Docket 40-8768 PDR

**KERR-McGEE CORPORATION**

KERR-McGEE CENTER • OKLAHOMA CITY, OKLAHOMA 73125

ENVIRONMENT AND HEALTH MANAGEMENT DIVISION

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May 29, 1981

CERTIFIED MAIL - RETURN RECEIPT REQUESTED

Mr. John Linehan
US Nuclear Regulatory Commission
Washington, D. C. 20555

Re: Docket No. 40-8768
Kerr-McGee "Q" Sand In-Situ Project

Dear Mr. Linehan:

Please find attached a technical assessment of aquifer conditions of the "Q" Sand project established by the Kerr-McGee Corporation Hydrologic Department.

If you have any questions, please contact me.

Sincerely,

W J Shelley

W. J. Shelley, Vice President
Nuclear Licensing and Regulation

WJS/pls

Attachment

cc: Ms. Terry Vandel - USNRC

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Add'l Info

Enclosed is Kerr-McGee Corpora e Hydrology Group's assessment of leaky aquifer conditions at the Q Sand In Situ R & D Project, Converse County, Wyoming.

Observation well drawdown data from the April 1981 and December 1979 aquifer tests were plotted on log-log graph paper and subjected to the Hantush-Jacob (1955) graphical analysis technique described by Lohman in USGS Professional Paper - 708 (pertinent sections are included for your use). The Theis non-leaky type curve is drawn on each of the included graphs for visual comparison. Also, the v = 0.02 leakance deflection curve (where v is essentially equal to r/B) is drawn for the same purpose. Calculated aquifer system hydraulic properties are shown on individual graphs.

The early time (less than 100 minutes of pumping) leakance indication observed on the April 1981 plots is acknowledged, however, Kerr-McGee Hydrology believes this behavior results from aquitard storage release, a transient phenomenon which has no bearing on the long-term transfer potential of the aquifer system (Neuman and Witherspoon, 1969a and 1969b, pages 804 and 822, respectively). Similar early-time behavior was not observed on the December 1979 plots apparently as a result of variable discharge in the first 100 minutes of pumping (3% of total time).

The six drawdown plots do reveal a small leakage potential in later time. This behavior is reflected in the December 1979 plots by the slight deflection of the drawdown data track below the Theis curve and in the April 1981 plots by its incomplete return to the Theis curve following transient, early-time aquitard storage elease. The magnitude of leakance shown is generally in the v = 0.02 range where $v = \frac{r}{2}\sqrt{\frac{K'}{b'T}}$ (see attached reference).

The calculated vertical hydraulic conductivities of the confining shales for the December 1979 and April 1981 tests are in good agreement and average $2.7E^{-3}$ gpd/ft$^2$ ($9.7E^{-7}$ cm/sec) and $1.7E^{-3}$ gpd/ft$^2$ gpd/ft$^2$ ($5.9E^{-7}$ cm/sec) respectively. A combined average K' of $2.2E^{-3}$ gpd/ft$^2$ ($7.8E^{-7}$ cm/sec or $1.1E^{-1}$ ft/yr) is approximately one order of magnitude greater than the hydraulic conductivity Kerr-McGee Nuclear used in previous leakage rate calculations. The new figure is considered more representative. Previously submitted leakage rate calculations will herein be corrected for this change.

A negative hydrologic boundary in the form of a Q Sand pinch-out is not supported by the vast array of surface drill-hole geologic data in and around the project site. The sand thickness does vary markedly, however, the thinning recognized in the southwest part near monitor well QM-8 is effectively offset by an equal degree of sand thickening (relative to pumping well QP-3) to the northeast near QM-4. Also, the aforementioned thinning to the southwest does not terminate in a pinch-out. On the contrary, drill-hole data show an increase in Q Sand thickening immediately beyond QM-8.

The agruments and analyses presented in this supplement are considered technically sound and consistent with the hydro-geologic regime at the project site. Nevertheless, Kerr-McGee Hydrology realized that the myriad of variables involved in such an assessment precludes a precise all-encompassing definition of the aquifer system. Certainly we are willing to pursue any further aspects which may lead to a satisfactory scientific resolution.

Attachment 1

# REVISED R SHALE LEAKAGE CALCULATION
## Q SAND IN SITU R & D PROJECT
## CONVERSE COUNTY, WYOMING

| | | |
|---|---|---|
| Shale Vertical Hydraulic Conductivity | = $2.2E^{-3}$ gpd/ft$^2$ | (1) |
| Shale Thickness (minimum) | = 40 feet | |
| Static Fluid Level for Q Sand | = 5172 feet above MSL | (2) |
| Static Fluid Level for S Sand | = 5239 feet above MSL | (2) |
| Static Pressure Differential | = -67 feet of head | |
| Maximum Representative Stress from from Injection Without Production | = 55 feet of head | (3) |
| Pressure Differential under Maximum Stress Conditions | = -67 + 55 = -12 feet of head | |

Leakage Rate Equation:

$$v_{av} = \frac{K'I}{7.5\theta}$$

where $v_{av}$ = average velocity, in feet per day

$K'$ = vertical hydraulic conductivity of shale, in gpd/ft$^2$

$I$ = hydraulic gradient across shale, dimensionless

$\theta$ = effective porosity of shale, assumed = 0.15, dimensionless

Leakage Rate Calculations:

A - Static Condition

$$v_{av} = \frac{2.2E^{-3}(67/40)}{7.5(0.15)} = 3.3E^{-3} \text{ ft/day or } 1.2 \text{ ft/year}$$

Leakage from S Sand to Q Sand

B - Maximum Stress Condition

$$v_{av} = \frac{2.2E^{-3}(12/40)}{7.5(0.15)} = 5.9E^{-4} \text{ ft/day or } 0.2 \text{ ft/year}$$

Leakage from S Sand to Q Sand

NOTES:

(1) From leaky aquifer data analyses
(2) Hydrologic Report - Table 1
(3) Calculated pressure build-up at production well sites under injection only mode. Theis equation with superposition with T = 800 gpd/ft, S = $5E^{-5}$, t = 0.125 day, Q = 10gpm/injection well and r = 71, 158, 212, 255, and/or 292 feet. Results (in feet) are QP-1 = 52, QP-2 = 51, QP-3 = 55, QP-4 = 53, and QP-5 = 50.

