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INJECTION TESTING AT RRGI-4 RAFT RIVER, IDAHO
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INTRODUCTION

Injection testing of a 866 m (2840 ft) deep well, RRGI-4, within the Raft River KGRA began in March and concluded in June 1978. The purpose of the testing was to determine the hydrogeologic characteristics of an intermediate zone above and adjacent to the primary geothermal producing zone(s) and to ascertain the feasibility of injecting "cold," unaerated water into a zone hydraulically connected to the producing zone(s). This paper discusses the results and conclusions drawn from the longest duration test, conducted between May 30 and June 9, 1978, of the testing program. Reservoir Engineering hydrogeologists consider the data produced by this test to be the most representative of that portion of the Raft River KGRA penetrated by RRGI-4. The results of all testing, production, and injection conducted at RRGI-4 will be published at a later date by EG&G Idaho, Inc.

The Raft River facility is being developed to assist in the commercialization of moderate-temperature geothermal resources. The initial Raft River power system will attempt to generate five megawatts of electrical power from a 143 °C (290 °F) resource by using a binary organic cycle.[1]

Geologic Structure

Southern Idaho's Raft River valley (Figure 1) lies in a north-trending basin, warped and down-faulted in late Cenozoic time. The basin is filled to an inferred depth of 1800 to 2000 m (5900 to 6600 ft).[2] Faults located near the Raft River facility (Figure 2) include the Narrows Structure, thought to be a northeast-trending normal fault, dipping steeply toward the southeast, and the Bridge Fault, a north-trending fault, dipping steeply toward east.

RRGI-4 (Figure 3) located 475 m (1559 ft) south of RRGE-1 is 866 m (2840 ft) deep and is cased to a depth of 560 m (1840 ft). RRGI-4 penetrates alternating sand, gravel, silt, and tuff (Figure 2) of the Raft River and Salt Lake Formations. Geologic relationships (Figure 2) indicate that the Narrows Structure should have been penetrated by RRGI-4. No evidence of faulting was revealed from return drill cuttings to total depth and borehole geophysical logging to a depth of 554 m (1820 ft). Faulting is suggested by the anomalously high temperature of 120 °C (250 °F) at a depth of 560 m (1840 ft).

Well Construction

Table I lists construction characteristics of RRGI-4 and the observation wells used during the testing of RRGI-4. RRGE-1, RRGE-2, and RRGE-3 penetrate the geothermal resource. Monitor wells (MW) monitor pressure changes in aquifers, above the geothermal resource, which supply water for irrigation and domestic uses.

The variation in well depths and casing of observation wells and the complex and heterogeneous hydrogeologic system did not facilitate the interpretation of observation well data. The production, at various times, of RRGE-1, RRGE-2, and MW-2 and the drilling of RRGP-5 resulted in additional factors which had to be considered when interpreting the data. Observation well data were unsuitable to calculate or estimate the aquifer parameters: intrinsic transmissivity kh, transmissivity T, storativity ϕch, and/or storage coefficient S.

Hydrogeology

The spatial configuration of the fault zones, the Narrows Structure and the Bridge Fault, and the hydrogeologic characteristics of the fault zones and the surrounding rock are only generally understood with subsurface detail lacking.[2] RRGI-4 appears to be on the downthrown side of the Narrows Structure. Geothermal waters leaking from the fault zones migrate laterally toward the southeast as part of the valley flow system. Hot water can therefore be encountered in both the valley flow system, immediately down gradient of the fault zones, and in the fault zones.

Water chemistry data[3] indicate two sources for water in the geothermal resource. RRGE-1 and RRGE-2, which penetrate the Bridge Fault, represent one chemical type. RRGE-3, USGS-3, and RRGI-4, of the other chemical type, are thought to either penetrate the Narrows Structure or to be completed in a zone whose waters originate in the Narrows Structure.

If RRGI-4 penetrates the Narrows Structure, the injection of water into RRGI-4 can be expected to generate greater hydraulic responses in the upper portion of the fault zone than in unfractured rock. Observation well USGS-3 appears to be located in the upper portion of the fault zone. MW-1 apparently monitors the pressure in the unfractured rock adjacent to the Narrows Structure.

INJECTION TEST - MAY 30 TO JUNE 9, 1978

Method of Evaluation

The Jacob straight-line modification[4] of the Theis Nonequilibrium Equation was applied in analyzing pressure changes occurring within the Raft River KGRA during the RRGI-4 testing. The Jacob method utilizes a semilogarithmic graph of pressure buildup on the arithmetic scale versus the time since injection began on the logarithmic scale. The pressure drawdown or buildup data, plotted as a straight line when u, the Theis variable of integration, is less than or equal to 0.01. This condition occurred when the quantity of water being released from or taken into storage between the injection well and the point of observation was negligible compared to the changes in storage at a

TABLE I

Observation Wells Used During the Testing of RRGI-4

Well	Radius†	Depth	Casing‡
RRGE-1	1559 ft N 475 m	5000 ft 1524 m	3600 ft 1097 m
RRGE-2	5400 ft NNE 1650 m	6500 ft 1981 m	4200 ft 1280 m
RRGE-3	5300 ft SSE 1620 m (not monitored)	5400 ft 1645 m	4227 ft 1288 m
USGS-3	2300 ft W 700 m	1423 ft 434 m	900 ft 274 m
MW-1	700 ft SSE 210 m	1309 ft 399 m	1200 ft 366 m
MW-2	1850 ft SE 560 m	570 ft 170 m	540 ft 160 m
BLM	4000 ft NNW 1220 m	413 ft 126 m	--- ---
BLM Offset	4000 ft 1220 m	405 ft 123 m	65 ft 20 m
RRGI-4	--- ---	2840 ft 866 m	1820 ft 555 m

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†Distance in feet (ft) and metres (m) and direction from RRGI-4 with N = North, NW = Northwest, NNE = North-Northeast, W = West, SSE = South-Southeast, and SE = Southeast

‡Cased depth

radius greater than that of the observation point. The u condition was satisfied in RRGI-4 after less than one-tenth of a minute of injection, when the effective radius of RRGI-4 was assumed to be one foot.

