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Casing Storage Can Affect Pumping Test Data

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This article examines one of the shortcomings of conventional pumping test analysis techniques which can lead to errors in data interpretation and suggests a guide to use in obtaining proper interpretation of the data.

THE MODIFIED non-equilibrium formula of Jacob derived from the Theis equation is often used by hydrologists to compute aquifer characteristics from pumping tests. This well known method of analysis (described in detail in the March-April and May-June 1977 JOHNSON DRILLERS JOURNAL) generally provides useful and accurate information.

Many pumping tests, however, have been observed where the early data do not fit Jacob's theory precisely. Often this lack of agreement between Jacob's predictions and the actual data results from the removal of water from casing storage during the pumping test.

One of the basic assumptions made in deriving Theis's (and subsequently Jacob's) equation is that all of the water pumped from a well during a pumping test comes from the aquifer and none from storage within the well. Since this condition is not fulfilled in practice, Theis's and Jacob's equations are somewhat inaccurate and a different theory is required to properly describe the behavior of the water level in a pumping well.

In 1967, Papadopulos and Cooper presented an equation describing the discharge from a pumping well which takes into account the volume of water removed from casing storage.* Drawdown values calculated from their equation differ significantly from Theis's and Jacob's equations during the early portion of the pumping test when a relatively high percentage of the discharge comes from casing storage. During the later stages of the pumping test when only a negligible quantity of water is obtained from casing storage, the equations produce equal results.

Difference in Drawdown Values

This can be seen in Figure 1 which shows time drawdown graphs in the generalized form for both the Papadopulos-Cooper and Theis equation. Notice that for early values of time the graphs differ. As time increases they converge and at time t_c become virtually identical. (The time at which the two curves appear to coincide, t_c, has arbitrarily been selected in this article to be the time at which the difference in drawdown values becomes one per cent. This criterion has proved satisfactory for practical problem solving.)

Figure 2 shows another comparison of time drawdown graphs predicted by Papadopulos-Cooper and Jacob or Theis. These graphs were constructed from theoretical calculations based on the specific aquifer parameters and well geometry indicated. Data from an actual pumping test would follow the Papadopulos-Cooper curve shown on this graph.

Jacob's method has been used in Figure 2 to

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determine formation transmissivity (T) using the following equation:

$$T = \frac{264\ Q}{\Delta s}$$

where

T = transmissivity in gpd/ft

Q = pumping rate in gpm

Δs = slope of the line of best fit drawn through the data points (change in drawdown per log cycle of time)

Two distinct values of transmissivity, T_1 and T_2, have been calculated from the Papadopulos-Cooper curve. T_1, determined from the early portion of the pumping test, has a value of 3,360 gpd/ft. T_2, determined from the later stages of the pumping test, has a value of 10,000 gpd/ft. Clearly, the calculated value of T_1 is correct because of the exaggerated slope of the early time drawdown data. This is caused by the influence of casing storage. T_2, however, provides the correct transmissivity value since it has been calculated from data which are no longer affected by casing storage.

As a result of the effect of the casing storage on the time drawdown graph, it is possible to misinterpret the data and assume the erroneous T value to be the correct one. For instance, the early data (steep slope) could be interpreted as indicating the correct transmissivity and the later data (flatter slope) could be interpreted as indicating recharge. Furthermore, it might be possible to have a pumping test of such short duration that only the casing storage-sensitive data are seen and the "correct" slope never appears.