Attachment 2

# REVISED P SHALE LEAKAGE CALCULATION
## Q SAND IN SITU R & D PROJECT
## CONVERSE COUNTY, WYOMING

| | | |
|---|---|---|
| Shale Vertical Hydraulic Conductivity | = $2.2E^{-3}$ gpd/ft$^2$ | (1) |
| Shale Thickness (average) | = 62 feet | |
| Static Fluid Level for Q Sand | = 5172 feet above MSL | (2) |
| Top of O Sand | = 4982 feet above MSL | (2) |
| Static Pressure Differential | = 190 feet of head | |
| Maximum Representative Stress from Injection Without Production | = 55 feet of head | (3) |
| Pressure Differential under Maximum Stress Conditions | = 190 + 55 = 245 feet of head | |

Leakage Rate Equation:

$$v_{av} = \frac{K'I}{7.5\theta}$$

where $v_{av}$ = average velocity, in feet per day
$K'$ = vertical hydraulic conductivity of shale, in gpd/ft$^2$
$I$ = hydraulic gradient across shale, dimensionless
$\theta$ = effective porosity of shale, assumed = 0.15, dimensionless

Leakage Rate Calculation:

A - Static Condition

$$v_{av} = \frac{2.2E^{-3}(190/62)}{\&.5\ (0.15)} = 6.0E^{-3} \text{ ft/day or 2.2 ft/year}$$

Leakage from Q Sand to O Sand

B - Maximum Stress Condition

$$v_{av} = \frac{2.2E^{-3}(245/62)}{7.5(0.15)} = 7.7E^{-3} \text{ ft/day or 2.8 ft/year}$$

Leakage from Q Sand to O Sand

NOTES:

(1) From leaky aquifer data analyses
(2) Hydrologic Report - Table 1
(3) Calculated pressure build-up at production well sites under injection only mode. Theis equation with superposition with T = 800 gpd/ft, S = 5E$^{-5}$, t = 0.125 day, Q = 10 gpm/injection well and r = 71, 158, 212, 255, and/or 292 feet. Results (in feet) are QP-1 = 52, QP-2 = 51, QP-3 = 55, QP-4 = 53, and QP-5 = 50.

Q-Sand Hydraulic Property Calculations

Hantush - Jacob Method (Reference attached)

Phase II Observation wells - Drawdown (April 1981)

QI - 2

$L(u/v) = 1, s = 2.35$

$1/u = 1, t/r^2 = 1.77E^{-7}$

$v = 0.02$

$$T = \frac{(16.7)(1440)(1.0)}{(4\pi)(2.35)} = 814 \text{ gpd/ft.}$$

$$S = 4(814)\frac{1.77E^{-7}}{(7.48)(1.0)} = 7.7E^{-5}$$

$$K'/b' = \frac{(4)(814)}{(7.48)}\frac{(0.02)^2}{(158)^2} = 6.97E^{-6}\text{/day}$$

$$K' = (6.97E^{-6})(40)(7.48) = 2.1E^{-3} \text{ gpd/ft}^2 = 9.8E^{-8}\text{cm/sec}$$

QI - 7

$L(u/v) = 1, s = 2.45$

$1/u = 1, t/r^2 = 9.0E^{-8}$

$v - 0.015$

$$T = \frac{(16.7)(1440)(1.0)}{(4\pi)(2.45)} = 781 \text{ gpd/ft}$$

$$S = 4(781)\frac{9.0E^{-8}}{(7.48)(1.0)} = 3.8E^{-5}$$

$$K'/b' = \frac{4(781)}{(7.48)}\frac{(0.015)^2}{(158)^2} = 3.76E^{-6}\text{/day}$$

$$K' = 3.76E^{-6}(40)(7.48) = 1.1E^{-3}\text{gpd/ft}^2 = 5.3E^{-8} \text{ cm/sec}$$

QI-11

$L(u/v) = 1, s = 2.40$

$1/u = 1, t/r^2 = 9.7E^{-8}$

$v = 0.02$

$$T = \frac{(16.7)(1440)(1.0)}{(4\pi)(2.40)} = 797 \text{ gpd/ft}$$

$$S = 4\ (797/7.48)\left(\frac{9.7E^{-8}}{1.0}\right) = 4.1E^{-5}\text{/day}$$

$$K'/b' = 4(797/7.48)\left(\frac{0.02}{158}\right)^2 = 6.82^{-6}\text{/day}$$

$$K' = 6.83E^{-6}\ (40)(7.48) = 2.0E^{-3} \text{ gpd/ft}^2 = 9.6E^{-8} \text{ cm/sec}$$

Phase I Obsercation Wells - Drawdown (December 1979)

QI - 1

$L(u/v) = 1 \quad s = 3.1$
$1/u = 1 \quad t/r^2 = 6.2E^{-7} \quad v = 0.02$

$$T = \frac{(17.7)(1440)(1.0)}{(4\pi)(3.1)} = 654 \text{ gpd/ft}$$

$$S = 4\ (654/7.48)\ (\frac{6.2E^{-7}}{1.0}) = 2.2E^{-4}$$

$$K'/b' = r(654/7.48)\ (\frac{0.02}{137})^2 = 7.45\ E^{-6}/\text{day}$$

$$K' = 7.45E^{-6}\ (40)(7.48) = 2.2E^{-3} \text{gpd/ft}^2 = 7.9E^{-7} \text{cm/sec}$$

QP - 1

$L(u/v) = 1 \quad s = 4.00$
$1/u = 1 \quad t/r \quad = 1.20E^{-6}$
$v = 0.02$

$$T = \frac{(17.7)(1440)(1.0)}{(4\pi)\ 4.00} = 507 \text{ gpd/ft}$$

$$S = 4\ (507/7/48)(\frac{1.20E^{-6}}{1.0}) = 3.3E^{-4}$$

$$K'/b' = 4\ (507/7.48)(\frac{0.020}{67})^2 = 2.42E^{-5}$$

$$K' = 2.42E^{-5}\ (40)(7.48) = 7.2E^{-3} \text{ gpd/ft}^2 = 2.5E^{-6} \text{ cm/sec}$$

QM - 1

$L(u/v) = 1 \quad s = 2.78$
$1/u = 1 \quad t/r^2 = 2.75E^{-7}$
$v = 0.02$

$$T = \frac{17.7(1440)(1.0)}{(4\pi)(2.92)} = 730 \text{ gpd/ft}$$

$$S = 4(730/7.48)\frac{2.75E^{-7}}{1.0} = 1.1E^{-4}$$

$$K'/b' = 4(730/7.48)(\frac{0.02}{190})^2 = 4.33^{-6}/\text{day}$$

$$K' = 4.33\ E^{-6}(40)(7.48) = 1.3E^{-3} \text{ gpd/ft}^2 = 4.6E^{-7} \text{ cm/sec}$$

completion of $n$ bailing cycles, the following equation applies:

$$T=\frac{1}{4\pi s'}\left[\frac{V_1}{t_1}+\frac{V_2}{t_2}+\frac{V_3}{t_3}+\cdots+\frac{V_n}{t_n}\right]\qquad [L^2T^{-1}].\quad (83)$$

If approximately the same volume of water is bailed during each cycle, equation 83 becomes

$$T=\frac{V}{4\pi s'}\left[\frac{1}{t_1}+\frac{1}{t_2}+\frac{1}{t_3}+\cdots+\frac{1}{t_n}\right]\qquad [L^2T^{-1}].\quad (84)$$

Equation 84 is applied to single values of $V$ and $s'$ and the summation of the reciprocal of the elapsed time between the time each bailer was removed from the well and the time of observation of $s'$. If $T$ is to be expressed in square feet per day, then obviously $V$ should be expressed in cubic feet, $s'$ in feet, and $t$ in days, or suitable conversions of units should be made.

