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AMERICAN SOCIETY FOR TESTING AND MATERIALS
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Standard Test Method (Analytical Procedure) for Determining the Efficiency of a Production Well in a Confined Aquifer from a Constant Rate Pumping Test[1]

This standard is issued under the fixed designation D 6034; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes an analytical procedure for determining the hydraulic efficiency of a production well in a confined aquifer. It involves comparing the actual drawdown in the well to the theoretical minimum drawdown achievable and is based upon data and aquifer coefficients obtained from a constant rate pumping test.

1.2 This analytical procedure is used in conjunction with the field procedure, Test Method D 4050.

1.3 *Limitations*—The limitations of the technique for determination of well efficiency are related primarily to the correspondence between the field situation and the simplifying assumption of this test method.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

D 5521 Guide for Development of Ground-Water Monitoring Wells in Granular Aquifers[3]

D 5850 Test Method (Analytical Procedure) for Determining Transmissivity, Storage Coefficient, and Anisotropy Ratio from a Network of Partially Penetrating Wells Using Distance-Drawdown Data and Iterative Procedure[3]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, see Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *aquifer, confined*, *n*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.2.2 *confining bed*, *n*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.2.3 *control well*, *n*—a well by which the head and flow in the aquifer is changed, for example, by pumping, injection, or imposing a constant change of head.

3.2.4 *drawdown*, *n*—vertical distance the static head is lowered due to the removal of water.

3.2.5 *hydraulic conductivity*, *n*—(field aquifer test) the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction flow.

3.2.6 *observation well*, *n*—a well open to all or part of an aquifer.

3.2.7 *piezometer*, *n*—a device so constructed and sealed as to measure hydraulic head at a point in the subsurface.

3.2.8 *storage coefficient*, *n*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

3.2.9 *transmissivity*, *n*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.2.10 *well efficiency*, *n*—the ratio, usually expressed as a percentage, of the measured drawdown inside the control well divided into the theoretical drawdown which would occur in the aquifer just outside the borehole if there were no drilling damage, that is, no reduction in the natural permeability of the sediments in the vicinity of the borehole.

3.3 *Symbols:Symbols and Dimensions:*

3.3.1 K—hydraulic conductivity [LT^{-1}].

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigation.

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

3.3.1.1 *Discussion*—The use of the symbol K for the term hydraulic conductivity is the predominant usage in groundwater literature by hydrogeologists, whereas the symbol k is commonly used for this term in soil and rock mechanics and soil science.

3.3.2 K_r—hydraulic conductivity in the plane of the aquifer, radially from the control well (horizontal hydraulic conductivity) [LT^{-1}].

3.3.3 K_z—hydraulic conductivity normal to the plane of the aquifer (vertical hydraulic conductivity) [LT^{-1}].

3.3.4 $K_0(x)$—modified Bessel function of the second kind and zero order [nd].

3.3.5 Q—discharge [L^3T^{-1}].

3.3.6 S—storage coefficient [nd].

3.3.7 T—transmissivity [L^2T^{-1}].

3.3.8 s_r—drawdown in the aquifer at a distance r from the control well [L].

3.3.9 s_f—drawdown which would occur in response to pumping a fully penetrating well [L].

3.3.10 r_w—borehole radius of control well [L].

3.3.11 s_{rw}—theoretical drawdown which would occur in the aquifer just outside the borehole if there were no drilling damage, that is, no reduction in the natural permeability of the sediments in the vicinity of the borehole [L].

3.3.12 s_w—drawdown measured inside the control well [L].

3.3.13 u—$(r^2S)/(4Tt)$[nd].

3.3.14 $W(u)$—an exponential integral known in hydrology as the Theis well function of u [nd].

3.3.15 A—K_z/K_r, anisotropy ratio [nd].

3.3.16 b—thickness of aquifer [L].

3.3.17 d—distance from top of aquifer to top of screened interval of control well [L].

3.3.18 d'—distance from top of aquifer to top of screened interval of observation well [L].

3.3.19 f_s—incremental dimensionless drawdown component resulting from partial penetration [nd].

3.3.20 l—distance from top of aquifer to bottom of screened interval of control well [L].

3.3.21 l'—distance from top of aquifer to bottom of screened interval of observation well [L].