In order to avoid misinterpretation of the data in cases like these, it is necessary to have some method of determing how much of the pumping test data is affected by casing

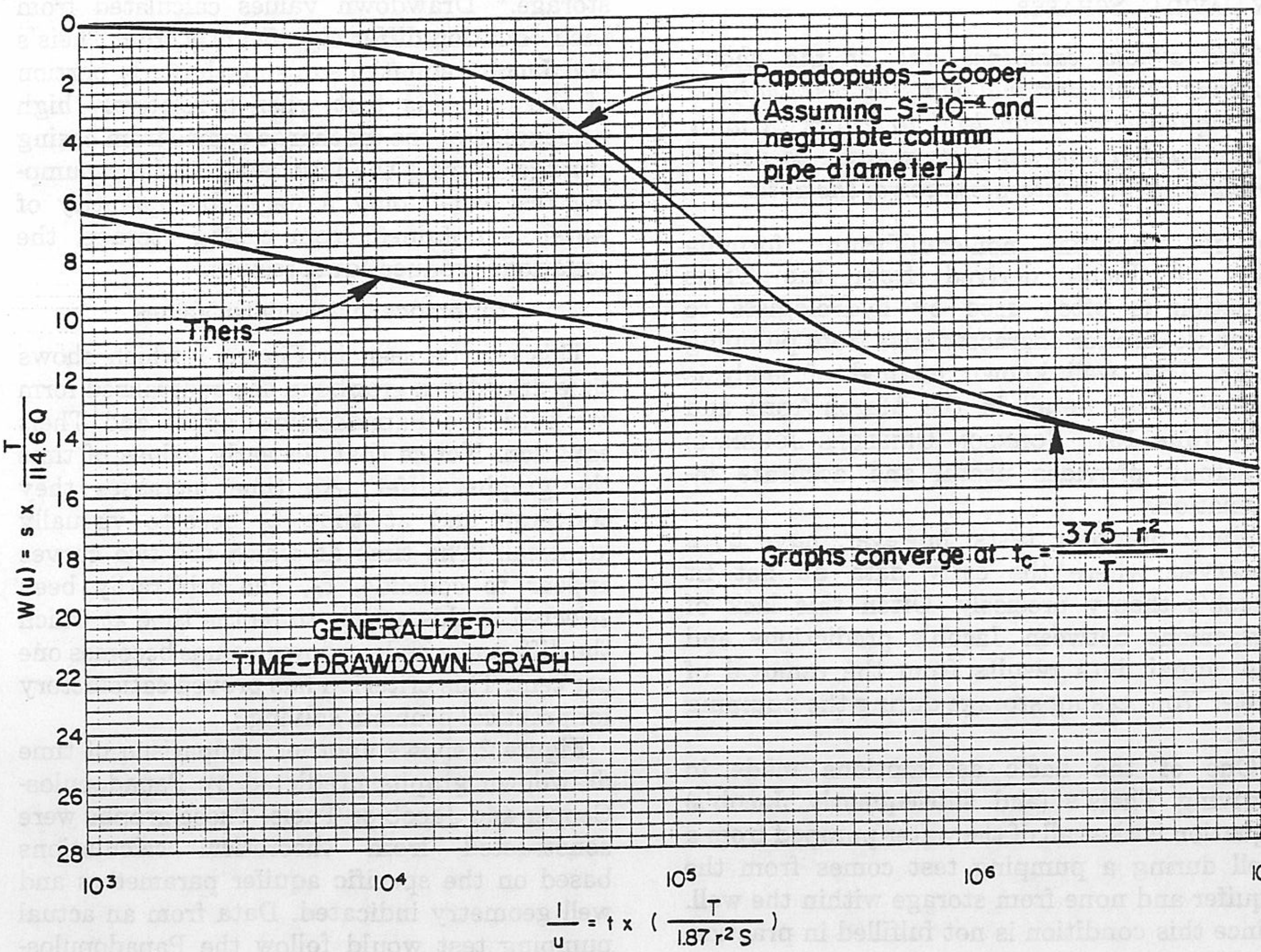

Fig. 1. When the Papadopolous and Cooper equation is applied to pumping test data, drawdown values for the early stages differ significantly from those obtained by the Theis equation.