When using the Modified Nonequilibrium Equation, the change in pressure in pounds per square inch (psi) per logarithmic cycle (s_{10}) is used to calculate T (the product obtained by multiplying the aquifer thickness by its hydraulic conductivity, a measure of the ease with which water, under field conditions, can be transmitted through a porous material) and kh (the product of the intrinsic permeability, k, of the aquifer and its thickness, h). Due to the heterogeneous hydrologic character of the Raft River KGRA, no T or kh was calculated. An apparent T and an apparent kh was estimated to use as a basis for comparing tests. The apparent kh, expressed in millidarcy-feet (md-ft), was estimated through the formula

$$kh = \frac{5759\ Q\mu}{s_{10}}$$

where

Q = injection rate in gallons per minute (gpm)
μ = water viscosity in centipoises (cp) at 120 °C, and
s_{10} = the change in psi per log cycle.

The apparent T, expressed in gallons per day per foot of buildup (gpd/ft), was estimated through the formula

$$T = \frac{kh}{1000}\left(\frac{\gamma}{\mu}\right)(.3284147)$$

with

kh = the aquifer intrinsic transmissivity
γ = the water density at 250 °F in pounds per cubic foot (lg/ft), and
μ = the water viscosity at 120 °C in cp.

The apparent T and the apparent kh are not considered to be factual hydrogeologic entities.

Data Collection

Wellhead pressures were measured at RRGI-4 with a Heise pressure gauge and a Soltec strip chart recorder. Injection rates were quantified by passing the water through an orifice of known diameter and measuring the pressure differential across it. The temperature of the injection water and the injection rate were recorded on continuous recorders. Surface instrumentation was used to monitor wells RRGE-1, RRGE-2, USGS-3, MW-1, and MW-2. This instrumentation consisted of a digiquartz pressure transducer model 2200-A-002 interfaced to a Hewlett-Packard thermal printer model 5150 via a Parascientific digiquartz pressure computer model 600. A 60-degree, V-notch weir was used to monitor changes in artesian flow at the BLM well. A Stevens A35 water level recorder was used to measure the depth to water level in the BLM offset well.

Unsuccessful attempts were made to measure downhole pressure changes within RRGI-4 with a Hewlett-Packard temperature-pressure probe. The borehole geophysical logging cable failed due to electrical shorting within the cable, perhaps caused by the corrosive and electrically conductive action of geothermal water leaking through the cable's teflon insulation.[5]

Test Results

A 700 gpm (44 lps) injection test was initiated May 30 and terminated June 9, 1978. The test was conducted for 13,300 minutes and was terminated because the water levels in RRGE-2, which supplied water for injection, dropped to the level of the pump bowls. Initial wellhead pressure at RRGI-4 was 25 psig, suggesting that the wellbore was relatively cold. The shutin pressure following injection was 298 psig.

The deviation of points from a linear trend during the initial 25 minutes of injection were related to fluctuations in the injection rate. The injection rate varied as much as ±10 percent. The lowest acceptable variation in the injection rate during a test should be ±3 percent, but greater control of injection rates could not be attained with the procedures and equipment used.

The increase in pressure above the linear trend to the high point at 100 minutes is caused by the density effects of injecting increasingly hotter water of lower density. The decrease in pressure between 100 to 120 minutes is perhaps related to aquifer adjustments to the lower viscosity injection water, relative to formation water.

Ten pump outages occurred during the test. The effect of a pump outage on pressure buildup can be seen in Figure 4 after 120 minutes as data points which lie below the linear trend.

An apparent kh of 31,000 md-ft and an apparent T of 2600 gpd/ft were estimated from a Jacob graph of pressure buildup. The placement of the straight line after 120 minutes may be slightly in error due to pump outages. No analyzable pressure falloff data was obtained due to failure of recording instruments.

Increased wellhead pressure was observed at USGS-3 after 500 minutes (Figure 5). Pressure changes at MW-1 (Figure 6) were difficult to interpret due to water sampling of the well prior to RRGI-4 injection. The pressure increase at USGS-3 after 10,000 minutes was apparently 2.82 times greater than the increase at MW-1. This comparison assumed an initial pressure at MW-1 equal to an earlier injection test. The larger response in wellhead pressure farther from the injection well suggests a heterogeneous and/or anisotropic aquifer system.

Discussion of Results

The temperature of injection water rose from 66 °C (150 °F), the minimum temperature of injection and transfer piping preheating, to 134 °C (273 °F) during the test (Figure 4). The temperature of water being driven from the wellbore into the receiving zone(s) therefore depended on the time since injection commenced.

Examination of Figure 4 reveals an upward deviation in the data occurring between 25 and 120 minutes. The deviation is believed to be caused by temporally dependent densities and viscosities related to temperature variations between the injection water, the water in the wellbore, and the formation water. Small temperature changes of the water entering the receiving zone(s) can be expected for probably at least 10 minutes following the initiation of injection. Borehole fluid density changes can also be expected to be small during this period. Pressure buildup data collected at the wellhead during the initial 10 minutes of injection can be expected to have relatively small errors.