3.3.22 r—radial distance from control well [L].

3.3.23 t—time since pumping began [T].

3.3.24 E—well efficiency [nd].

4. Summary of Test Method

4.1 This test method uses data from a constant rate pumping test to determine the well efficiency. The efficiency is calculated as the ratio of the theoretical drawdown in the aquifer just outside the well bore (s_{r_w}) to the drawdown measured inside the pumped well (s_w). The theoretical drawdown in the aquifer (s_{r_w}) is determined from the pumping test data by either extrapolation or direct calculation.

4.2 During the drilling of a well, the hydraulic conductivity of the sediments in the vicinity of the borehole wall is reduced significantly by the drilling operation. Damaging effects of drilling include mixing of fine and coarse formation grains, invasion of drilling mud, smearing of the borehole wall by the drilling tools, and compaction of sand grains near the borehole. The added head loss (drawdown) associated with the permeability reduction due to drilling damage increases the drawdown in the pumped well and reduces its efficiency (see Fig. 1). Well development procedures help repair the damage (see Guide D 5521) but generally cannot restore the sediments to their original, natural permeability.

4.2.1 Additional drawdown occurs from head loss associated with flow through the filter pack, through the well screen and vertically upward inside the well casing to the pump intake. While these drawdown components contribute to inefficiency, they usually are minor in comparison to the head loss resulting from drilling damage.

4.2.2 The well efficiency, usually expressed as a percentage, is defined as the theoretical drawdown, also called aquifer drawdown, which would have occurred just outside the well if there were no drilling damage divided by the actual drawdown inside the well. The head losses contributing to inefficiency generally are constant with time while aquifer drawdown gradually increases with time. This causes the computed efficiency to increase slightly with time. Because the efficiency is somewhat time dependent, usually it is assumed that the well efficiency is the calculated drawdown ratio achieved after one day of continuous pumping. It is acceptable, however, to use other pumping times, as long as the time that was used in the efficiency calculation is specified. The only restriction on the pumping time is that sufficient time must have passed so that wellbore storage effects are insignificant. In the vast majority of cases, after one day of pumping, the effects of wellbore storage have long since become negligible.

4.2.3 Efficiency is also somewhat discharge dependent. Both the aquifer drawdown and the inefficiency drawdown can include both laminar (first order) and turbulent (approximately second order) components. Because the proportion of laminar versus turbulent flow can be different in the undisturbed aquifer than it is in the damaged zone and inside the well, the aquifer drawdown and inefficiency drawdown can increase at different rates as Q increases. When this happens, the calculated efficiency is different for different pumping rates. Because of this discharge dependence, efficiency testing usually is performed at or near the design discharge rate.

4.3 The drawdown in the aquifer around a well pumped at a constant rate can be described by one of several equations.

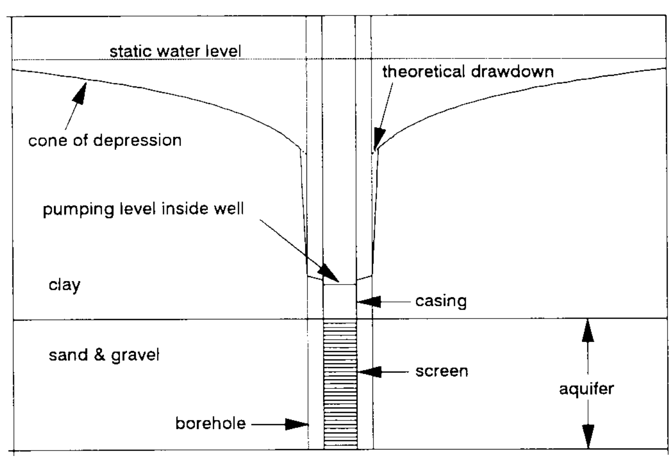

FIG. 1 Illustration of Drawdown Inside and Outside Pumping Well

4.3.1 For fully penetrating wells, the Theis equation **(1)**[4] is used.

$$s_r = \frac{Q}{4\pi T} W(u) \tag{1}$$

where:

$$W(u) = \int_u^{\infty} \frac{e^{-x}}{x} dx \tag{2}$$

and

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

4.3.2 For sufficiently small values of u, the Theis equation may be approximated by the Cooper-Jacob equation **(2)**.

$$s_r = \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{r^2 S}\right) \tag{4}$$

4.3.2.1 Examples of errors in this approximation for some u values are as follows:

u	Error
0.01	0.25 %
0.03	1.01 %
0.05	2.00 %
0.10	5.35 %

4.3.3 For partially penetrating wells, the drawdown can be described by either the Hantush equation **(3-5)** or the Kozeny equation **(6)**.

