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HYDROGEOLOGICAL INVESTIGATIONS OF A COAL SEAM NEAR HALKIRK, ALBERTA

by

R. I. J. Vogwill

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CONTENTS

TABLES

FIGURES

1. INTRODUCTION AND HISTORY

In August 1974 the Groundwater Division, Alberta Research Council, was approached by the Engineering Division, Physical Sciences Branch, Alberta Research Council, concerning permeability determinations for an underground coal gasification test. From subsequent discussions it was concluded that aquifer testing of the coal seam would be a viable method to obtain magnitudes, orientations and distribution of permeabilities within the coal seam and thus aid in planning a proposed underground coal gasification test.

A drilling program and a 4000 minute aquifer test were completed in October 1975 and a second 4000 minute aquifer test (at a higher pumping rate) was completed in April 1976.

This report describes the results obtained.

2. LOCATION

The test site (Fig. 1(a,b)) is located approximately 15 miles north of Halkirk and one mile southeast of the Battle River Power Station, or approximately 130 miles southeast of Edmonton.

All of the piezometers were drilled on land owned or leased by the Cordel-Vesta Mine (operated by Manalta Coal Ltd.) and are located near the high wall (bench) of an abandoned stripping excavation.

3. PURPOSE AND AIMS

It was felt that if an aquifer test indicated anisotropic, horizontal permeability distribution within the coal seam, the direction and magnitude of higher permeability could control the direction of burning coal during the gasification test. This would eliminate the need for mechanical linking (by drilling horizontal holes from the high wall) to ensure a known direction of air circulation (and thus burn direction) prior to ignition of the coal for gasification.

In addition, any relationship established between air and water permeability within the coal seam could perhaps be applied to future underground gasification tests.

Original aims of the aquifer testing were:

(1) To determine the horizontal permeability of the coal seam, anisotropy (if any), and coincidence of anisotropy with the major and/or minor cleat (fracture) directions as proposed by J. D. Campbell, Alberta Research Council.

(2) To establish if hydraulic continuity exists between the water in the abandoned stripping excavation (where a portion of the coal seam had been removed) and groundwater in the coal seam.

(3) To determine the vertical permeability of the caprock (above coal) and the baserock (below coal) and thus evaluate the possibility of gas leakage during gasification.

(4) To determine the coefficient of storage of the coal seam, baserock and caprock.

Because the first aquifer test (1) established anisotropic permeability effects in the coal seam, and (2) did not induce a response in the piezometers completed above and below the coal seam, it was decided to conduct a second aquifer test.

The aims of the second aquifer test were:

(1) To pump the coal seam at the highest possible continuous rate in an attempt to measure vertical permeability of the sediments above and below the coal.

(2) To confirm the anisotropy of the horizontal permeability in the coal seam.

4. GENERAL GEOLOGY AND HYDROGEOLOGY

A 940-foot (287 m) drilling program was completed October 6-18, 1975, and consisted of (Fig. 1a) a pilot hole, pumping well, nine piezometers completed in the coal seam, and one piezometer completed above and below the coal respectively. Piezometers were drilled along major and minor cleat directions (see below) and also near the abandoned stripping excavation which is filled with surface water (Fig. 1(b)).

Drilling results and completion details are summarized in Table 1.

The coal seam is within the Cretaceous Horseshoe Canyon Formation and is overlain and underlain by an alternating series of bentonitic sandstones and shales. Stratigraphic correlation above the coal seam is very complex (J. D. Campbell, pers. comm.) and may not exist. Except for local flexures caused by glaciation the coal seam is relatively flat. An extensive series of vertical fractures (major and minor cleats) are present within the coal seam and have average strike values of 054 and 144, respectively (J. D. Campbell, pers. comm.). Horizontal partings (associated with chert bands) are also present and the basal parting (approximately 1 1/2 feet (.5 m) above the base of the coal) is an important aquifer zone. Average total thickness of the coal seam in the immediate area is 10 feet (3 m) although only the top 6-8 feet are mined.

Confined groundwater occurs throughout the coal seam but mainly in the bottom 5 feet (1.5 m) and is under sufficient pressure to rise 8-10 feet (2.4-3 m) above the top of the coal in individual piezometers. An average storage coefficient of 6×10^{-5} (Tables 2 and 3) and excellent correlation of piezometric levels and barometric pressure (an average barometric efficiency of 0.26 — Figs. 2a & 3a), also indicate confined conditions.

Groundwater movement within the coal seam occurs along horizontal and vertical fractures and is generally to the southeast away from the old workings. In this respect, the water level in the abandoned stripping excavation (Fig. 1b) does have a long-term influence on groundwater movement within the coal seam but the bentonitic mud lining the bottom of the excavation is an effective short-term seal.

Groundwater also occurs in the sediments above and below the coal (Table 1) but no additional information is available.

5. HYDROCHEMISTRY

As is typical of the Horseshoe Canyon Formation, the groundwater within the coal seam is a Na/HCO_3 type with total dissolved solids of 1690 ppm. Because of movement through the coal seam, however, the groundwater contains appreciable sulphates (400 ppm) and high H_2S (2.9 ppm).

Surface water in the abandoned stripping excavation is a Na/SO_4-HCO_3 type with total dissolved solids of 5120 ppm, an SO_4 content of 2000 ppm and an iron content of 4.4 ppm. This is atypical of surface waters and is caused by the large amount of bentonitic material washed into the excavation.

During the aquifer test, no change in groundwater chemistry was noted in the High Wall piezometers. This confirms the observation that no hydraulic continuity exists between the excavation and coal seam in the short term.

6. AQUIFER TESTS

The first aquifer test was conducted for approximately 4000 minutes from October 28 to October 31, 1975, at a constant flowrate of 0.25 imperial gallons per minute (1.1 litres per minute) and caused a total drawdown in the pumping well of 2.86 feet (0.87 metres). Total available drawdown (i.e. to the top of the coal seam) in the pumping well is 8 feet (2.44 m).

As no change in water level was induced in either piezometer E1 (below coal) or W1 (above coal) it was decided to conduct a second aquifer test at a higher pumping rate (using all available drawdown in the pumping well) in an attempt to affect these piezometers.

The second aquifer test was conducted for approximately 4300 minutes from April 12 to April 15, 1976, at a constant flowrate of 0.67 igpm (3.1 l/min) and caused a total drawdown of 12.5 feet (3.8 m) in the pumping well.

Two methods of aquifer test analysis were used: the type curve method (drawdown vs time on log-log paper) and the straight line method (drawdown vs time on semi-log paper). A third method, distance from pumping well vs drawdown (on both log-log and semi-log paper) was not used due to the distorted cone of depression that developed during the test.

Figures 5(a-t) show semi-log and log-log plots of the drawdown data and the calculation of aquifer coefficients for individual piezometers and the pumping well (the straight lines and the type curve traces shown on the plots represent idealized drawdowns); figures 2(a,b) and 3(a,b) show the effects of barometric pressure changes on water levels before, after, and during the aquifer tests; figures 6(a-e) show the progressive development of the cone of depression during the aquifer tests, and tables 2, 3 and 4 show summaries of the calculated aquifer coefficients.

(a) Barometric Pressure Fluctuations

Figures 2(a,b) and 3(a,b) show that there is an excellent correlation between changes in barometric pressure and changes in water levels. This is a common situation in confined aquifers as changes in barometric pressure are more easily transmitted into the aquifer through a piezometer than through the overlying confining strata. Therefore an increase in barometric pressure will cause a drop in water levels and vice versa.

The barometric efficiency can be interpreted as a measure of the competence of the overlying confining beds to resist pressure changes. The average barometric efficiency (Fig. 2a) of the strata overlying the coal seam is 26% which is an acceptable value for a thinly confined aquifer especially when the soft pliable consistency of the overlying sediments is considered.

Figures 2(b) and (3b) show the effects of barometric pressure changes on drawdown fluctuations during the tests. Normally, large drawdown fluctuations are corrected for changes in barometric pressure. In this case, however, the fluctuations are quite obvious, generally small, and have been compensated for in the curve matching procedures. Good examples of these fluctuations are present in the plots for piezometers S1, E2, E3, HWE, HWC and HWW.

(b) Development of the Cone of Depression

In a homogeneous, isotropic aquifer drawdown contours will form a concentric circular pattern away from the pumping well. Any deviation from a circular pattern may indicate an anisotropic permeability distribution which is especially common in fractured rocks. In the anisotropic case drawdown contours will form an ellipse (ideally) with the transverse axes along the maximum permeability axis and the conjugate axes along the minimum permeability axis.

During the Halkirk aquifers tests, it became obvious that there was excellent hydraulic connection between the pumping well and piezometer HWE causing abnormally large drawdowns and suggesting a horizontal permeability anisotropy. Figures 6(a-c) show the development of the cone of depression during the tests, confirm that an elongate drawdown trough had formed, and show excellent correlation of the development of the cone of depression for the two aquifer tests.

Subsequent analysis of the aquifer test data confirmed that the coal seam is anisotropic with the major permeability axis trending towards piezometer HWE.

(c) Results - Aquifer Coefficients

Tables 2, 3 and 4 show summaries of the calculated transmissivities, permeabilities, and storage coefficients for the coal seam. Transmissivity and storage coefficient calculations are shown on figures 5(a-t). Permeabilities have been calculated by dividing the transmissivity by the thickness of the coal seam. Two aquifer thicknesses have been used: (1) 10 feet, assuming that the whole of the coal seam contributes equally to groundwater movement, P(1); and (2) 2 feet, assuming that the zone associated with the basal parting is the only zone in which groundwater movement takes place, P(2). An exact value is probably somewhere within these limits.

As can be seen from the above tables, values obtained from the two aquifer tests are in general agreement. The most meaningful result, however, for gasification purposes, is the magnitude and orientation of the major permeability axis. This may determine both the rate and direction of burning coal.

(d) Permeability Anisotropy - Discussion

Transmissivities along the major and minor axes of anisotropy have been calculated using the method of Papadopulos (1965). The ratio of permeability along the major axis to that along the minor axis is approximately 2.5-7 to 1. Effective transmissivities (Fig. 7) have been calculated for each aquifer test and are in general agreement with values obtained from individual piezometers.

The orientation of the average major permeability axis is 36° north (counter clockwise) from the major cleat (Fig. 7) as calculated by J. D. Campbell and seems to be a resultant of his minor and major cleat directions.

The repetition of this same anisotropy pattern anywhere in the coal seam is dependent on the uniformity (i.e. spacing, size, and orientation) of the fracture systems. If the fracture systems are uniform the results described in this report are valid everywhere within the coal seam. Because the drawdown plots for each piezometer closely follow the Theis type curve the fractured coal appears to react to groundwater withdrawals as a homogeneous medium. The anisotropy established, however, suggests that regionally the fracture pattern in the coal is not consistently the same.

If nonuniformity of fracture systems in a coal seam is suspected, two important points should be noted:

(1) The results obtained by aquifer testing the coal seam may only be valid for the immediate area around the pumping well, and

(2) Groundwater withdrawals should take place at more than one location in the piezometer configuration to establish the uniformity of the fracture pattern.

The relationship between water permeability and pressurized air permeability is not yet established for the Halkirk coal seam. In fractured aquifers with large permeabilities and coefficients of storage the difference may not be significant. It is conceivable, however, that in a fractured coal seam with small values of aquifer coefficients, the injection of pressurized air could expand and/or rearrange fracture systems and thus alter the permeability distribution.

7. CONCLUSIONS

(1) The horizontal permeability within the coal seam is anisotropic. The orientation of the average major permeability axis is 018 (N18°C) and it has a permeability of between 3 and 14 darcys. The orientation of the average minor permeability axis is 108° (E18°S) and it has a permeability of between 0.4 and 4 darcys. These orientations are rotated 36° north (counter clockwise) from J. D. Campbell's major and minor cleat directions.

The repetition of this anisotropy pattern anywhere in the coal seam is dependent on the uniformity of the fracture systems. It is suspected that the Halkirk coal seam does not exhibit a uniform fracture pattern and therefore that the results obtained from the aquifer tests may only be valid if air injection takes place in or near the pumping well location. In addition, it is conceivable that pressurized air injected into an aquifer with such small values of aquifer parameters may change the permeability pattern significantly.

No vertical permeabilities can be calculated for the caprock or baserock due to the lack of response of piezometers completed above and below the coal. It is therefore assumed that the vertical permeability of the sediments above and below the coal is negligible in the short term.

(2) The Average Storage Coefficient for the coal seam is 6×10^{-5}.

(3) In the short term, there is no hydraulic connection between the surface water in the old workings and groundwater in the coal seam. In order to maintain this seal no dredging or water removal should take place in the old workings.

(4) The natural direction of groundwater movement in the coal seam is to the southeast away from the old workings. In this regard the high water levels in the old workings do have an effect on the potential distribution of groundwater in the coal seam, an effect that has taken years to establish itself.

(5) It is concluded that in coal seams planned for gasification a more viable way of establishing nonuniformity of fracture systems is to conduct several aquifer tests in the well field using different piezometers as the pumping source.

(6) It is concluded that aquifer testing is the most useful method in the early stages of assessing a coal seam planned for underground gasification.

8. RECOMMENDATIONS

It is recommended that:

(1) Monitoring of both the water levels and hydrochemistry continue until the gasification experiments are completed.

(2) No dredging or water removal should take place in the old working.

(3) A third aquifer test to be conducted on completion of gasification experiments to establish any changes in permeability distributions within the coal seam.

(4) Further studies are needed concerning the role of aquifer testing in underground coal gasification. Questions such as those listed below need to be answered.

1) Can aquifer testing reduce the number of exploration holes required to conduct air acceptance tests and therefore (especially in the case of deeply buried coal seams) reduce costs of underground gasification?

2) Can pressurized air injection change aquifer parameters in coal seams with low permeabilities and storage? Is this a permanent change? What is the relationship between pressurized air and water permeability?

3) How does coal gasification alter groundwater distribution and movement? Will it contaminate other aquifers?

In view of these problems, it would be timely to establish an aquifer test-pressurized air test site. Experimental results at such a site would contribute to the development of underground coal gasification in Alberta.

9. ACKNOWLEDGMENTS

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- A. Roehl, L. Holloway, G. Sjostrom and M. Walls for their help in the field
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- Mrs. D. Borneuf for typing
- Miss C. Newton for computer plots of aquifer tests
- Atmospheric Environment for supplying barometric pressures.

10. REFERENCES

Papadopulos, I. S., 1965. Nonsteady Flow to a Well in an Infinite Anisotropic Aquifer; Symp. Intern. Assoc. Sci. Hydrology, Dubrovnik.

TABLES

Table 1

Halkirk - Aquifer Testing

Summary - Hole Details

Hole Number	r*	Surface Elev./SWL (ft) / Elev. Piezo. Surface	Depth (ft)	Completion - Aquifer Interval (ft)	Remarks
Pilot Hole	≃50 ft	** 2431.00/-	98	No completion - coal 62-74	Abandoned
Pumping Well	-	2431.1/54.19 2376.9	72	5" Screen in coal 62.5-72	Main water 70.5-72.0
N1	50 ft NW	2430.05/53.20 2376.85	71	Slotted liner - coal - 60-70	
N2	100 ft NW	2429.45/52.65 2376.80	70.0	Slotted liner - coal - 60-70	
S1	250 ft SE	2434.95/59.04 2375.91	78.0	Slotted liner - coal - 68-78	
E1	25 ft NE	2430.7/94.97 2335.73	95.5	Slotted liner - ss & sh - 85-95	Completed below coal - very little water
E2	200 ft NE	2428.2/51.53 2376.7	72	Slotted liner - coal - 62-72	
E3	500 ft NE	2418.1/41.66 2376.44	59.5	Slotted liner - coal - 49.5-59.5	
W1	25 ft SW	2431.6/48.30 2383.3	55.5	Slotted liner - ss & sh - 46-55.5	Completed above coal - very little water
W2	100 ft SW	2430.0/56.22 2376.8	74.0	Slotted liner - coal - 64-74	
HWE	400 ft NE	2420/41.98 2378.27	59.0	Slotted liner - coal - 49-59	
HWC	310 ft N	2424.75/45.92 2378.83	67.0	Slotted liner - coal - 57-67	
HWW	420 ft NW	2427.9/49.07 2378.83	69.0	Slotted liner - coal - 59-69	

*distance to pumping well

**SWL and elev. piezo. surface for April/75

Table 2

Halkirk Aquifer Testing

First Aquifer Test - October 1975

Summary of Aquifer Coefficients

Hole	Distance to pump well (ft)	$T_{(1)}$ Log-Log igpd/ft (m^2/day)	$T_{(2)}$ Semi-Log (igpd/ft (m^2/day)	$S_{(1)}$ Log-Log ($\times 10^{-5}$))	$S_{(2)}$ Semi-Log ($\times 10^{-5}$)	Remarks
Pumping Well	-	64 (0.95)	78 (1.16)	-	-	
W1	25	-	-	-	-	Completed above coal; no response
E1	25	-	-	-	-	Completed below coal; no response
N1	50	99 (1.48)	110 (1.64)	16.2	12.1	
N2	100	110 (1.64)	88 (1.31)	4.8	5.1	
W2	100	92 (1.37)	110 (1.64)	3.9	3.3	
S1	250	260 (3.9)	287 (4.28)	12.2	9.4	Good producing hole
E2	200	185 (2.76)	194 (2.89)	7.4	6.1	Good producing hole
E3	500	151 (2.25)	112 (1.67)	4.7	1.9	
HWE	400	115 (1.72)	120 (1.79)	2.3	1.9	Good producing hole
HWC	310	117 (1.75)	135 (2.01)	2.5	1.9	
HWW	420	92 (1.37)	114 (1.7)	4.3	3.2	

Major permeability axis	297 (4.43)
Minor permeability axis	44 (0.66)
Effective transmissivity	114 (1.71)

Table 3

Second Aquifer Test - April 1976

Summary of Aquifer Coefficients

Hole	Distance to pump well (ft)	T(1) Log-Log igpd/ft (m^2/day)	$T_{(2)}$ Semi-Log igpd/ft (m^2/day)	$S_{(1)}$ Log-Log (x 10^{-5}))	$S_{(2)}$ Semi-Log (x 10^{-5})	Remarks
Pumping Well	-	56 (0.83)	75 (1.12)	-	-	
W1	25	-	-	-	-	Completed above coal; no response
E1	25	-	-	-	-	Completed below coal; no response
N1	50	108 (1.61)	121 (1.81)	10.2	7.7	
N2	100	98 (1.46)	112 (1.67)	4.3	3.4	
W2	100	104 (1.55)	118 (1.76)	4.3	3.2	
S1	250	187 (2.80)	177 (2.64)	12.4	12.7	
E2	200	154 (2.29)	136 (2.03)	8.3	10.2	
E3	500	126 (1.88)	145 (2.16)	5.8	4.4	
HWE	400	107 (1.60)	114 (1.70)	2.7	2.6	
HWC	310	91 (1.36)	114 (1.70)	5.3	4.2	
HWW	420	73 (1.09)	92 (1.37)	6.8	5.0	

Major permeability axis 176 (2.62)

Minor permeability axis 78 (1.16)

Effective transmissivity 117 (1.75)

Table 4

Halkirk - Aquifer Tests

Summary of Average Aquifer Permeabilities

Well	Permeability							
	10 ft thickness gpd/ft^2 $P_{(1)}$		2 ft thickness gpd/ft^2 $P_{(2)}$		10 ft thickness darcys $P_{(1)}$		2 ft thickness darcys $P_{(2)}$	
	Oct./75	April/76	Oct./75	April/76	Oct./75	April/76	Oct./75	April/76
Pumping Well	7.1	6.6	36	33	0.65	0.60	3.30	3.00
W1	-	-	-	-	-	-	-	-
E1	-	-	-	-	-	-	-	-
N1	10.5	11.5	53	57	0.96	1.05	4.80	5.19
N2	10.0	10.5	50	53	0.91	0.96	4.55	4.82
W2	10.1	11.1	50	56	0.92	1.01	4.55	5.10
S1	27.4	18.2	137	91	2.49	1.66	12.47	8.28
E2	19.0	14.5	95	73	1.70	1.32	8.65	6.64
E3	13.2	13.6	66	68	1.20	1.24	6.01	6.19
HWE	11.8	11.1	59	55	1.07	1.01	5.37	5.01
HWC	12.6	10.3	63	51	1.15	0.94	5.73	4.64
HWW	10.3	8.3	52	41	0.94	0.76	4.73	3.73
Major permeability axis	29.7	17.6	149	88	2.70	1.60	13.56	8.01
Minor permeability axis	4.4	7.8	22	39	0.40	0.71	2.00	3.55
Effective valve	11.4	11.7	57	59	1.04	1.06	5.19	5.37