The linear segment in Figure 4 from 0.45 to 25 minutes implies that relatively small viscosity and density effects were occurring during this period, assuming no boundary effects. A large portion of the point scatter in the first 25 minutes is caused by variations in injection rate. Twenty minutes is the time required to inject approximately one borehole volume of water to a depth of 710 m (2340 ft). The increase in pressure, after 25 minutes, above the initial linear trend is presumed to be caused by the decreasing water density and viscosity of the hotter water as injection progresses with viscosity. The linear trend after 120 minutes has approximately the same slope as the initial linear trend. The authors believe that thermal quasi-equilibrium was established after 120 minutes. At that time the viscosity and density of the injection water was stabilized. The decline in wellhead pressure between 30 and 120 minutes is caused by the lower viscosity of the higher temperature injection water.

The maximum upward displacement of the pressure buildup above the initial linear trend appears to be related to the wellhead pressure immediately prior to injection. This wellhead pressure is strongly influenced by wellhead water temperature and the extent of preheating of the injection well. An injection test conducted on March 30, 1978 (Figure 7) did not show the upward displacement of pressure buildup as the well was thoroughly preheated before injection began, as shown by the initial wellhead pressure of 66 psig.

CONCLUSIONS

Conclusions derived from the May 30 to June 9, 1978 injection test at RRGI-4 include:

1. The response of the observation wells to injection into RRGI-4 confirmed the hydrogeologic conclusions indicated by geologic and geochemical relationships that RRGI-4 and USGS-3 penetrate the same fracture or fracture system, the Narrows Structure. The pressure responses in USGS-3, 700 m (2100 ft) to the west of RRGI-4, were greater than those in MW-1, 210 m (700 ft) to the south-southeast. It is concluded that MW-1 does not penetrate the fracture system but is in unfractured rock adjacent to and overlying the Narrows Structure. RRGI-4 and USGS-3 are on the downthrown side of the Narrows Structure with the structure being penetrated at shallower depths in USGS-3 than in RRGI-4.

2. No boundaries were detected during 222 hours of injection into RRGI-4. Although RRGI-4 penetrates a fault zone, it is believed that no boundaries were detected as pressure responses were integrated very rapidly within the fault zone and adjacent unfractured rock.

3. The temporally dependent borehole fluid temperature during injection is a significant factor which must be considered when analyzing the pressure buildup data. Downhole temperature-pressure probes must be used to determine aquifer responses during testing. The probe should be opposite the top of the uppermost highly transmissive zone and it should remain in the borehole until pressure changes occurring within the borehole correspond with those at the wellhead.

4. The aquifer parameters, intrinsic transmissivity kh, transmissivity T, storativity ϕch, and storage coefficient S, could not be determined quantitatively due to the heterogeneous and complex nature of the hydrogeology of the Raft River KGRA and the variation in well depths and casing of observation wells.

5. The wellhead and the injection water should approximate aquifer temperature before and during injection testing, to prevent pressure changes related to temporally dependent densities and viscosities.

References

1. "Regional Hydrothermal Commercialization Plan, Rocky Mountain Basin and Range Region," Dept. of Energy, 1978.
2. P. L. Williams, D. R. Mabey, A. A. Zohdy, H. Ackermann, D. B. Hoover, K. L. Pierce, and S. S. Oriel, "Geology and Geophysics of the Southern Raft River Valley Geothermal Area, Idaho, USA," Second U.N. Symposium on the Development and Use of Geothermal Resources, Proc., Vol. 2, 1976, p. 1273-1282.
3. H. L. Overton, "Hot Water Flow in Raft River Reservoir," in publication, 1978.
4. P. A. Domenico, Concepts and Models in Ground-Water Hydrology, McGraw-Hill, 1972, p. 405.
5. R. C. Stoker, personal communication, 1978.

