MILESTONE REPORT

HYDROLOGIC AND HYDROCHEMICAL RESULTS FROM PUMPING TESTS CONDUCTED AT THE 11-14 POND, PANTEX PLANT, TEXAS

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SUMMARY

Results from pumping tests conducted in monitoring wells located at the 11-14 pond significantly increase our understanding of the hydrogeology of perched aquifers at the Pantex Plant, the U.S. Department of Energy weapons plant serving as the final assembly and disassembly point for the nuclear arsenal and also as a test facility for high explosives. The mean transmissivity and hydraulic conductivity calculated for all four wells based on delayed yield analyses was 488 ± 250 ft^2 d^{-1} and 33.8 ± 17.9 ft d^{-1} (45.3 ± 23.2 m^2 d^{-1} and 10.3 ± 5.4 m d^{-1}), respectively. On the basis of these hydraulic conditions, a ground-water velocity in the 11-14 pond area of 0.85 ft d^{-1} (0.26 m d^{-1}) was calculated.

Results of chemical analyses on water samples collected at three different times during the pumping test were relatively consistent. This consistency indicates that, within the volume of the perched aquifer from which water was pumped, no compositional stratification or lateral compositional trends could be conclusively identified.

INTRODUCTION

The purpose of the 11-14 pumping tests was to collect data needed to begin an evaluation of the spatial variability of hydrologic parameters of perched aquifers delineated in the area of the Pantex Plant. Hydrologic results such as those reported here will be critical for the development and calibration of deterministic mathematical models of ground-water flow and solute transport in perched aquifers at the Pantex Plant. Only then can reasonable remediation strategies be formulated for the facility.

Previous hydrogeologic investigations of the perched aquifer at the Pantex Plant documented the need for multiple-well pumping tests to measure transmissivity (T), hydraulic conductivity (K), specific yield (S_Y), and their spatial variability (Mullican and others, 1994). On October 31 through November 4, 1994, a series of three pumping tests was conducted at the Pantex Plant in perched aquifer monitoring wells (PM-101, PM-102, PM-103, and PM-104) in the area formerly occupied by the 11-14 wastewater discharge pond. The 11-14 pond site was selected for testing because of the availability of multiple nearby observation wells. Of the six wells in other areas of the plant at which pumping tests had been previously performed, only results from PM-106 are fully defensible because of the significant stress to the aquifer during testing. The accuracy of the other five (PM-19, PM-20, PM-38, PM-44, and PM-45) may be limited, owing to the short duration of the tests and low discharge rates.

All previous measurements of T and K for perched aquifers at the Pantex Plant have been based upon single-well slug tests and single-well pumping tests using low discharge rates. Locations of the four monitoring wells used during pumping tests at the 11-14 pond site are illustrated in figure 1. These wells were completed in the main perched aquifer and fully penetrate the saturated section. Specific well completion information used during testing and analysis is included in table 1.

Logistical constraints at the Pantex Plant throughout these pumping tests were significant. Contaminants were previously detected at low levels in ground-water samples collected from the wells selected for testing. Therefore, waste management requirements stipulated that all ground water produced during pumping tests had to be contained for treatment and disposal offsite. Because of the expense and logistics of this requirement, it was determined that the maximum volume of ground water to be produced throughout the pumping tests was approximately 8,000 gallons (30,280 L). The length of time both before and after the drawdown phase of the pumping test was also limited due to security requirements.

The major impacts of restricted monitoring on the performance and analysis of pumping tests were threefold. First, collecting baseline data prior to the test to evaluate barometric efficiencies within each well was impossible. Second, monitoring of water levels as part of the pumping test had to be terminated before 100-percent recovery was achieved. Finally, the limited storage capacity for produced ground water determined the duration of the drawdown phase. In this case, this duration was not adequate to completely satisfy ideal test objectives, which would have been to better define late-phase drawdown with a longer period of pumping.

Because the perched aquifer is a relatively deep, thin, unconfined aquifer and because there were significant barometric-pressure fluctuations during the pumping tests, multiple water-level corrections had to be made prior to analysis. These were corrections to measured water levels in the pumping well due to amount of drawdown experienced relative to the original saturated thickness and corrections to water levels in observation wells due to the effects of barometric-pressure fluctuations on water levels in the perched aquifer, independent of the effects of pumping. In addition, throughout the drawdown phase of the main pumping test, water chemistry was monitored for any changes that might occur as the result of pumping.

