTINUED)
(GVT 2)

SUMMARY OF DRILLING, LOGGING, CEMENTING AND GEOLOGIC DATA

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(Page 2 of 2)

DATE		DRILL		CUTTER		REMARKS		CORE DATA	
DATE	TIME	DRILL	TIME	CUTTER	TIME	REMARKS	REMARKS	DEPTH	DIAMETER
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1962	10:05	100	10:05	100	10:05	100	100	100	100
1962	10:10	100	10:10	100	10:10	100	100	100	100
1962	10:15	100	10:15	100	10:15	100	100	100	100
1962	10:20	100	10:20	100	10:20	100	100	100	100
1962	10:25	100	10:25	100	10:25	100	100	100	100
1962	10:30	100	10:30	100	10:30	100	100	100	100
1962	10:35	100	10:35	100	10:35	100	100	100	100
1962	10:40	100	10:40	100	10:40	100	100	100	100
1962	10:45	100	10:45	100	10:45	100	100	100	100
1962	10:50	100	10:50	100	10:50	100	100	100	100
1962	10:55	100	10:55	100	10:55	100	100	100	100
1962	11:00	100	11:00	100	11:00	100	100	100	100
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1962	11:30	100	11:30	100	11:30	100	100	100	100
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1962	12:05	100	12:05	100	12:05	100	100	100	100
1962	12:10	100	12:10	100	12:10	100	100	100	100
1962	12:15	100	12:15	100	12:15	100	100	100	100
1962	12:20	100	12:20	100	12:20	100	100	100	100
1962	12:25	100	12:25	100	12:25	100	100	100	100
1962	12:30	100	12:30	100	12:30	100	100	100	100
1962	12:35	100	12:35	100	12:35	100	100	100	100
1962	12:40	100	12:40	100	12:40	100	100	100	100
1962	12:45	100	12:45	100	12:45	100	100	100	100
1962	12:50	100	12:50	100	12:50	100	100	100	100
1962	12:55	100	12:55	100	12:55	100	100	100	100
1962	13:00	100	13:00	100	13:00	100	100	100	100
1962	13:05	100	13:05	100	13:05	100	100		