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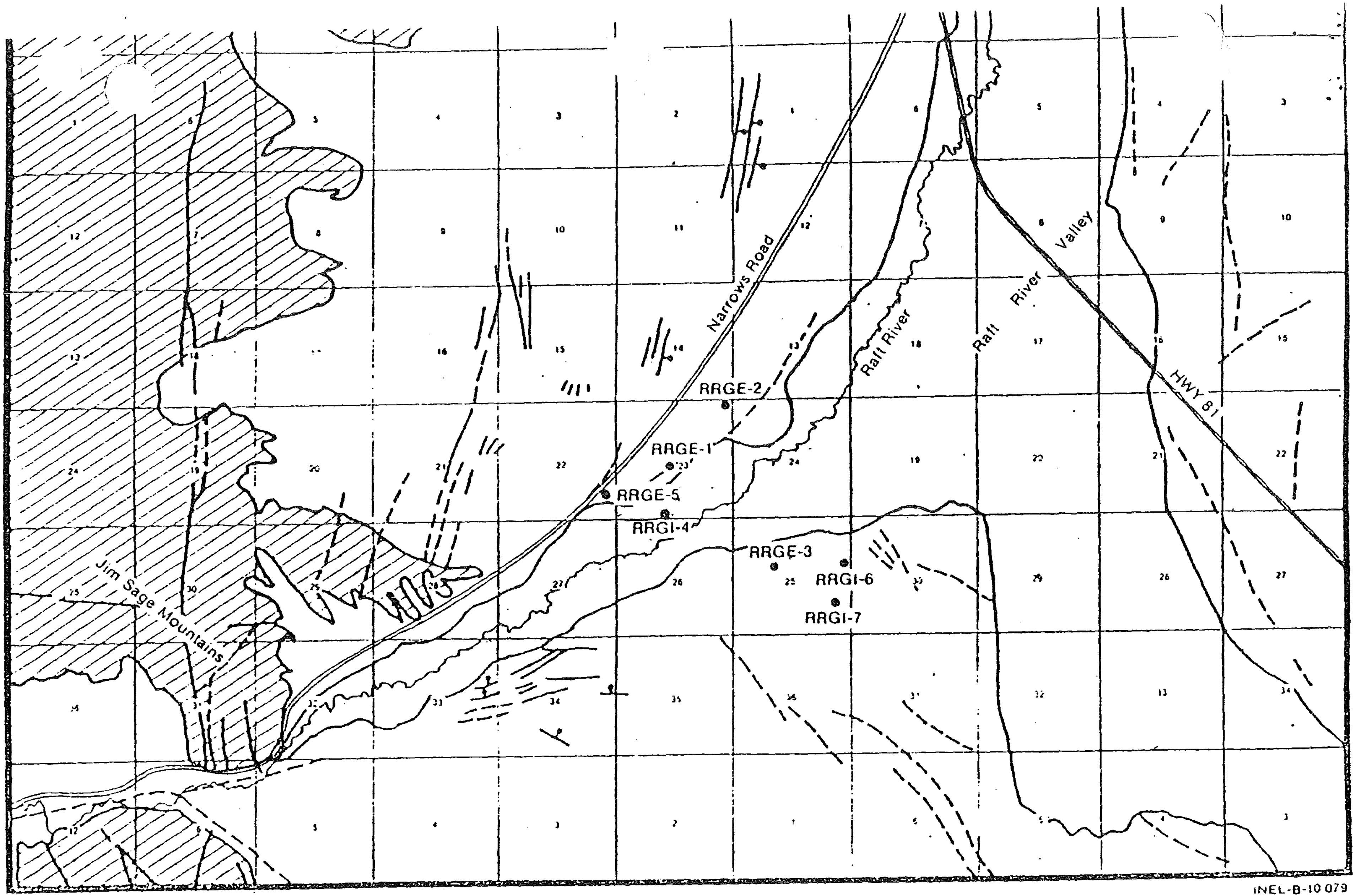


Description of Map Units

☐ Fan Alluvium (pleistocene): Undifferentiated gravels

☐ Alluvium of Major Drainages (pleistocene). Undifferentiated gravels

▨ Rocks of Jim Sage Mountains, tuffs, ash flows and lava flows (pliocene? and miocene?):