The bailer method should give satisfactory *estimates* of $T$ for wells in confined aquifers having sufficiently shallow water levels to permit short time intervals between bailing cycles. In wells in unconfined aquifers, or in wells having relatively deep water levels, the method should be used with considerable judgment or not at all. (See also "Precautions.")

Unfortunately, I have no data available with which to illustrate the bailer method.

## LEAKY CONFINED AQUIFERS WITH VERTICAL MOVEMENT

The flow equations for confined aquifers under conditions of both constant discharge and constant drawdown discussed in earlier sections of this report all are based upon the assumptions that the confining beds are impermeable (or have very low permeability), that they release no water from storage, and that vertical flow components are negligible. It is well known that no rocks are wholly impermeable and that some confining beds have finite permeability. We will now take up the equations for both steady and nonsteady radial flow from infinite aquifers whose confining beds leak water either from or to the aquifer.

### CONSTANT DISCHARGE

#### STEADY FLOW

Consider an aquifer overlain by a confining bed of low but finite permeability, which in turn is overlain by an unconfined aquifer. When discharge occurs from a well in a confined aquifer, the potentiometric surface is lowered throughout a large circular area (Cooper, 1963, p. 48). This lowering changes the relative head between the confined and unconfined aquifers and results in turn in a change in the rate of leakage through the confining bed. The change may be either a decrease in the rate of leakage out of the aquifer or an increase in the rate of leakage into the aquifer, but either way the change results in a net increase in the supply of water to the aquifer and, therefore, constitutes capture of water.

Jacob (1946) derived an equation of steady flow near a well discharging at a constant rate from such an infinite leaky confined aquifer and described a graphical method for determining the transmissivity of the aquifer and the "leakance" of the confining bed. The leakance is the ratio $K'/b'$, in which $K'$ and $b'$ are the vertical hydraulic conductivity and the thickness, respectively, of the confining beds. Hantush and Jacob (1954) derived equations for steady flow in variously bounded leaky confined aquifers. Later, equations for the more generally encountered nonsteady flow in such aquifers were developed, and these will now be taken up.

#### NONSTEADY FLOW

##### HANTUSH-JACOB METHOD

Hantush and Jacob (1955) derived the following equation for nonsteady radial flow in an infinite leaky confined aquifer:

$$\frac{s}{Q/4\pi T}=2K_0(2v)-\int_{v^2/u}^{\infty}\frac{1}{y}\exp\left(\frac{-y-v^2}{y}\right)dy$$

[dimensionless form], (85)

where

$K_0$ = the modified Bessel function of the second kind of zero order,

and

$$v=\frac{r}{2}\sqrt{\frac{K'}{b'T}}\qquad \text{[dimensionless]},\qquad (86)$$

where

$K'$ = the vertical hydraulic conductivity of the confining bed $[LT^{-1}]$,
$b'$ = the thickness of the confining bed $[L]$, and
$T$ = the transmissivity of the aquifer $[L^2T^{-1}]$,

and

$u=r^2S/4Tt$ [dimensionless], and
$y$ = the variable of integration.

The authors gave two series expressions for the formal solutions of equation 85—one for large values of $t$ and one for small values—and gave a few examples in both tabular and graphic form. In January 1956, Hilton H. Cooper, Jr., computed many values and prepared two families of type curves which were later published (Cooper, 1963, pl. 4). Meanwhile, unknown to Cooper, Hantush (1955) also had computed many values. (See also Hantush, 1956.)

TABLE 11.—*Postulated water-level drawdowns in three observation wells during a hypothetical test of an infinite leaky confined aquifer*

[Pumped well began discharging 1,000 gal min$^{-1}$ at $t=0$ min.] From Cooper (1963, p. 54)

| Time since pumping began, $t$ | | Well 1 ($r=100$ ft) | | Well 2 ($r=500$ ft) | | Well 3 ($r=1{,}000$ ft) | |
|---|---|---|---|---|---|---|---|
| Min | Day | $\frac{t}{r^2}$ (day ft$^{-2}$) | Drawdown, $s$ (ft) | $\frac{t}{r^2}$ (day ft$^{-2}$) | Drawdown, $s$ (ft) | $\frac{t}{r^2}$ (day ft$^{-2}$) | Drawdown, $s$ (ft) |
| 0.2 | 0.000139 | $1.39\times10^{-8}$ | 1.76 | $5.56\times10^{-10}$ | 0.01 | $1.39\times10^{-10}$ | 0.00 |
| .5 | .000347 | $3.47\times10^{-8}$ | 2.75 | $1.39\times10^{-9}$ | .14 | $3.47\times10^{-10}$ | .00 |
| 1 | .000694 | $6.94\times10^{-8}$ | 3.59 | $2.78\times10^{-9}$ | .45 | $6.94\times10^{-10}$ | .02 |
| 2 | .00139 | $1.39\times10^{-7}$ | 4.26 | $5.56\times10^{-9}$ | .93 | $1.39\times10^{-9}$ | .14 |
| 5 | .00347 | $3.47\times10^{-7}$ | 5.28 | $1.39\times10^{-8}$ | 1.76 | $3.47\times10^{-9}$ | .55 |
| 10 | .00694 | $6.94\times10^{-7}$ | 5.90 | $2.78\times10^{-8}$ | 2.34 | $6.94\times10^{-9}$ | .99 |
| 20 | .0139 | $1.39\times10^{-6}$ | 6.47 | $5.56\times10^{-8}$ | 2.85 | $1.39\times10^{-8}$ | 1.46 |
| 50 | .0347 | $3.47\times10^{-6}$ | 6.92 | $1.39\times10^{-7}$ | 3.31 | $3.47\times10^{-8}$ | 1.95 |
| 100 | .0694 | $6.94\times10^{-6}$ | 7.11 | $2.78\times10^{-7}$ | 3.50 | $6.94\times10^{-8}$ | 2.10 |
| 200 | .139 | $1.39\times10^{-5}$ | 7.20 | $5.56\times10^{-7}$ | 3.51 | $1.39\times10^{-7}$ | 2.11 |
| 500 | .347 | $3.47\times10^{-5}$ | 7.21 | $1.39\times10^{-6}$ | 3.52 | $3.47\times10^{-7}$ | 2.11 |
| 1,000 | .694 | $6.94\times10^{-5}$ | 7.21 | $2.78\times10^{-6}$ | 3.52 | $6.94\times10^{-7}$ | 2.11 |

