UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

MEMORANDUM ON MULTIPLE-STEP DRAWDOWN TESTS, SOUTHWEST WELL FIELD, HOUSTON, TEXAS
FEBRUARY 1949

By

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TESTS CONDUCTED IN COOPERATION WITH THE CITY OF HOUSTON AND
THE TEXAS STATE BOARD OF WATER ENGINEERS

SEPTEMBER 1949

REPRINTED AUGUST 1951

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INTRODUCTION

In November 1948, F. N. Baldwin, Director of Utilities, City of Houston, Texas, asked in a letter to W. L. Broadhurst, district geologist, Ground Water Branch, U. S. Geological Survey, whether the Survey would be interested in running tests on some of the city wells for the purpose of field checking recently developed theory on head losses in wells. The tests would also provide additional information on the transmissibility and storage coefficient of the water-bearing sands in the Houston area. The offer by the City of Houston to permit use of their deep wells presented an opportunity to try the multiple-step drawdown test under field conditions not encountered in the shallow sands in which previous tests had been made. The offer was accepted and in February 1949 the writer visited Houston to supervise the tests.

City officials cooperated fully by adjusting the operation schedule of other wells so as to provide as nearly steady flow conditions as possible.

Theory of multiple-step test

C. E. Jacob [1] prepared an article in May 1946 discussing losses of head in wells and presenting a method of separation of formational loss (loss of head in the aquifer) from well losses (loss of head in the turbulent-flow zone in and near the well screen). Since that time additional study of the method has been made by the writer and other members of the Geological Survey. The method presented by Jacob has been revised so as to treat the problem in a more generalized manner. The exponent which Jacob assumed as the square has been treated as an unknown constant. The revised basic equation is

$$s_w = BQ + CQ$$

where

s_w is the drawdown in the well at a given time and at a constant pumping rate. (s_w is the sum of the incremental drawdowns used by Jacob, that is, $s_w = \Delta s_1 + \Delta s_2 + \Delta s_3$ -----------------)

B is a constant for the formation

C is a constant for the turbulent-flow zone

Q is the discharge at any step

n expresses the variation of head losses in the turbulent-flow zone with discharge.

The term BQ represents the formational head loss in the zone of laminar flow between the external boundary of the aquifer and the zone of turbulent flow near the well. The term CQ^n represents the "well losses" or head loss in the turbulent-flow zone in and near the screen. This term also includes the pipe losses caused by turbulent vertical flow up the well.

The equation may be put in the form

$$\log (s_w/Q - B) = \log C + (N-1) \log Q$$

This equation should plot a straight line on log-log paper where Q is plotted against $(s_w/Q - B)$. By assuming values of B and plotting on log-log paper a family of curves is obtained. The value of B which produces a straight line is the final solution for B. The term C is obtained

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[1] Jacob, C. E. Drawdown test to determine effective radius of artesian well: Am. Soc. Civil Eng. Trans., vol. 112, paper no. 2321, p. 1047, 1947.

from the intercept where Q is unity. The value of n is determined from the slope of the line which equals (n - 1).

The solution obtained by this method is empirical. However, it has been shown that the method will yield results which have practical application.

Test procedure

Wells 7 and 8 in the Southwest well field at Houston, Texas, were selected for the tests. These wells were selected because they are equipped with measuring pipes and because reasonable control could be maintained on other wells being pumped in the area. Each well-discharge line is equipped with a Sparling meter.

A 5-hour step test was made on well 7 on February 11, 1949. Following the procedure outlined by Jacob, [2] the well was pumped for an hour at each of five progressively increasing rates. An interference test was made on February 14 and 15, 1949, during which well 7 was pumped and well 8 was observed. A similar 5-hour step test was made on well 8 on February 17, 1949, followed by an interference test on February 18, during which well 8 was pumped and well 7 was observed. This interference test had to be stopped after about 5¼ hours because of heavy rain which made measuring impossible.

During all the tests, wells 2, 4, 5, and 6 were pumped continuously, well 3 remained idle, and changes in pumpage to meet the needs of the city were made by intermittent operation of well 1. Both step tests were made during periods when well 1 was operating continuously Well 1, which had operated for 24 hours prior to starting the first interference test, was shut off 8 hours after the test began.