4.3.3.1 The Hantush equation is similar to the Theis equation but includes a correction factor for partial penetration.

$$s_r = \frac{Q}{4\pi T}(W(u) + f_s) \tag{5}$$

4.3.3.2 According to Hantush, at late pumping times, when $t > b^2S/(2TA)$, f_s can be expressed as follows:

$$f_s = \frac{4b^2}{\pi^2(l-d)(l'-d')} \sum_{n=1}^{\infty} \left(\frac{1}{n^2}\right) K_0 \left(\frac{n\pi r\sqrt{K_z/K_r}}{b}\right) \left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right]\left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right] \tag{6}$$

4.3.3.3 The Kozeny equation is as follows:

$$s_r = \frac{s_f}{\frac{l-d}{b}\left(1 + 7\sqrt{\frac{r}{2(l-d)}}\cos\frac{\pi(l-d)}{2b}\right)} \tag{7}$$

4.3.3.4 In this equation, s_f is the drawdown for a fully penetrating well system and can be computed from Eq 1-4. While easier to compute than the Hantush equation, the Kozeny equation is not as accurate. It does not incorporate pumping time or anisotropy and assumes that the screen in the control well reaches either the top or the bottom of the aquifer.

4.3.4 The presence of a positive boundary (for example, recharge) causes the drawdown in the aquifer to be less than predicted by Eq 1-6, while a negative boundary (for example, the aquifer pinching out) results in more drawdown. The boundary-induced increases or decreases in drawdown usually can be determined from the pumping test data. These increases/decreases can be combined with calculations using Eq 1-7 to determine the drawdown just outside the well bore.

4.4 The efficiency of a production well is calculated as follows:

$$E = \frac{s_{r_w}}{s_w} \tag{8}$$

where:

s_w = denominator, the drawdown measured inside the well, and

s_{rw} = numerator, must be determined from field data.

Two procedures are available for determining s_{rw}—extrapolation and direct calculation.

4.4.1 *Extrapolation*—Extrapolation can be used to determine s_{r_w} if data from two or more observation wells are available. Distance drawdown data can be plotted from these wells on either log-log or semilog graphs. If a log-log plot is used, the Theis type curve is used to extrapolate the drawdown data to the borehole radius to determine s_{r_w}. If a semilog plot is used, extrapolation is done using a straight line of best fit. The semilog method can be used only if the u value for each observation well is sufficiently small that the error introduced by the log approximation to the Theis equation is minimal.

4.4.1.1 For partially penetrating wells, the observation wells must be located beyond the zone affected by partial penetration, that is, at a distance r from the pumped well such that:

$$r \geq \frac{1.5b}{\sqrt{K_z/K_r}} \tag{9}$$

4.4.1.2 The extrapolated drawdown obtained in this case is s_f, the theoretical drawdown, which would have occurred just outside the borehole of a fully penetrating pumped well. The aquifer drawdown corresponding to partial penetration is then computed with the Hantush equation as follows:

$$s_{r_w} = s_f + \frac{Q}{4\pi T} f_s \tag{10}$$

4.4.1.3 The second term on the right-hand side of Eq 10 represents the incremental aquifer drawdown caused by partial penetration.

4.4.1.4 Using the Kozeny equation, the aquifer drawdown for partial penetration is computed from Eq 7 with r set equal to the borehole radius r_w:

$$s_{r_w} = \frac{s_f}{\frac{l-d}{b}\left(1 + 7\sqrt{\frac{r_w}{2(l-d)}}\cos\frac{\pi(l-d)}{2b}\right)} \tag{11}$$

4.4.1.5 If the extrapolation method is used for determining aquifer drawdown, it is not necessary to make a separate adjustment to account for boundaries or recharge.