FIGURES

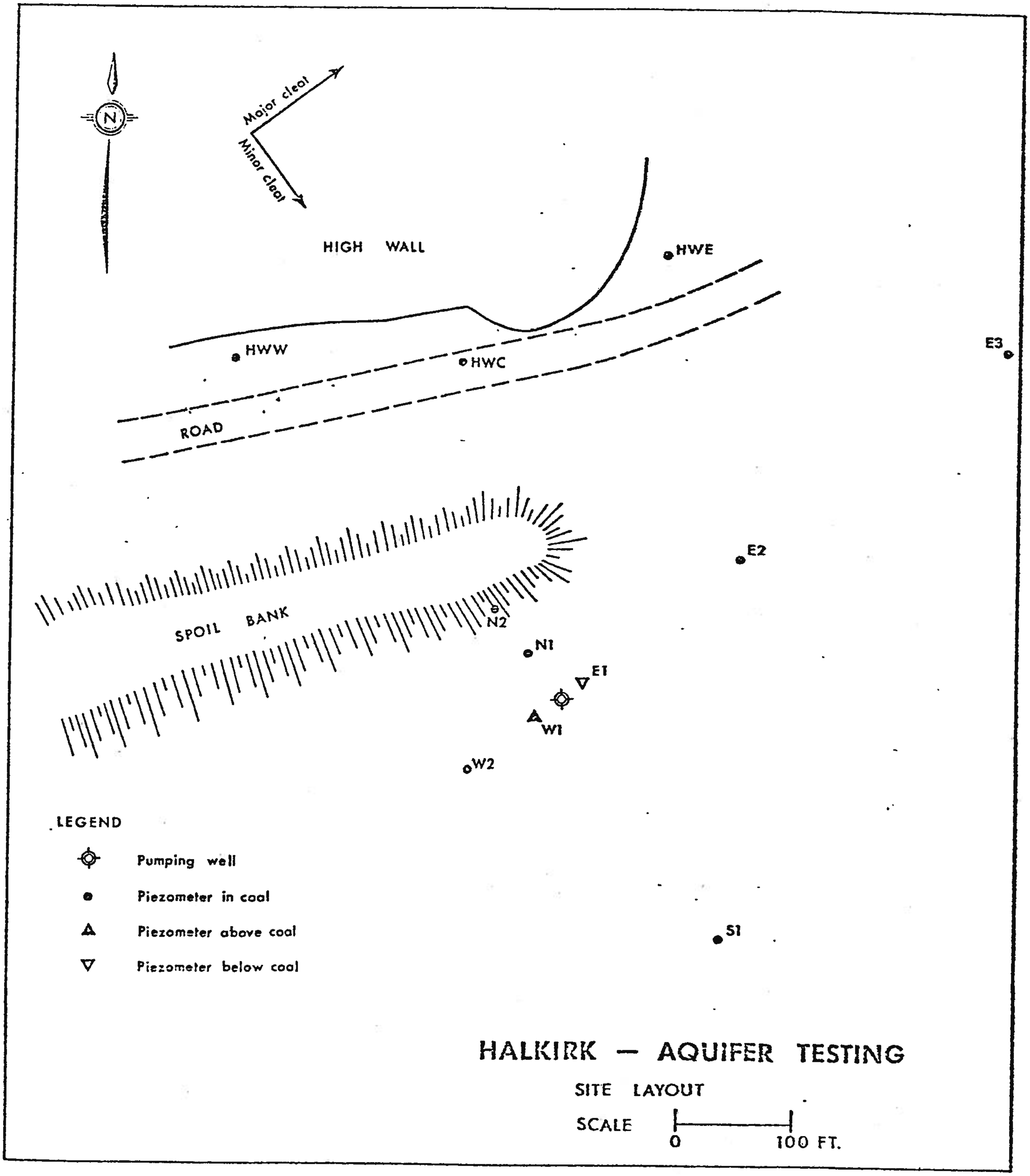

N
Major cleat
Minor cleat
HIGH WALL
HWE
HWW
HWC
E3
ROAD
E2
SPOIL BANK
N2
N1
E1
W1
W2
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
S1
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 1(a)

HALKIRK - AQUIFER TESTING

DIAGRAMMATIC CROSS - SECTION THROUGH SITE

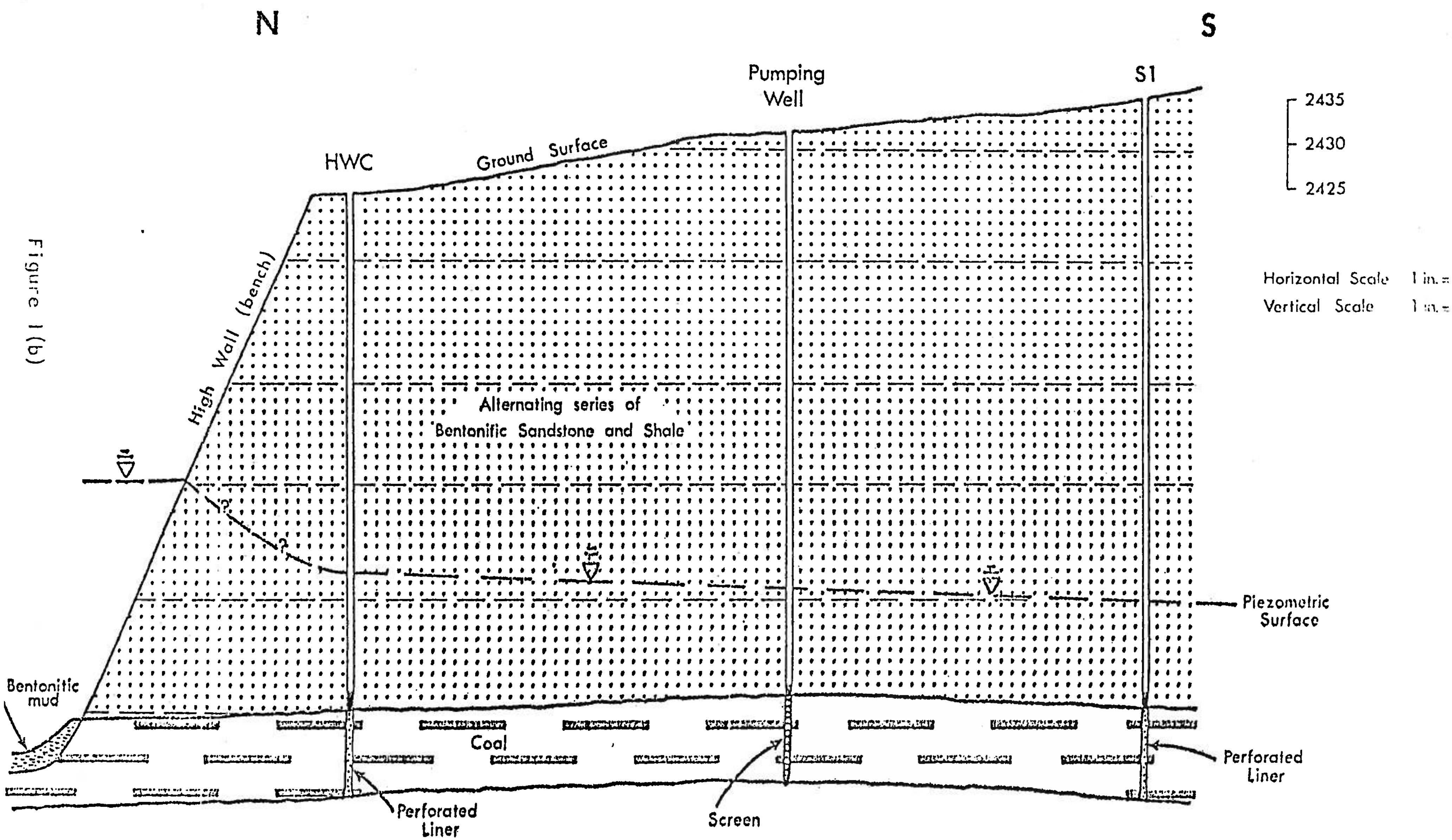
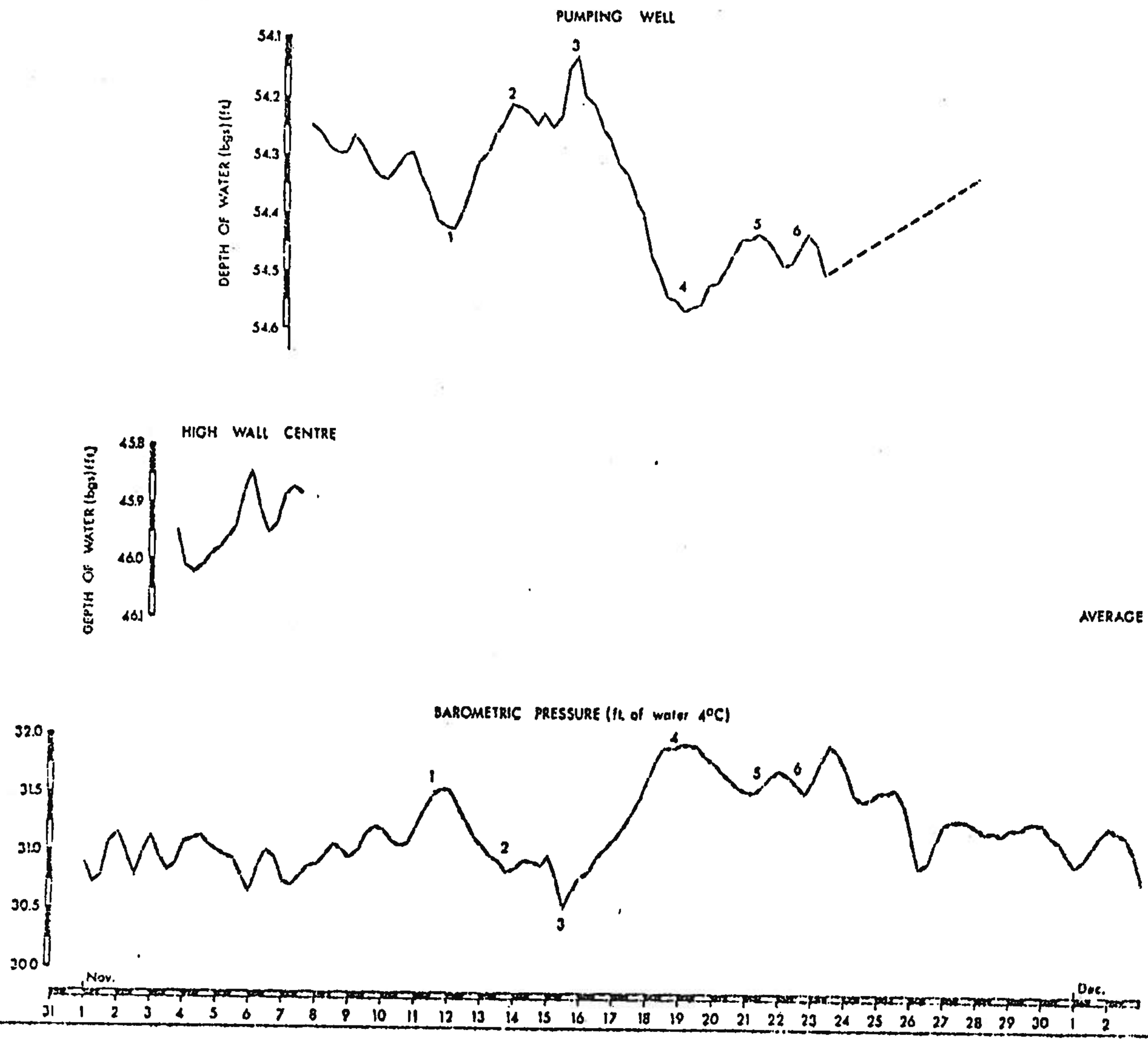


Figure 1(b)

AQUIFER TEST – HALKIRK

POST – TEST FLUCTUATIONS

BAROMETRIC & PIEZOMETRIC



AVERAGE BAROMETRIC EFFICIENCY (using peaks 1,2,3,4,5,6)

$= \frac{28.9 + 31.2 + 31.1 + 33 + 27.8 + 29}{6}$

$= 30.1\%$

Figure 2(a)

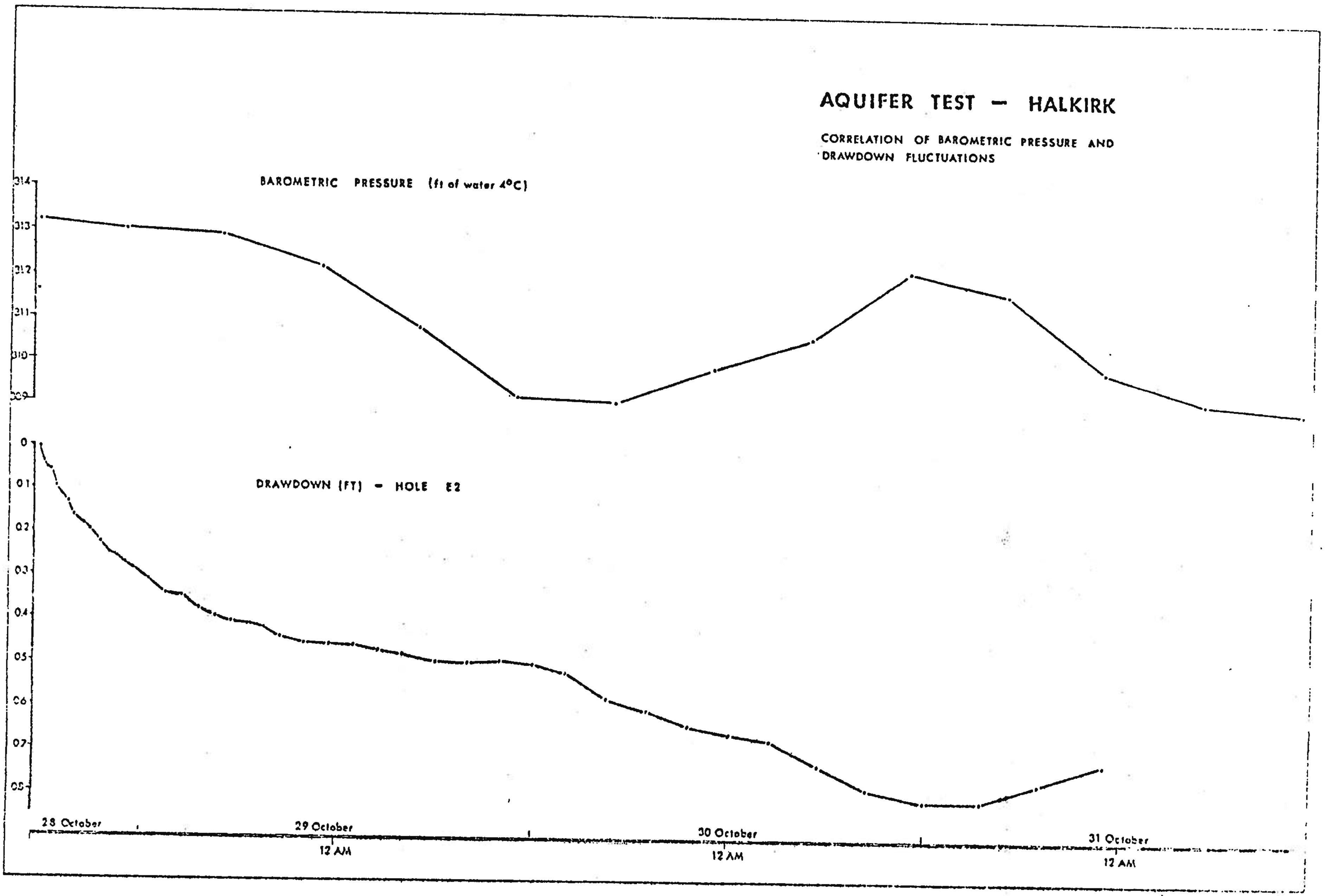
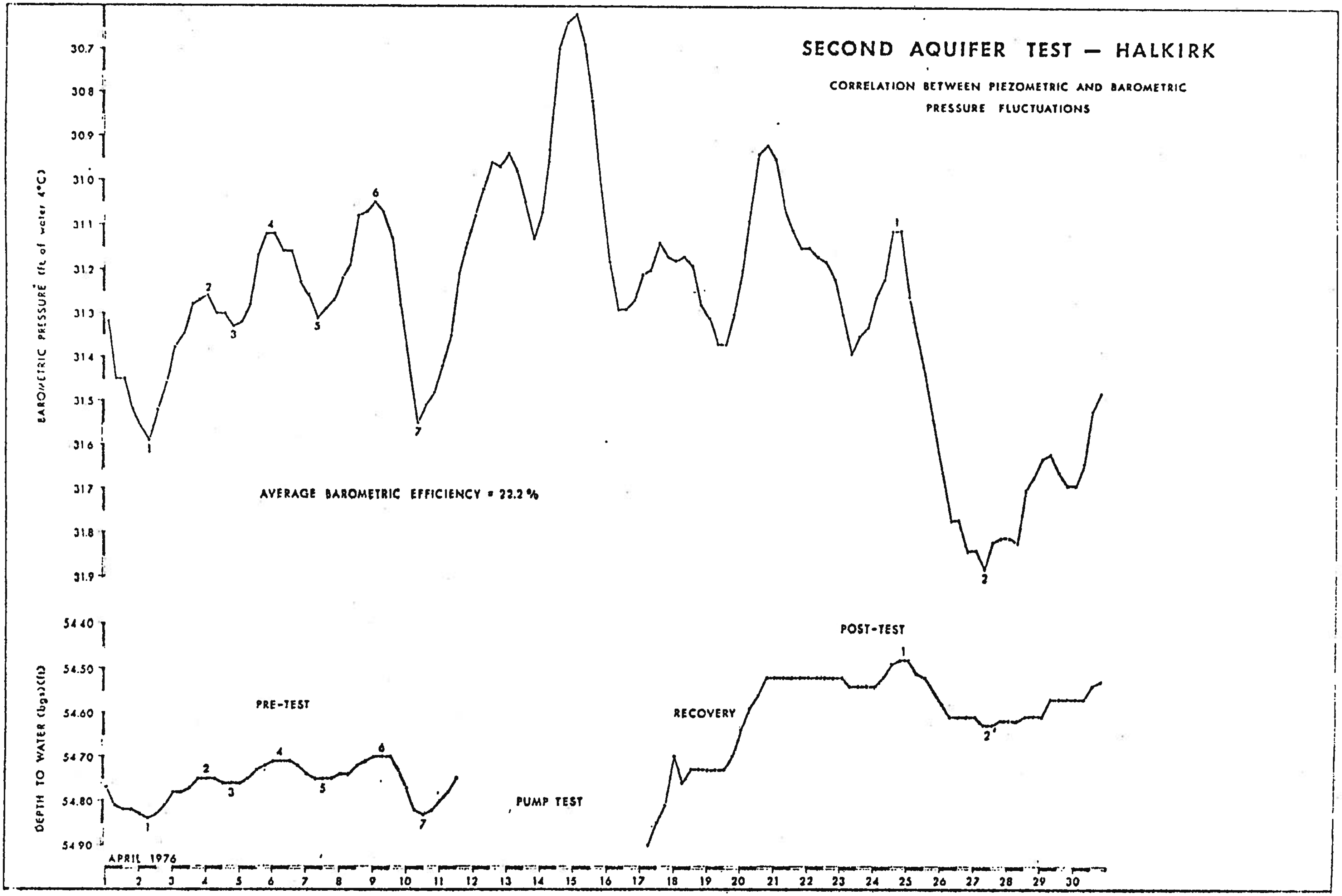

AQUIFER TEST – HALKIRK
CORRELATION OF BAROMETRIC PRESSURE AND DRAWDOWN FLUCTUATIONS
BAROMETRIC PRESSURE (ft of water 4°C)
DRAWDOWN (FT) – HOLE E2
28 October
29 October
12 AM
30 October
12 AM
31 October
12 AM

Figure 2(b)



SECOND AQUIFER TEST — HALKIRK
CORRELATION BETWEEN PIEZOMETRIC AND BAROMETRIC PRESSURE FLUCTUATIONS
BAROMETRIC PRESSURE (ft of water 4°C)
AVERAGE BAROMETRIC EFFICIENCY = 22.2 %
DEPTH TO WATER (bgs)(ft)
PRE-TEST
PUMP TEST
RECOVERY
POST-TEST
APRIL 1976

Figure 3(a)