HYDROGEOLOGIC SETTING

The aquifer tested for this study is one of many naturally occurring perched aquifers above the regional Ogallala (High Plains) aquifer throughout the Southern High Plains. The perched aquifer is within the Tertiary Ogallala Formation, which underlies the Southern High Plains of Texas and eastern New Mexico. The Ogallala Formation consists of alluvial sediments (primarily sands and gravels) partly filling paleovalleys eroded into the pre-Ogallala surface and extensive, thick, eolian sediments (silty, very fine sand or loamy sands with numerous buried calcic soils) capping paleo-uplands and most fluvial sections (Gustavson and Winkler, 1988). The Ogallala Formation unconformably overlies Permian and Triassic strata and is overlain by sediments of the Quaternary Blackwater Draw Formation.

Lithologic logs describe the saturated section in PM-101 as tan, medium to very coarse grained sand, with little to some gravel up to 3.9 inches (10 cm) in diameter, well graded, and well rounded. Similar lithologies are described for the saturated section of the other wells. Lithologically, PM-102 appears to be finer textured relative to the other three wells. For example, the thickness of gravels in the saturated section of this well is 5 ft (1.8 m), whereas in the other three wells the thickness of gravels within the saturated section is 13 to 15 ft (4.0 to 4.6 m). Additional subtle, yet possibly significant geologic differences are described in the lithologic logs (Engineering-Science, Inc., 1992). For example, the maximum cobble size reported for the four wells ranged from 1.2 inch (3 cm) in PM-103 to 3.9 inches (10 cm) in PM-101.

METHODS

The general approach used in this study was to (1) reanalyze small-scale pumping tests reported by Engineering-Science, Inc. (1992), (2) use these results with an analytical model to optimize discharge rates for the pumping test, (3) conduct pumping test and monitor water levels and water chemistry, and (4) analyze and interpret results.

Reanalysis of Small-Scale Pumping Tests

Security requirements related to conducting field work at the Pantex Plant necessitate extensive preliminary efforts so that time in secured areas was as brief and productive as possible. In this case, preliminary pumping test data collected when the wells were initially drilled as part of 11-14 pond closure investigations (Engineering-Science, Inc., 1992) were obtained and reanalyzed using the Theis recovery method (Theis, 1935). These tests were reanalyzed by placing greater emphasis on late time recovery data than was done by Engineering-Science, Inc.

Optimization of Discharge Rates

Before the pumping test, an analytical model was used to select discharge rates to achieve the greatest drawdowns in the observation wells without dewatering the pumping well and considering the limited capacity for storage of produced ground water. Transmissivities determined from the reanalysis of the small-scale pumping tests were used with SUPRPUMP (Bohling and others, 1990) to determine the optimal discharge rates.

Pumping Test

Design and performance of the pumping tests followed Specific Work Instruction 3.8 of the Bureau of Economic Geology (1988). The pumping test involved (1) instrumentation, (2) water-level monitoring, and (3) water-chemistry monitoring and sampling.

Instrumentation

The Bureau's CME Model 75 drill rig was used to install a 1 horsepower submersible pump with a 1-inch (2.54-cm) diameter galvanized steel production pipe in PM-101, the designated pumping well. Static water levels were established in each of the four wells prior to the test using an electric wire-line probe. Throughout the tests, in order to reduce or prevent data loss due to electrical or mechanical failure, an effort was made to incorporate as much redundancy as possible into the monitoring system. Two pressure transducers were installed in each of the four 11-14 wells (PM-101, PM-102, PM-103, and PM-104) to redundantly monitor water levels throughout the drawdown and recovery phases. The static water level measured prior to instrumentation was used to calibrate the transducers to initial "static" conditions. Three flow meters were installed in the discharge line, both to provide redundancy and to evaluate different types of flow meters. A flow cell and sampling tubes were installed into discharge lines from the pumping well. Discharge lines were run to the storage tanks placed near the test site. The Bureau's Field Laboratory was used to house water-level and water-quality monitoring equipment throughout the test.