4.4.2 *Direct Calculation*—If the aquifer drawdown s_{rw} cannot be obtained by extrapolation, direct calculation must be used to determine its value.

4.4.2.1 For fully penetrating wells, s_{rw} can be obtained by direct calculation using either the Theis or Cooper-Jacob equations (Eq 1-4).

4.4.2.2 For partially penetrating wells, s_{r_w} is calculated from the Hantush equation (Eq 5 and Eq 6) or the Kozeny equation (Eq 11).

4.4.2.3 The presence of aquifer boundaries or recharge will tend to increase or decrease, respectively, the drawdown in and

[4] The boldface numbers in parentheses refer to the list of references at the end of this test method.

around the pumped well. When they are present, the calculated value of s_{r_w} must be adjusted to reflect the impact of the boundary conditions.

5. Significance and Use

5.1 This test method allows the user to compute the true hydraulic efficiency of a pumped well in a confined aquifer from a constant rate pumping test. The procedures described constitute the only valid method of determining well efficiency. Some practitioners have confused well efficiency with percentage of head loss associated with laminar flow, a parameter commonly determined from a step-drawdown test. Well efficiency, however, cannot be determined from a step-drawdown test but only can be determined from a constant rate test.

5.2 *Assumptions*:

5.2.1 Control well discharges at a constant rate, *Q*.

5.2.2 Control well is of infinitesimal diameter.

5.2.3 Data are obtained from the control well and, if available, a number of observation wells.

5.2.4 The aquifer is confined, homogeneous, and areally extensive. The aquifer may be anisotropic, and if so, the directions of maximum and minimum hydraulic conductivity are horizontal and vertical, respectively.

5.2.5 Discharge from the well is derived exclusively from storage in the aquifer.

5.3 *Calculation Requirements*—For the special case of partially penetrating wells, application of this test method may be computationally intensive. The function f_s shown in Eq 6 must be evaluated using arbitrary input parameters. It is not practical to use existing, somewhat limited, tables of values for f_s and, because this equation is rather formidable, it is not readily tractable by hand. Because of this, it is assumed the practitioner using this test method will have available a computerized procedure for evaluating the function f_s. This can be accomplished using commercially available mathematical software including some spreadsheet applications or by writing programs in languages, such as Fortran or *C*. If calculating f_s is not practical, it is possible to substitute the Kozeny equation for the Hantush equation as previously described.

6. Apparatus

6.1 Apparatus for withdrawal tests is given in Test Method D 4050. The following apparatus are those components of the apparatus that require special attributes for this specific test.

6.2 *Construction of the Control Well*—Install the control well in the aquifer and equip with a pump capable of discharging water from the well at a constant rate for the duration of the test. A fully penetrating control well is preferred though not essential.

6.3 *Construction and Placement of Observation Wells*—If observation wells are used, they should be located on a straight line extending from the control well and positioned at different distances so that they span a good portion of the anticipated cone of depression. It is preferable that the wells be fully penetrating but not essential. If the control well and observation wells are partially penetrating, the extrapolation method of determining well efficiency can be used only if the observation wells are located outside the zone effected by partial penetration.

7. Procedure

7.1 Pretest preparations, pumping test guidelines, and post-test procedures associated with the pumping test itself are described in Test Method D 4050.

7.2 Verify the quality of the data set. Review the record of measured flow rates to make sure the rate was held constant during the test. Check to see that hand measurements of drawdown agree well with electronically measured values. Finally, check the background water-level fluctuations observed prior to or following the pumping test to see if adjustments must be made to the observed drawdown values to account for background fluctuations. If appropriate, adjust the observed drawdown values accordingly.

7.3 Analysis of the field data is described in Section 8.

8. Calculation and Interpretation of Test Data

8.1 *Methods*:

8.1.1 *Extrapolation*—This test method relies on extrapolating observation well drawdown data to estimate the theoretical drawdown just outside the well bore. It requires a single drawdown observation for the control well and each observation well used in the test, preferably after one day of continuous pumping. If the wells are penetrating partially, the observation wells must be located outside the zone effected by partial penetration as described by Eq 9.