storage. To accomplish this, Papadopulos and Cooper developed an equation for calculating t_c, the time at which the correct slope is observed on the time drawdown graph. The following is a slight modification of their formula:

$$t_c = \frac{375\,(r_c{}^2 - r_p{}^2)}{T} \quad (1)$$

where

t_c = time in days after which the effect of casing storage can be ignored (assuming a one per cent error in drawdown values as mentioned earlier)

r_c = radius (in feet) of well casing (inside dimension) over which the water level changes are occurring

r_p = radius (in feet) of pump column pipe (outside dimension)

T = transmissivity in gpd/ft

The form of equation (1) shows that t_c is directly proportional to the annular space between the well casing and column pipe and inversely proportional to the formation transmissivity. In general, then, t_c will be large when either the well radius is large or the T value is small.

Equation (1) has two limitations, however, which restrict its use in practical problem solving. First of all, it is necessary to already know the correct T value in order to calculate t_c. Second, the formula is valid only for wells which are 100 per cent efficient.

For inefficient wells, a solution obtained by H. J. Ramey provides a more accurate estimate of t_c than equation (1).†‡ In fact, evidence suggests that Ramey's equation is the most accurate one available for estimating t_c. An approximation of Ramey's equation is as follows:

$$t_c = \left[\frac{375\,(r_c{}^2 - r_p{}^2)}{T}\right]\left[\frac{2E + 1}{3E}\right] \quad (2)$$