As described by Cooper (1963), if the right-hand side of equation 85 is represented by $L(u, v)$, the $L$, or leakance, function of $u$ and $v$, equation 85 may be written

$$s=\frac{Q}{4\pi T}L(u,v) \qquad [L]. \qquad (87)$$

$S$ is determined by

$$S=4T\frac{t/r^2}{1/u} \qquad [\text{dimensionless}] \qquad (88)$$

and

$$\frac{K'}{b'}=4T\frac{v^2}{r^2}=\frac{S\left(\frac{v^2}{u}\right)}{t} \qquad [T^{-1}]. \qquad (89)$$

When $K'$ and, hence, $v$ *approach* zero, it can be shown that $L(u, v)$ approaches $W(u)$, and equation 87 becomes equation 46, the Theis equation. An enlargement of two families of type curves of $L(u, v)$ versus $1/u$ prepared by Cooper (1963, pl. 4) is shown on plate 3*A*. In one family of curves, $v$ is the parameter; in the other, $v^2/u$ is the parameter. The solid-line type curves ($v$) correspond to a plot of $s$ (vertical) versus $t$ at some constant $r$, plotted as $t/r^2$ (horizontal). The dashed-line curves ($v^2/u$) correspond to a plot of $s$ versus $t/r^2$ at some constant $t$.

EXAMPLE

Table 11 from Cooper (1963, p. 54) gives postulated drawdowns in observation wells at distances of 100, 500, and 1,000 ft from a well discharging at the constant rate of 1,000 gpm for 1,000 min from a leaky confined aquifer. Values of $s$ versus $t/r^2$ for the three wells are shown on plate 3*B* superposed on the type curves. Note that a match point was chosen where $\alpha(u, v)=1.0$, $1/u=1.0$, $s=1.15$ ft, and $t/r^2=1.87\times10^{-9}$ day ft$^{-2}$. Substituting appropriate values in equations 87 (solved for $T$) and 88 gives, respectively,

$$T=\frac{(1{,}000 \text{ gal min}^{-1})(1{,}440 \text{ min day}^{-1})(1.0)}{(4\pi)(1.15 \text{ ft})(7.48 \text{ gal ft}^{-3})}$$

$$=13{,}300 \text{ ft}^2 \text{ day}^{-1} \text{ (rounded)}$$

and

$$S=(4)(13{,}300 \text{ ft}^2 \text{ day}^{-1})\frac{(1.87\times10^{-9} \text{ day ft}^{-2})}{1.0}$$

$$=10^{-4} \text{ (rounded)}.$$

The plotted values for observation well 1 fall slightly below the solid-line curve for $v=0.02$, or at about 0.025. Substituting $r=100$ ft, $v=0.025$, and $T=13{,}300$ ft$^2$ day$^{-1}$ in the first part of equation 89 gives

$$\frac{K'}{b'}=(4)(13{,}300 \text{ ft}^2 \text{ day}^{-1})\frac{(0.025)^2}{(100 \text{ ft})^2}=0.0033 \text{ day}^{-1}.$$

Assume $b'=100$ ft, then $K'=0.33$ ft day$^{-1}$.

As the data in table 11 represent idealized conditions, the same values for $K'/b'$ would be obtained using the data for observation wells 2 and 3. Also, the same values of $K'/b'$ would be obtained using the dashed-line curves by plotting the values of $s$ for each observation well for some constant $t$, say 100 min (0.0694 day), and substituting the value of $v^2/u$, $s$, and $t$ in the second part of equation 89.

Cooper (1963, p. 55) gives the following pertinent conclusions in regard to this method:

> Because the adjustment of the hydraulic gradient through a confining bed generally lags considerably behind the decline in head, the water yielded by an artesian aquifer is derived largely, if not entirely, from storage in the confining bed. For this reason, most time-drawdown plots deviate from the Theis curve to a greater degree than if leakage alone were involved. The method for determining leakance is presented with reservation because, if applied under the mistaken assumption that the deviations are due to leakage, it yields erroneously large values. However, whenever the results of an aquifer test indicate that leakage occurs, the deter-

**mination of $T$ and $S$ by use of the family of type curves described in this paper has advantages over that by use of the Theis type curve alone.**

### HANTUSH MODIFIED METHOD

Hantush (1960) presented an important modification of the theory of leaky confined aquifers in which the storage of water in the semipervious confining bed or beds is taken into account. His main equations are:

$$T=\frac{Q}{4\pi s}H(u,\beta) \qquad [L^2T^{-1}], \tag{90}$$

where

$$H(u,\beta)=\int_u^\infty \frac{e^{-y}}{y}\operatorname{erfc}\left(\frac{\beta/\sqrt{u}}{\sqrt{y(y-u)}}\right)dy \quad [\text{dimensionless}], \tag{91}$$

$$u=\frac{r^2S}{4Tt} \qquad [\text{dimensionless}],$$

as in the Theis equation, and

$$\beta=\frac{r}{4b}\left(\sqrt{\frac{K'S_s'}{KS_s}}+\sqrt{\frac{K''S_s''}{KS_s}}\right) \qquad [\text{dimensionless}], \tag{92}$$

where

$K$ = hydraulic conductivity of main aquifer,
$K', K''$ = hydraulic conductivities of semipervious confining layers,
$S=bS_s$, $S'=b'S_s'$, $S''=b''S_s''$ = Storage coefficients of the main aquifer and of the semipervious confining layers, respectively, and
$S_s, S_s', S_s''$ = specific storage (storage coefficient per vertical unit of thickness) of the main aquifer and confining layers ($b$, $b'$, and $b''$), respectively.

The versatility of equations 90 through 92 lies in the fact that they are the general solutions for the drawdown distribution in all confined aquifers, whether they are leaky or nonleaky. Thus, if $K'$ and $K''$ approach zero or are made equal to zero, $\beta$ approaches or equals zero, and equation 90 becomes equation 46, the Theis equation for nonleaky confined aquifers. Hantush (1960, p. 3716–3718) gives general solutions for three different configurations of aquifers and sets of confining beds. If $K''$, $S'$, and $S''$ approach zero or are made equal to zero, two of these solutions become equal to equation 85 of Hantush and Jacob (1955)—the equation for leaky confined aquifers for which release of stored water from the confining beds is considered negligible.

Plate 4 is a logarithmic plot of $1/u$ versus $H(u,\beta)$ for various indicated values of $\beta$, copied from a plot made by E. J. McClelland, U.S. Geological Survey, Sacramento, Calif., in 1961 from tabulated values by Hantush (1961). Time-drawdown or time-recovery data from tests in aquifers whose confining bed or beds are suspected of releasing water from storage are plotted (as $s$ versus $t$) on 3×5-cycle logarithmic paper having the same scale as plate 4 (such as K & E 359–125G or 46–7522), and this is superposed on plate 4 until a fit is obtained on one of the type curves by the usual curve-matching procedure. From values of the four parameters at a convenient match point, $T$ and $S$ may be determined from equations 90 and 47, respectively.