8.1.1.1 *Log-Log Method*—Plot the observation well distance drawdown data on a log-log graph with drawdown on the vertical axis and the reciprocal of the distance squared on the horizontal axis. On a separate graph having the same scale as the data graph, prepare a standard Theis type curve by plotting *W(u)* on the vertical axis versus *l/u* on the horizontal axis (Fig. 2). Overlay the data plot on the type curve, and while keeping the coordinate axes of the two plots parallel, shift the data plot to align with the type curve effecting a match position. On the data graph, follow the type curve to a horizontal axis coordinate of l/r_w^2 and read s_{r_w} from the graph. For partially penetrating wells, the extrapolated value must be corrected for partial penetration using Eq 10 or Eq 11. Calculate well efficiency using Eq 8.

8.1.1.2 *Semilog Method*—This test method can be used if the *u* value for each observation well is sufficiently small that

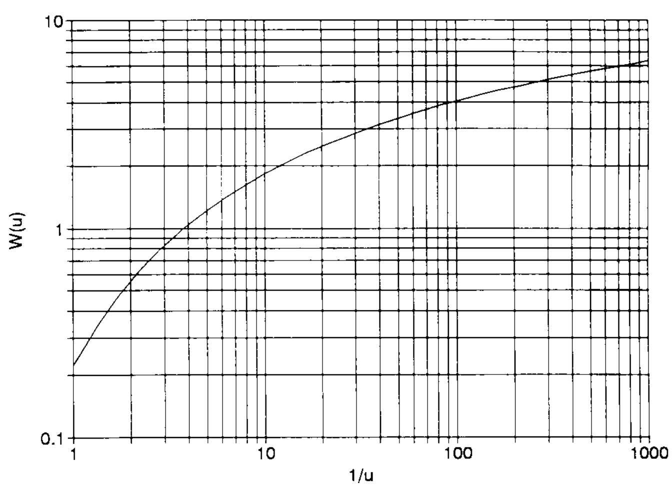

FIG. 2 Theis Type Curve

the Cooper-Jacob equation represents an adequate approximation to the Theis equation. Plot the observation well distance drawdown data on a semilog graph with drawdown on the linear scale and distance on the log scale. Construct a straight line of best fit through the data points and extrapolate it to a radius value of r_w. Read s_{r_w} from the graph. If the control well is partially penetrating, the extrapolated value must be corrected for partial penetration using Eq 10 or Eq 11. Calculate well efficiency using Eq 8.

8.1.2 *Direct Calculation*—Aquifer parameters including transmissivity, storage coefficient, and anisotropy ratio (T, S, A) are determined using conventional pumping test analysis techniques. Then s_{rw} is computed directly from Eq 1-7 and Eq 11.

8.1.2.1 *Fully Penetrating Wells*—Determine T and S from the pumping test. If no observation wells are available, it will not be possible to determine S from the test data. In this case, S must be estimated.

NOTE 1—An acceptable procedure for estimating S is to multiply the aquifer thickness in feet by a factor between 10^{-5} and 10^{-6}. Determine the aquifer drawdown, s_{rw}, by direct calculation using either Eq 1-3 or Eq 4. The time parameter used in the calculation should be the time at which s_w was measured inside the control well. Determine well efficiency using Eq 8.

8.1.2.2 *Partially Penetrating Wells*—Determine T, S, and A from the pumping test. Often it is difficult to determine the anisotropy ratio, A, accurately from the pumping test data. If this is the case, A must be estimated. Likewise, if S cannot be calculated from the data, it must be estimated. Calculate s_{r_w} from Eq 5 and Eq 6 or Eq 11 and well efficiency from Eq 8.

8.1.2.3 *Boundary Conditions*—If boundary conditions affect the magnitude of the observed drawdown, follow 8.1.2.1 or 8.1.2.2 to calculate an initial value for s_{r_w}. This value then must be increased or decreased by the magnitude of the boundary effect. Determine this value in accordance with 8.1.2.4.

8.1.2.4 Use the time drawdown graph for either the control well or any observation well where the u value is sufficiently small (approximately $u < 0.05$). Extrapolate the early time drawdown trend to a pumping time of one day to obtain the drawdown that would have been observed if no boundary had been present. Determine the difference between this value and the actual drawdown at one day. Increase (negative boundary) or decrease (positive boundary) the initial value of s_{rw} by this amount to obtain a final value for s_{rw}. Use Eq 8 to compute well efficiency.