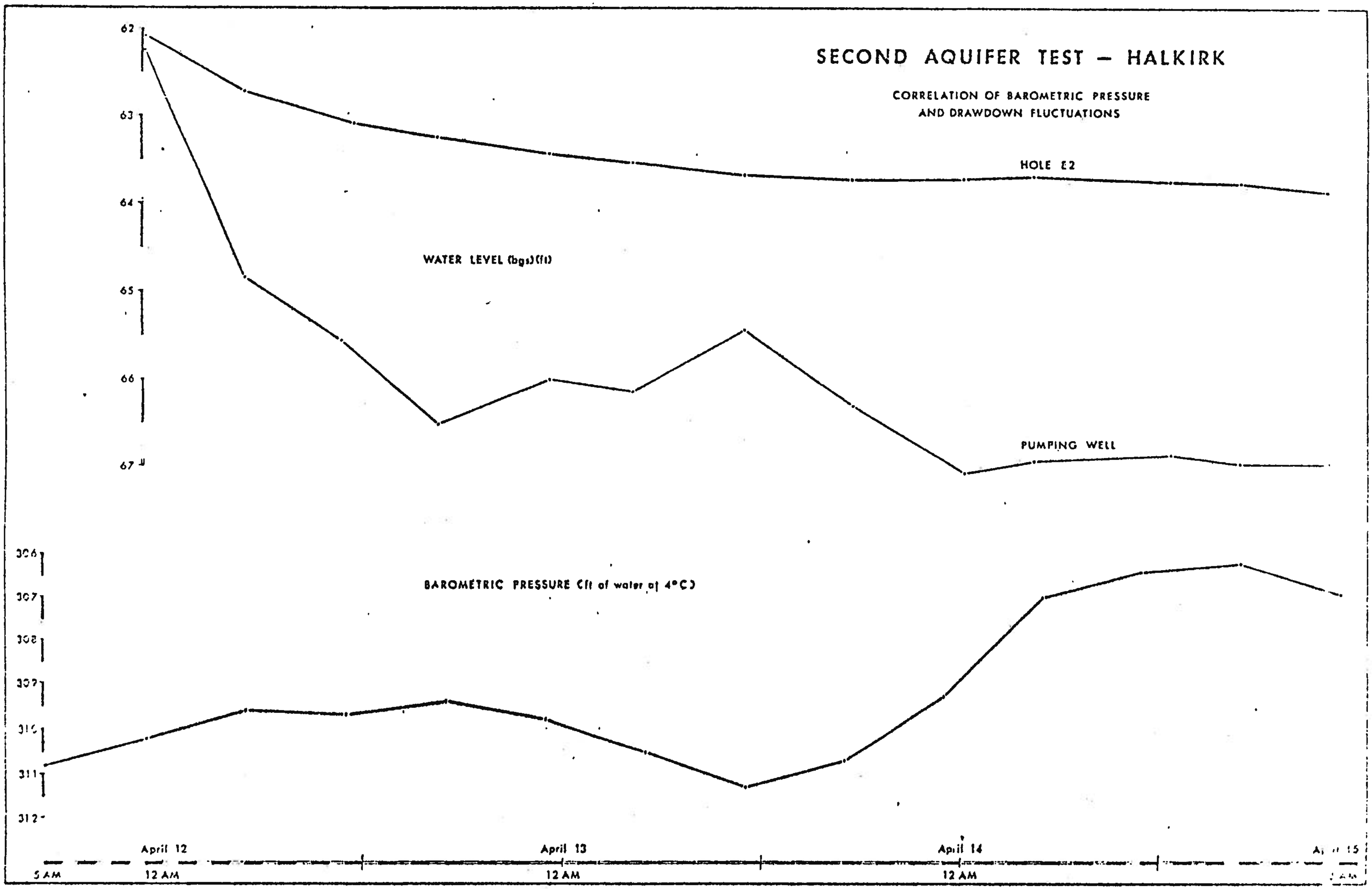
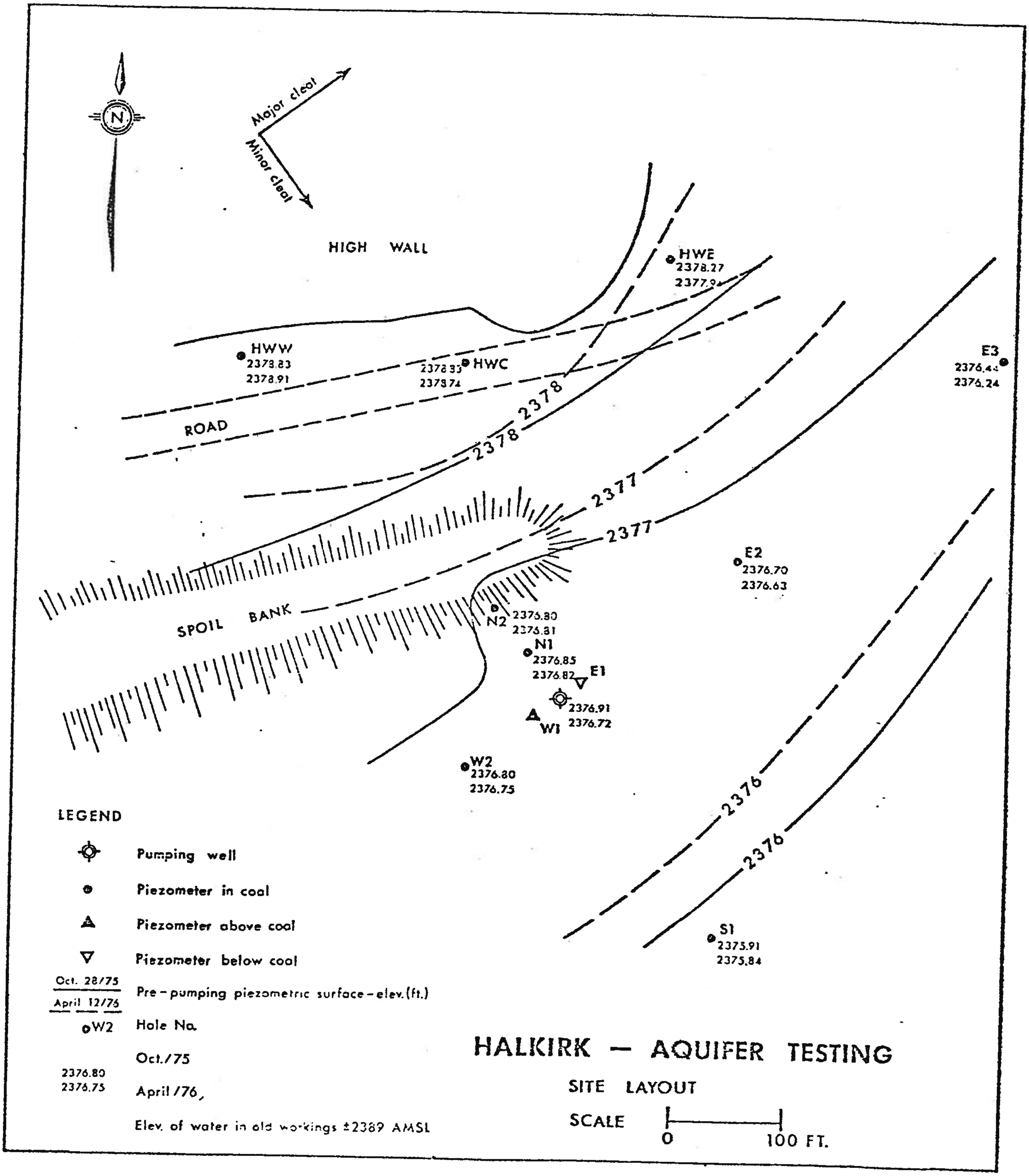
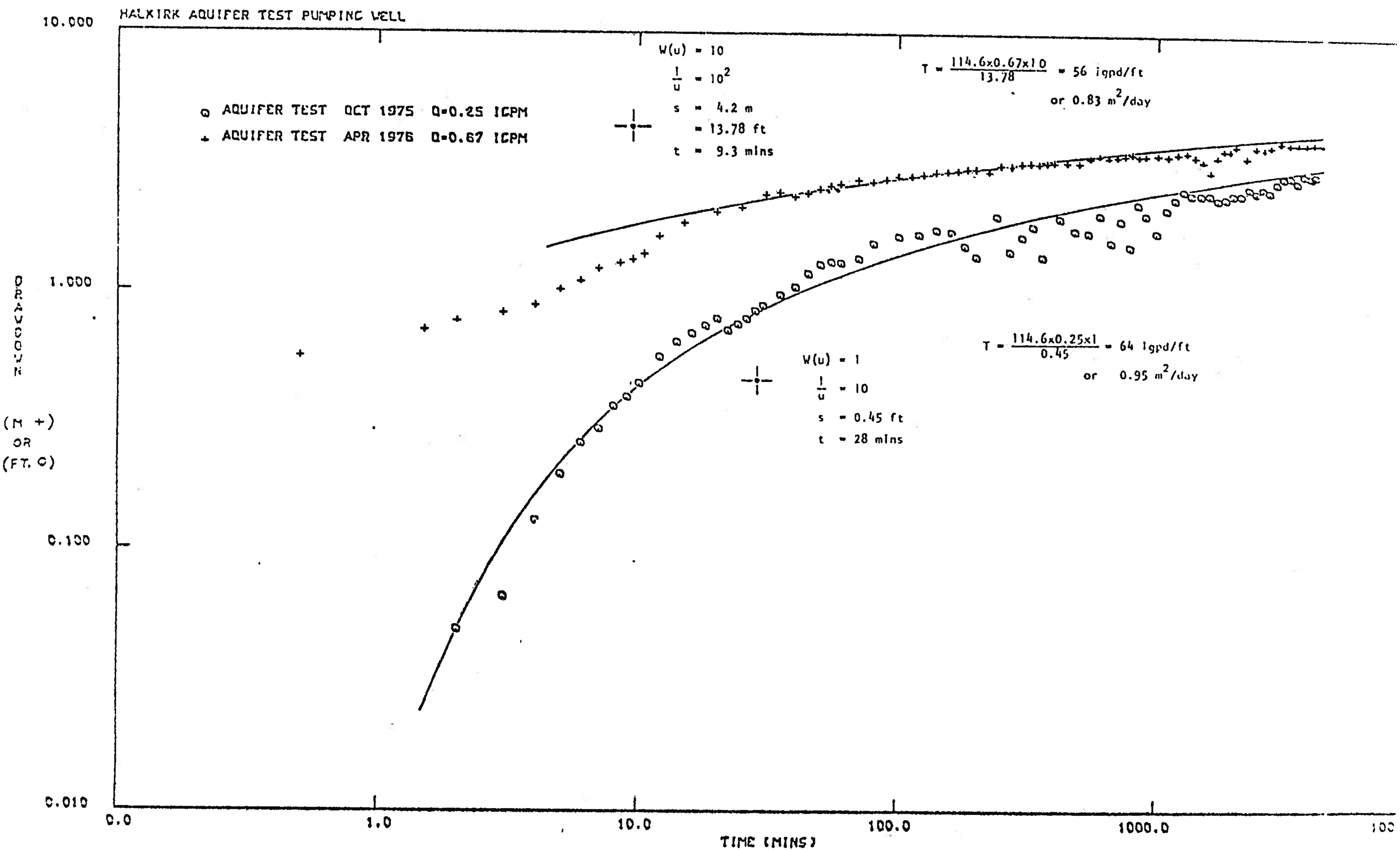

SECOND AQUIFER TEST — HALKIRK
CORRELATION OF BAROMETRIC PRESSURE
AND DRAWDOWN FLUCTUATIONS
HOLE E2
WATER LEVEL (bgs)(ft)
PUMPING WELL
BAROMETRIC PRESSURE (ft of water at 4°C)
62
63
64
65
66
67
306
307
308
309
311
312
April 12
April 13
April 14
12 AM
12 AM
12 AM

Figure 3(b)



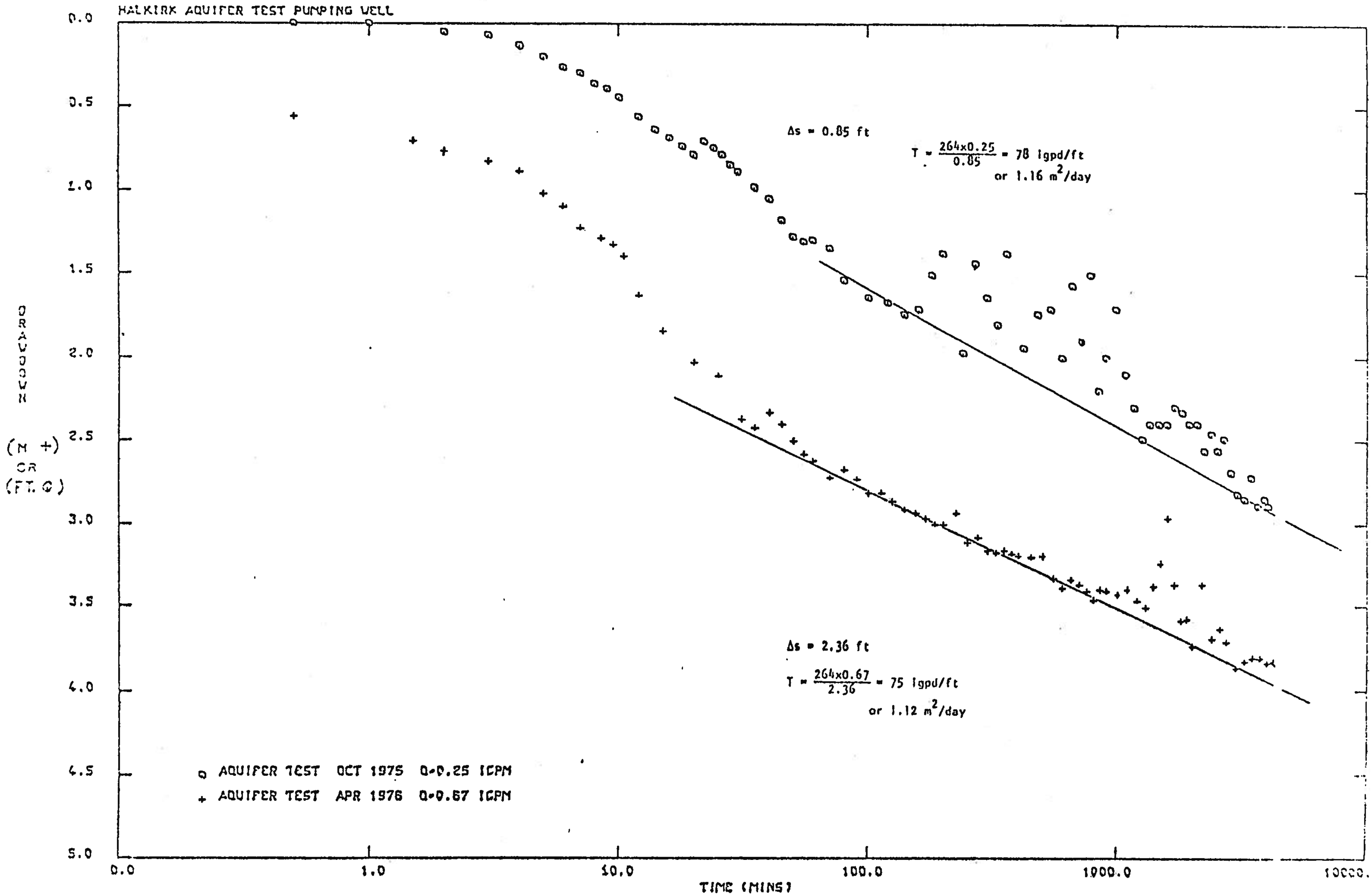
N
Major cleat
Minor cleat
HIGH WALL
HWE
2378.27
2377.9
HWW
2378.83
2378.91
2378.83
2378.74
HWC
ROAD
2378
2378
2377
2377
SPOIL BANK
E3
2376.44
2376.24
E2
2376.70
2376.63
N2
2376.80
2376.81
N1
2376.85
2376.82
E1
2376.91
2376.72
W1
W2
2376.80
2376.75
2376
2376
S1
2375.91
2375.84
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
Oct. 28/75
April 12/76
Pre-pumping piezometric surface-elev.(ft.)
W2
Hole No.
Oct./75
2376.80
2376.75
April/76
Elev. of water in old workings ±2389 AMSL
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 4



HALKIRK AQUIFER TEST PUMPING WELL
10.000
1.000
0.100
0.010
DRAWDOWN
(M +)
OR
(FT. O)
O AQUIFER TEST OCT 1975 Q=0.25 IGPM
+ AQUIFER TEST APR 1976 Q=0.67 IGPM
W(u) = 10
1/u = 10²
s = 4.2 m
= 13.78 ft
t = 9.3 mins
T = 114.6x0.67x10 / 13.78 = 56 igpd/ft
or 0.83 m²/day
W(u) = 1
1/u = 10
s = 0.45 ft
t = 28 mins
T = 114.6x0.25x1 / 0.45 = 64 igpd/ft
or 0.95 m²/day
0.0
1.0
10.0
100.0
1000.0
TIME (MINS)

Figure 5(a)



HALKIRK AQUIFER TEST PUMPING WELL
Δs = 0.85 ft
T = 264x0.25 / 0.85 = 78 Igpd/ft
or 1.16 m²/day
Δs = 2.36 ft
T = 264x0.67 / 2.36 = 75 Igpd/ft
or 1.12 m²/day
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM
DRAWDOWN
(M +)
OR
(FT. O)
TIME (MINS)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
1.0
10.0
100.0
1000.0
10000.

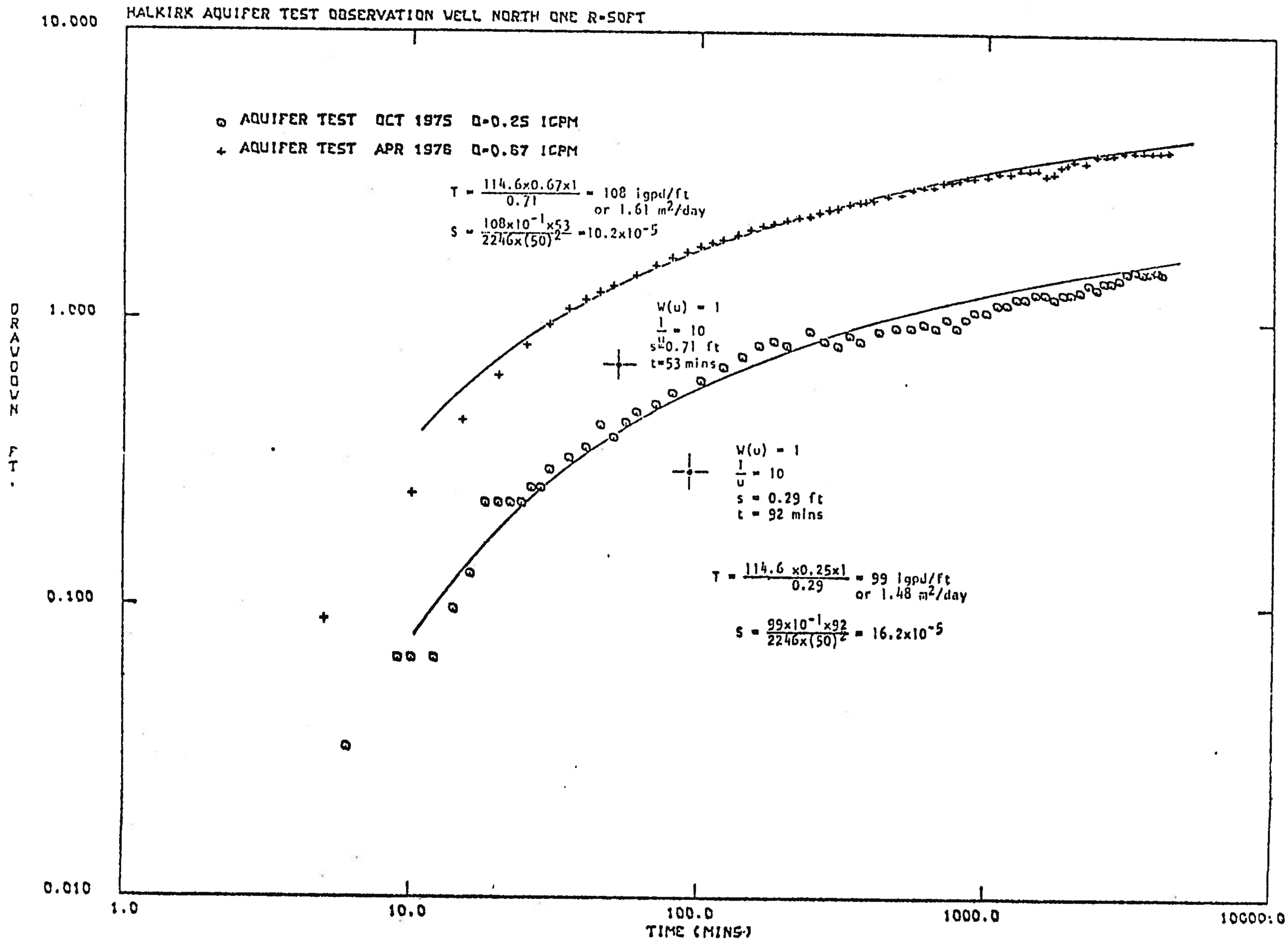
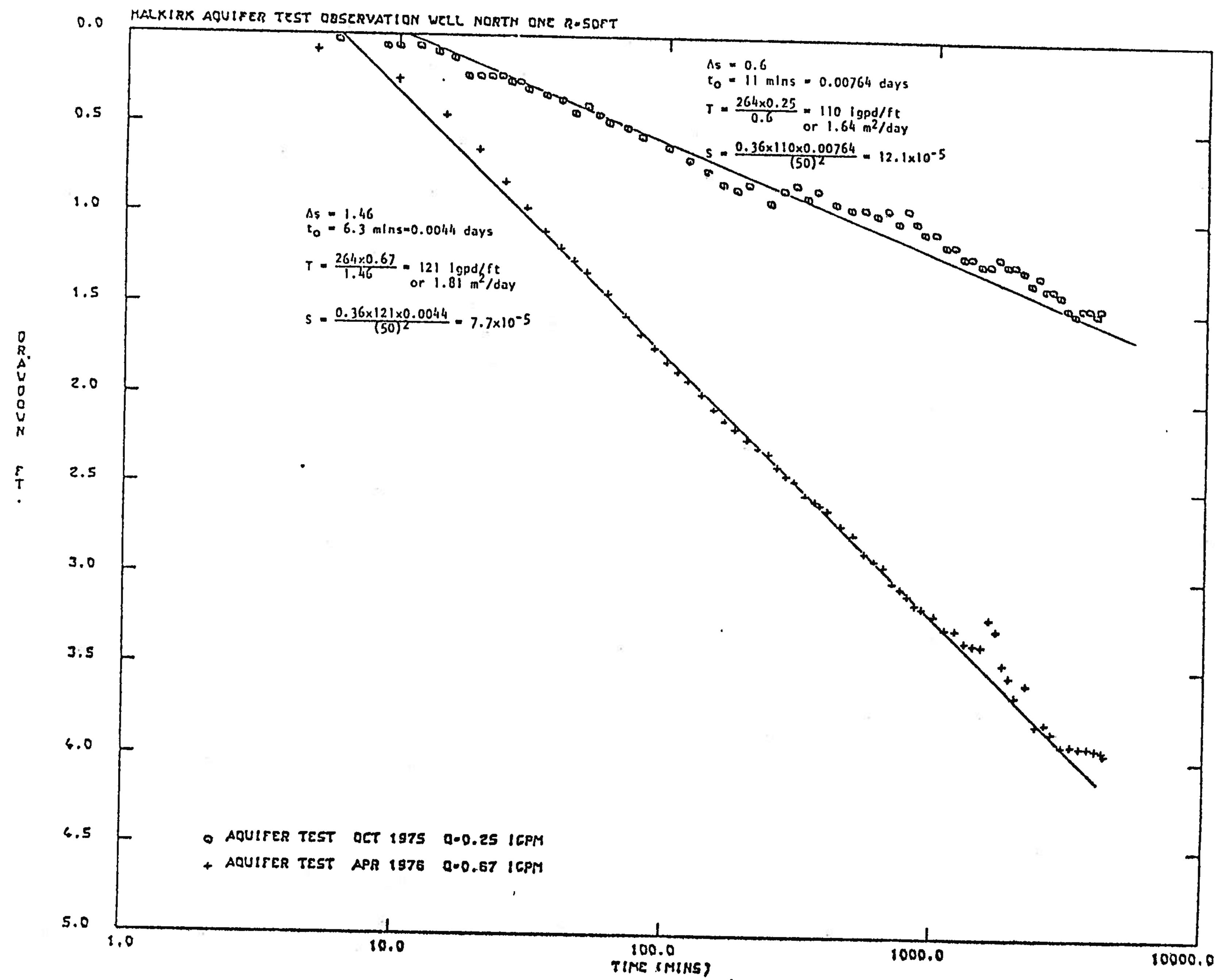