where t_c, r_c, r_p and T are as stated for equation

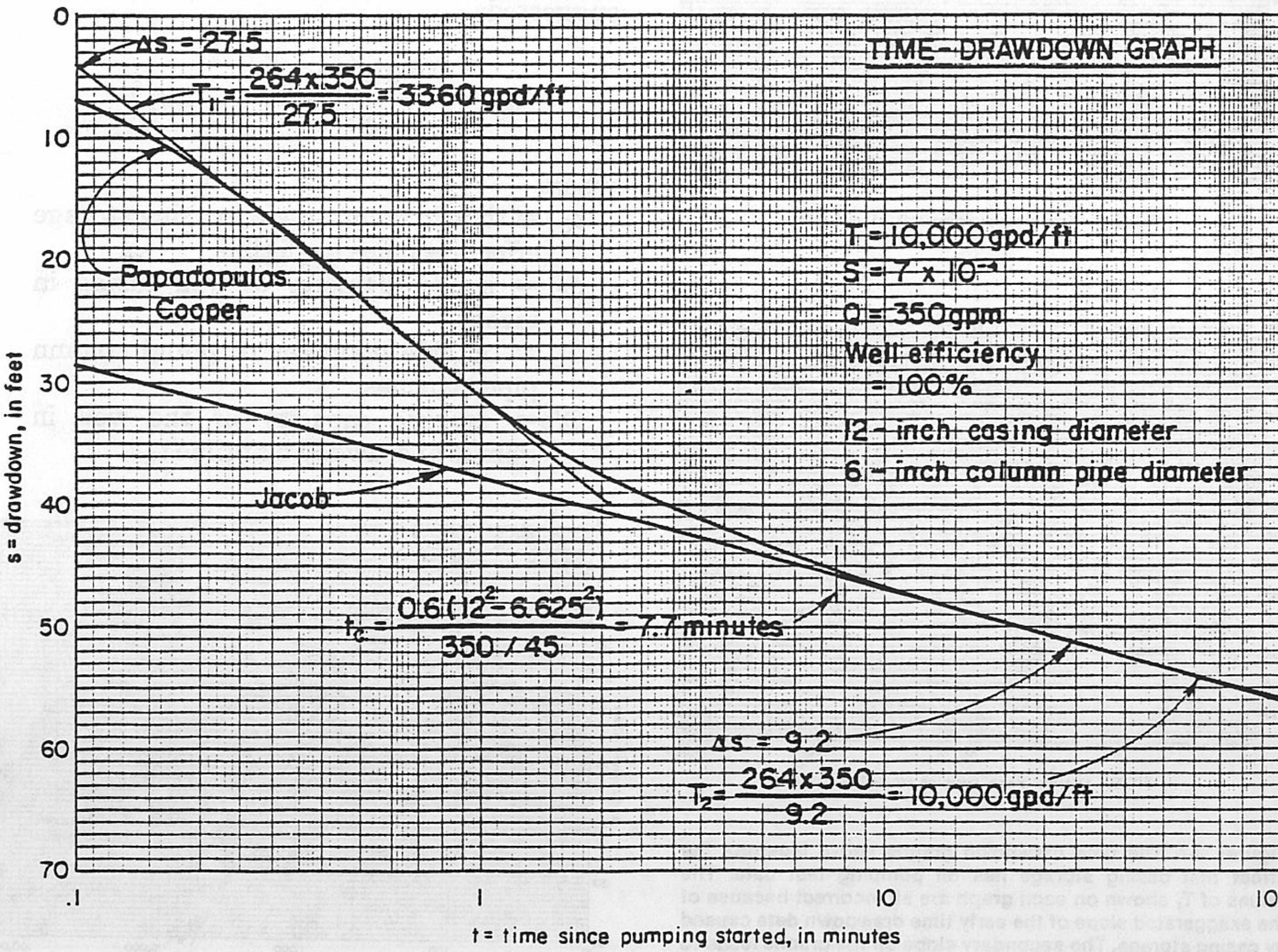

Fig. 2. The influence of casing storage on the transmissivity, T_1, is considerable, whereas transmissivity, T_2, is no longer affected by casing storage and thus it provides the correct value.