Water-Level Monitoring

Water-levels were measured electronically before, during, and after pumping of PM-101 in all four wells in the 11-14 pond. In addition, water-level data were recorded manually onto field data sheets. After installation of the pump, transducers, and discharge line, the flowmeters were calibrated by running the pump for 10 minutes and measuring discharge. Water levels recovered quickly after this brief pumping period and were measured continuously overnight for baseline water-level data. The pumping test was started the following morning and ran for approximately 18 hr. Water-level monitoring continued for about 50 hr after pumping stopped. Electronic data files were downloaded several times during the test, and final files were copied onto two other sets of disks to protect against data loss.

Water-Chemistry Monitoring and Sampling

During the pumping test, water samples for chemical and isotopic analyses were collected according to Specific Work Instruction 3.1 of the Bureau of Economic Geology

(1989). Water temperature, pH, Eh, and conductivity were monitored continuously using an in-line flow cell until it was deemed to have stabilized. Of these parameters, Eh is the most sensitive in determining when produced ground water is representative of formational water (Puls and Powell, 1992). Eh electrodes were calibrated against ZoBell's solution (0.141% $K_4Fe(CN)_6 \cdot 3H_2O$, 0.141% $K_3Fe(CN)_6 \cdot 3H_2O$, and 0.746% KCl); pH electrodes were calibrated against pH 4, 7, and 10 buffer solutions. Initial samples (ID no. 1194-1) were collected at 14:06, November 1, after Eh values had stabilized to ±5 mV for a period of approximately 30 min. To examine variability in water chemistry with drawdown, monitoring of temperature, pH, and Eh continued throughout the test, and additional ground-water samples were collected at 22:46, November 1 (ID no. 1194-2) and at 04:50 November 2 (ID no. 1194-3). Following the pumping test, after the pump and pipe had been pulled from well PM-101, several liters of distilled water were pumped through the pipe and collected as a blank sample (ID no. 1194-1B).

Samples were passed through in-line filters (0.45-µm membrane) and collected for analyses of major, minor, and trace dissolved ions, dissolved organic carbon, tritium (^3H), and volatile organic compounds (VOCs). In addition, unfiltered samples were collected for total organic carbon and total (dissolved and particulate) concentrations of metals. To eliminate the possibility of changes in composition that could result from volatilization during storage, samples for ^3H and VOCs were collected so that no headspace remained in the sample bottles. Samples for cation and organic carbon analyses were preserved by adding 5 mL of 6N HCl to approximately 500 mL of water. All samples were chilled during storage.

Data Analysis

Data analysis consisted of (1) correcting water-level responses to fluctuations in atmospheric pressure, (2) correcting water-level response to decrease in saturated thickness, (3) analyzing pumping test data, and (4) analyzing water samples.

Atmospheric Pressure Correction

Atmospheric-pressure fluctuations, associated with passing weather systems as well as the daily pressure fluctuation cycle induced by the warming and cooling of the atmosphere during day and night, can cause water levels to fluctuate in wells penetrating confined and deep, unconfined aquifers (see, for example, Jacob, 1940; Weeks, 1979). These fluctuations are induced because the water column in a well is directly exposed to the atmosphere, whereas the aquifer is isolated from the atmosphere, either by a confining layer in confined aquifers or a thick unsaturated zone in an unconfined aquifer such as the perched aquifer. In both confined and deep unconfined aquifers, water levels in a well fall in response to increases in atmospheric pressure and a rise in response to decreases in atmospheric pressure.

Atmospherically induced water-level fluctuations can significantly affect water levels measured in observation wells during pumping tests and mask or magnify water-level drawdown and recovery due to pumping of the aquifer, especially if the water-level change induced by pumping is small. There are two end members in the relationship between barometric pressure and water level response during a pumping test. If, for example, the barometric pressure is falling due to a major weather system during the drawdown phase of a pumping test, the declining water levels will be buffered or reduced in magnitude. Conversely, if barometric pressure is falling due to a major weather system during the recovery phase, then the recovering water levels will be magnified. Therefore, in any pumping test in a confined or deep unconfined aquifer where water-level fluctuations are expected to be small, an evaluation of barometric-pressure fluctuations during the test is warranted.