HALKIRK AQUIFER TEST OBSERVATION WELL NORTH ONE R-SOFT
10.000
1.000
0.100
0.010
DRAWDOWN FT.
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM
T = 114.6x0.67x1 / 0.71 = 108 igpd/ft
or 1.61 m²/day
S = 108x10⁻¹x53 / 2246x(50)² = 10.2x10⁻⁵
W(u) = 1
1/u = 10
s=0.71 ft
t=53 mins
W(u) = 1
1/u = 10
s = 0.29 ft
t = 92 mins
T = 114.6 x0.25x1 / 0.29 = 99 igpd/ft
or 1.48 m²/day
S = 99x10⁻¹x92 / 2246x(50)² = 16.2x10⁻⁵
1.0
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(c)



HALKIRK AQUIFER TEST OBSERVATION WELL NORTH ONE R=50FT
Δs = 0.6
to = 11 mins = 0.00764 days
T = 264x0.25 / 0.6 = 110 Igpd/ft
or 1.64 m2/day
S = 0.36x110x0.00764 / (50)2 = 12.1x10-5
Δs = 1.46
to = 6.3 mins=0.0044 days
T = 264x0.67 / 1.46 = 121 Igpd/ft
or 1.81 m2/day
S = 0.36x121x0.0044 / (50)2 = 7.7x10-5
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM
DRAWDOWN FT.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
1.0
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(d)

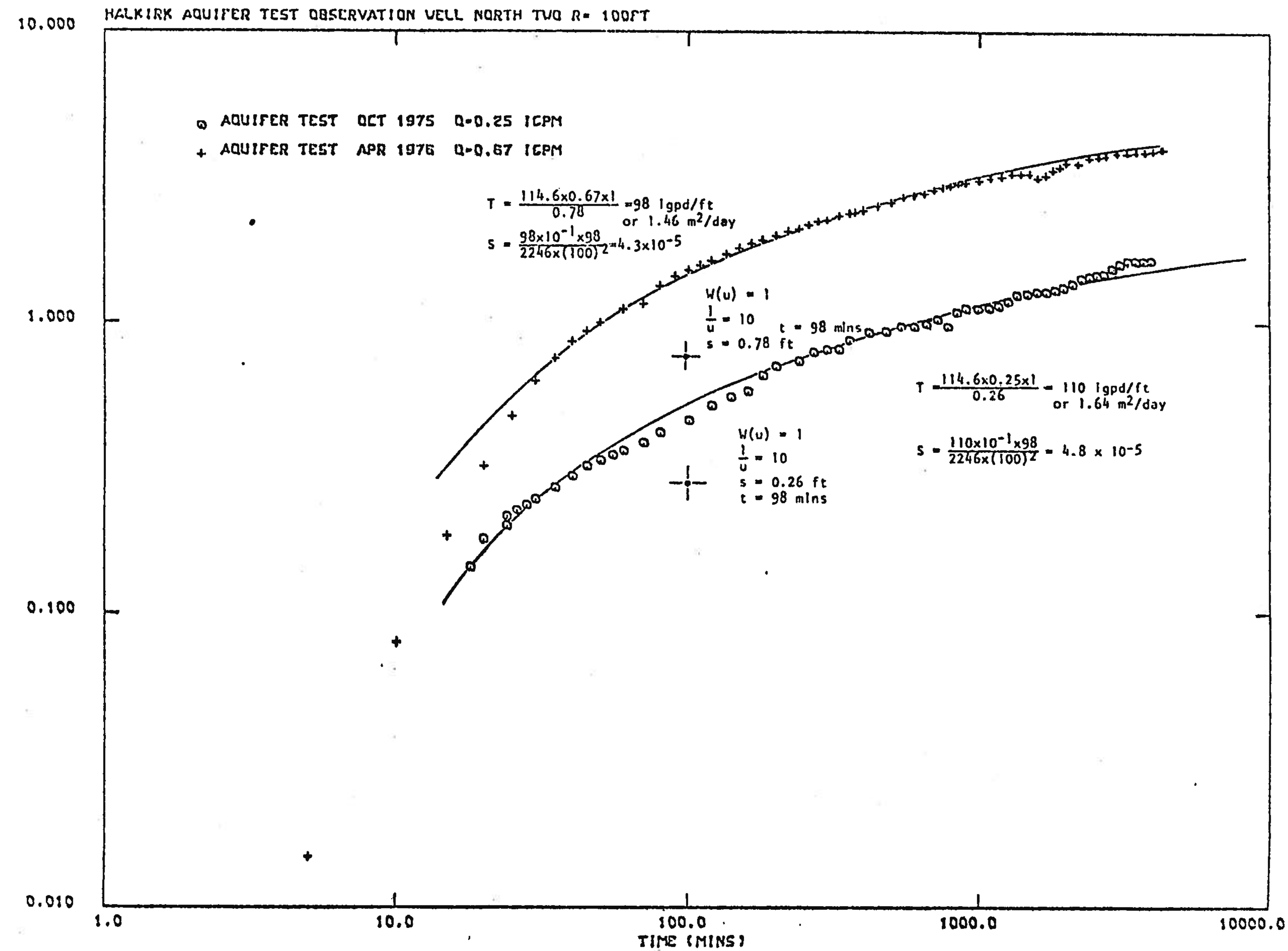

HALKIRK AQUIFER TEST OBSERVATION WELL NORTH TWO R= 100FT
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM
T = 114.6x0.67x1 / 0.78 =98 Igpd/ft or 1.46 m2/day
S = 98x10-1x98 / 2246x(100)2 =4.3x10-5
W(u) = 1
1/u = 10
t = 98 mins
s = 0.78 ft
T = 114.6x0.25x1 / 0.26 = 110 Igpd/ft or 1.64 m2/day
S = 110x10-1x98 / 2246x(100)2 = 4.8 x 10-5
W(u) = 1
1/u = 10
s = 0.26 ft
t = 98 mins
DRAWDOWN FT.
TIME (MINS)
10.000
1.000
0.100
0.010
1.0
10.0
100.0
1000.0
10000.0

Figure 5(e)

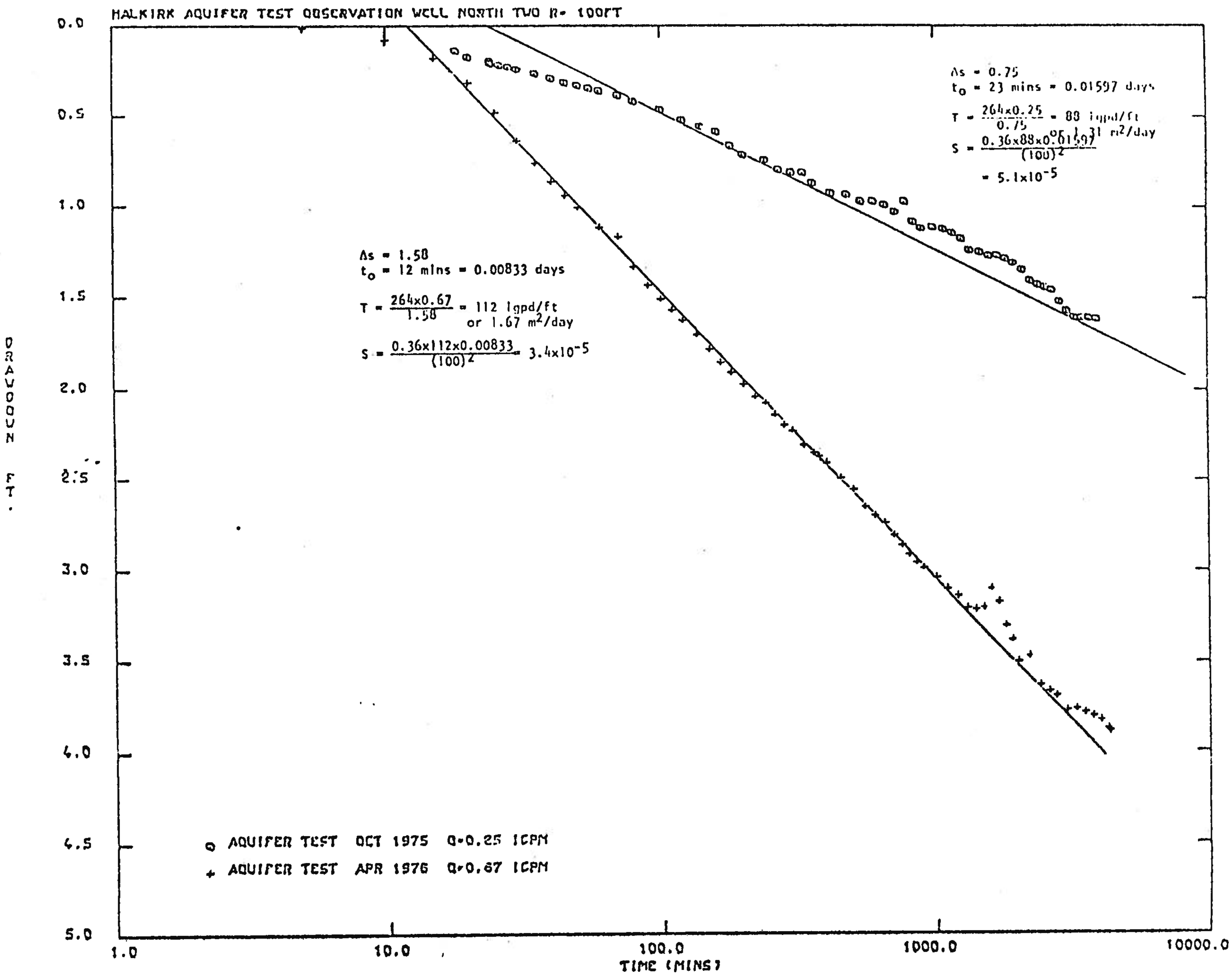
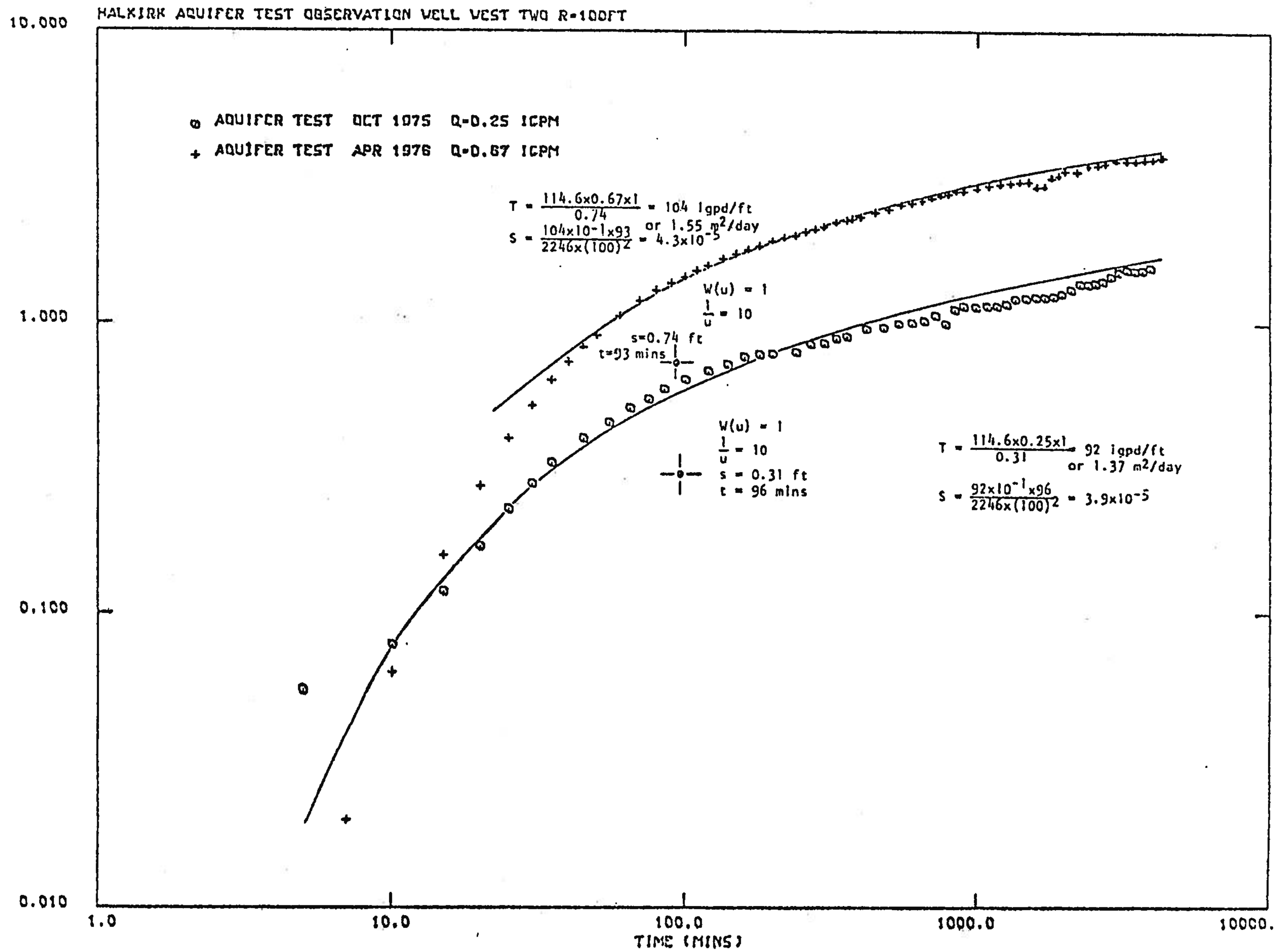

HALKIRK AQUIFER TEST OBSERVATION WELL NORTH TWO R= 100FT
DRAWDOWN FT.
TIME (MINS)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
1.0
10.0
100.0
1000.0
10000.0
Δs = 0.75
t₀ = 23 mins = 0.01597 days
T = 264x0.25 / 0.75 = 88 igpd/ft or 1.31 m²/day
S = 0.36x88x0.01597 / (100)²
= 5.1x10⁻⁵
Δs = 1.58
t₀ = 12 mins = 0.00833 days
T = 264x0.67 / 1.58 = 112 igpd/ft or 1.67 m²/day
S = 0.36x112x0.00833 / (100)² = 3.4x10⁻⁵
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM

Figure 5(f)



HALKIRK AQUIFER TEST OBSERVATION WELL WEST TWO R=100FT
AQUIFER TEST OCT 1975 Q=0.25 ICPM
AQUIFER TEST APR 1976 Q=0.67 ICPM
T = 114.6x0.67x1 / 0.74 = 104 Igpd/ft or 1.55 m2/day
S = 104x10-1x93 / 2246x(100)2 = 4.3x10-5
W(u) = 1
1/u = 10
s=0.74 ft
t=93 mins
W(u) = 1
1/u = 10
s = 0.31 ft
t = 96 mins
T = 114.6x0.25x1 / 0.31 = 92 Igpd/ft or 1.37 m2/day
S = 92x10-1x96 / 2246x(100)2 = 3.9x10-5
DRAWDOWN FT.
10.000
1.000
0.100
0.010
1.0
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(g)