Figure 1: Surfacial Geology and Faults of the Raft River Valley

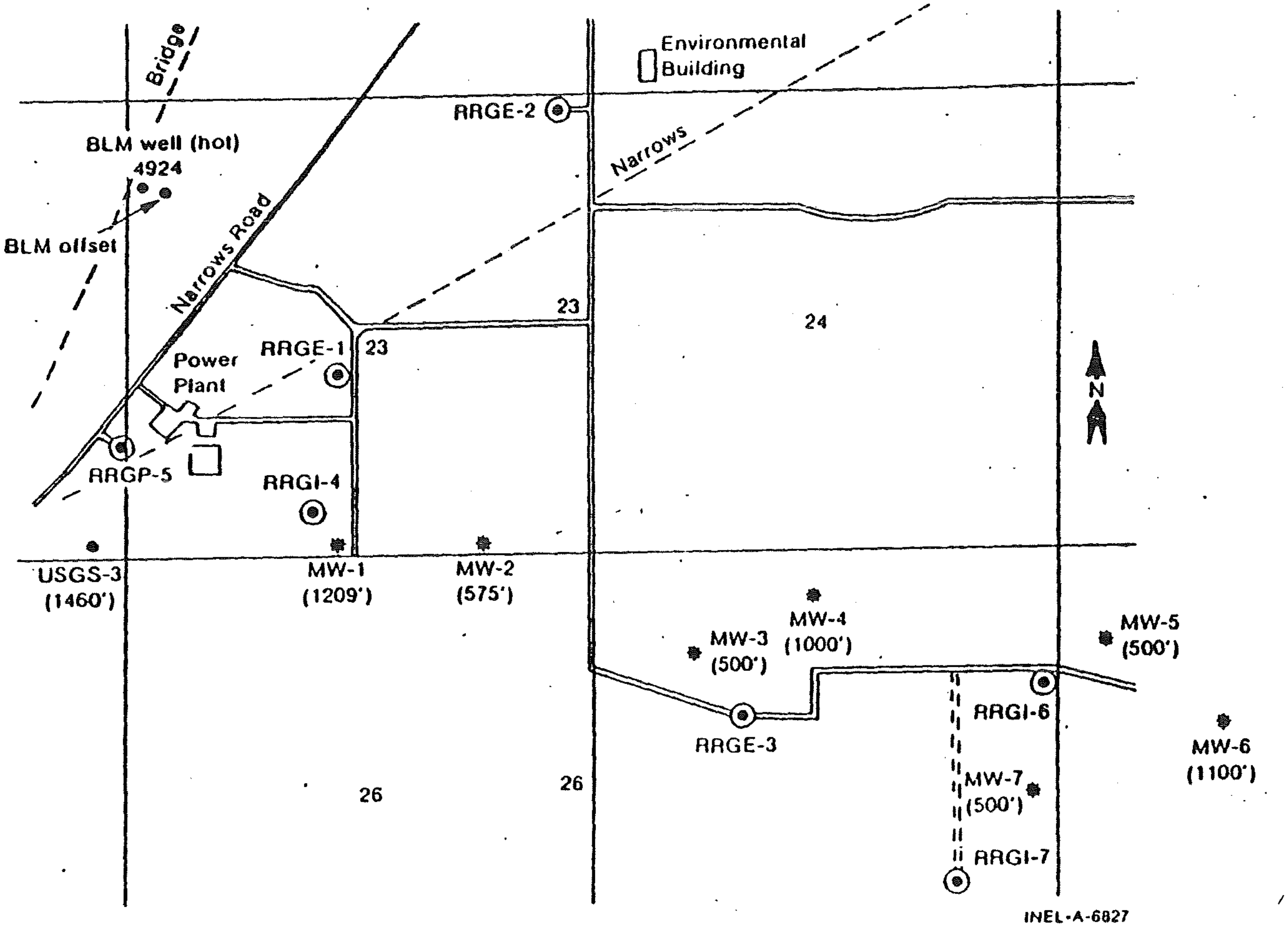