Thorough knowledge of the geology, including the character of the confining beds, should indicate in advance which of the two leaky-aquifer type curves to use, or whether to use the Theis type curve for nonleaky aquifers.

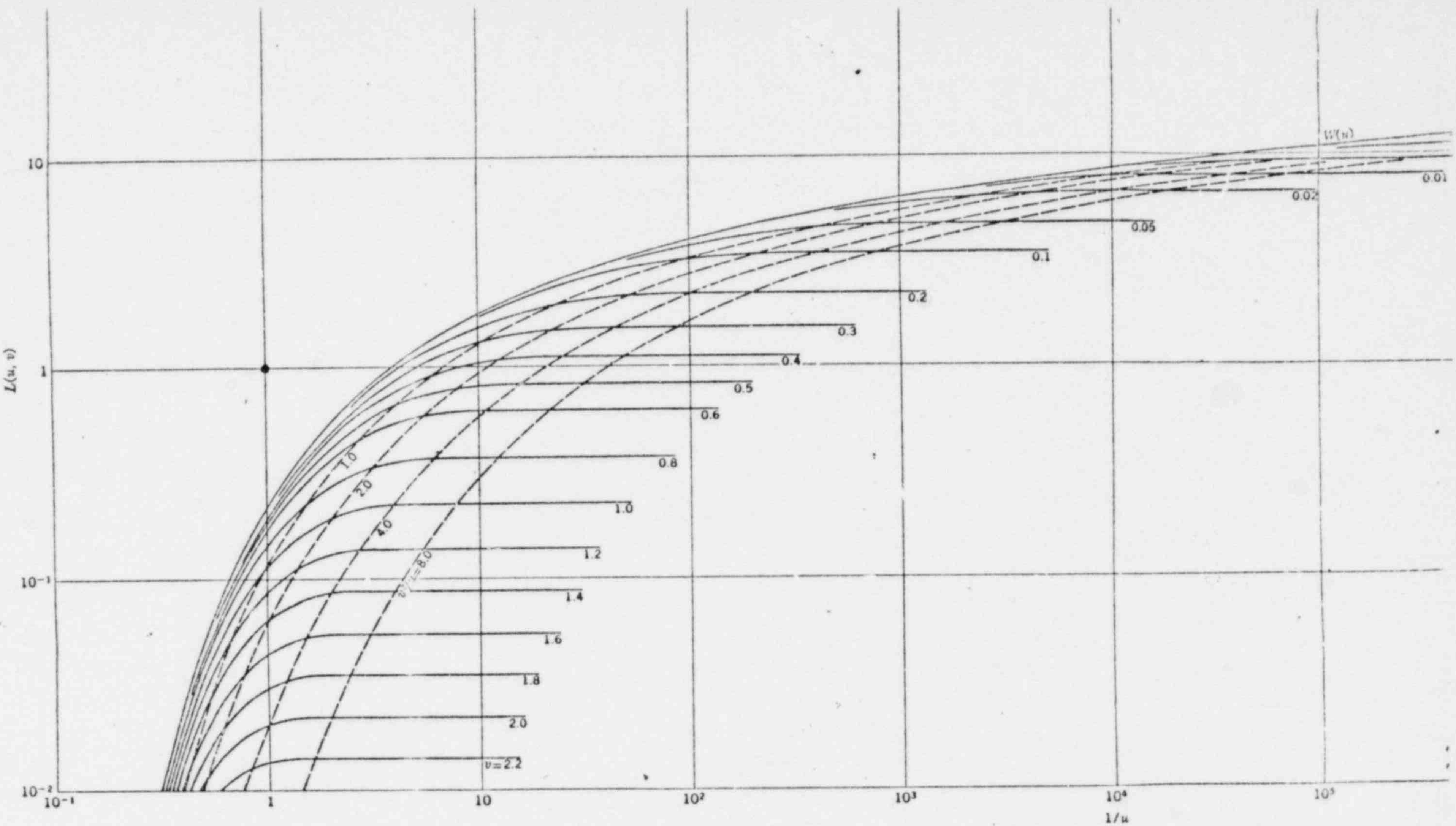
#### EXAMPLE

Table 12 gives the time-drawdown measurements in an observation well at Pixley, Calif., 1,400 ft from a well pumping 750 gpm, supplied by Francis S. Riley (U.S. Geological Survey, Sacramento, Calif., written commun., March 5, 1968). The pumped well, which is 600 ft deep, obtains water from gravel, sand, sandy clay, and clay of the Tulare Formation in an area where considerable land subsidence has resulted from prolonged pumping from confined aquifers containing appreciable amounts of clay.

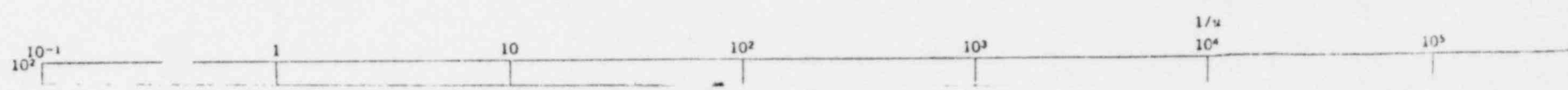
TABLE 12.—*Drawdown of water level in observation well 23S/25E-17Q2, 1,400 ft from a well pumping at constant rate of 750 gpm, at Pixley, Calif., March 13, 1963*

[Drawdown corrected for pretest trend. Data from Francis S. Riley (written commun., March 5, 1968)]

| Time since pumping began, $t$ (min) | Drawdown, $s$ (ft) | Time since pumping began, $t$ (min) | Drawdown, $s$ (ft) |
|---|---|---|---|
| 6.37 | 0.01 | 90 | 0.75 |
| 8.58 | .02 | 100 | .82 |
| 10.23 | .03 | 137 | 1.04 |
| 11.90 | .04 | 150 | 1.12 |
| 12.95 | .05 | 160 | 1.17 |
| 14.42 | .06 | 173 | 1.24 |
| 15.10 | .07 | 184 | 1.27 |
| 16.88 | .08 | 200 | 1.35 |
| 17.92 | .10 | 210 | 1.40 |
| 21.35 | .12 | 278 | 1.68 |
| 21.70 | .13 | 300 | 1.76 |
| 22.70 | .14 | 315 | 1.83 |
| 23.58 | .15 | 335 | 1.87 |
| 24.65 | .17 | 365 | 1.99 |
| 29 | .21 | 390 | 2.10 |
| 30 | .22 | 410 | 2.13 |
| 32 | .24 | 430 | 2.20 |
| 34 | .26 | 450 | 2.23 |
| 36 | .28 | 470 | 2.29 |
| 38 | .30 | 490 | 2.32 |
| 41 | .33 | 510 | 2.39 |
| 44 | .36 | 560 | 2.48 |
| 47 | .38 | 740 | 2.92 |
| 50 | .42 | 810 | 3.05 |
| 54 | .46 | 890 | 3.19 |
| 60 | .52 | ,255 | 3.66 |
| 65 | .56 | 1,400 | 3.81 |
| 70 | .60 | 1,440 | 3.86 |
| 80 | .65 | 1,485 | 3.90 |