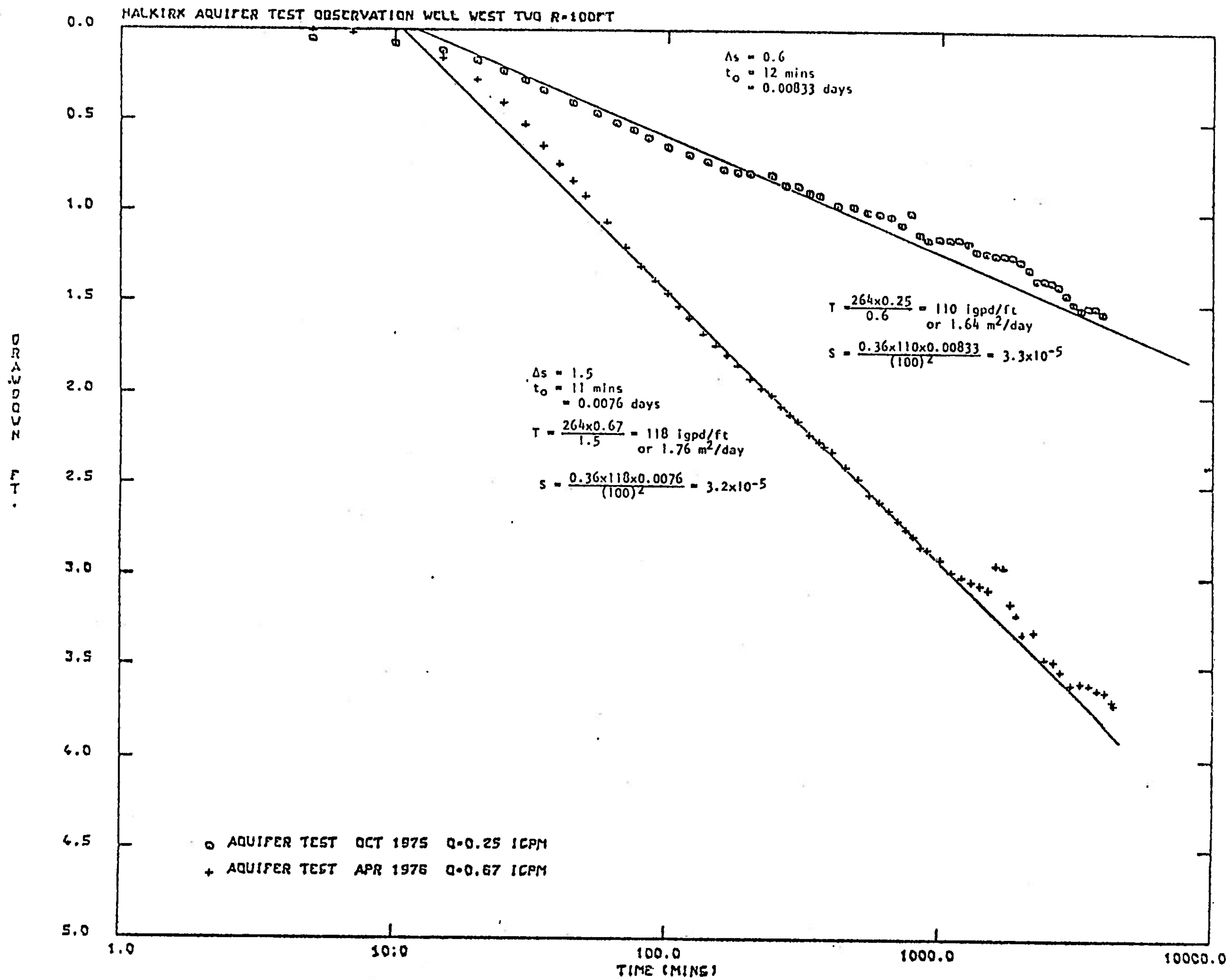
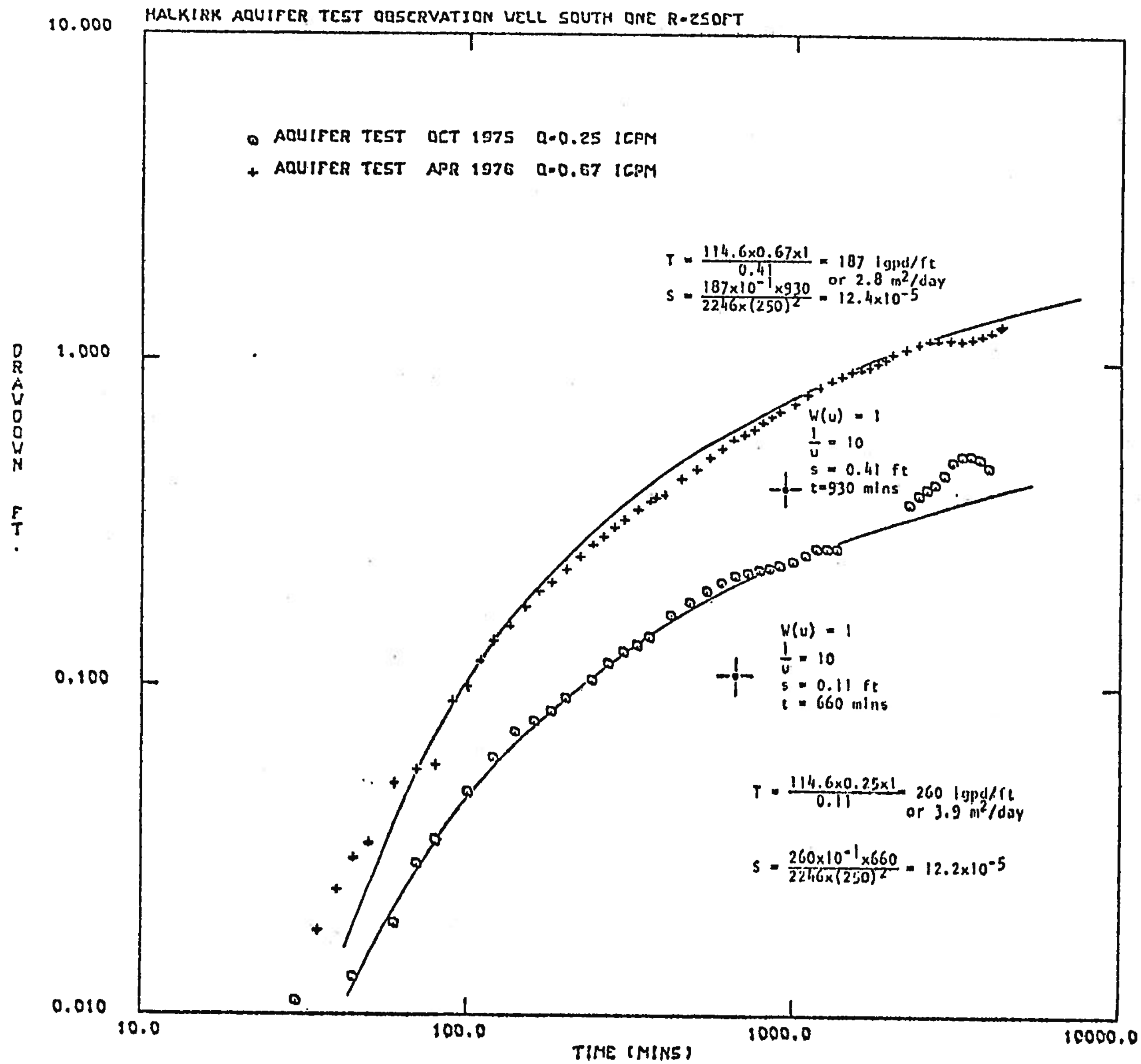

HALKIRK AQUIFER TEST OBSERVATION WELL WEST TWO R=100FT
DRAWDOWN FT.
TIME (MINS)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
1.0
10.0
100.0
1000.0
10000.0
Δs = 0.6
t₀ = 12 mins
= 0.00833 days
T = 264x0.25 / 0.6 = 110 igpd/ft
or 1.64 m²/day
S = 0.36x110x0.00833 / (100)² = 3.3x10⁻⁵
Δs = 1.5
t₀ = 11 mins
= 0.0076 days
T = 264x0.67 / 1.5 = 118 igpd/ft
or 1.76 m²/day
S = 0.36x118x0.0076 / (100)² = 3.2x10⁻⁵
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM

Figure 5(h)



HALKIRK AQUIFER TEST OBSERVATION WELL SOUTH ONE R=250FT
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM
T = 114.6x0.67x1 / 0.41 = 187 Igpd/ft or 2.8 m2/day
S = 187x10-1x930 / 2246x(250)2 = 12.4x10-5
W(u) = 1
1/u = 10
s = 0.41 ft
t=930 mins
W(u) = 1
1/u = 10
s = 0.11 ft
t = 660 mins
T = 114.6x0.25x1 / 0.11 = 260 Igpd/ft or 3.9 m2/day
S = 260x10-1x660 / 2246x(250)2 = 12.2x10-5
DRAWDOWN FT.
10.000
1.000
0.100
0.010
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(i)

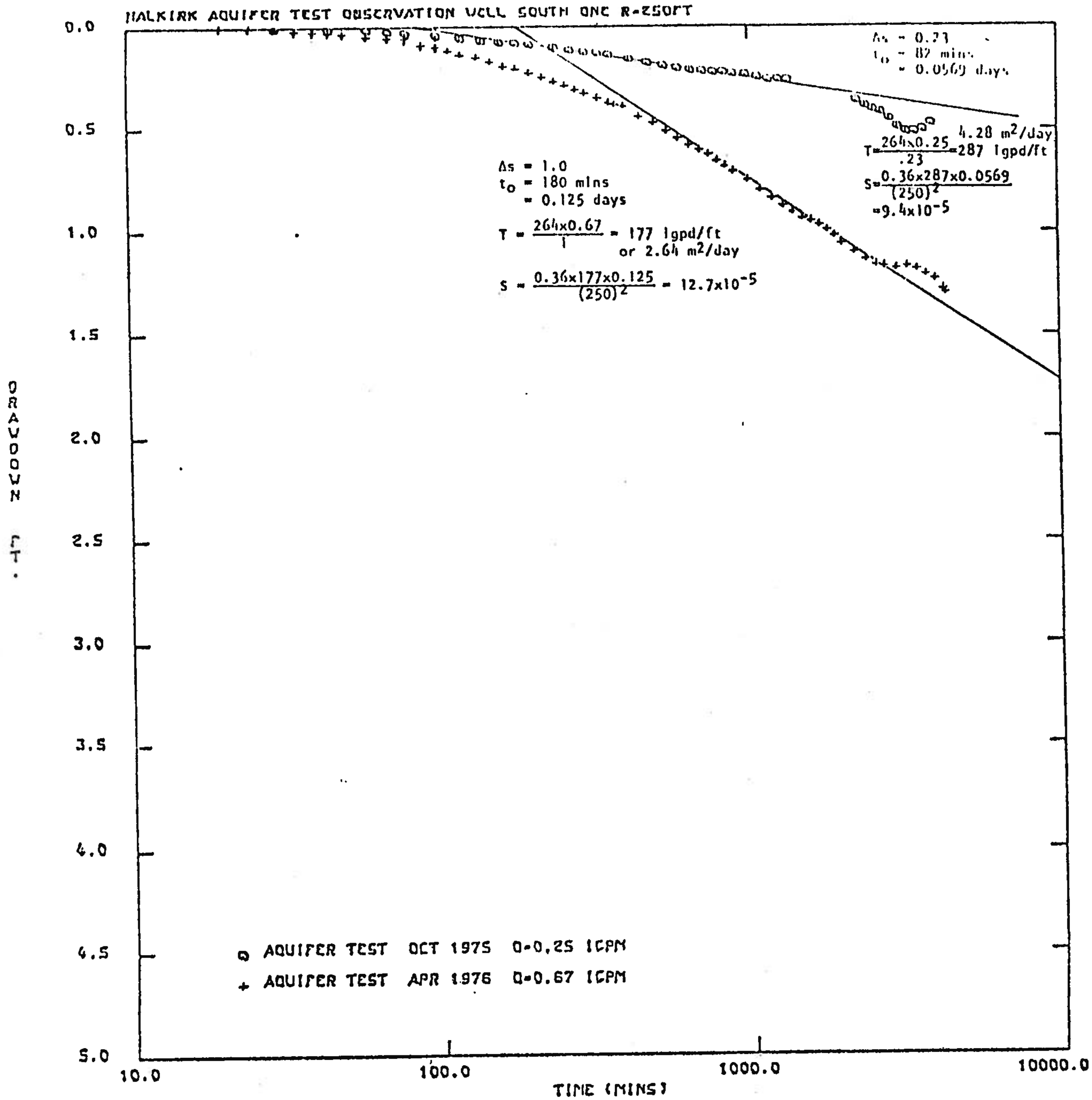
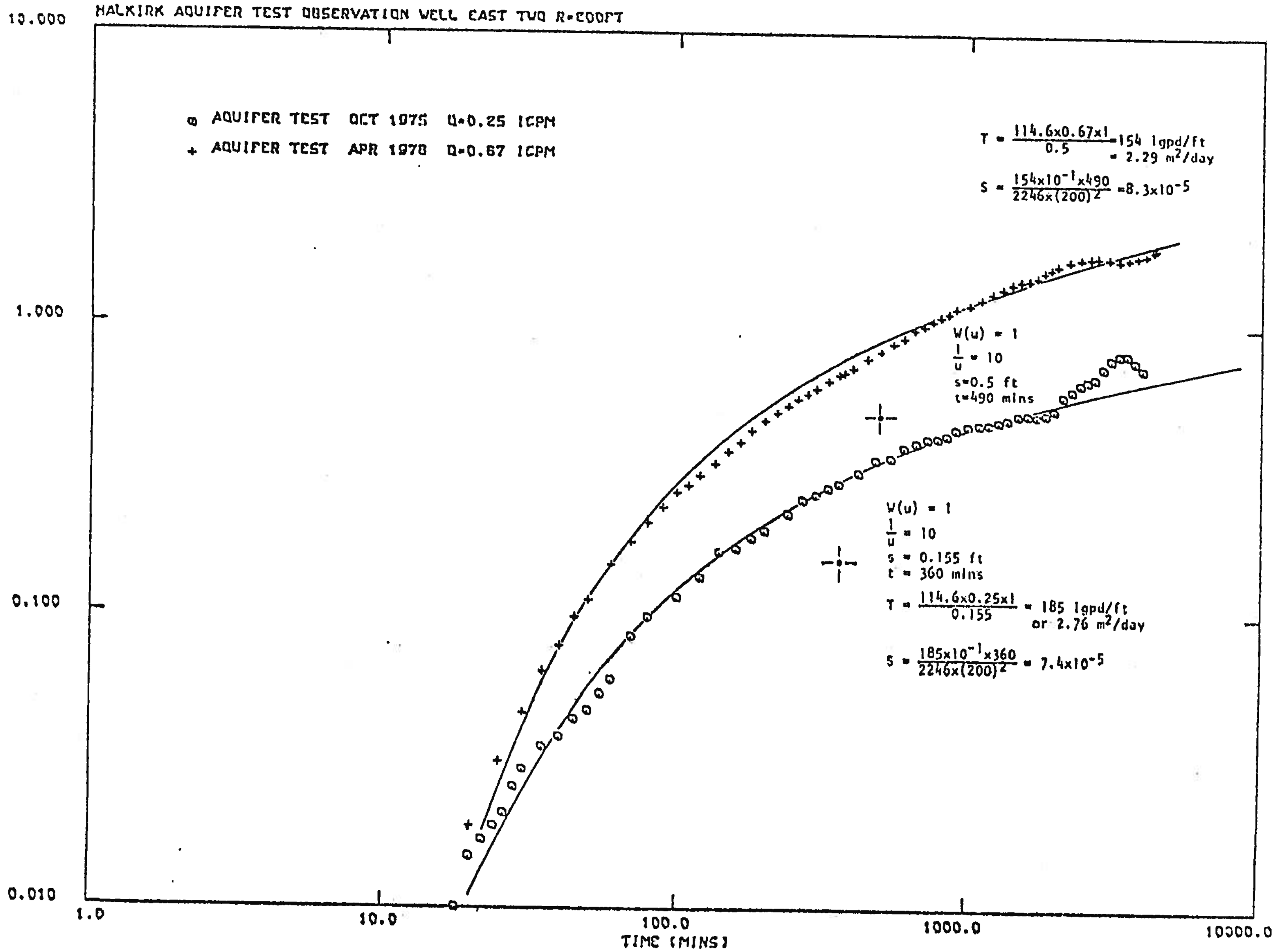

HALKIRK AQUIFER TEST OBSERVATION WELL SOUTH ONE R=250FT
Δs = 0.23
t₀ = 82 mins
= 0.0569 days
T = 264x0.25 / .23 = 287 Igpd/ft
4.28 m²/day
S = 0.36x287x0.0569 / (250)²
= 9.4x10⁻⁵
Δs = 1.0
t₀ = 180 mins
= 0.125 days
T = 264x0.67 / 1 = 177 Igpd/ft
or 2.64 m²/day
S = 0.36x177x0.125 / (250)² = 12.7x10⁻⁵
DRAWDOWN FT.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
10.0
100.0
1000.0
10000.0
TIME (MINS)
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM

Figure 5(j)



HALKIRK AQUIFER TEST OBSERVATION WELL EAST TWO R=200FT
o AQUIFER TEST OCT 1975 Q=0.25 ICPM
+ AQUIFER TEST APR 1978 Q=0.67 ICPM
T = 114.6x0.67x1 / 0.5 =154 Igpd/ft = 2.29 m2/day
S = 154x10-1x490 / 2246x(200)2 =8.3x10-5
W(u) = 1
1/u = 10
s=0.5 ft
t=490 mins
W(u) = 1
1/u = 10
s = 0.155 ft
t = 360 mins
T = 114.6x0.25x1 / 0.155 = 185 Igpd/ft or 2.76 m2/day
S = 185x10-1x360 / 2246x(200)2 = 7.4x10-5
DRAWDOWN FT.
10.000
1.000
0.100
0.010
1.0
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(k)

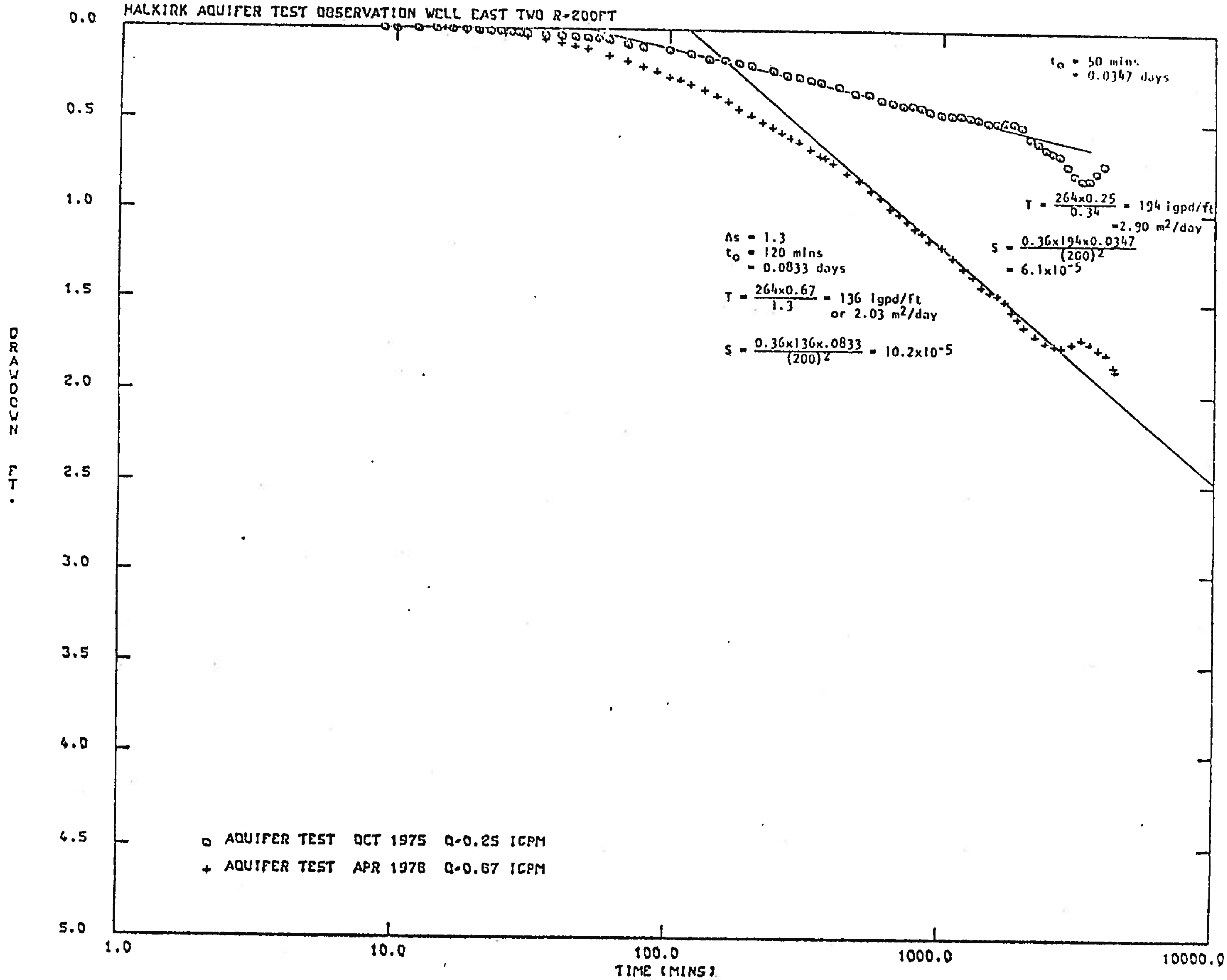

HALKIRK AQUIFER TEST OBSERVATION WELL EAST TWO R=200FT
DRAWDOWN FT.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
1.0
10.0
100.0
1000.0
10000.0
TIME (MINS)
t0 = 50 mins
= 0.0347 days
T = 264x0.25 / 0.34 = 194 igpd/ft
=2.90 m2/day
S = 0.36x194x0.0347 / (200)2
= 6.1x10-5
As = 1.3
t0 = 120 mins
= 0.0833 days
T = 264x0.67 / 1.3 = 136 igpd/ft
or 2.03 m2/day
S = 0.36x136x.0833 / (200)2 = 10.2x10-5
AQUIFER TEST OCT 1975 Q=0.25 ICPM
AQUIFER TEST APR 1978 Q=0.67 ICPM

Figure 5(1)