Factors affecting test results

Conditions during the tests were far from ideal. The discharge lines from the eight wells in the field are connected to the storage reservoir at the pumping station through a common pipe line. Shut-down of well 1, which caused a pressure drop in the line, resulted in a small increase in discharge from well 7, and water level fluctuations of several feet in the storage reservoir also affected the discharge from well 7.

The step-test theory is based on constant discharge during each step, but the meters available made it impracticable to maintain constant pumping rates by adjusting the shut-off valves. The tests were made with a constant valve setting, consequently discharge rates were not constant but declined during each step. During the first step on well 7, the decline was from 1,200 to 900 gallons a minute, but during the remaining steps the declines were relatively small. Recorded discharge from the meter on well 7, which is obtained electrically at the pump station, showed inconsistent behavior at different pumping rates. Substantial declines in discharge from well 8 were noted during steps 1 and 3, whereas during steps 2, 4, and 5 the rates of discharge were relatively constant. The behavior of the discharge, as obtained from meter readings and from charts, suggests that the discharges were not as constant nor the measurements as accurate as could be desired for testing a new theory. Analysis of the step test data shows that relatively small errors in discharge will produce relatively large errors in the final results.

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[2] Op. cit.

In one phase of the analysis, pumping at very low rates would be desirable. Pressure limits in the pipe line between the pump and the control valve made it impossible to conduct tests at discharge rates below 900 gallons a minute.

The aquifer itself cannot be considered ideal. The wells penetrate about 1,500 feet of sediments consisting of water-bearing sands which are separated by layers of clay and shale ranging up to 80 feet in thickness. The wells are constructed with 12-inch screen opposite the sands and 12-inch blank casing opposite the clays and shales. The wells have a gravel pack 30 inches in diameter. Approximately the lower 1,000 feet of the aquifer is used and the average total screen length is about 400 feet. The first 400 feet of material below the land surface is thought to be separated from the screened zone by relatively impervious material. The clay and shale beds between the screen sections may or may not be continuous. If the water-bearing beds are inter-connected, it is probable that the well should be considered as partially penetrating. Uncertainties as to the exact geologic conditions, and lack of adequate methods for determining head losses for partial-penetration effects, where multiple screens are used, made it impracticable to compute step-test results beyond the point of separation of aquifer and well losses.

Analysis of step tests requires extension of the drawdown curve for each step in order to determine incremental drawdown resulting from the change in discharge. Variable discharge rates during several of the steps complicated the problem considerably, and the accuracy of the extension in those steps is considered poor.

Analysis of test data

Hydrologic factors

Values of transmissibility and storage coefficient were computed by the Theis method[3/] from drawdown curves from well 8 when well 7 was pumping. Values of transmissibility were obtained from drawdown curves in the pumped well at both wells 7 and 8 and from a recovery curve following pumping at well 7. Results are shown in table 1.

It was found that transmissibility varied with time; that is, as the cone expanded it reached areas having a different transmissibility. At well 7 the computed transmissibility values increased with time, indicating that locally the transmissibility may be low relative to that some distance away. At well 8 the computed transmissibility decreased with time, indicating that the transmissibility near the well may be higher than that away from the well. Inspection of electrical logs of the two wells shows that at well 8 the total thickness of water-bearing sands is approximately 20 percent greater than at well 7.

Values of transmissibility were obtained from interference tests on wells in the Houston area by Jacob[4/] and Guyton[5/]. Later interference tests on wells 1 through 6 in the Southwest well field gave an average value of transmissibility of 140,000 gallons a foot per day[6/]. The transmissibility determined from observation well 8 checks closely with this value. Values obtained from time-drawdown and recovery curves in the pumped well were smaller than those obtained from curves for the observation well.

[3/] Theis, C. V., The relation between the lowering of the piezometric surface and the rate of duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., 1935, pp. 519-524.

[4/] Jacob, C. E., Coefficients of storage and transmissibility obtained from pumping tests in the Houston district, Texas:Trans. Amer. Geophys. Union, pp. 744-756, 1941.

[5/] Guyton, W. F., Application of coefficients of transmissibility and storage to regional problems in the Houston district, Texas: Trans. Amer. Geophys. Union, pp. 756-770, 1941.

[6/] Lang, J. W., and Sandstrom, R. W., Ground-water resources of the Houston district, Texas, with a section on results of pumping tests at new Southwest pumping plant: Texas Board of Water Engineers, Dec. 1946.