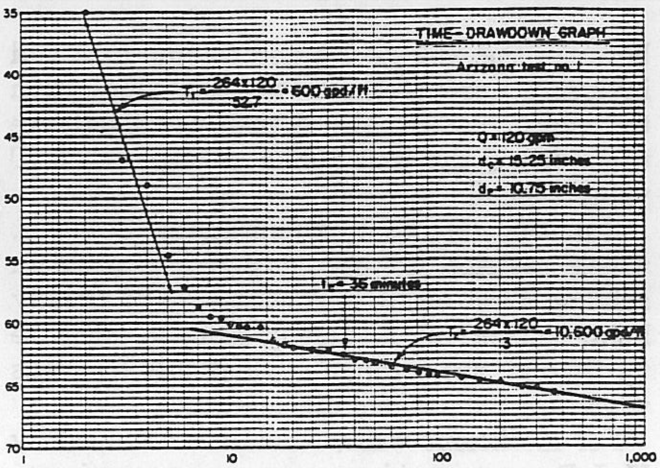

FIG. 4. t = time since pumping started, in minutes

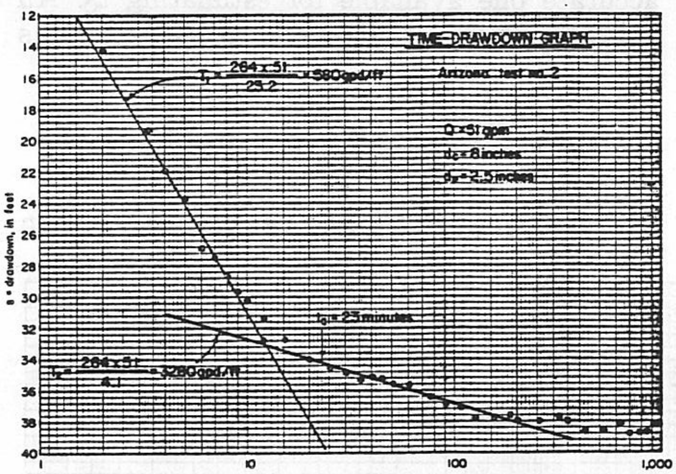

FIG. 5. t = time since pumping started, in minutes

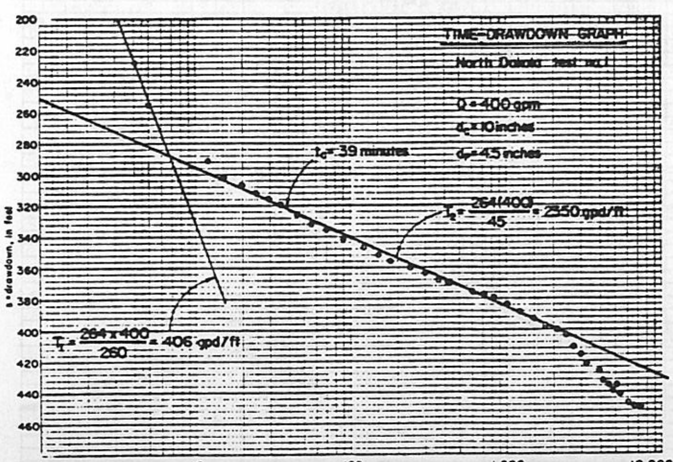

FIG. 6. t = time since pumping started, in minutes

Figures 3-7. The time drawdown graphs above illustrate the effect that casing storage has on pumping test data. The values of T_1 shown on each graph are all incorrect because of the exaggerated slope of the early time drawdown data caused by casing storage. The secondary slope on the graphs leads to the calculated values of T_2 which indicate the correct formation transmissivites.

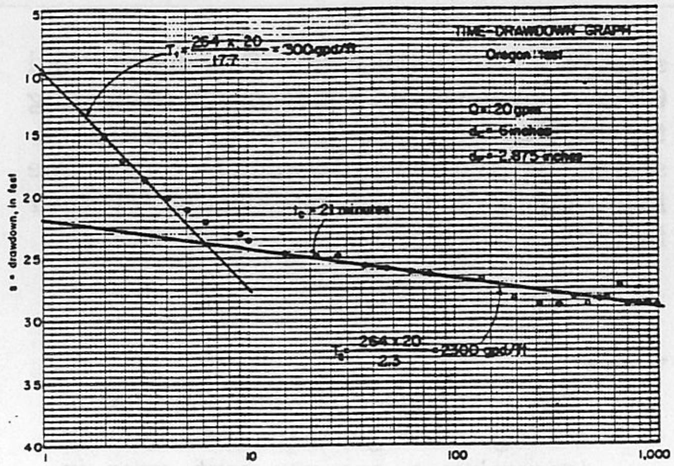

FIG. 3. t = time since pumping started, in minutes

(1), and E = well efficiency at time t_c.

In order to use equation (2), however, it is still necessary to know the correct T value and well efficiency.

In order to provide an estimate of t_c which compensates for well efficiency and which does not require prior knowledge of formation and well characteristics, the following equation is suggested:

$$t_c = \frac{0.6\,(d_c^{\,2} - d_p^{\,2})}{Q/s} \qquad (3)\ \S$$

where

t_c = time in minutes when casing storage effect becomes negligible

d_c = inside diameter of well casing in inches

d_p = outside diameter of pump column pipe in inches

Q/s = specific capacity of the well in gpm/ft of drawdown at time t_c ||

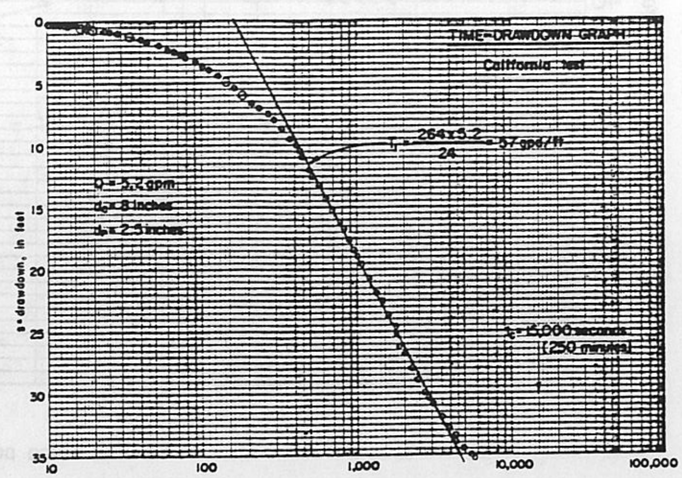

FIG. 7. t = time since pump started, in seconds

All of the parameters in equation (3) are readily obtainable from any pumping test. Thus t_c can always be determined.