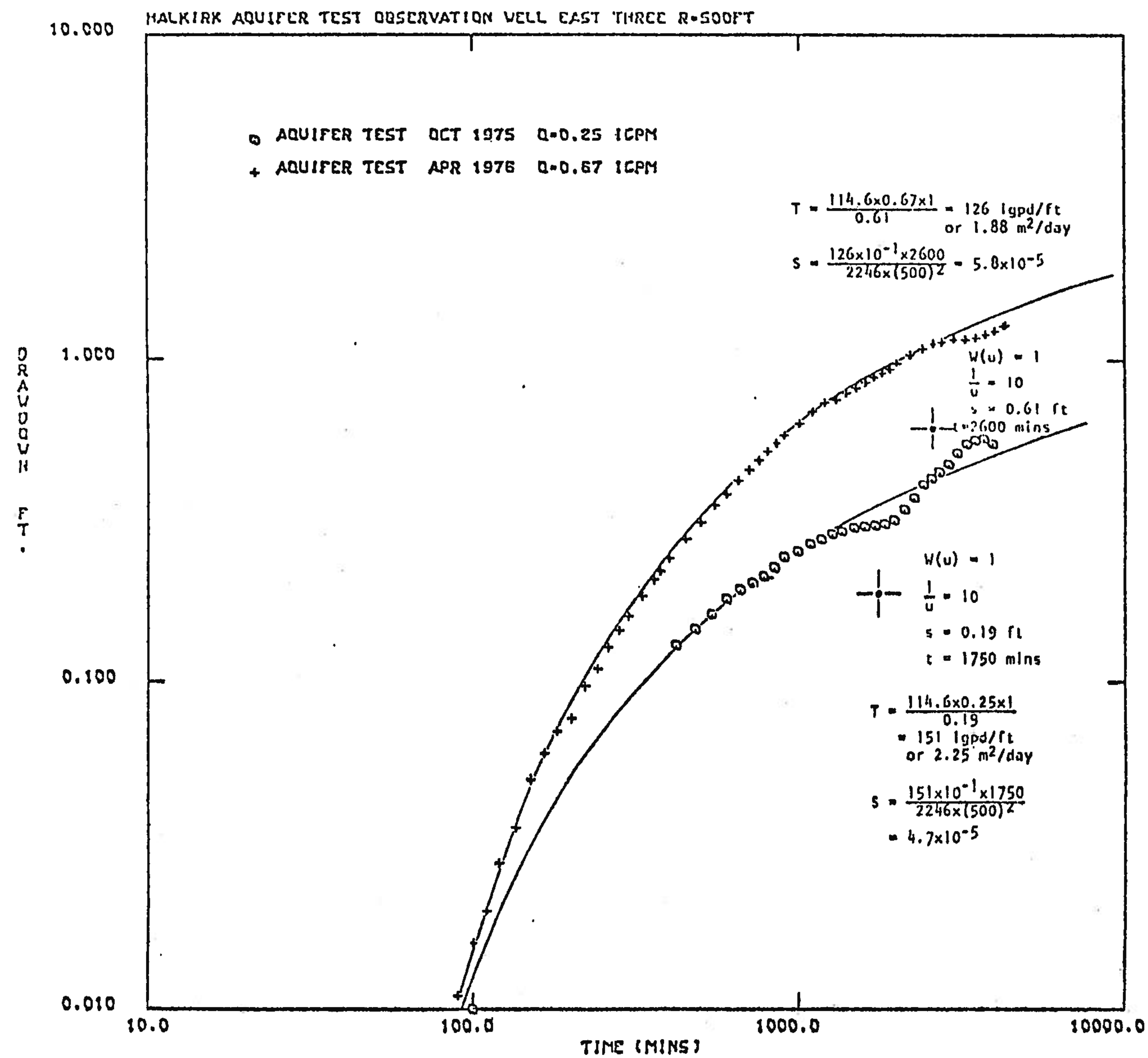
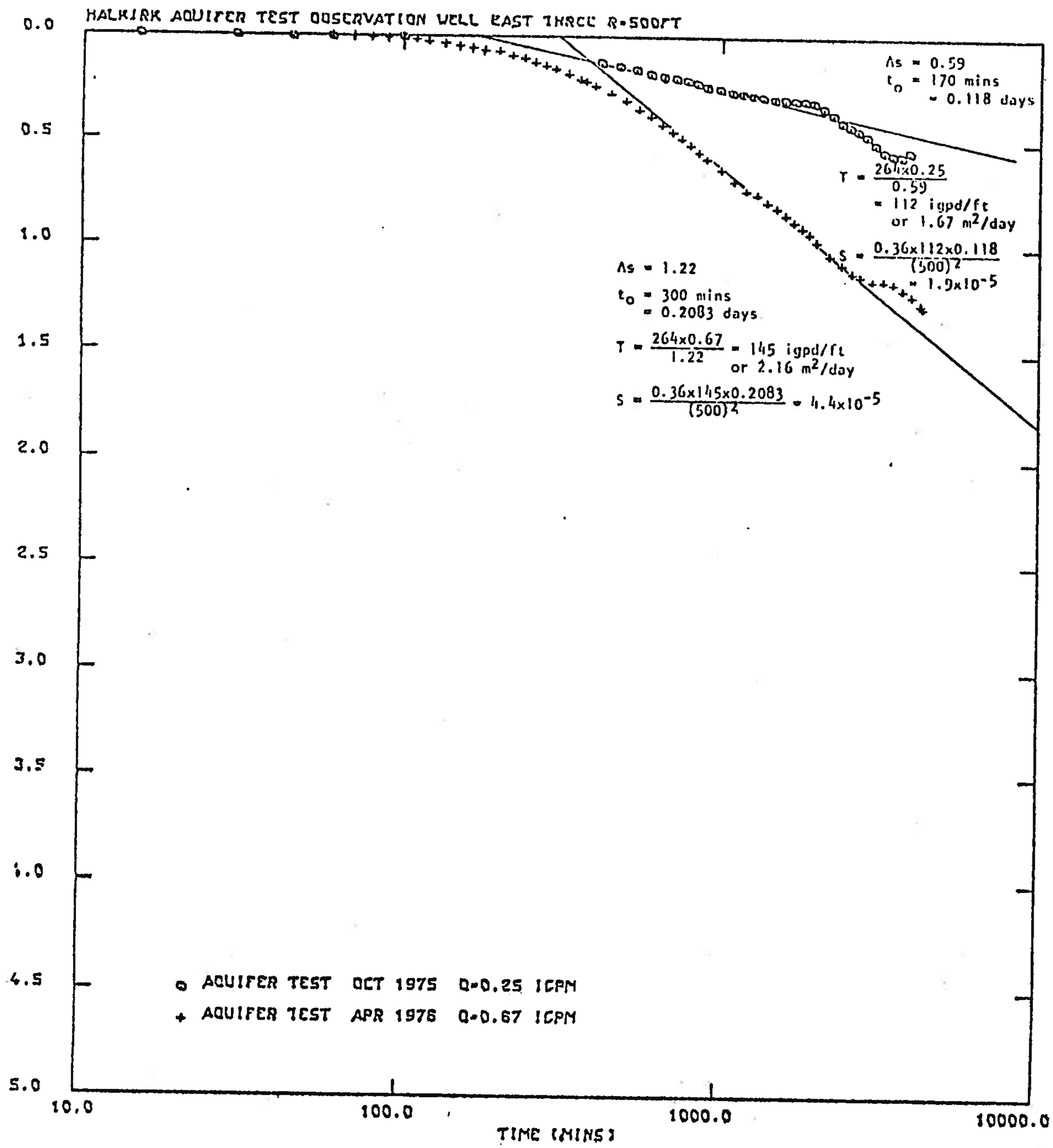
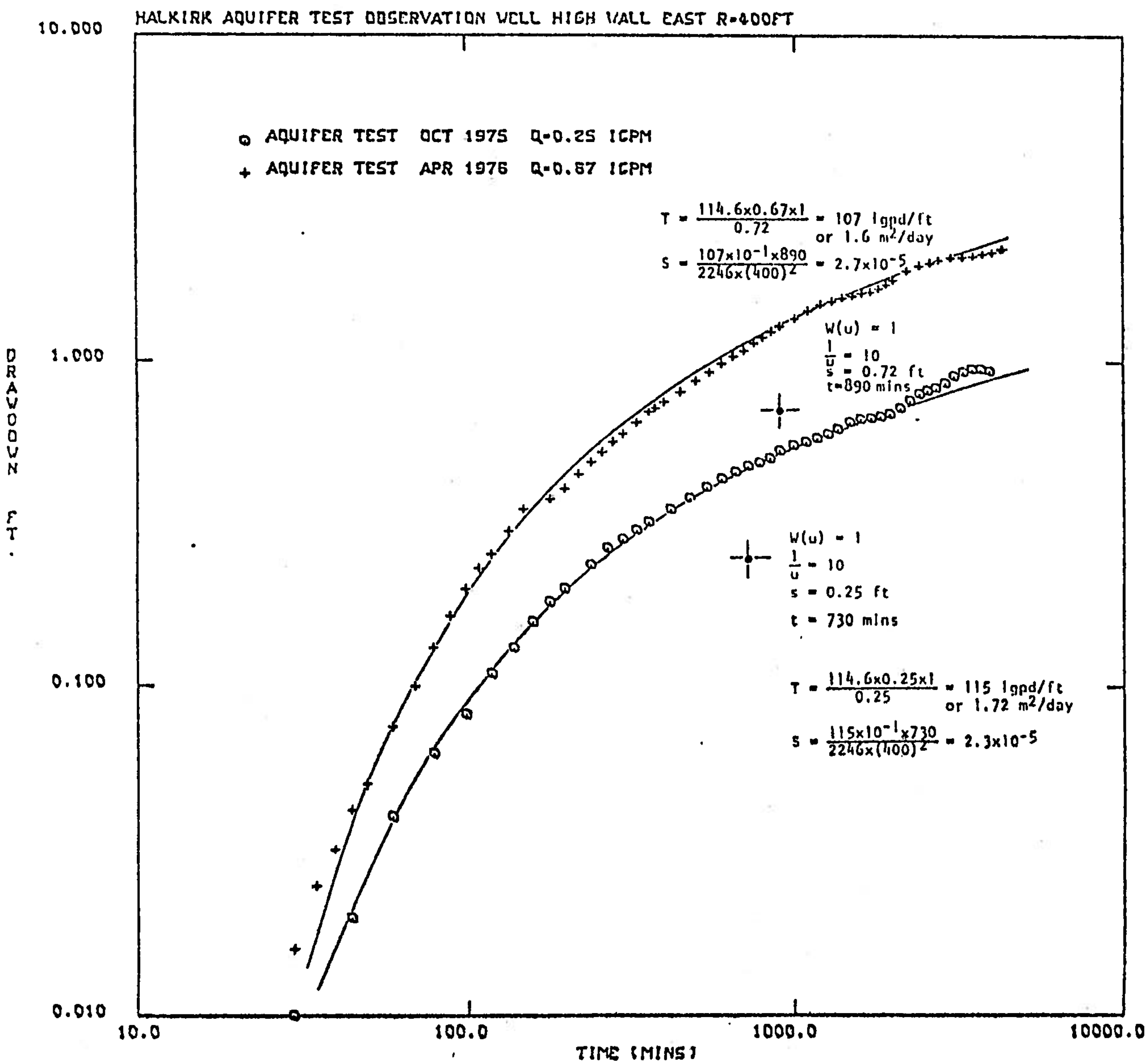

HALKIRK AQUIFER TEST OBSERVATION WELL EAST THREE R=500FT
10.000
1.000
0.100
0.010
DRAWDOWN FT.
10.0
100.0
1000.0
10000.0
TIME (MINS)
o AQUIFER TEST OCT 1975 Q=0.25 IGPM
+ AQUIFER TEST APR 1976 Q=0.67 IGPM
T = 114.6x0.67x1 / 0.61 = 126 Igpd/ft
or 1.88 m²/day
S = 126x10⁻¹x2600 / 2246x(500)² = 5.8x10⁻⁵
W(u) = 1
1/u = 10
s = 0.61 ft
t=2600 mins
W(u) = 1
1/u = 10
s = 0.19 ft
t = 1750 mins
T = 114.6x0.25x1 / 0.19
= 151 Igpd/ft
or 2.25 m²/day
S = 151x10⁻¹x1750 / 2246x(500)²
= 4.7x10⁻⁵

Figure 5(m)



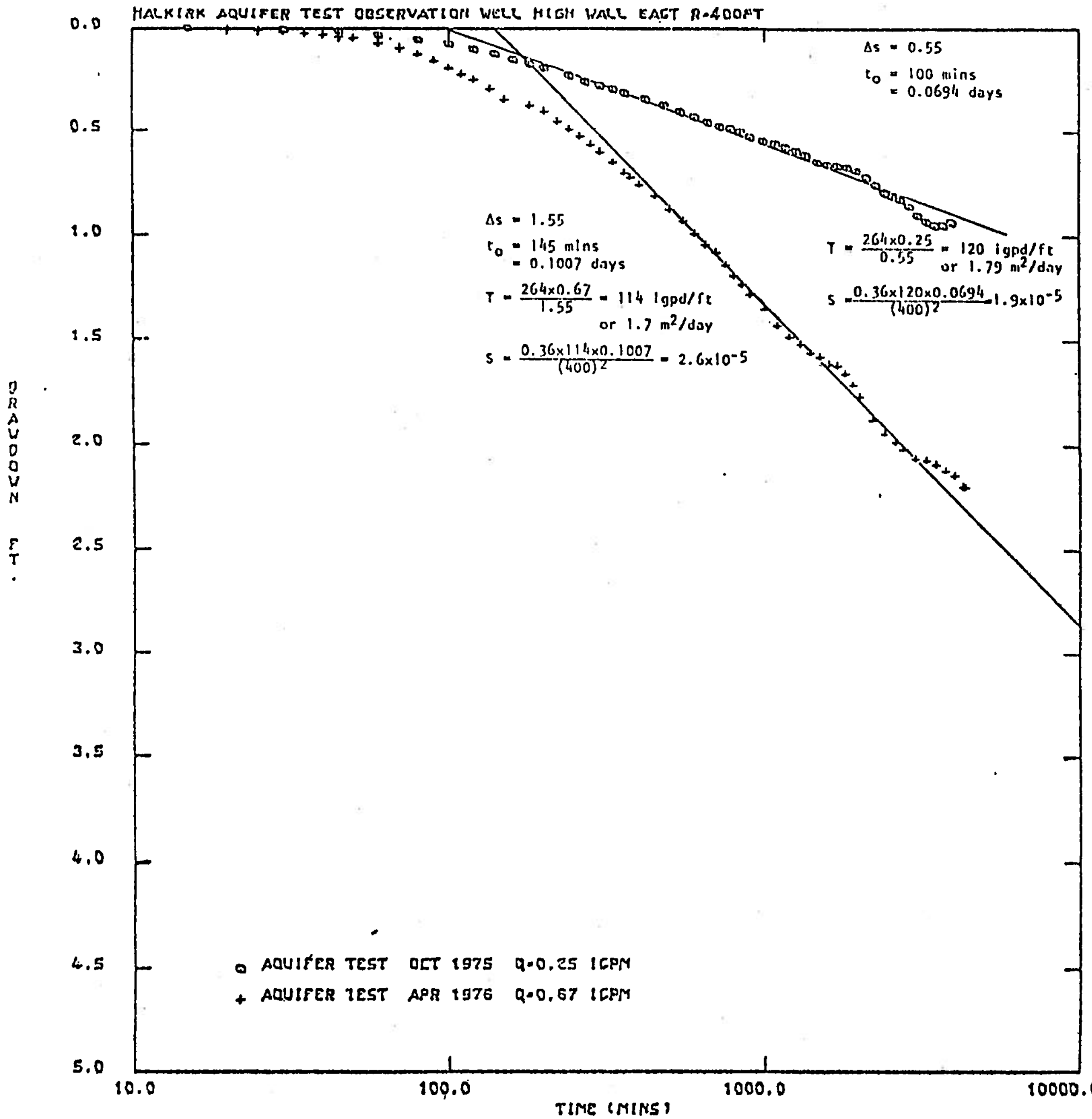
HALKIRK AQUIFER TEST OBSERVATION WELL EAST THREE R=500FT
Δs = 0.59
t0 = 170 mins
= 0.118 days
T = 264x0.25 / 0.59
= 112 igpd/ft
or 1.67 m2/day
S = 0.36x112x0.118 / (500)2
= 1.9x10-5
Δs = 1.22
t0 = 300 mins
= 0.2083 days
T = 264x0.67 / 1.22 = 145 igpd/ft
or 2.16 m2/day
S = 0.36x145x0.2083 / (500)2 = 4.4x10-5
DRAWDOWN FT.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
10.0
100.0
1000.0
10000.0
TIME (MINS)
o AQUIFER TEST OCT 1975 Q=0.25 IGPM
+ AQUIFER TEST APR 1976 Q=0.67 IGPM

Figure 5(n)



HALKIRK AQUIFER TEST OBSERVATION WELL HIGH WALL EAST R=400FT
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM
T = 114.6x0.67x1 / 0.72 = 107 Igpd/ft or 1.6 m2/day
S = 107x10-1x890 / 2246x(400)2 = 2.7x10-5
W(u) = 1
1/u = 10
s = 0.72 ft
t=890 mins
W(u) = 1
1/u = 10
s = 0.25 ft
t = 730 mins
T = 114.6x0.25x1 / 0.25 = 115 Igpd/ft or 1.72 m2/day
S = 115x10-1x730 / 2246x(400)2 = 2.3x10-5
DRAWDOWN FT.
10.000
1.000
0.100
0.010
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(o)



HALKIRK AQUIFER TEST OBSERVATION WELL HIGH WALL EAST R=400FT
Δs = 0.55
to = 100 mins
= 0.0694 days
T = 264x0.25 / 0.55 = 120 Igpd/ft
or 1.79 m2/day
S = 0.36x120x0.0694 / (400)2 = 1.9x10-5
Δs = 1.55
to = 145 mins
= 0.1007 days
T = 264x0.67 / 1.55 = 114 Igpd/ft
or 1.7 m2/day
S = 0.36x114x0.1007 / (400)2 = 2.6x10-5
DRAWDOWN FT.
TIME (MINS)
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
10.0
100.0
1000.0
10000.0

Figure 5(p)

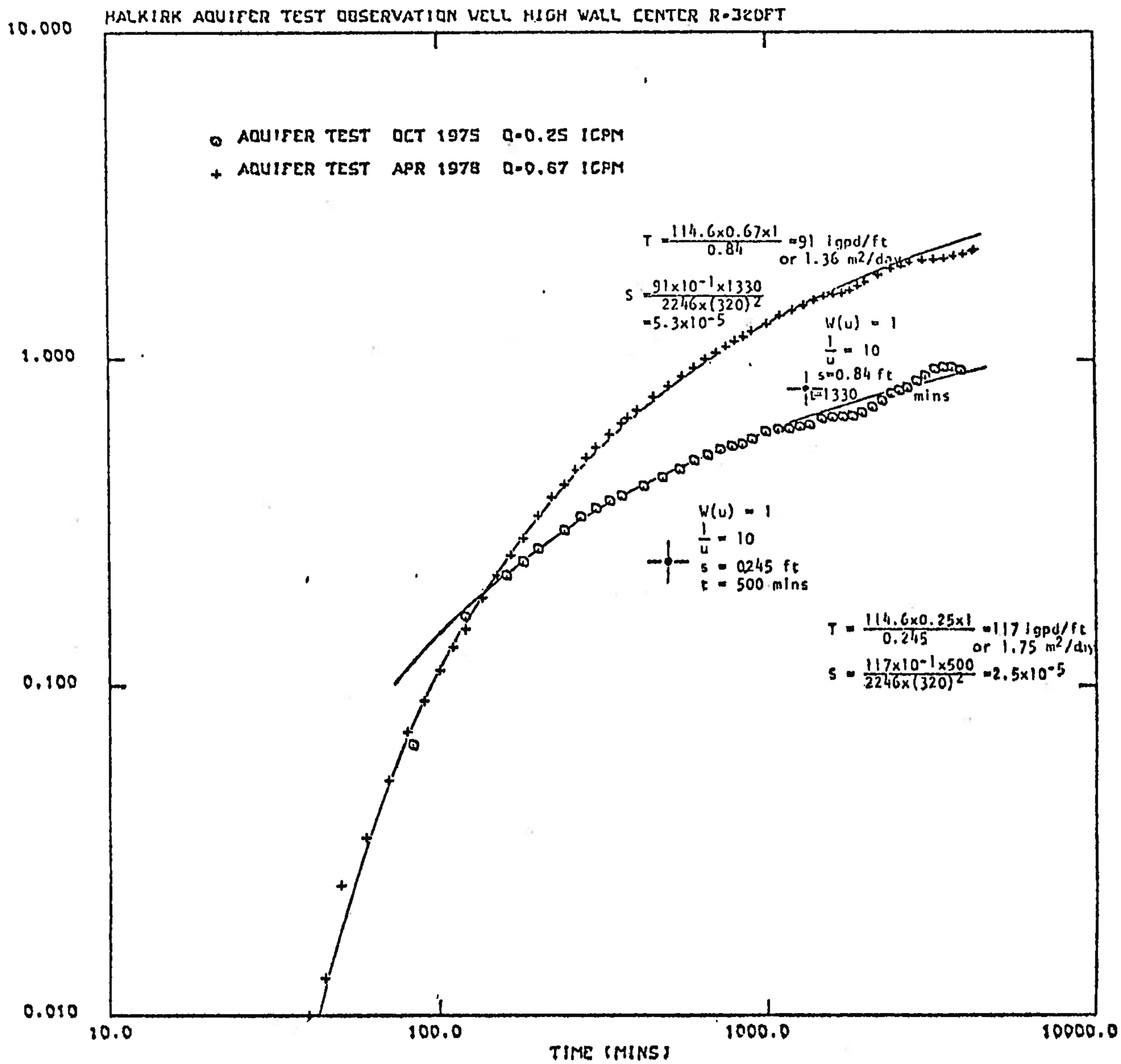

HALKIRK AQUIFER TEST OBSERVATION WELL HIGH WALL CENTER R=320FT
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1978 Q=0.67 IGPM
T = 114.6x0.67x1 / 0.84 =91 igpd/ft
or 1.36 m2/day
S = 91x10-1x1330 / 2246x(320)2
=5.3x10-5
W(u) = 1
1/u = 10
s=0.84 ft
t=1330 mins
W(u) = 1
1/u = 10
s = 0245 ft
t = 500 mins
T = 114.6x0.25x1 / 0.245 =117 igpd/ft
or 1.75 m2/day
S = 117x10-1x500 / 2246x(320)2 =2.5x10-5
DRAWDOWN FT.
10.000
1.000
0.100
0.010
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(q)