Table 1. Values of transmissibility and storage coefficient

Well number		Time (minutes)	Transmissibility (gallons per day per foot)	Storage coefficient
Pumping	Observed			
7	7	10 to 100	95,000	
		100 to 1,000	99,000	
		1,000 to 2,500	105,000	
	7 (recovery)	1,000 to 2,500	105,000	
		Average for 3,500	82,500	
7	8	200 to 600	173,000	0.0014
		300 to 1,700	142,000	.0013
	8 (recovery)	100 to 1,000	142,000	.0014
8	8	100 to 300	108,000	
		Average for 300	116,000	

Step-test analysis

Date for the step test at well 8 are shown in table 2. The incremental drawdowns shown in the third column were obtained by extending the time-drawdown curve of the preceding step according to the Theis relation and subtracting from the observed drawdown at the end (1 hour) of the step in question. Drawdowns in the fourth column are the cumulative sums of the incremental drawdowns in the third column, and are the 1-hour drawdowns for each pumping rate that would have occurred if the well had been allowed to recover between steps. The last group of columns show data for various assumed values of B used in development of the family of curves on figure 1. The parameter which produces a straight line provides the final solution. The solution for well 8 is:

$$s_w = 12\,Q + 0.54\,Q^{2.43}$$

Step 4 was not given weight as it plotted off the curves. For the four remaining steps, no trial assumption of B would produce a perfect fit. The solution used gives less weight to step 3. A very small change in discharge would put this point on the curve. Note that several solutions are possible, depending on which point is given less weight. Data for step 5 appear to be good, since the 1-hour point of the interference test checked the step test within very close limits.

Table 2. Date for step test at well 8

Step number	Discharge Q (cfs)	One-hour incremental drawdown (feet)	One-hour drawdowns s_w (feet)	$\frac{s_w}{Q}$ (sec.-ft.^{2})	s_w/Q - B		
					B = 11	B = 12	B = 13
1	2.67	37.96 12.19	37.96	14.22	3.22	2.22	1.22
2	3.84		50.15	15.01	4.01	3.01	2.01
3	4.06	14.15 13.08	64.30	15.84	4.84	3.84	2.84
4	4.49	12.06	77.38	17.23	6.23	5.23	4.23
5	5.09		89.44	17.57	6.57	5.57	4.57
Interference test	5.09		89.38	17.56	6.56	5.56	4.56

For well 7, the pumpage data are poor. Depending on the interpretation given to the discharge, two solutions are given:

$$s_w = 13.5\ Q + 0.225\ Q^{2.82}$$
$$s_w = 13.8\ Q + 0.147\ Q^{3.05}$$

The equations are for the drawdown s_w (in feet) in the pumped well after pumping 1 hour at any discharge rate Q (in cfs.). The first term on the right side of the equation represents the loss of head attributed to the formation; the last term, the loss of head ("well losses") in the turbulent-flow zone near the well, in the screen, and in vertical flow up the well.

Figure 2 shows a plotting of discharge versus drawdown for the step test at well 8. The curve through the observed points was obtained by plotting the solution $s_w = 12\ Q + 0.54\ Q^{2.43}$. Also shown is the formational loss (BQ) and the theoretical loss as computed by the Theis equation. The difference between the formational loss by the Theis method and that obtained from the step test is about 25 feet at step 5.

Two explanations might account for the large difference.

First, the difference may be the result of partial penetration--the available methods of adjusting for this factor do not cover the case of multiple screens. If the well is considered as partially penetrating, the term BQ would be broken down into formational loss, which would vary with time, and the head loss due to distortion of flow, which would be expected to be constant with time.

Second, if the well were considered to be fully penetrating, the fact that the formational loss as computed from the step test is so much greater than the theoretical might be explained by the existence of a zone of low transmissibility near the well. This leads to the question as to the effectiveness of the development of the well. In construction of the well, it is necessary to maintain pressure in the hole to avoid collapse. Flow of water is maintained outward from the hole into the aquifer. Drilling mud or fine material in the well cuttings penetrates the face of the hole. After the gravel is placed, the well is developed by pumping or surging. Computation of the velocity of the water at the contact between the aquifer and the gravel shows that the average developing velocity was on the order of less than 1 foot per minute, which may not have effectively removed the drilling mud from the face of the aquifer. It is possible that a large loss of head occurs in this zone; however, until further field tests and laboratory studies have been made, no definite conclusion can be reached regarding this point.