During the 11-14 pond pumping tests, water levels measured in the pumping well and observation wells were strongly influenced by atmospheric-pressure fluctuations. Therefore, all measured water levels were corrected for atmospheric effects before analyzing pumping test results. This correction involved (1) determining an appropriate barometric efficiency for the main perched aquifer and (2) removing the effects of atmospheric pressure fluctuations from water-level data during the tests.

Barometric efficiency is a measure of how effectively atmospheric pressure influences water levels. Barometric efficiency, B_e, is defined as

$$B_e = \frac{\Delta h}{\Delta P_a}, \quad (1)$$

where

Δh = change in water level

ΔP_a = change in atmospheric or barometric pressure.

Because B_e is dimensionless, the change in water level and barometric pressure must be reported in the same units (e.g., in feet of water). B_e is determined from simultaneous water level and barometric pressure measurements. For this study, hourly measurements of water levels and barometric pressure were used. The method of quantifying B_e for this effort was to manually measure the peak-to-peak change in barometric pressure and the corresponding peak-to-peak change in water levels within a well and determine the individual well's B_e using equation 1. If this is done for a large number of pressure and water-level fluctuation cycles in a well, a mean B_e is realized.

Atmospheric-pressure effects were removed from the drawdown and recovery data by first selecting a common reference point between the water-level records and the barometric-pressure record. This reference point is logically at the beginning of the test at the instant before pumping started. Any deviation of the barometric pressure, P_a, from the barometric pressure measured at the beginning of the pumping test, P_{ao}, warranted correcting the observed water level in the observation wells. The corrected water level, h_c, was determined from

$$h_c = h + B_e(P_a - P_{ao}), \quad (2)$$

where h is the water level measured in the well.

Saturated Thickness Correction

One of the fundamental assumptions and conditions required for analysis of unsteady-state flow in an unconfined aquifer is that *the aquifer is homogeneous and of uniform thickness over the area influenced by the test* (Kruseman and de Ridder, 1990). When the amount of drawdown in an unconfined aquifer is large in comparison to the aquifer's original saturated thickness, the assumption of a uniform thickness is not valid. This was the case with drawdown measured in the pumping well, PM-101. At the end of drawdown, saturated thickness in PM-101 declined from 14.76 ft (4.5 m) to 6.18 ft (1.88 m), a 58-percent decrease. In this case the observed drawdown must be corrected using an equation first proposed by Jacob (1944, as reported by Kruseman and de Ridder, 1990):

$$s' = s - (s^2/2b), \qquad (3)$$

where

s' = corrected drawdown

s = observed drawdown

b = original aquifer saturated thickness.

Neuman (1975) suggested that the Jacob correction is only valid for the late phase of the pumping test when flow is predominantly horizontal. However, early and intermediate phase drawdown should be corrected due to the decrease in saturated thickness near the well. Unfortunately, no established method to make this correction was available. Therefore, T values determined with uncorrected early and intermediate phase drawdown are underestimated.

Pumping Test Analysis

Once water levels were corrected for atmospheric and saturated thickness effects, data from drawdown and recovery periods were analyzed with standard analytical techniques. Analysis of drawdown data was performed using the Boulton method (Boulton, 1963) for unconfined aquifers with delayed yield as modified by Neuman (1975). During the early phase of drawdown, an unconfined aquifer responds in the same way as a confined aquifer owing to the expansion of water and matrix compaction of the aquifer (Kruseman and de Ridder, 1990). Therefore, methods usually reserved for confined aquifers, such as the Jacob method (Cooper and Jacob, 1946), can be used to analyze drawdown data in unconfined aquifers (this Jacob method should not be confused with the Jacob correction). Similarly, late phase drawdown behaves in like manner to a confined aquifer and can therefore also be interpreted with confined aquifer techniques.

Neuman (1975) illustrated that in an unconfined aquifer with delayed yield, the water table response was fully reversible. Therefore, the Theis recovery method was used, but only for late time recovery data after the effects of elastic storage subsided.

Water Sample Analysis

All laboratory analyses except for ^{3}H and organic carbon were conducted at the Bureau of Economic Geology's Mineral Studies Laboratory. Metals (primarily cations) and metalloids were analyzed by means of inductively coupled plasma optical emission spectrometry, anions by means of ion chromatography, HCO_3^- by potentiometric titration, and NH_3 by steam distillation. Organic carbon was measured by persulfate oxidation in a carbon analyzer at Controls for Environmental Pollution, Inc. (Santa Fe, New Mexico) and ^{3}H was analyzed by electrolytic enrichment and gas proportional liquid-scintillation counting at the University of Miami (Florida) Tritium Laboratory.