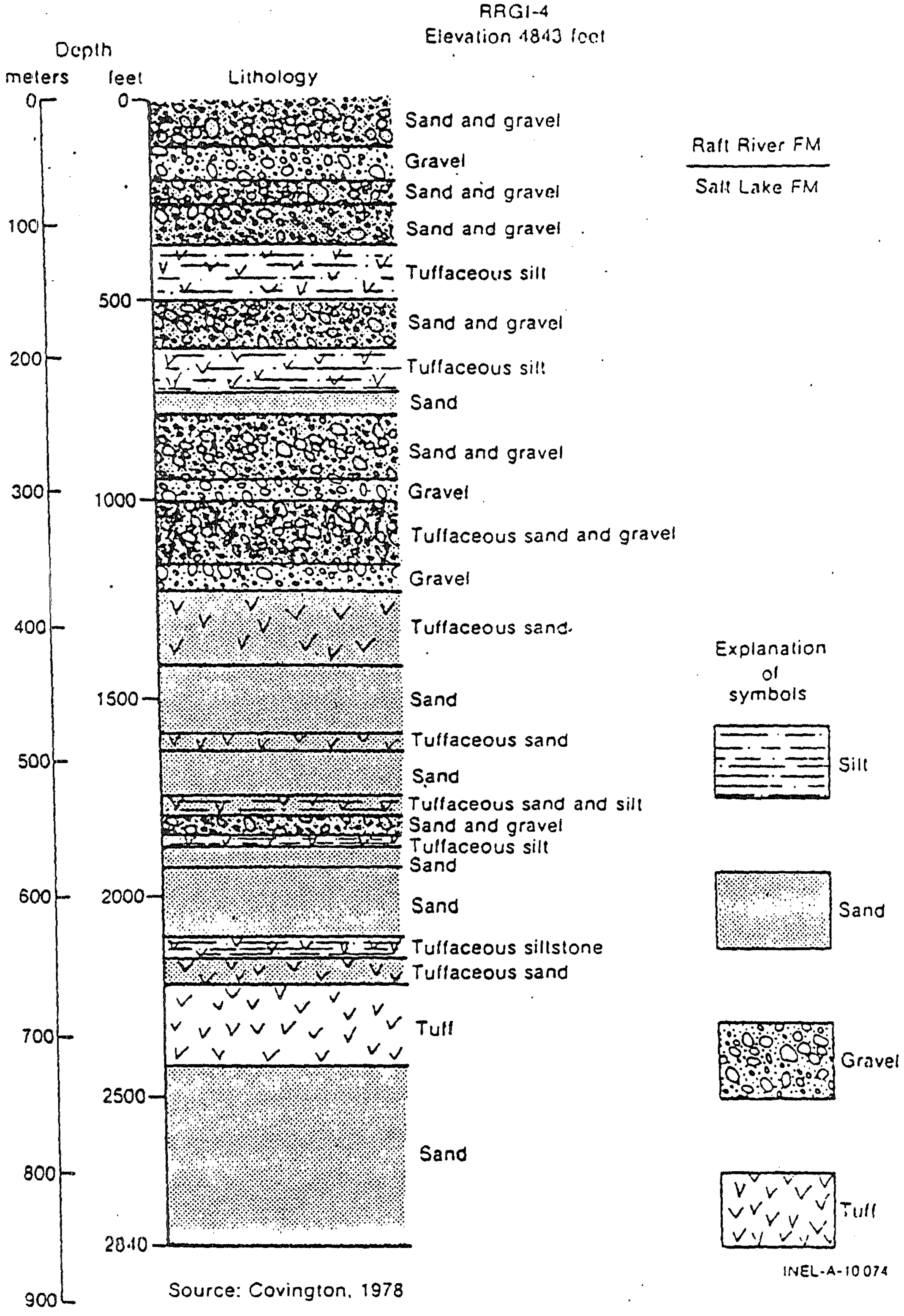
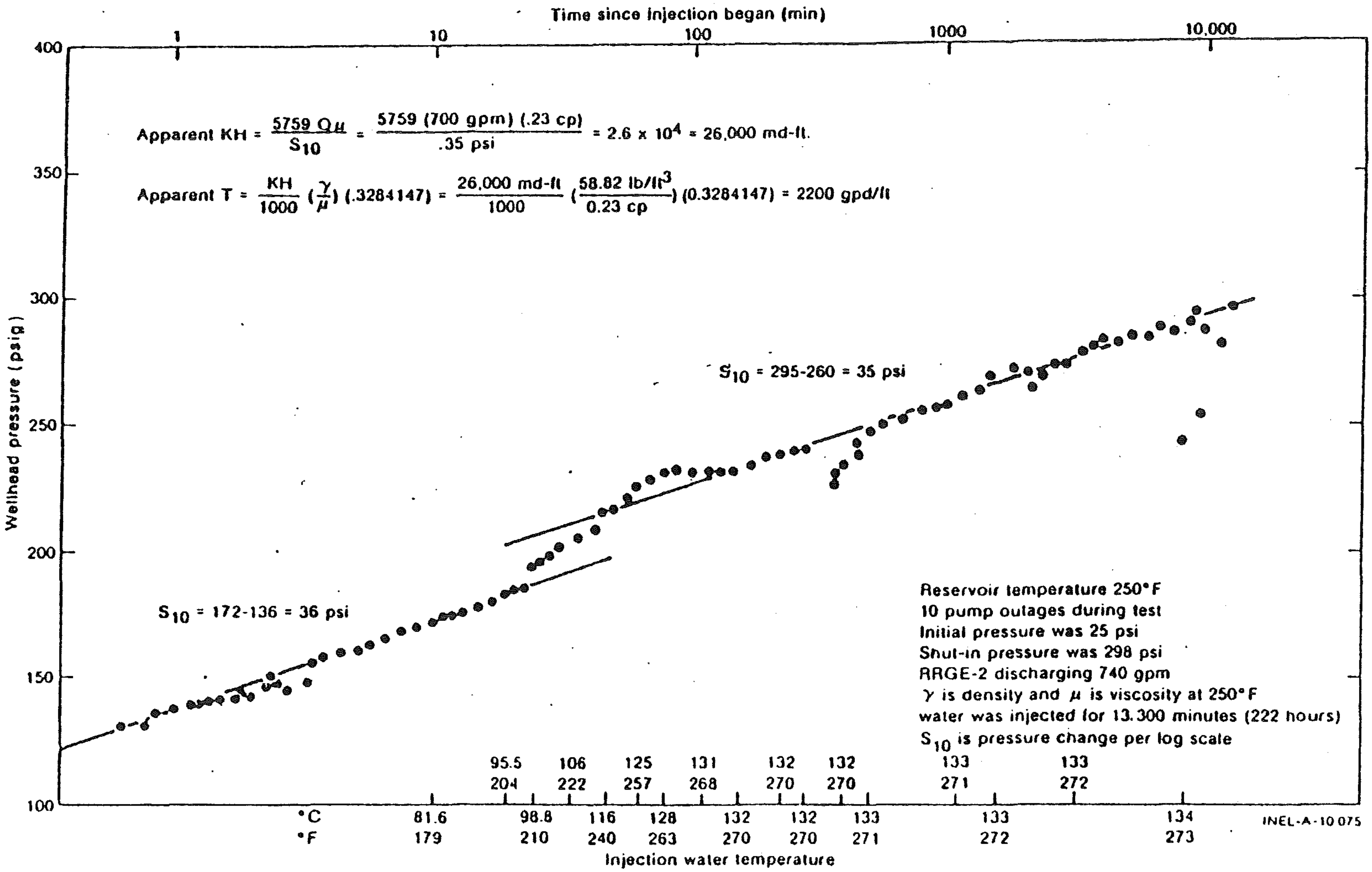