In order to investigate the validity of the casing storage theory, and in particular equation (3), a number of pumping tests were analyzed. Figures 3 through 10 show either time drawdown or recovery graphs for eight different pumping tests along with calculated values of T_1, T_2, and t_c based on equation (3).

Note that T_2 could not be determined for the California test in Figure 7 because the pumping period was not long enough. The test duration was only 90 minutes compared to a required pumping time (t_c) of 250 minutes to reach the beginning of the correct straight line slope.

Casing Storage Phenomenon

Based upon supporting data from each pumping test (not included here) it has been determined that without exception the T_1 values shown are incorrect, i.e., not indicative of true formation characteristics, whereas the T_2 values shown are correct. In other words, the steep slope on each graph is a result of the casing storage phenomenon.

In addition, it can be seen that the values of t_c are reasonably reliable (though perhaps somewhat conservative) in determining the start of the correct straight line slope.

Thus, pumping test data that heretofore were considered anomalous or were simply misinterpreted altogether, now appear explainable. In addition, equation (3) provides a useful guide in determining where the "anomalous" data end and the reliable data begin.

A question arises then concerning the potential usefulness of early data gathered from a pumping test. That these data are still useful can be seen as follows.

Evidence suggests that for wells in which the efficiency E is greater than about 20 or 30 per cent, the following relationship exists between T_1 and T_2:

$$T_2 = \frac{4\,T_1}{E} \qquad (4)^{\#}$$

This conjecture has been tested by comparing values of T_2 to those of $\frac{4T_1}{E}$ (listed in Table 1) for the seven pumping tests shown in

(continued on page 10)