RESULTS

Reanalysis of Small-Scale Pumping Tests

Results from reanalysis using the small-scale pumping tests conducted at the four monitor wells (PM-101, PM-102, PM-103, and PM-104) by Engineering-Science, Inc. (1992) using the Theis recovery method are presented in table 2. Values of T range from 133 to 385 ft^2 d^{-1} (12.3 to 35.8 m^2 d^{-1}) with a mean value of 272 ft^2 d^{-1} (25.2 m^2 d^{-1}) and a standard deviation of 122 ft^{2}d^{-1} (11.3 m^2 d^{-1}). The mean K for these tests was 18 ft d^{-1} (5.6 m d^{-1}) with a standard deviation of 7.8 ft d^{-1}(2.4 m d^{-1}). For comparison, values of T reported by Engineering-Science, Inc. (1992) have a mean value of 231.5 ft^2 d^{-1} (21.5 m^2 d^{-1}) and a standard deviation of 59.4 ft^{2}d^{-1} (5.5 m^2 d^{-1}) and values of K have a mean of 17.8 ft d^{-1} (5.4 m d^{-1}) with a standard deviation of 5.0 ft d^{-1} (1.5 m d^{-1}).

Engineering-Science, Inc. (1992) did not fully describe how they determined the saturated thickness of the perched aquifer. Table 4.6 from the Engineering-Science, Inc. (1992) report uses the term "Screened aquifer thickness" to describe the saturated thickness. Each well was installed with 20 ft (6.1 m) of stainless steel screen, which was 6 to 9 ft (1.8 to 2.7 m) greater than the reported saturated thickness. Since the initial static water levels reported by Engineering-Science, Inc. (1992) are within 1.0 ft (0.3 m) of water levels measured at the start of our pumping tests, the large discrepancy between the previously reported saturated thickness and our values is unclear. It is improbable that there is a 2.95-ft (0.9-m) difference in the saturated thickness between PM-102 and PM-104 (as reported by Engineering-Science, Inc., 1992) because these two wells are only 46.2 ft (14.1 m) apart. For the current study, the saturated thickness of the perched aquifer was determined by subtracting the depth to water from the total depth of the well.

Another problem with results presented in Table 4.6 of the Engineering-Science, Inc. (1992) report is that the method used to determine transmissivity, as stated, was to "multiply hydraulic conductivity values by the screened aquifer thickness." This would appear to be reversed, since the Theis recovery method solves for transmissivity, not hydraulic conductivity.

Optimization of Discharge Rates

SUPRPUMP (Bohling and others, 1990) was used with the T values determined from the above reanalysis to optimize the discharge rate for the pump test. Using both the mean T and the T value for PM-101 (the pumping well), a maximum predicted drawdown of approximately 0.3 ft (0.09 m) in PM-103, the closest observation well, was achieved using a discharge rate of between 7.0 and 7.5 gpm (26.5 and 28.4 Lpm). This pumping rate was then initially used for the long-term pumping test.

Pumping Test Results

Pumping test results include (1) test performance, (2) barometric efficiencies, and (3) analysis of drawdown and recovery hydrographs.

Test Performance

The first pumping test was conducted on October 31 and was simply used to calibrate monitoring equipment and to establish a desired discharge rate of 7.0 gpm (26.5 Lpm). Owing to the short duration of this test (approximately 10 min) and variable discharge rates, no analysis from the first pumping test was performed. Recovery was allowed to occur overnight with water levels recorded in all wells.

Drawdown for the second test was initiated on November 1, at 09:42 and terminated at 10:18. Discharge during the second test averaged approximately 6.95 gpm (26.3 Lpm) and maximum drawdown was 4.14 ft (1.26 m) when production was terminated after approximately 36 min. The second test was terminated because drawdown in the production well had already slowed or flattened out significantly and an increase in discharge rates was needed to better stress the aquifer. Recovery from the second test was monitored in PM-101 until residual drawdown was measured at 0.07 ft (0.02 m), or 98.3 percent recovery. Extensive analysis was impossible for this test because no drawdown was observed in the observation wells.

