



Designation: D6034 – 96 (Reapproved 2004)

Standard Test Method (Analytical Procedure) for Determining the Efficiency of a Production Well in a Confined Aquifer from a Constant Rate Pumping Test¹

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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 D4050.

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*:²

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D4050 Test Method for (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems

D5521 Guide for Development of Ground-Water Monitoring Wells in Granular Aquifers

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, see Terminology D653.

¹ This test method is under the jurisdiction of ASTM Committee D18 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 For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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}].

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) [$L T^{-1}$].

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

3.3.5 Q —discharge [$L^3 T^{-1}$].

3.3.6 S —storage coefficient [nd].

3.3.7 T —transmissivity [$L^2 T^{-1}$].

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 $u = (r^2 S)/(4 T t)$ [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_{rw}) to the drawdown measured inside the pumped well (s_w). The theoretical drawdown in the aquifer (s_{rw}) 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 D5521) 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

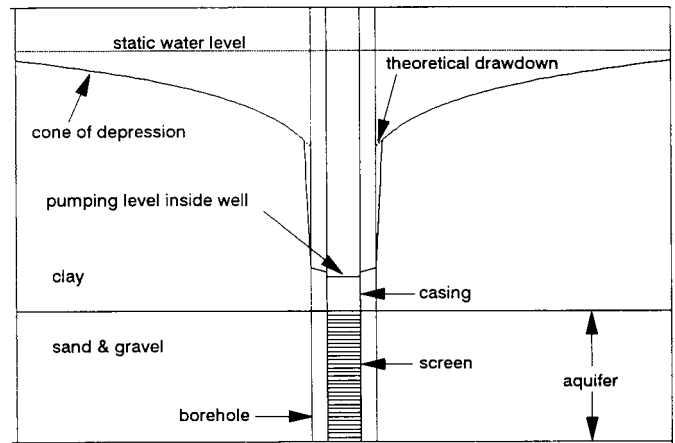


FIG. 1 Illustration of Drawdown Inside and Outside Pumping Well

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.

4.3.1 For fully penetrating wells, the Theis equation (1)³ is used.

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

where:

³ The boldface numbers in parentheses refer to the list of references at the end of this test method.

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

and

$$u = \frac{r^2 S}{4Tt} \quad (3)$$

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

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

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.

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

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

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

4.3.3.3 The Kozeny equation is as follows:

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

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:

$$E = \frac{s_{r_w}}{s_w} \quad (8)$$

where:

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

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

Two procedures are available for determining s_{r_w} —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:

$$r \geq \frac{1.5b}{\sqrt{K_z/K_r}} \quad (9)$$

4.4.1.2 The extrapolated drawdown obtained in this case is s_{f_s} 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:

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

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 :

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_{r_w} cannot be obtained by extrapolation, direct calculation must be used to determine its value.

4.4.2.1 For fully penetrating wells, s_{r_w} 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 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 D4050. 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 D4050.

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 $1/u$ 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 $1/r_w^2$ 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 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

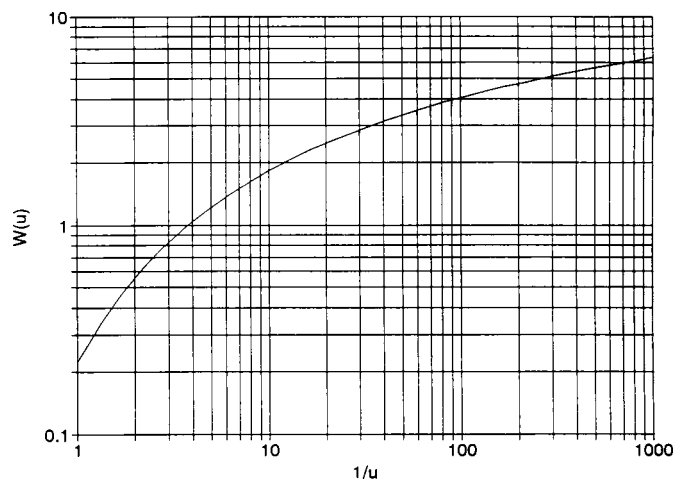


FIG. 2 Theis Type Curve