Extension of step-test results for time

Assuming that the difference between the values of formational loss discussed in the previous section resulted from partial-penetration effect, the diagram in figure 3 has been developed for well 8. In computing the diagram, "well losses" were computed from the step test ($CQ^n=0.54\ Q^{2.43}$), the formational loss was computed by the Theis equation, and the penetration correction was assumed to be constant with time and to be equal to the difference between the BQ term of the step-test and the formational loss determined by the Theis equation.

The diagram (fig. 3) shows the computed drawdown for any period of time up to 20 years resulting from pumping the well continuously at a constant rate. This diagram is for the pumped well itself and does not include the interference effects of other wells. It also assumes constant transmissibility and storage coefficient and an aquifer of infinite areal extent.

Figure 4 is a diagram for well 8 which demonstrates the variation of specific capacity with discharge and also with time. The assumptions are the same as for figure 3.

At the time well 8 was drilled its specific capacity, as determined from a 10-minute recovery following a 72-hour test at 2,500 gallons per minute, was 30 gallons per minute per foot. Diagram 4 gives a value of 25.7 for 10 minutes of pumping at 2,500 gallons per minute. While specific capacities, one based on recovery and one based on drawdown, are not strictly comparable, the difference is considerably more than would be expected. The tests at well 8 show a specific capacity of 26.8 gallons per minute per foot for pumping 10 minutes at 2,283 gallons per minute, compared to 27.0 gallons per minute per foot computed on basis of the 10-minute recovery following the step test. At well 7, the 10-minute specific capacity for a pumping rate of 2,138 gallons per minute was 27.3 gallons per minute per foot, compared to a 10-minute recovery value of 27.9 gallons per minute per foot following 29 hours of continuous pumping. The difference over the longer period for well 8 indicates that the 10-minute specific capacity of that well has fallen off about 10 percent since it was drilled. The fact that the well is less efficient now than when drilled may indicate that fine material from the aquifer is entering the gravel pack or that the head loss in the turbulent zone has increased. Inasmuch as the aquifer is primarily artesian and only the lower sands are screened, the regional and local decline of water levels should not affect the well efficiency as measured by the step test. Jacob pointed out that a step test should be run when a well is first drilled. A second-step-test at a later date would show whether the decreased efficiency was in the formation or in the well, as would be indicated by a change in the value of B or C.

Summary and conclusions

Step tests run on two deep artesian wells of gravel-packed construction in the Southwest field at Houston, Texas, were only partially successful. Values of transmissibility for tests at wells 7 and 8, based on drawdown and recovery averaged about 140,000 gallons per day per foot, a figure which is in close agreement with that determined in 1945 at wells 1 through 6. The storage coefficient was determined as 0.0014. Analysis of the step tests yielded the solutions:

For well 8

$$s_w = 12\ Q + 0.54\ Q^{2.43}$$

For well 7 (depending on interpretation of discharge)

$$s_w = 13.5\ Q + 0.225\ Q^{2.82}$$

or

$$s_w = 13.8\ Q + 0.147\ Q^{3.05}$$

Comparison of values of specific capacity indicate that the efficiency of well 8 has declined about 10 percent since it was constructed, possibly an indication that fine material from the aquifer is entering the gravel-packed zone.

The results of the step test are less reliable than they might be because field conditions were not ideal. The physical set-up was such that discharge rates could not be held constant. The measurement of discharge was not sufficiently accurate for best results. Very small errors in discharge will cause relatively large errors in values of B, C, and n.

The aquifer consists of alternate beds of sand and clay or shale; the extent of interconnection between the water-bearing sands is not known. Location of multiple screens opposite the sand formations presents an uncertainty as to handling of the penetration problem. The step-test theory had been developed on the basis of data from conventional wells in sand and gravel. Application of the theory to gravel-packed wells may be satisfactory for separation of the well loss and formational loss, but may not be satisfactory in solving for the distribution of head loss outside the well.

The formational loss computed by the step method was considerably larger than that computed by the Theis method. The difference may be the result of partial-penetration effects, or may indicate a zone of low transmissibility near the well. Laboratory and field investigations are needed to determine where the loss occurs. It may be possible to improve methods of well construction to eliminate part of this loss, although, from a practical viewpoint, the problem promises to be difficult.

Conditions during the test and uncertainties involved in the analysis make it impractical to attempt to appraise the value of the step-test method.