The drawdown phase of the third pumping test was initiated at 12:20 on November 1 and was terminated at 06:05 on November 2 (for a duration of 1065 min). Recovery was then monitored until 08:36 on November 4 (for a duration of 3031 min). During the third pumping test, discharge control valves were opened to maximum capacity. Discharge rates from the three flow meters used during the test are illustrated in figure 3a and 3b. Flow meter 1 (FM1) was a Sensus mechanical flow meter, and readings were recorded manually at approximately 10-min intervals. Thus, slight fluctuations in discharge rates over short time intervals were not detected (due to coarseness of measurement intervals). FM1 was, however, the most accurate indicator of cumulative production. Flow meters 2 and 3 (FM2 and FM3) were two different models of Signet digital flow meters. Figure 3b would seem to suggest, based on a comparison with figure 3a, that FM2 was the most accurate digital flow meter throughout the pumping test. The deviations in discharge recorded by FM2 and FM3 as compared to FM1 are not clear and will require further laboratory testing to reconcile. The cause or causes for the significant increase in discharge rates recorded by FM3 (fig. 3b) during the late stage of drawdown are unknown, but mechanical drift in the calibration is a likely possibility. The gradual, slight reduction in discharge rate as measured by FM2 throughout the test could be the result of increasing head on the pump due to decreasing water levels throughout the drawdown phase of the test. This decreasing trend is not recorded by FM1. The increase in discharge rate at an elapsed time of approximately 30,000 s (0830 hr) (fig. 3b) was attributed to the reduction in head on the discharge line due to the transfer of the discharge line to the second tanker truck. The mean discharge rate calculated for FM1 was 7.48 gpm (28.31 L).

Barometric Efficiencies

Because of the limited baseline water-level data recorded in the four 11-14 monitoring wells prior to the drawdown phase (16 hr), barometric efficiency, B_e, was determined using extensive water-level records measured during 1991 in PM-19, PM-20, PM-38, and PM-45. These monitoring wells are also completed in the main perched aquifer at the Pantex Plant. Barometric-pressure data recorded at the Amarillo International Airport, which is located approximately 10 mi (16 km) southwest of the test site, were obtained and used to estimate B_e. The B_e values for the four monitoring wells are presented in table 3. The mean value, 0.96, is very close to unity and suggests that atmospheric-pressure changes are nearly 100 percent efficient at changing water levels in wells. In the final analysis of T and K for each well analyzed from these pumping tests, it should be noted that the results are sensitive to the value selected as the representative B_e, especially in wells where measured drawdowns are small. Though it is physically unreasonable for B_e to exceed unity (a B_e of greater than 1.0), there are possible explanations for this result. Weeks (1979), for example, explained this paradoxical relationship by noting that at times there is a phase lag of nearly 180° between the soil gas pneumatic head change at the water table and the atmospheric-pressure change. Under these conditions, the soil gas head is declining due to the previous low in barometric pressure while the actual barometric pressure is rising. Other possible explanations include measurement errors and the distance between the Pantex Plant and the Amarillo International Airport.

Fluctuations in atmospheric pressure during the week of the 11-14 pond pumping tests, October 31 through November 4, 1994, and corresponding uncorrected water level data for PM-103 with the period of drawdown and recovery noted are illustrated in figure 2.

Figures 4 through 7 illustrate the various graphical presentations of water-level responses in the four monitoring wells used for analysis of the third pumping test. Analyses of water-level responses prior to corrections for the influence of atmospheric pressure were problematic because of the inverse relationship between the expected and observed water-level responses throughout the tests. Figures 5a and 7a, for example, illustrate that for a significant portion of the drawdown phase, measured water levels in PM-102 and PM-104 were actually rising (illustrated as decreasing drawdown), instead of falling as would be expected. This is because the magnitude of rise in the water table caused by a significant lowering of barometric pressure was greater than the magnitude of fall in the water table caused by pumping. After correcting water levels using barometric-pressure fluctuations and barometric efficiencies as described previously, pumping test analysis using conventional methods was possible.