8.2 *Example Calculations*:

8.2.1 *Semilog Extrapolation*:

8.2.1.1 Table 1 shows distance drawdown data obtained from a 24-h constant rate pumping test incorporating three observation wells located 30 ft, 100 ft, and 400 ft from the control well. The control well was completed with a 24-in. diameter borehole (radius = 1 ft).

8.2.1.2 The distance drawdown data have been plotted on the graph shown in Fig. 3. A straight line of best fit constructed through the data points extrapolates to a drawdown value of 34 ft at the borehole radius. The actual drawdown measured in the pumped well is 46.2 ft. The efficiency is calculated as follows:

TABLE 1 Distance-Drawdown Data After 24 h of Continuous Pumping at 600 gpm (115 000 cfd)

Well	Distance, ft	Drawdown at 24 h, ft
Control well	1[A]	46.2
Observation Well 1	30	20.3
Observation Well 2	100	15.5
Observation Well 3	400	9.7

[A] Borehole radius.

$$E = \frac{34}{46.2} = 74\ \% \qquad (12)$$

8.2.2 *Log-Log Extrapolation*—The data from Table 1 have been replotted on the log-log graph shown in Fig. 4. On this graph, drawdown is plotted against the reciprocal of the square of the distance to the observation well. Theis type curve matching results in the type curve position shown on the graph. The extrapolated drawdown corresponding to the borehole radius of 1 ft is 34 ft, the same as the value obtained from the semilog analysis. The efficiency calculation is identical to that in the previous section.

8.2.3 *Direct Calculation*:

8.2.3.1 Fig. 5 shows a semilog time drawdown graph for a control well pumped at 800 gpm for 24 h. The transmissivity determined using standard analysis techniques from the early time drawdown trend is 8690 ft^2/day.

8.2.3.2 About 100 min into the test, the influence of a negative boundary is seen in the data plot. Extrapolating the early time drawdown trend to a pumping time of one day results in a predicted drawdown of 35.3 ft. The measured one-day drawdown in the well was 43.9 ft. The difference of 8.6 ft is the incremental drawdown attributable to the presence of the negative boundary.

8.2.3.3 Since there were no observation wells available for this pumping test, direct calculation must be used to determine well efficiency. Eq 4 is used to compute a trial value for s_{rw},