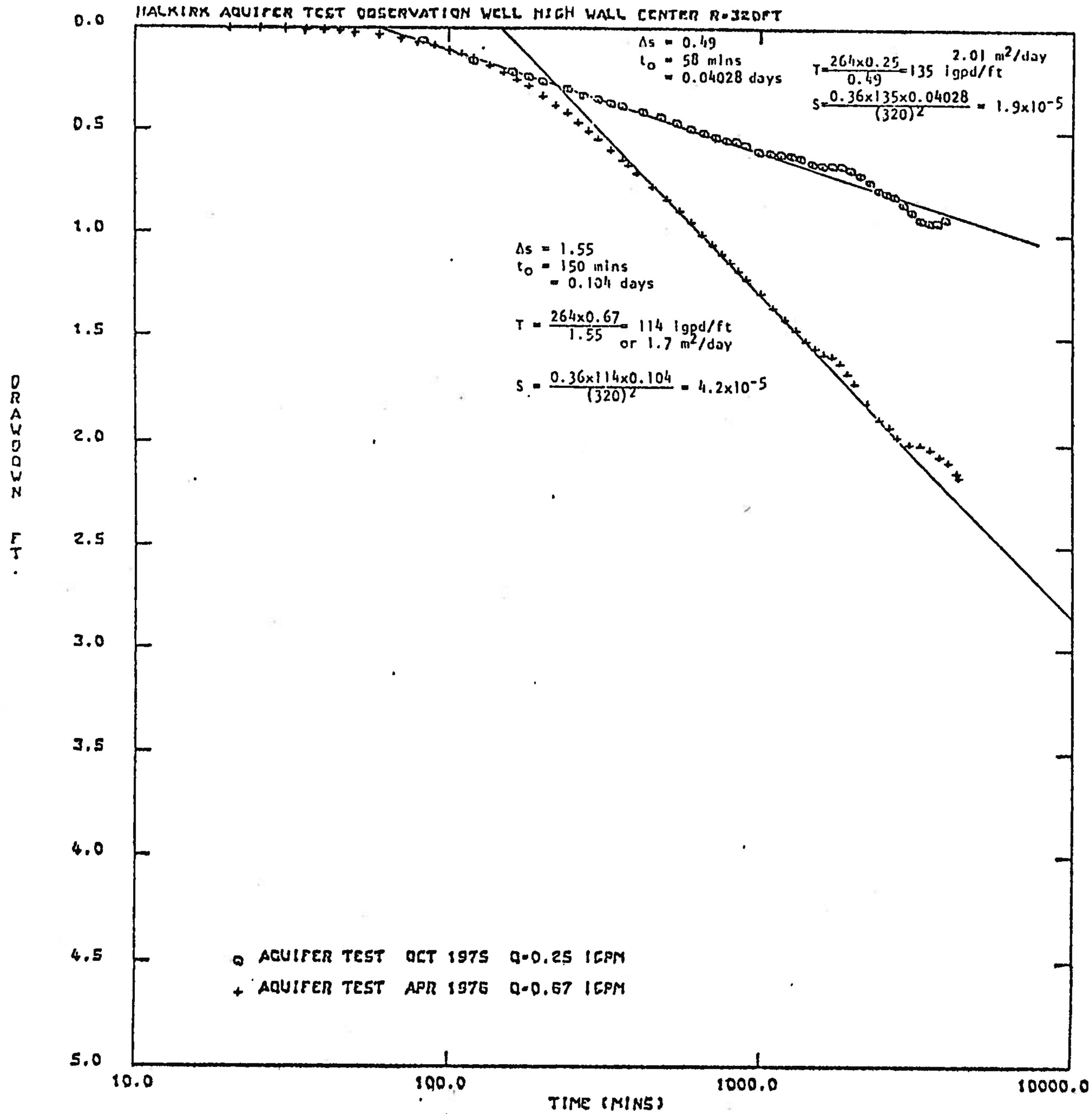

HALKIRK AQUIFER TEST OBSERVATION WELL HIGH WALL CENTER R=320FT
Δs = 0.49
to = 58 mins
= 0.04028 days
T=264x0.25/0.49=135 igpd/ft
2.01 m2/day
S=0.36x135x0.04028/(320)2 = 1.9x10-5
Δs = 1.55
to = 150 mins
= 0.104 days
T = 264x0.67/1.55 = 114 igpd/ft
or 1.7 m2/day
S = 0.36x114x0.104/(320)2 = 4.2x10-5
DRAWDOWN FT.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
10.0
100.0
1000.0
10000.0
TIME (MINS)
AQUIFER TEST OCT 1975 Q=0.25 IGPM
AQUIFER TEST APR 1976 Q=0.67 IGPM

Figure 5(r)

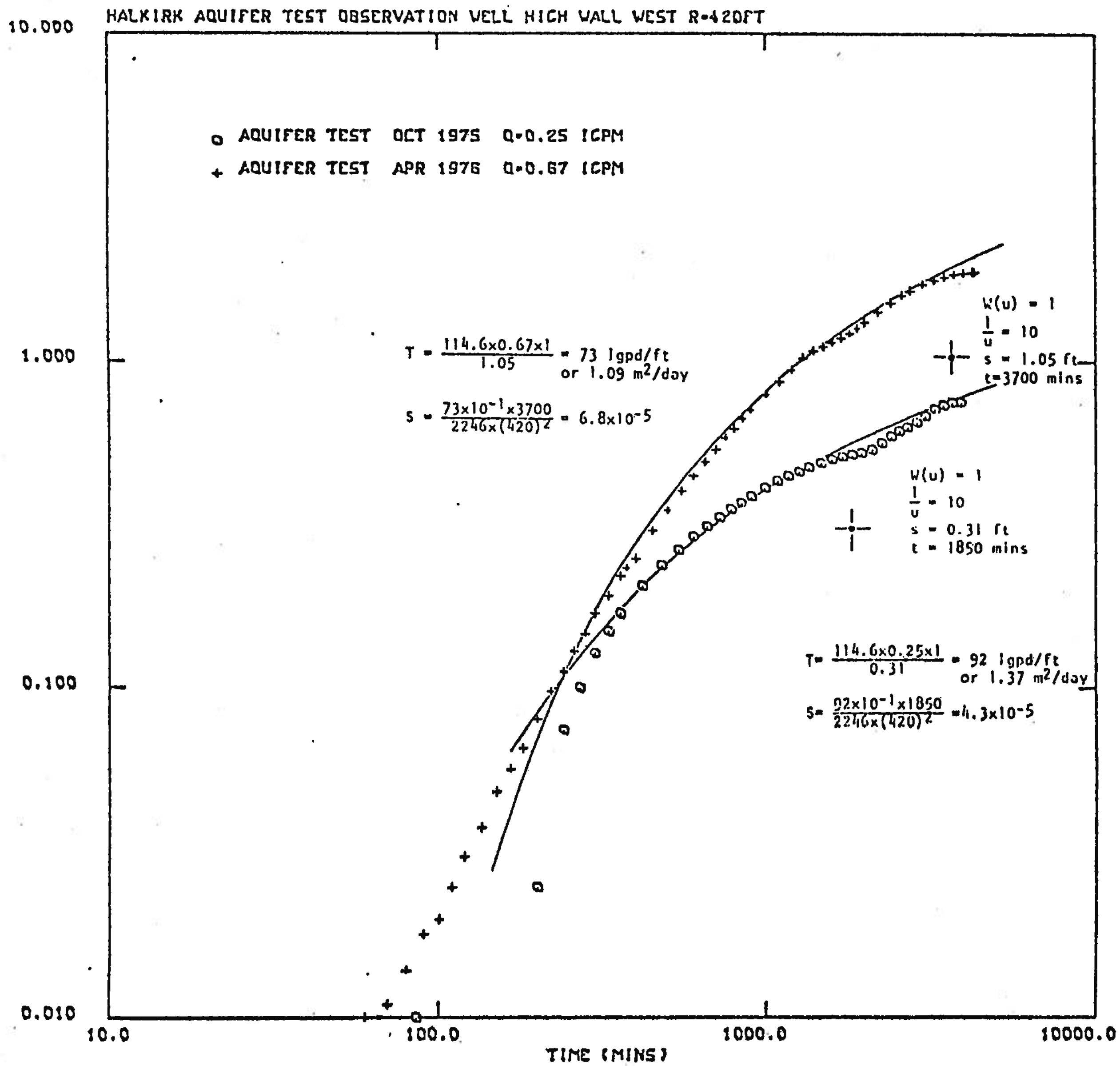
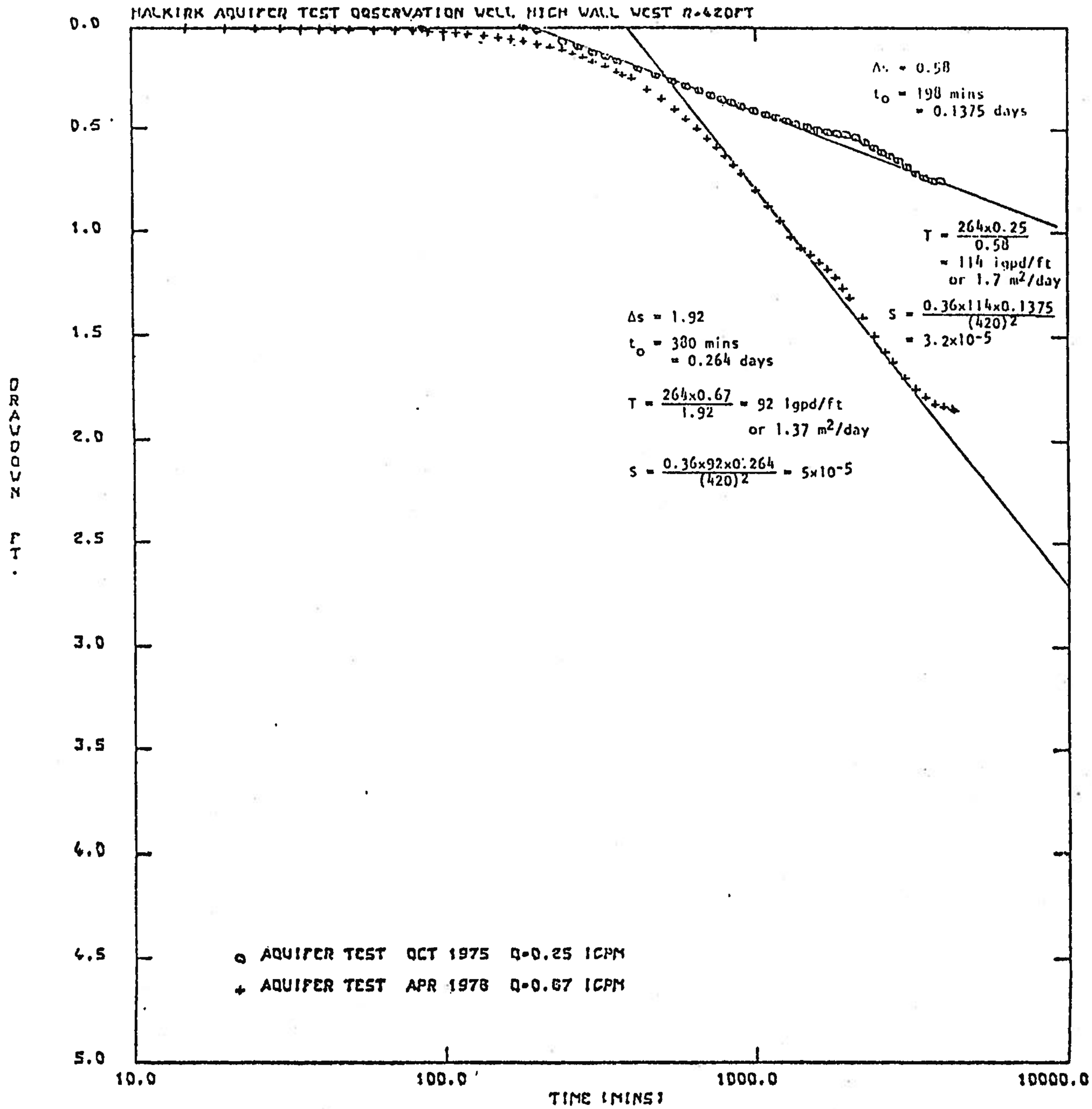
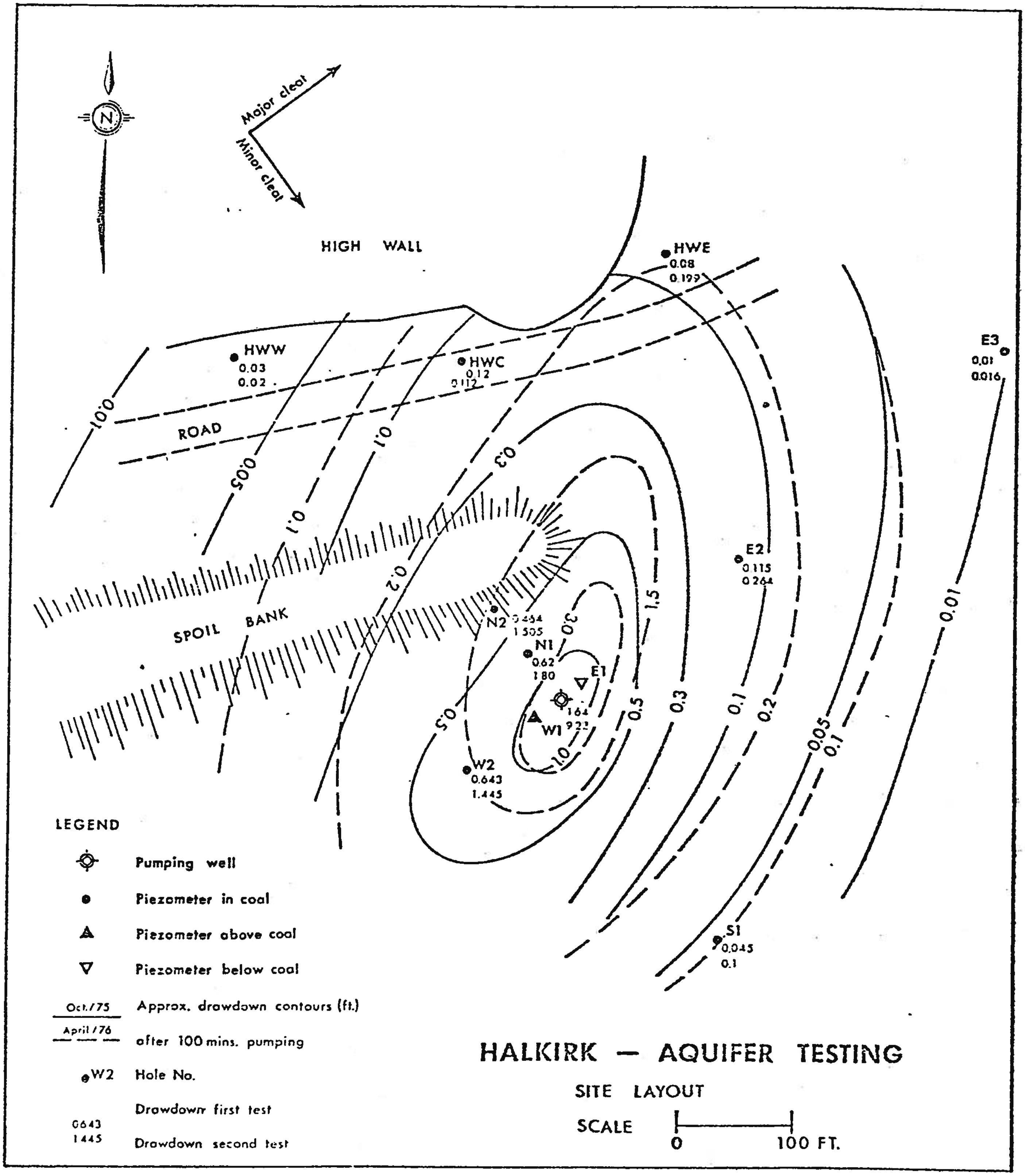

HALKIRK AQUIFER TEST OBSERVATION WELL HIGH WALL WEST R=420FT
o AQUIFER TEST OCT 1975 Q=0.25 ICPM
+ AQUIFER TEST APR 1976 Q=0.67 ICPM
T = 114.6x0.67x1 / 1.05 = 73 Igpd/ft or 1.09 m2/day
S = 73x10-1x3700 / 2246x(420)2 = 6.8x10-5
W(u) = 1
1/u = 10
s = 1.05 ft
t=3700 mins
W(u) = 1
1/u = 10
s = 0.31 ft
t = 1850 mins
T= 114.6x0.25x1 / 0.31 = 92 Igpd/ft or 1.37 m2/day
S= 92x10-1x1850 / 2246x(420)2 =4.3x10-5
DRAWDOWN FT.
10.000
1.000
0.100
0.010
10.0
100.0
1000.0
10000.0
TIME (MINS)

Figure 5(s)



HALKIRK AQUIFER TEST OBSERVATION WELL HIGH WALL WEST R=420FT
DRAWDOWN FT.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
10.0
100.0
1000.0
10000.0
TIME (MINS)
Δs = 0.58
t_o = 198 mins
= 0.1375 days
T = 264x0.25 / 0.58
= 114 igpd/ft
or 1.7 m2/day
S = 0.36x114x0.1375 / (420)2
= 3.2x10-5
Δs = 1.92
t_o = 380 mins
= 0.264 days
T = 264x0.67 / 1.92 = 92 igpd/ft
or 1.37 m2/day
S = 0.36x92x0.264 / (420)2 = 5x10-5
o AQUIFER TEST OCT 1975 Q=0.25 IGPM
+ AQUIFER TEST APR 1978 Q=0.67 IGPM

Figure 5(t)



N
Major cleat
Minor cleat
HIGH WALL
HWE
0.08
0.199
HWW
0.03
0.02
HWC
0.12
0.112
E3
0.01
0.016
ROAD
SPOIL BANK
E2
0.115
0.264
N2
0.454
1.505
N1
0.62
1.80
E1
W1
1.64
9.23
W2
0.643
1.445
S1
0.045
0.1
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
Oct./75
April/76
Approx. drawdown contours (ft.)
after 100 mins. pumping
W2
Hole No.
0.643
1.445
Drawdown first test
Drawdown second test
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 6(a)