A. TYPE CURVES

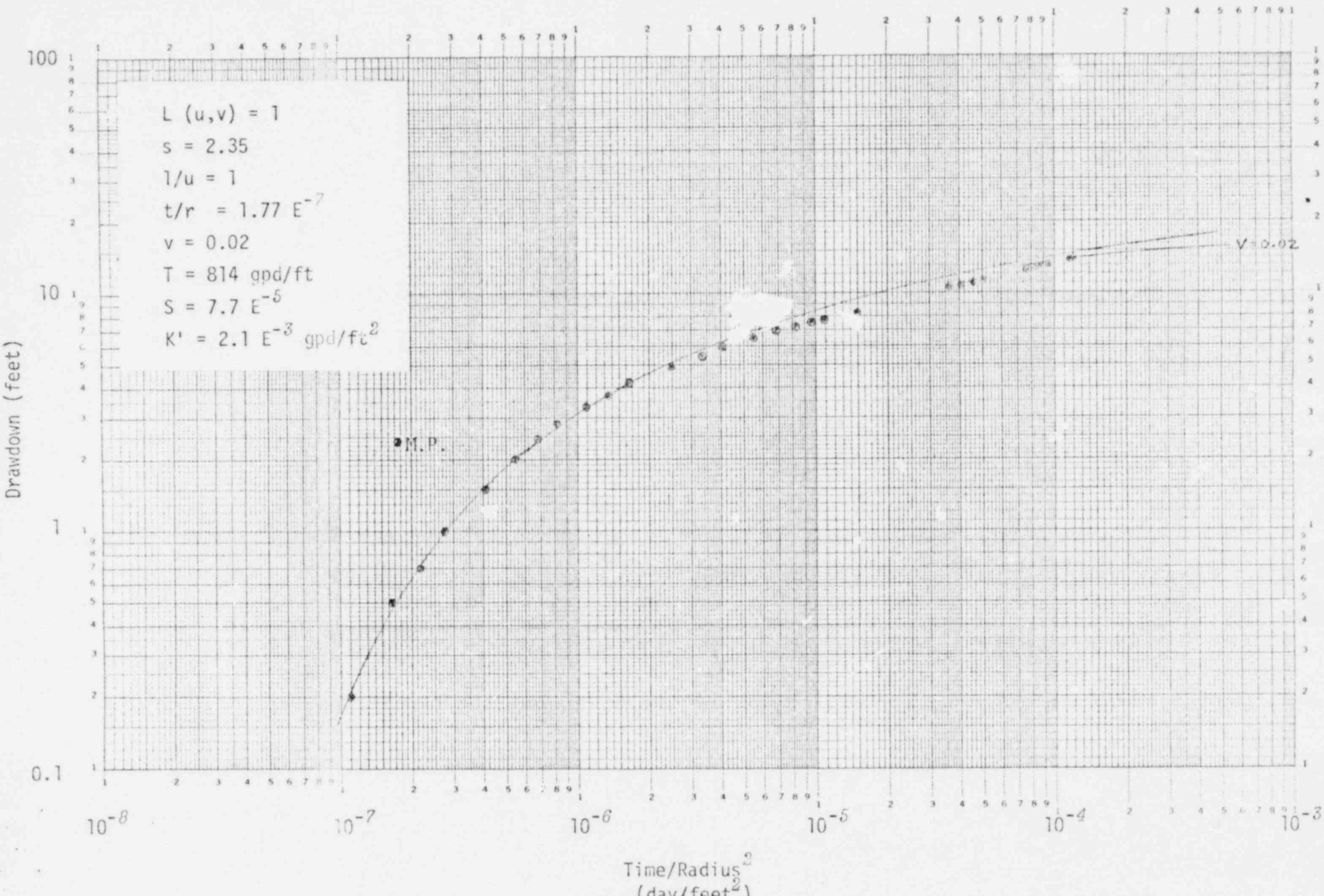


SOUTH POWDER RIVER BASIN

Q-SAND PHASE II AQUIFER TEST

APRIL, 1981

QI-2

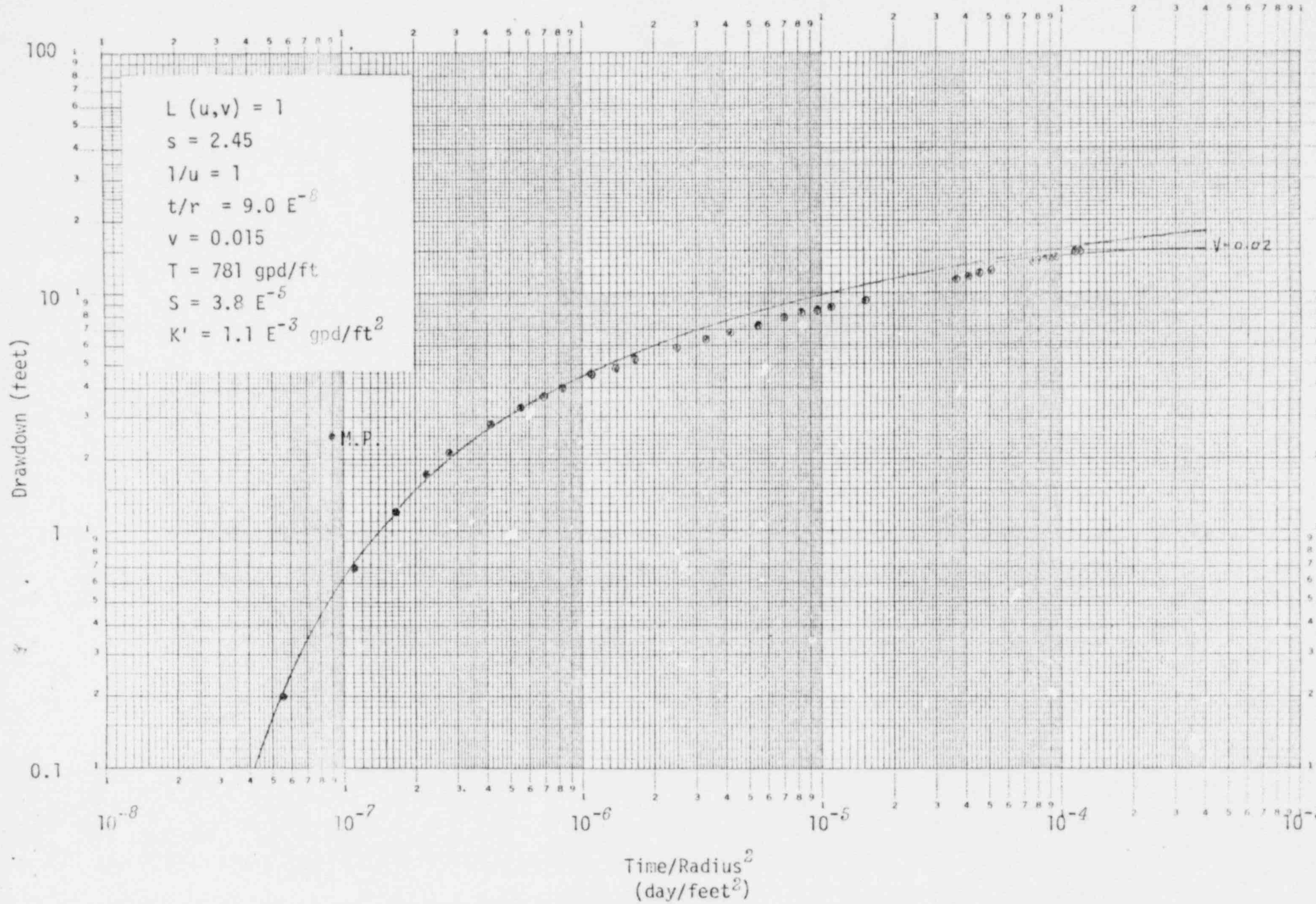


SOUTH POWDER RIVER BASIN

Q-SAND PHASE II AQUIFER TEST