Need for additional study

1. The step-test method should be field checked at locations where geologic conditions are as nearly ideal as possible and at locations where constant, accurate discharges can be obtained. These tests should include:

(a) Open holes fully penetrating consolidated sandstones under both artesian and water-table conditions.

(b) Fully penetrating wells in unconsolidated sand and gravel under both artesian and water-table conditions.

2. The entire problem of partial penetration, including multiple screens, should be investigated.

3. Laboratory investigations should be run on gravels of various size to determine critical Reynold's numbers and constants of head loss under both laminar-and turbulent-flow conditions. This information will be important in determining proper size material for gravel packs and in analysis of head losses outside the screen in conventional wells.

4. Field and laboratory work is needed to determine the head-loss distribution near and through a gravel-packed well. The Houston tests indicate that work might be done toward improving the efficiency of this type of well.

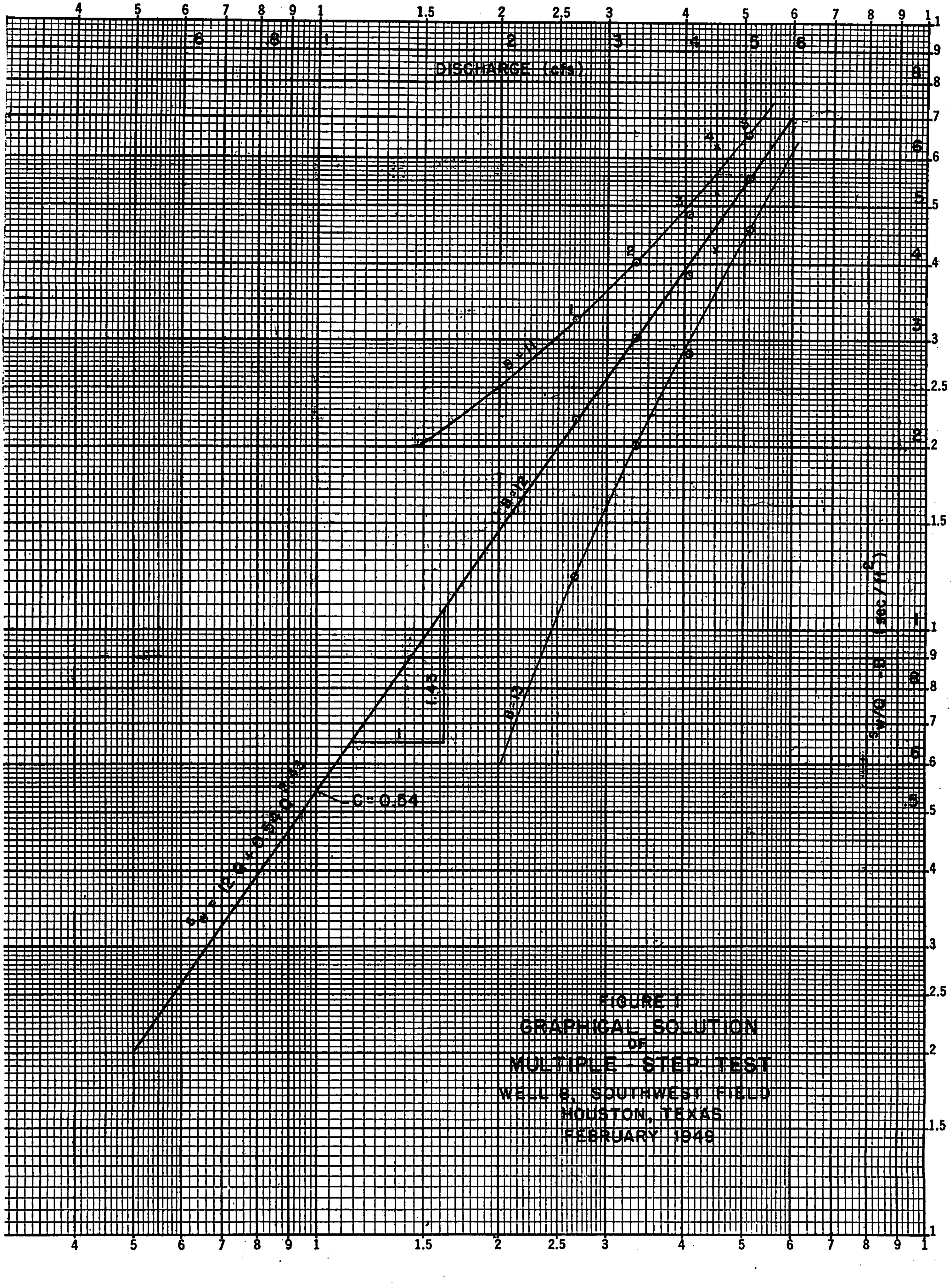

FIGURE 1
GRAPHICAL SOLUTION
OF
MULTIPLE - STEP TEST
WELL 8, SOUTHWEST FIELD
HOUSTON, TEXAS
FEBRUARY 1949

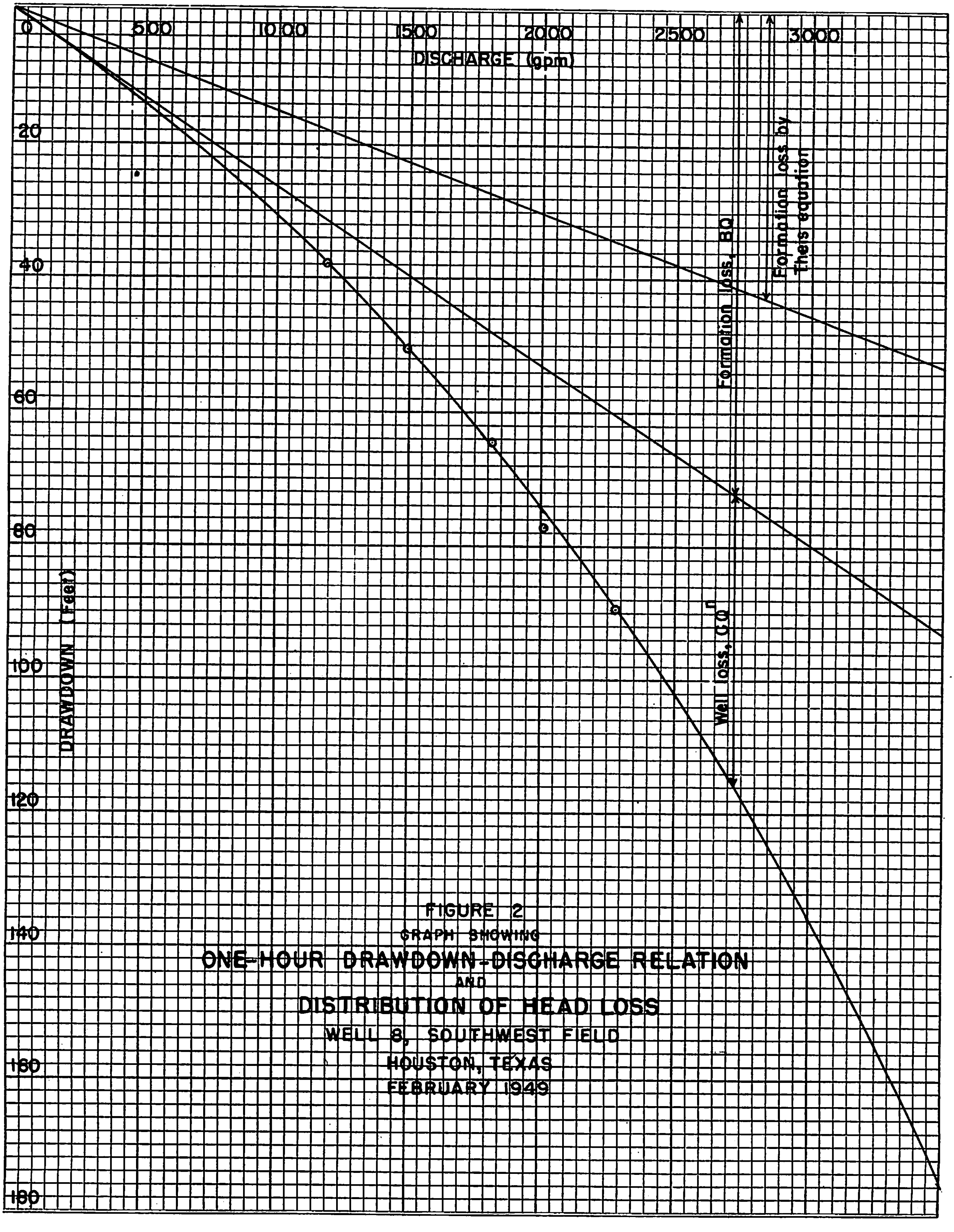

FIGURE 2

GRAPH SHOWING

ONE-HOUR DRAWDOWN-DISCHARGE RELATION

AND

DISTRIBUTION OF HEAD LOSS

WELL 8, SOUTHWEST FIELD

HOUSTON, TEXAS

FEBRUARY 1949

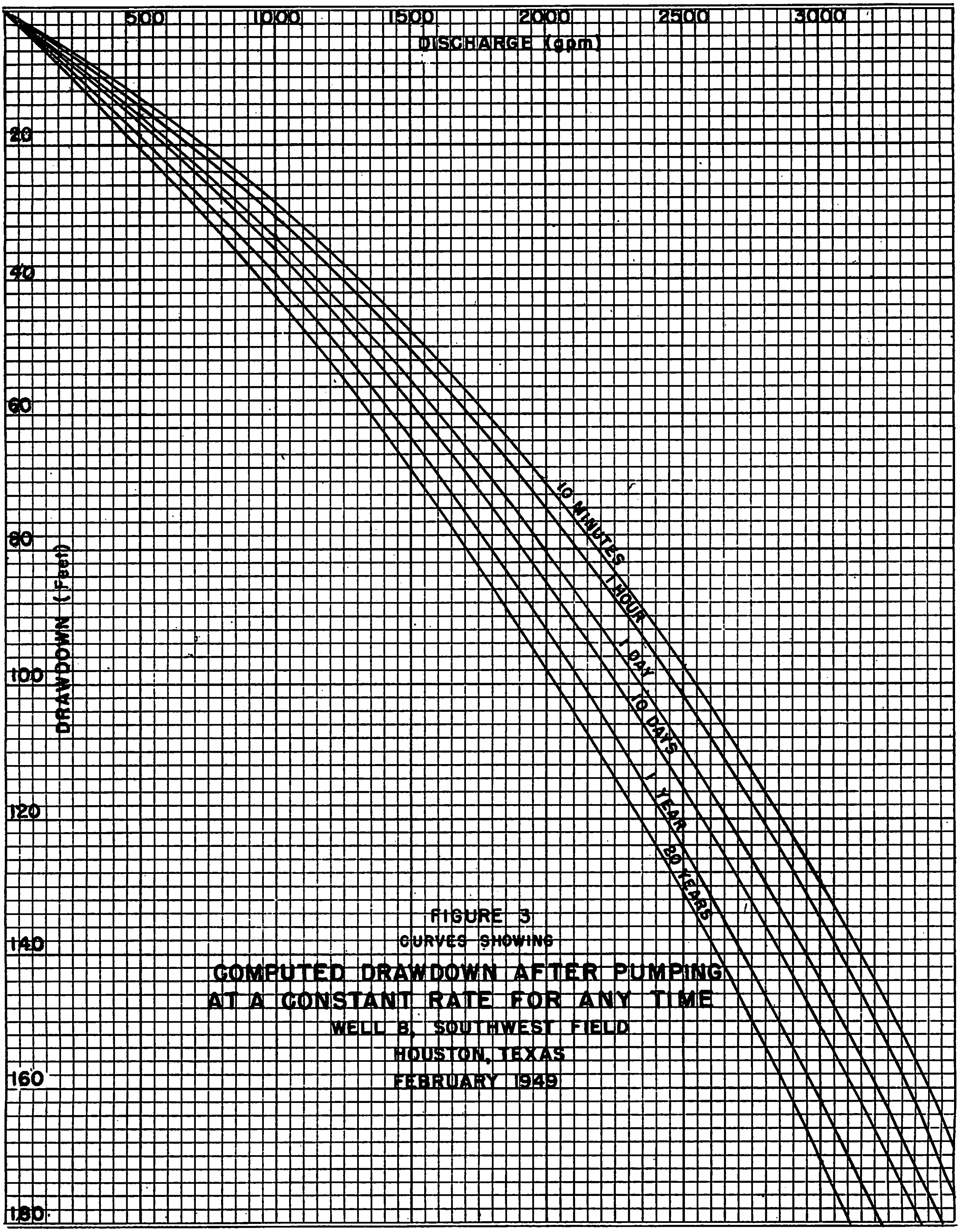

FIGURE 3
CURVES SHOWING
COMPUTED DRAWDOWN AFTER PUMPING
AT A CONSTANT RATE FOR ANY TIME
WELL 8, SOUTHWEST FIELD
HOUSTON, TEXAS
FEBRUARY 1949