Figure 2: Raft River Facility with Geologic Structure and Well Location



Source: Covington, 1978

Figure 3: Lithologic Log RRGI-4



Apparent KH = $\frac{5759\ Q\mu}{S_{10}} = \frac{5759\ (700\ \text{gpm})\ (.23\ \text{cp})}{.35\ \text{psi}} = 2.6 \times 10^4 = 26{,}000$ md-ft.

Apparent T = $\frac{KH}{1000}\left(\frac{\gamma}{\mu}\right)(.3284147) = \frac{26{,}000\ \text{md-ft}}{1000}\left(\frac{58.82\ \text{lb/ft}^3}{0.23\ \text{cp}}\right)(0.3284147) = 2200$ gpd/ft

S_{10} = 172-136 = 36 psi

S_{10} = 295-260 = 35 psi

Reservoir temperature 250°F
10 pump outages during test
Initial pressure was 25 psi
Shut-in pressure was 298 psi
RRGE-2 discharging 740 gpm
γ is density and μ is viscosity at 250°F
water was injected for 13.300 minutes (222 hours)
S_{10} is pressure change per log scale

Figure 4: Pressure Buildup at RRGI-4 During May 30, 1978, 700 gpm Injection Test

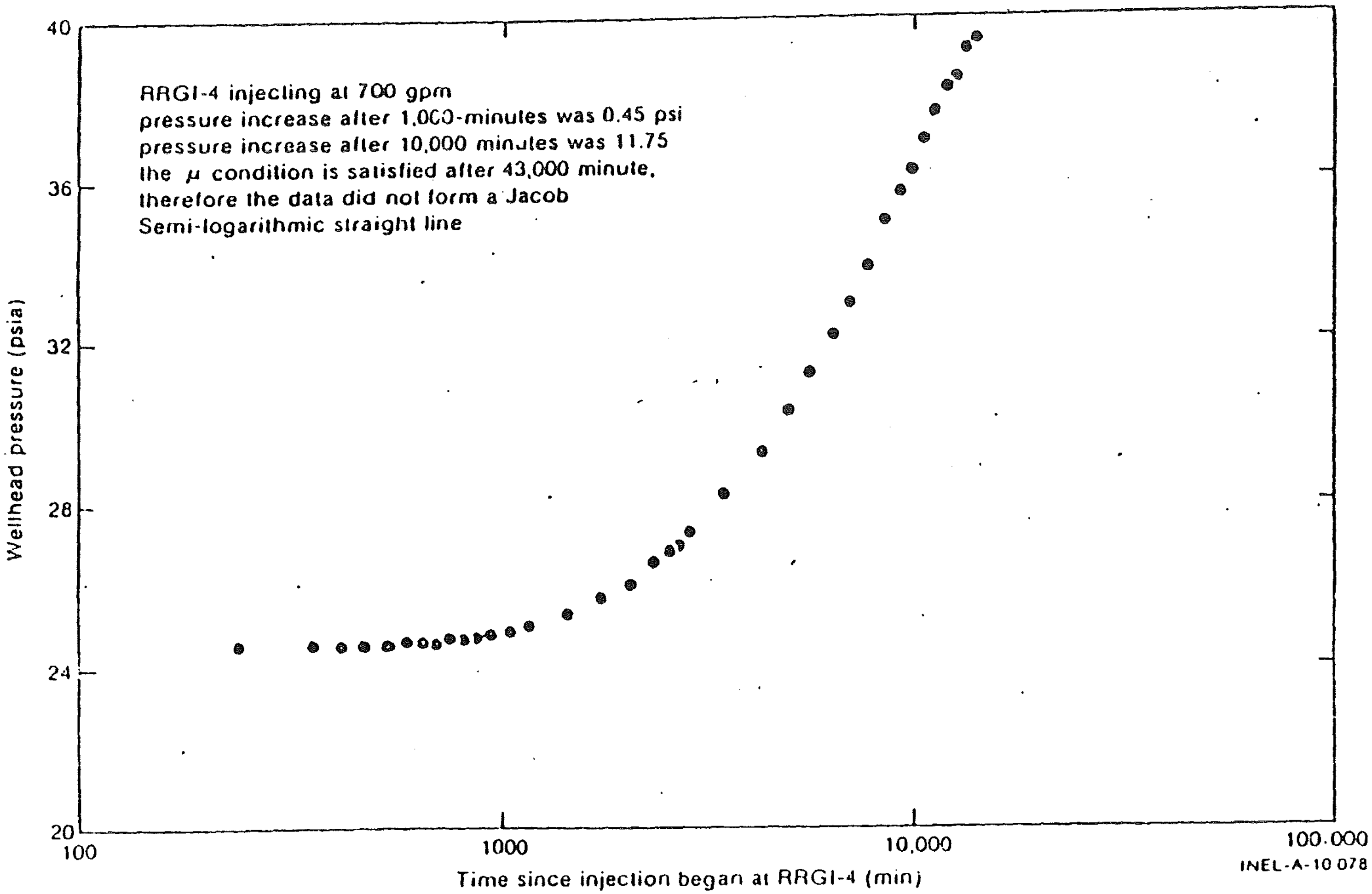


Figure 5: Pressure Buildup at USGS-3 During May 30, 1978, Injection Test at RRGI-4