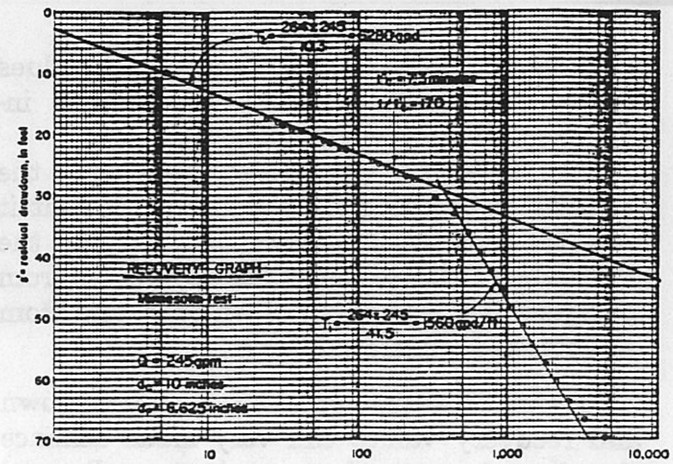

FIG. 8. t/t' = time since pumping started divided by time since pumping stopped

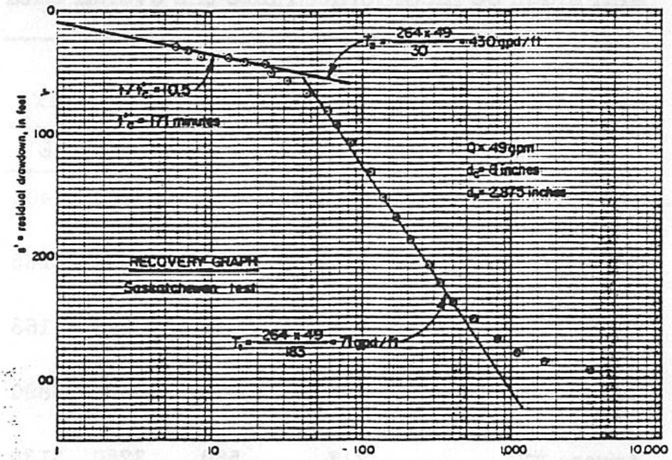

FIG. 9. t/t' = time since pumping started divided by time since pumping stopped

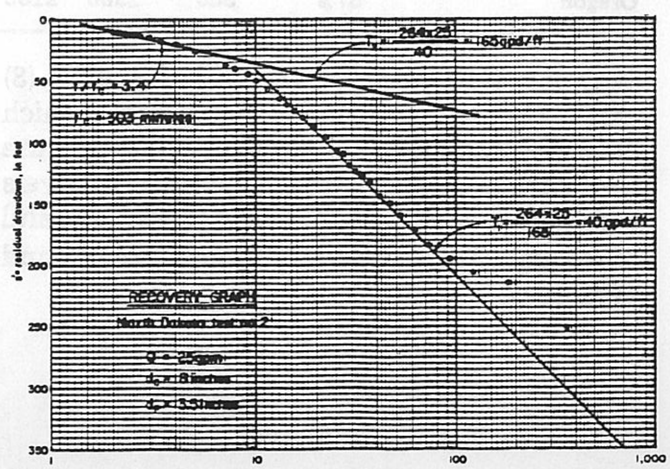

FIG. 10. t/t' = time since pumping started divided by time since pumping stopped

Figures 8-10. These recovery graphs show how the pumping test data have been affected by casing storage. The T_1 values calculated from the casing storage sensitive data are in error. The T_2 values, however, are correct, since they have been determined from data which are no longer affected by casing storage.

Figures 3-6 and 8-10. The well efficiency values shown in Table 1 were determined independently for each pumping test.

The excellent agreement supports the validity of equation (4). This suggests that it can be used as a means of checking the calculated T values and efficiency values from pumping tests especially when only data from the pumped well are available.

Careful collection of early time drawdown and recovery values can very much enhance the data base used to evaluate wells and aquifers. The effect, however, of casing storage on the early measurements cannot be ignored and must be incorporated into the overall data analysis. Estimation of t_c with equation (3) aids in the interpretation by determining which data are influenced by casing storage and are therefore not subject to conventional analysis techniques. Equation (4) then provides a useful check on obtained values of transmissivity and efficiency.

TABLE 1

Pumping Test	Efficiency, E	T_1	T_2	$\frac{4T_1}{E}$
Saskatchewan	70%	71	430	406
North Dakota #1	75%	406	2350	2165
North Dakota #2	95%	40	165	168
Arizona #1	27%	600	10600	8890
Arizona #2	74%	580	3280	3135
Minnesota #1	100%	1560	6280	6240
Oregon	57%	300	2300	2105

References

* Papadopulos and Cooper, "Drawdown in a Well of Large Diameter," Water Resources Research (1st quarter 1967).

† Ramey, H. J., Jr., Kumar, A., and Gulati, M. S., "Gas Well Test Analysis under Water-Drive Conditions," American Gas Association Monograph (1973).

‡ Society of Petroleum Engineers of AIME, Paper #SPE 5878 (April 1976).

§ Equation (3) was obtained by dividing Papadopulos and Cooper's result, equation (1), by the well efficiency and making some mathematical substitutions and simplifications.

|| Equation (3) requires that the drawdown s at time t_c be known and thus it appears that there are two unknowns, s and t_c. Initially, however, any drawdown value s_1 can be chosen and a trial t_c value can be calculated. Using the trial value of t_c and the time drawdown graph, a new drawdown value, s_2 is obtained which can be used in equation (3) to calculate a second trial value of t_c. This procedure is repeated two or three times until the calculated value for t_c does not change.

\# For more accuracy, the constant 4 could be replaced by —log S (negative logarithm of the storage coefficient).