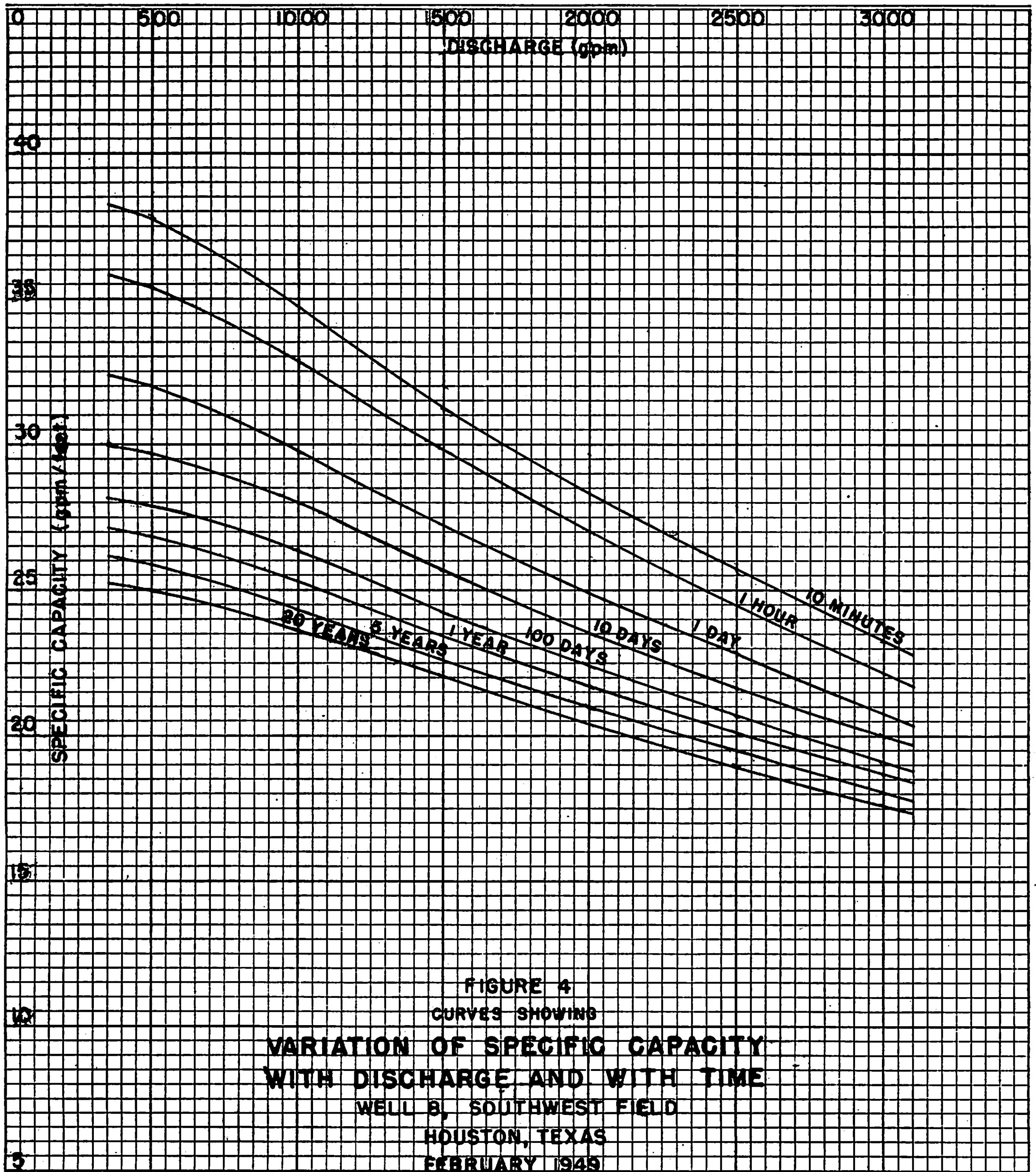

FIGURE 4
CURVES SHOWING
VARIATION OF SPECIFIC CAPACITY
WITH DISCHARGE AND WITH TIME
WELL 8, SOUTHWEST FIELD
HOUSTON, TEXAS
FEBRUARY 1949