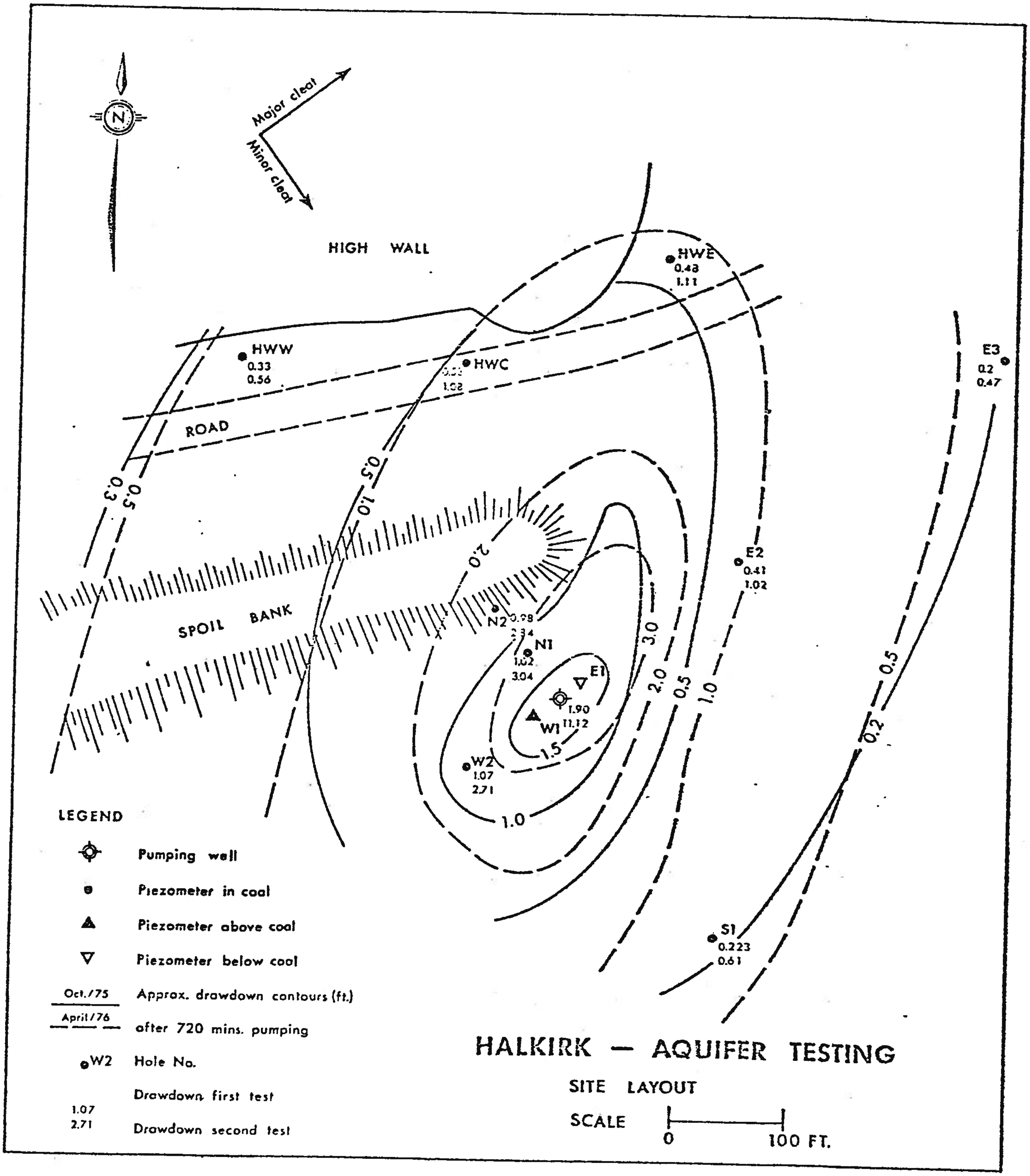
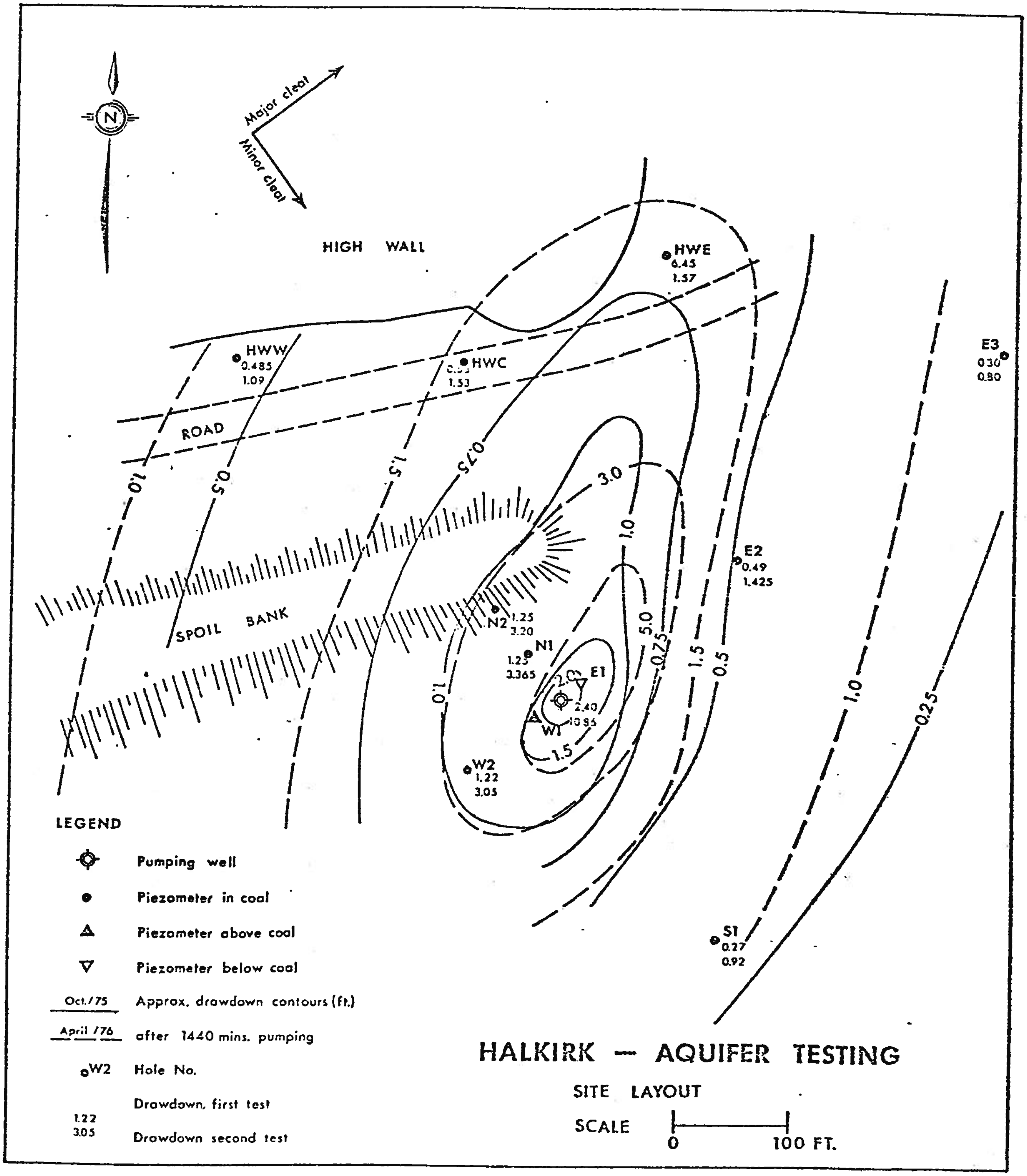

N
Major cleat
Minor cleat
HIGH WALL
HWE
0.48
1.11
HWW
0.33
0.56
HWC
1.02
ROAD
E3
0.2
0.47
0.3
0.5
0.5
1.0
2.0
SPOIL BANK
E2
0.41
1.02
N2
0.98
N1
1.02
3.04
E1
1.90
11.12
W1
1.5
3.0
2.0
0.5
1.0
0.5
0.2
W2
1.07
2.71
1.0
S1
0.223
0.61
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
Oct./75
April/76
Approx. drawdown contours (ft.)
after 720 mins. pumping
W2
Hole No.
Drawdown first test
1.07
2.71
Drawdown second test
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 6(b)



N
Major cleat
Minor cleat
HIGH WALL
HWE
6.45
1.57
HWW
0.485
1.09
HWC
1.53
E3
0.30
0.80
ROAD
1.0
0.5
1.5
0.75
3.0
1.0
E2
0.49
1.425
SPOIL BANK
N2
1.25
3.20
N1
1.25
3.365
E1
2.0
2.40
10.85
W1
1.5
5.0
0.75
1.5
0.5
1.0
0.25
1.0
W2
1.22
3.05
S1
0.27
0.92
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
Oct./75
April /76
Approx. drawdown contours (ft.)
after 1440 mins. pumping
W2
Hole No.
1.22
3.05
Drawdown, first test
Drawdown second test
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 6(c)

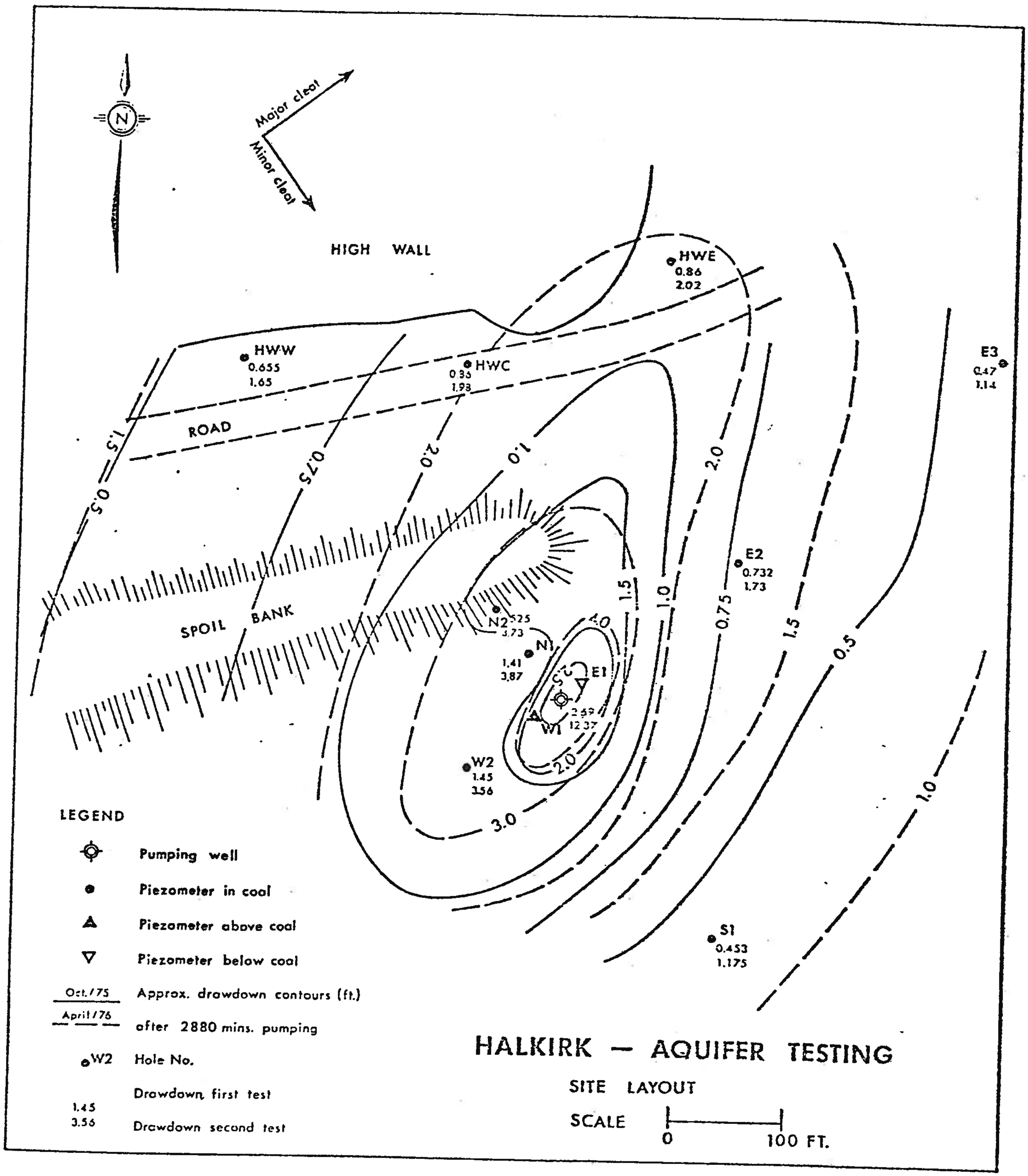
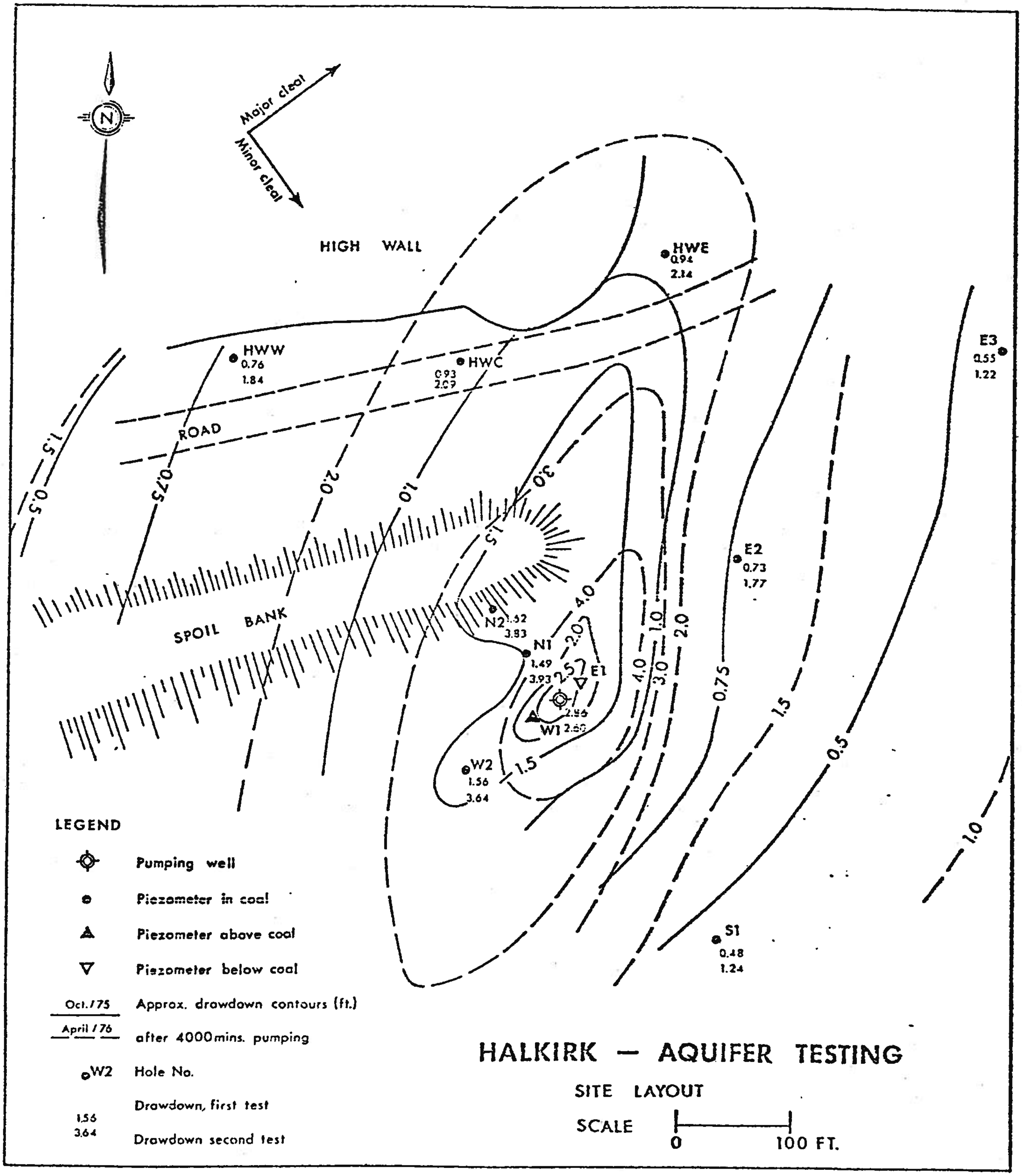
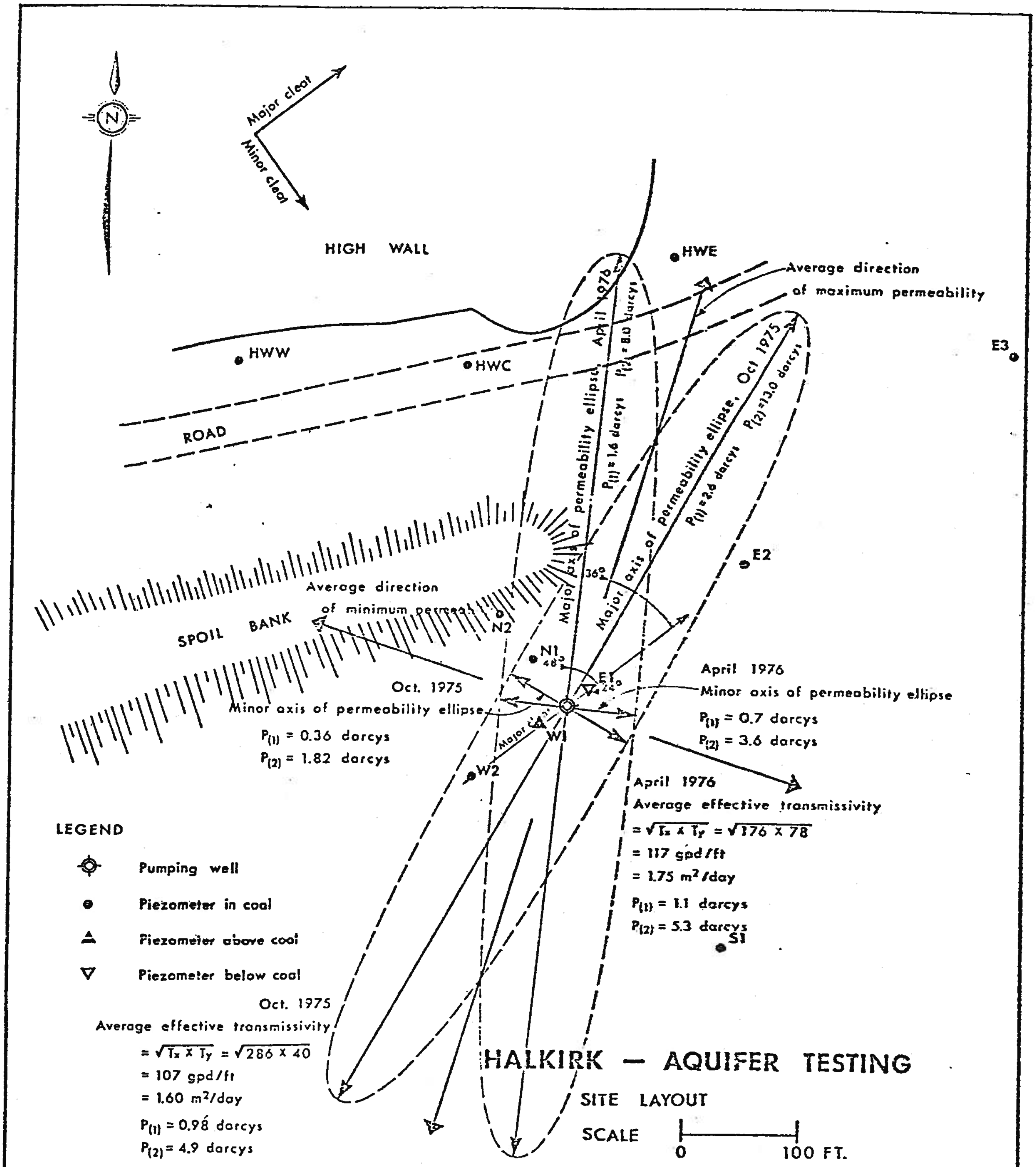

N
Major cleat
Minor cleat
HIGH WALL
HWE
0.86
2.02
HWW
0.655
1.65
HWC
1.98
E3
1.14
ROAD
SPOIL BANK
E2
0.732
1.73
N2
3.73
N1
1.41
3.87
E1
W1
W2
1.45
3.56
S1
0.453
1.175
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
Oct./75 Approx. drawdown contours (ft.)
April/76 after 2880 mins. pumping
W2 Hole No.
1.45 Drawdown first test
3.56 Drawdown second test
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 6(d)



N
Major cleat
Minor cleat
HIGH WALL
HWE
0.94
2.14
HWW
0.76
1.84
HWC
0.93
2.09
ROAD
SPOIL BANK
E3
0.55
1.22
E2
0.73
1.77
N2
1.52
3.83
N1
1.49
3.93
E1
W1
2.86
2.60
W2
1.56
3.64
S1
0.48
1.24
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
Oct./75
April/76
Approx. drawdown contours (ft.)
after 4000mins. pumping
W2
Hole No.
Drawdown, first test
1.56
3.64
Drawdown second test
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 6(e)



N
Major cleat
Minor cleat
HIGH WALL
HWE
HWW
HWC
E3
ROAD
Average direction
of maximum permeability
April 1976
Major axis of permeability ellipse
P(1) = 1.6 darcys
P(2) = 8.0 darcys
Major axis of permeability ellipse, Oct 1975
P(1) = 2.6 darcys
P(2) = 13.0 darcys
E2
SPOIL BANK
Average direction
of minimum permeab
N2
N1
E1
W1
W2
S1
Oct. 1975
Minor axis of permeability ellipse
P(1) = 0.36 darcys
P(2) = 1.82 darcys
April 1976
Minor axis of permeability ellipse
P(1) = 0.7 darcys
P(2) = 3.6 darcys
April 1976
Average effective transmissivity
= √Tx x Ty = √176 x 78
= 117 gpd/ft
= 1.75 m²/day
P(1) = 1.1 darcys
P(2) = 5.3 darcys
LEGEND
Pumping well
Piezometer in coal
Piezometer above coal
Piezometer below coal
Oct. 1975
Average effective transmissivity
= √Tx x Ty = √286 x 40
= 107 gpd/ft
= 1.60 m²/day
P(1) = 0.98 darcys
P(2) = 4.9 darcys
HALKIRK — AQUIFER TESTING
SITE LAYOUT
SCALE
0
100 FT.

Figure 7