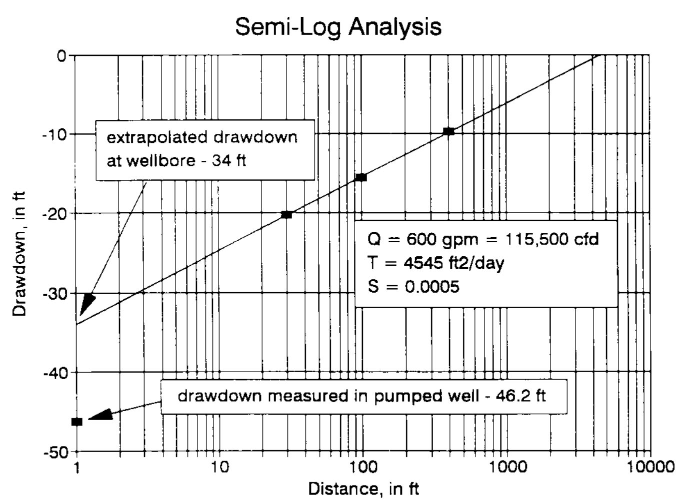

FIG. 3 Extrapolation of Straight Line on Semilog Graph

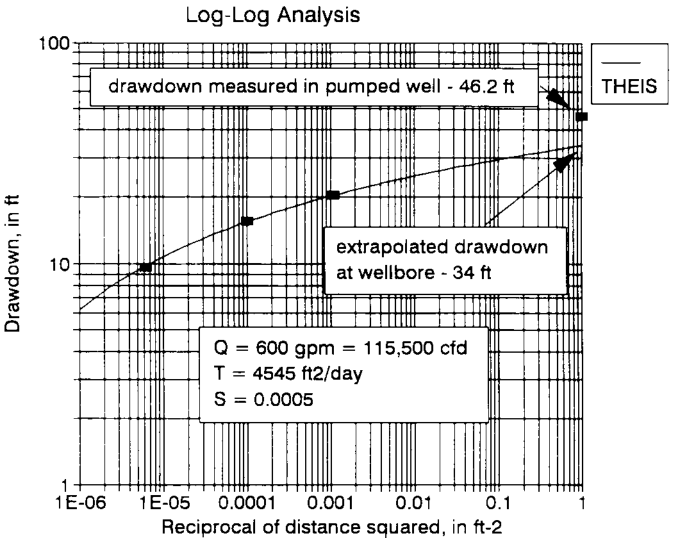

FIG. 4 Extrapolation of Theis Type Curve on Log-Log Graph

that is, the expected theoretical aquifer drawdown assuming no boundary condition. Inputs to the equation are as follows:

Q = 154 000 cfd,
T = 8690 ft^2/day,
S = 5×10^{-4}(estimated),
r_w = 1 ft, and
t = 1 day

NOTE 2—Storage coefficient had to be estimated to facilitate the calculation. The trial value for s_{rw} is as follows:

$$\text{trial } s_{r_w} = \frac{2.3 \times 154\,000}{4\pi 8690} \log\left(\frac{2.25 \times 8690 \times 1}{1^2 0.0005}\right) = 24.6 \text{ ft} \quad (13)$$

8.2.3.4 Since it is known that the presence of the boundary causes an additional 8.6 ft of drawdown above that which would be theoretically predicted, the theoretical aquifer drawdown at the borehole face including the effect of the boundary is as follows:

$$s_{r_w} = 24.6 + 8.6 \quad (14)$$

$$= 33.2 \text{ ft}$$

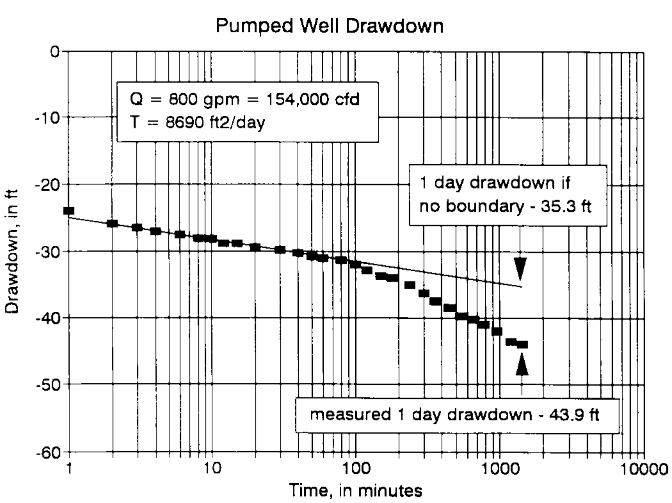

FIG. 5 Pumped Well Time-Drawdown Graph

8.2.3.5 Finally, the efficiency is calculated from Eq 8 as follows:

$$E = \frac{33.2}{43.9} = 76\ \% \quad (15)$$

8.2.4 *Log-Log Extrapolation with Partial Penetration*—Table 2 shows distance drawdown data obtained from a 90-gpm, 24-h constant rate pumping test incorporating two observation wells located 360 and 2200 ft from the control well. The control well was completed with an 18-in. diameter borehole (radius = 0.75 ft) and penetrated 30 ft of an 80-ft thick aquifer.

8.2.5 Fig. 6 shows a Theis curve match from which transmissivity and storage coefficient were computed as 485 ft^2/day and 0.00034, respectively. This analysis assumes that both observation wells lie outside the zone affected by partial penetration, a reasonable assumption for moderately antisotropic to isotropic conditions. The theoretical drawdown extrapolated at the borehole radius of 0.75 ft ($1/r^2$ = 1.78 ft^{-2}) is 44 ft as shown on the figure.

8.2.5.1 The calculated value of u for the distant observation well using Eq 3 is as follows:

$$u = \frac{2200^2 = \ \times 0.00034}{4 \times 485 \times 1} \quad (16)$$

$$= 0.848$$

This large value of u precludes using the straight-line, semilog method for extrapolating theoretical drawdown at the borehole.