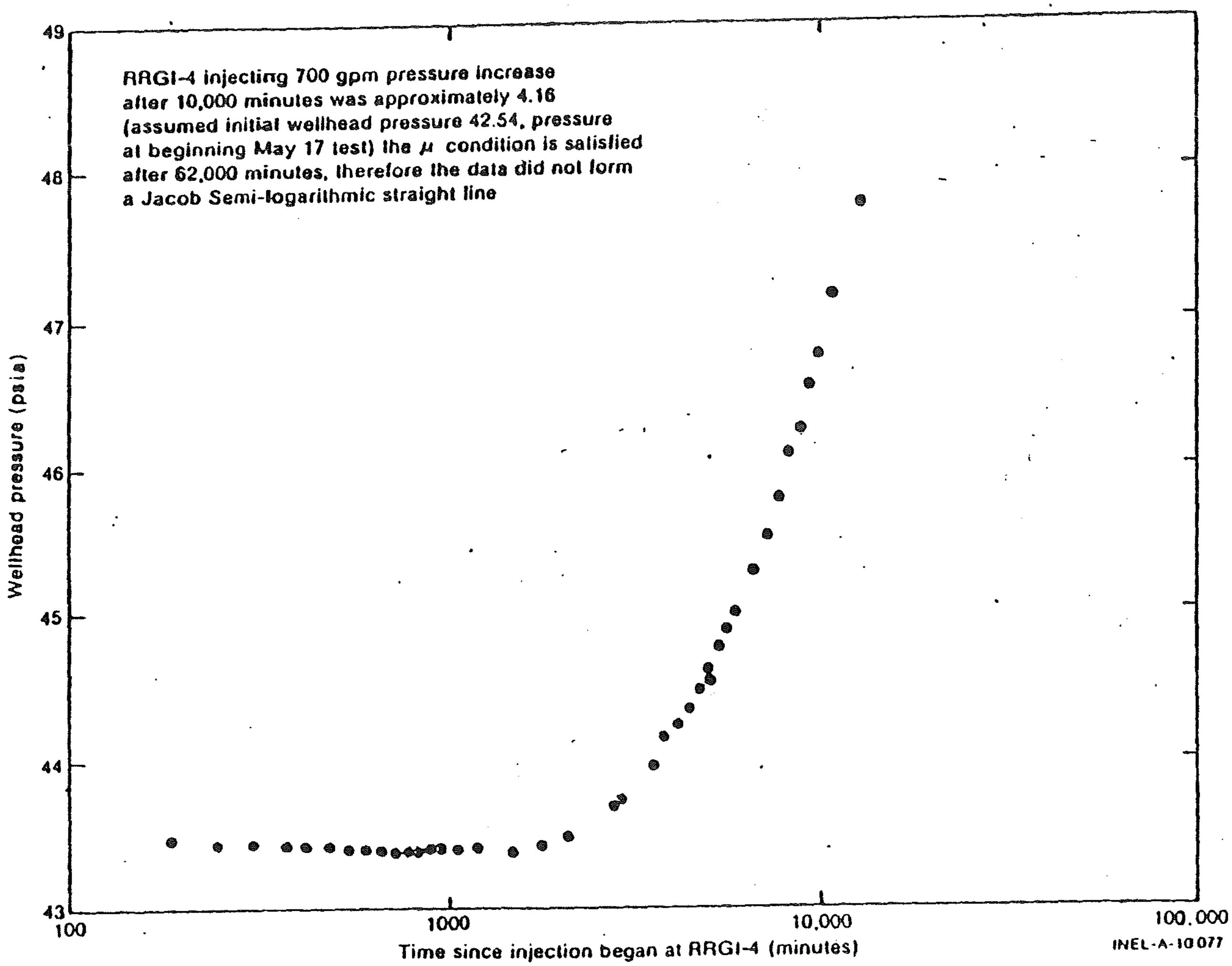
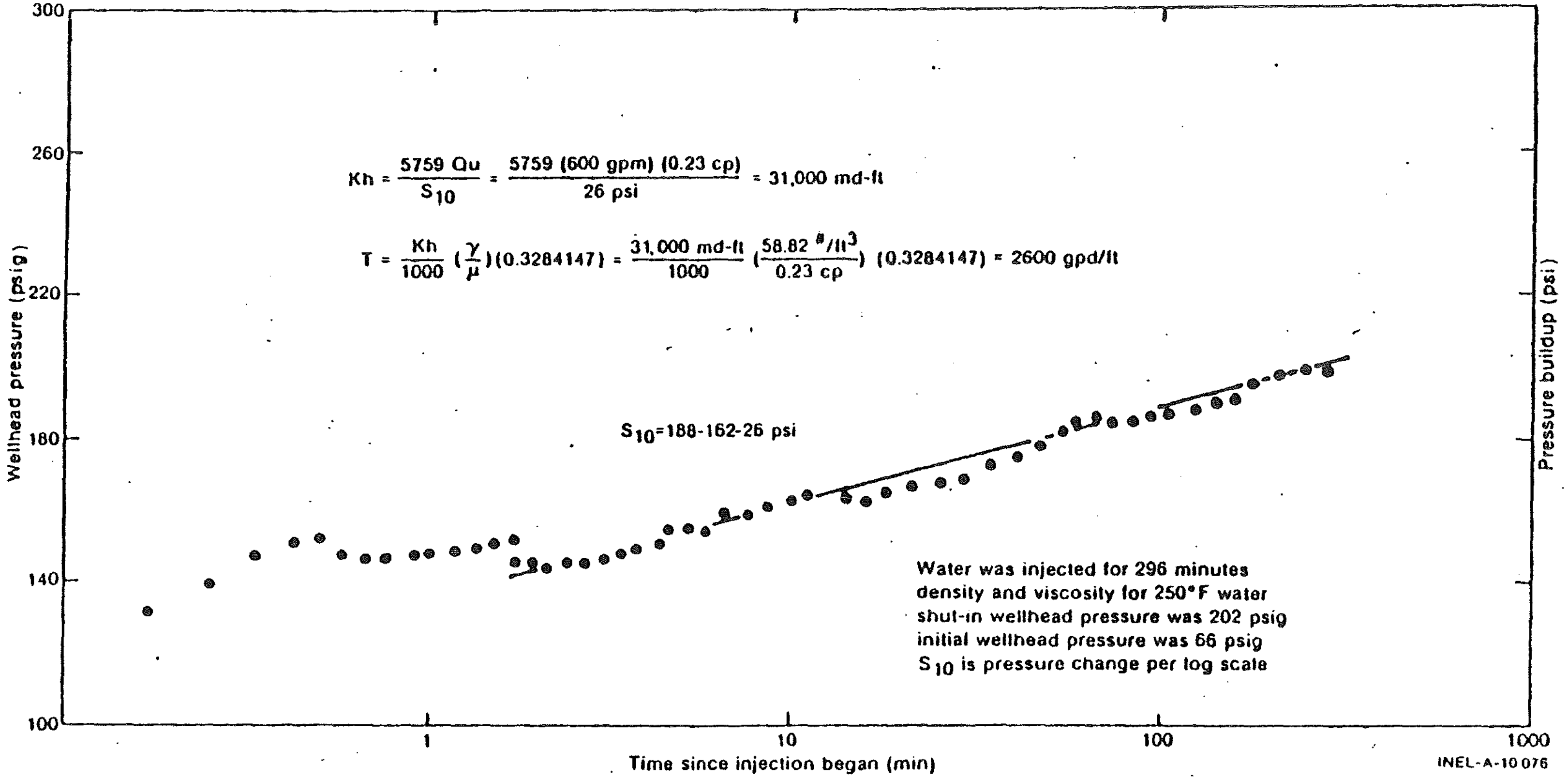


Figure 6: Pressure Buildup at MW-1 During
May 30, 1978, Injection Test at RRGI-4



$$Kh = \frac{5759\ Q\mu}{S_{10}} = \frac{5759\ (600\ \text{gpm})\ (0.23\ \text{cp})}{26\ \text{psi}} = 31{,}000\ \text{md-ft}$$

$$T = \frac{Kh}{1000}\left(\frac{\gamma}{\mu}\right)(0.3284147) = \frac{31{,}000\ \text{md-ft}}{1000}\left(\frac{58.82\ \#/\text{ft}^3}{0.23\ \text{cp}}\right)(0.3284147) = 2600\ \text{gpd/ft}$$

Water was injected for 296 minutes
density and viscosity for 250°F water
shut-in wellhead pressure was 202 psig
initial wellhead pressure was 66 psig
S_{10} is pressure change per log scale

Figure 7: Pressure Buildup at RRGI-4 During March 30, 1978, 600 gpm Injection Test