APRIL, 1981

QI-7

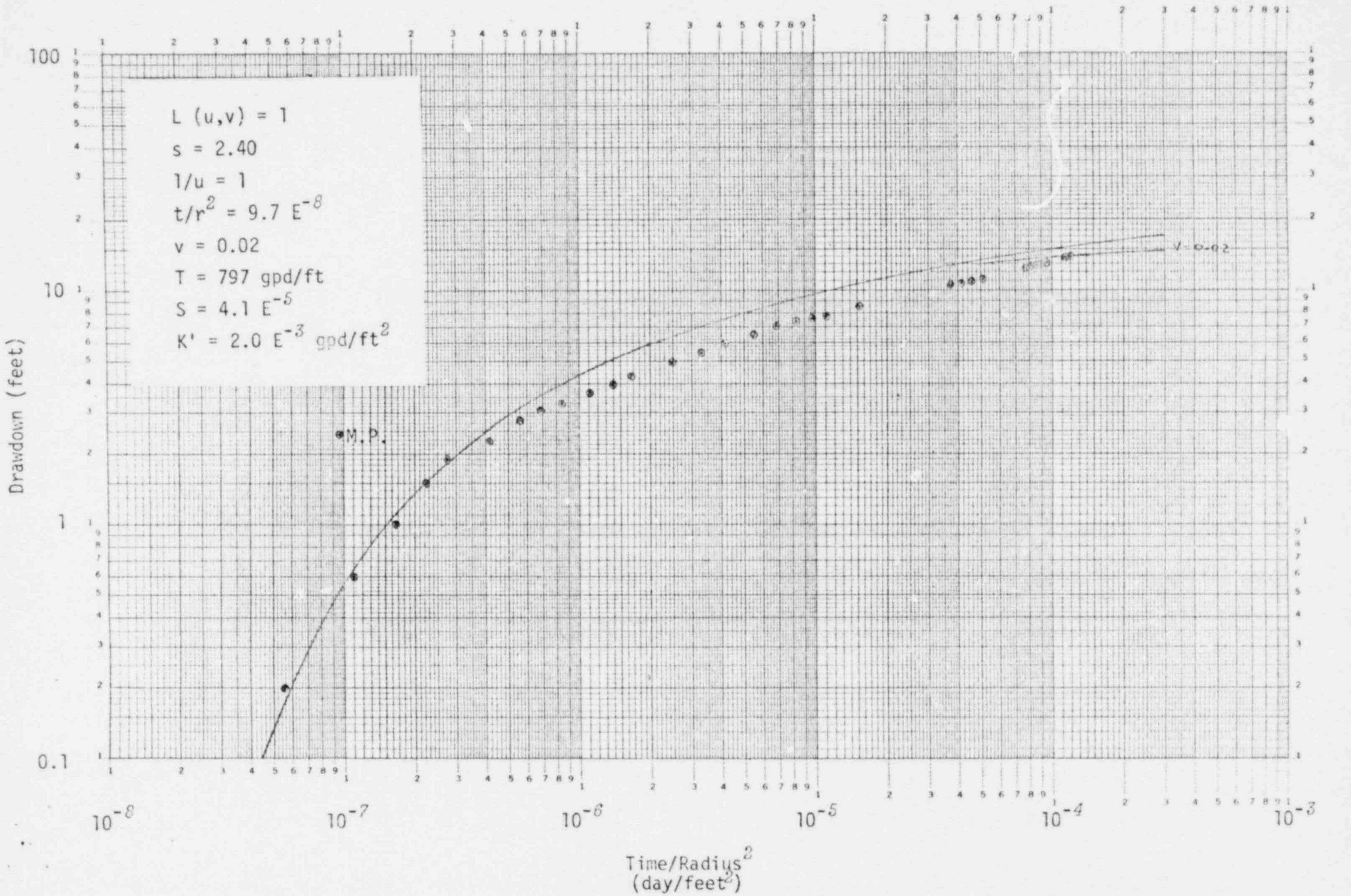


SOUTH POWDER RIVER BASIN

Q-SAND PHASE II AQUIFER TEST

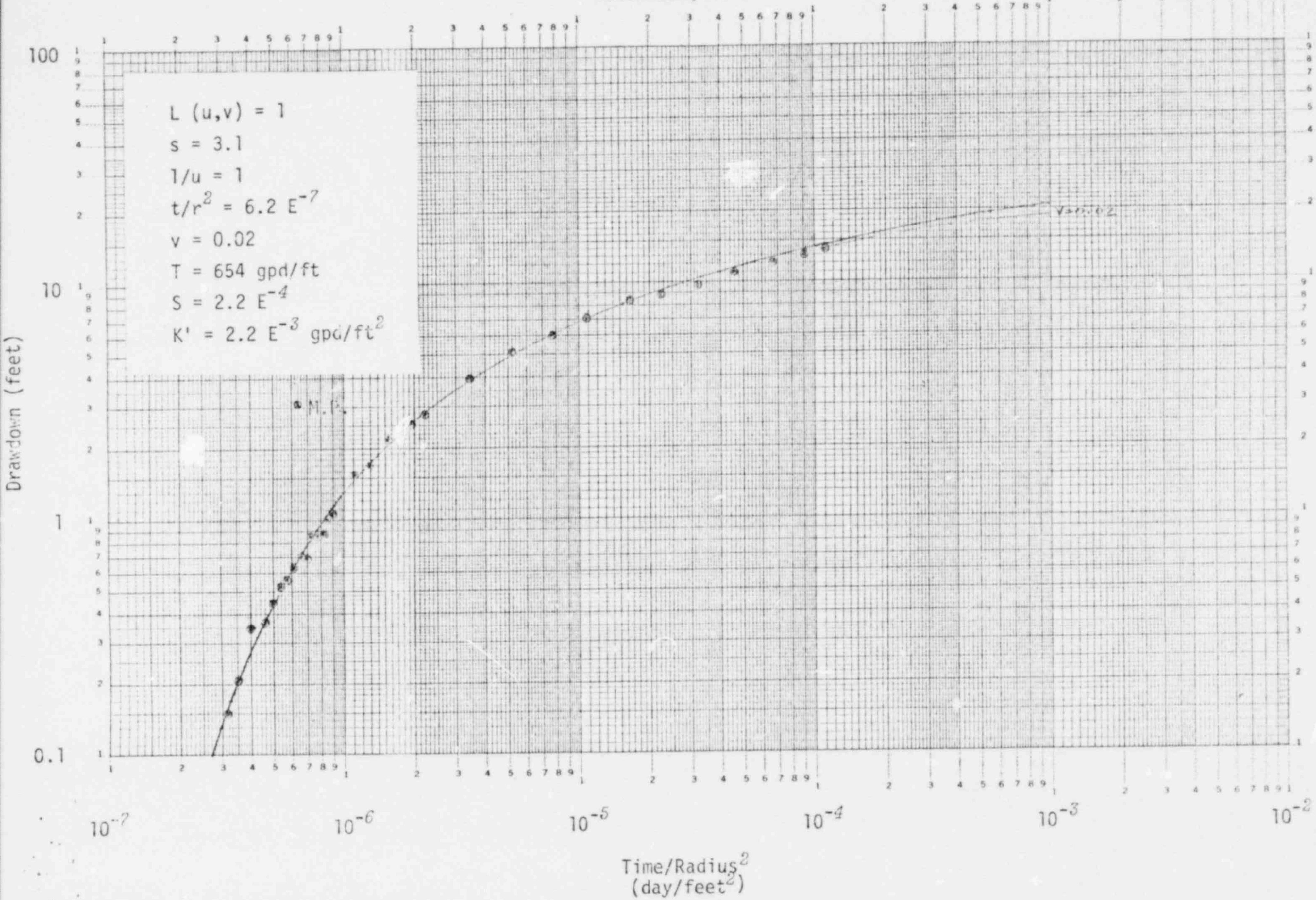
APRIL, 1981

QI-11



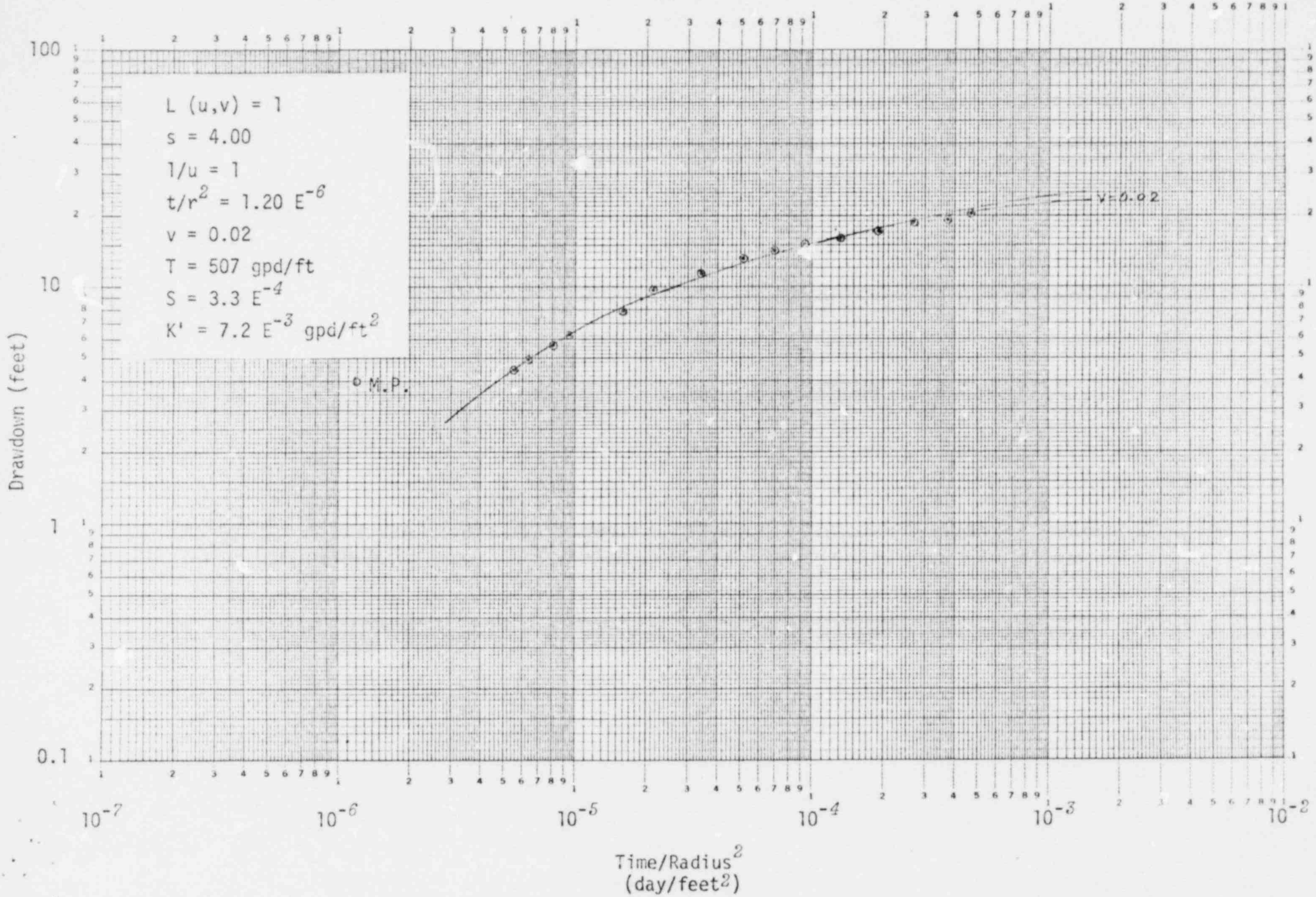
SOUTH POWDER RIVER BASIN
Q-SAND PHASE I AQUIFER TEST
DECEMBER, 1979

QI-1



SOUTH POWDER RIVER BASIN
Q-SAND PHASE I AQUIFER TEST
DECEMBER, 1979

QP-1



SOUTH POWDER RIVER BASIN

Q-SAND PHASE I AQUIFER TEST

DECEMBER, 1979

QM-1