8.2.5.2 Because the control well does not fully penetrate the aquifer, the extrapolated drawdown must be corrected for partial penetration using either Eq 10 or Eq 11. Since no antisotropy information is available, a value of A must be estimated if Eq 10 is used. In this example, Eq 11 will be used to determine the corrected drawdown value. Inputs to the equation are as follows:

l = 30 ft,
d = 0 ft,
b = 80 ft,
r_w = 0.75 ft, and
s_f = 44 ft (extrapolated from graph).

From Eq 11:

$$s_{r_w} = \frac{44}{\frac{30}{80}\left(1 + 7\sqrt{\frac{0.75}{2 \times 30}} \cos \frac{\pi 30}{2 \times 80}\right)} \quad (17)$$

$$= 68.5\ ft$$

Finally, the efficiency is calculated from Eq 8 as follows:

TABLE 2 Distance-Drawdown Data After 24 h of Continuous Pumping at 90 gpm (17 325 cfd)

Well	Distance, ft	Drawdown at 24 h, ft
Control Well	0.75[A]	116.0
Observation Well 1	360	9.2
Observation Well 2	2200	0.8

[A] Borehole radius

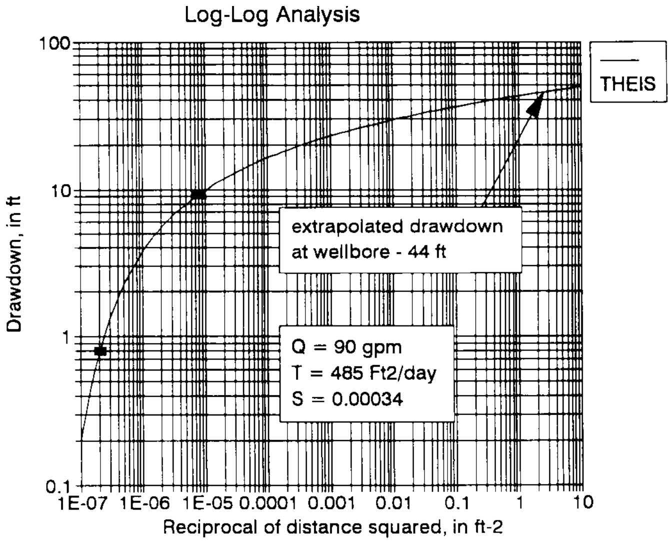

FIG. 6 Extrapolated Drawdown for Partially Penetrating Well

$$E = \frac{68.5}{116} = 59\ \% \tag{18}$$

9. Report

9.1 Report the following information:

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the test method for determining the efficiency of a pumped well in a confined aquifer. Briefly summarize the field hydrogeologic conditions and the field equipment and instrumentation, including the construction of the control well and observation wells, the method of measurement of discharge and water levels, and the duration of the test and pumping rate.

9.1.2 *Conceptual Model*—Review the information available on the hydrogeology of the site. Interpret and describe the hydrogeology of the site as it pertains to the selection of this test method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions in the solution to the aquifer test method.

9.1.3 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction; diameter; depth of screened and filter-packed intervals; location of control well and pumping equipment; and the construction, diameter, depth, and screened interval of observation wells.

9.1.4 *Instrumentation*—Describe the field instrumentation for observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to this test method. Include a list of measuring devices used during the test method; the manufacturer's name, model number, and basic specifications for each major item; and the name, date, and method of the last calibration, if applicable.

9.1.5 *Testing Procedures*—List the steps taken in conducting pretest, drawdown, and recovery phases of the test. Include the frequency of measurements of discharge rate, water level in observation wells, and other environmental data recorded during the testing procedure.

9.1.6 *Presentation and Interpretation of Test Results*:

9.1.6.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for background water-level and barometric changes and calculation of drawdown and residual drawdown.

9.1.6.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curve with match points and corresponding values of parameters at match points.

9.1.7 Evaluate qualitatively the overall accuracy of the test, the corrections and adjustments made to the original water-level measurements, the adequacy and accuracy of instrumentation, accuracy of observations of stress and response, and the conformance of the hydrogeologic conditions and the conformance of the test to the model assumptions.

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 anisotropy; aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; observation wells; storage coefficient; transmissivity; well efficiency

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