Analysis of Drawdown and Recovery

PM-101, the pumping well, was the only well with two distinct segments of drawdown that were consistent with the hydrogeologic setting and unconfined water-table conditions. The maximum uncorrected and corrected drawdown in PM-101 was 8.58 and 6.09 ft (2.61 and 1.86 m), respectively (using the Jacob correction [1944], as reported by Kruseman and de Ridder, 1990) (figs. 4a and 4b). Since PM-101 was the pumping well, no S_Y could be determined in this well.

In unconfined aquifers such as this aquifer, the two segments of drawdown typically represent the response of the aquifer before and after delayed yield. The shape of the drawdown curve in PM-101 and the close agreement between calculated T and K for early and late phases strongly suggest a delayed yield response (figs. 4a and 4b). These distinct segments are also illustrated in the semilogarithmic analysis using the

Jacob method (fig. 4c). Of responses from the four wells tested, the drawdown in PM-103 is most problematic and does not clearly follow delayed yield behavior as illustrated by the multiple segments of the drawdown curve that can be matched to type curve (fig. 6a). An alternative explanation of the multiple segments of drawdown recorded in PM-103 would be the effects of local heterogeneities or boundaries encountered by the expanding cone of depression. If the aquifer is homogeneous, then T calculated before and after the influence of delayed yield should be basically equal, as was the case in PM-101. If a lower permeability zone is encountered late in the test, however, calculated T may be significantly lower and, since this response is controlled to some unknown extent by an area of low permeability, any calculated T for this late phase may not be directly applicable. Analysis is further hampered in PM-103 by the relatively small amount of observed drawdowns and atmospheric effects. Nevertheless, type curves were fit to interpreted early- and late-phase drawdown. Figure 6b illustrates the application of the Jacob method to corresponding time periods of drawdown data. Calculated T and K values are presented in table 4.

In PM-101 and PM-103, the mean T values determined from late-phase drawdown are 3 and 59 percent lower than T from early-phase drawdown. This reduction in T observed in PM-103 may be within the range of acceptable variations in T before, during, and after the influence of delayed yield. Neuman (1975) states, however, that T values calculated from the early and late phase should be "approximately equal" as observed in PM-101. The bounds of what is "approximately equal," are not defined, however. The decrease in T may also be due to local heterogeneities in the perched aquifer, such as variations in the thickness and thus distribution of channel gravels described earlier. The lower T calculated for PM-103 during the late phase of drawdown may also suggest the presence of a low-permeability boundary such as might be expected along the walls of a gravel channel.

Only one phase of drawdown was observed in PM-102 and PM-104 (figs. 5a and 5b and 7a and 7b), which was probably late-phase drawdown because water level responses were either too small to be accurately measured or the observation wells were not affected by early-phase drawdown due to their distance from the pumping well. Table 4 reports statistical averages based on analyses assuming delayed yield.

Hydrochemistry Results

In general, no systematic changes in ground-water chemistry during pumping were evident (table 5). The temperature measured in the flow-cell decreased 0.4°C during the 16.5 hr of monitoring (from 1220 hr on November 1 to 0450 hr on November 2) (Fig. 8). This decrease probably reflects the effect of the nocturnal decrease in air temperature on above-ground production pipe and the flow cell. Measurements of pH, which did not vary systematically (fig. 8), automatically compensated for fluctuations in temperature and were recalibrated twice during the test. For unknown reasons, Eh (oxidation-reduction potential) values measured between 12:24 and 14:06 were greater than those measured between 18:00 and 22:46, although values decreased during each of those periods (fig. 9). The Eh values obtained are suspect, because the difference between observed and theoretical potentials for ZoBell's solution was beyond the margin of ±10 mV recommended by Wood (1970b). In any event, Eh values are commonly deemed to be of only qualitative significance (Wood, 1970b). Concentrations of Na^+, Mg^{2+}, and Ca^{2+} increased slightly (by <1.7 mg L^{-1}) during the course of sampling, but no other constituents either systematically increased or decreased (table 5). Although trichloroethylene and 1,2-dichloroethane had been detected in wells PM-101, PM-102, and PM-103 in 1993 (Battelle Pantex, 1994), concentrations of all VOCs analyzed in samples collected during the pumping test were below laboratory detection limits. Therefore, within the volume of perched aquifer from which water was pumped, no compositional stratification or lateral compositional trends could be conclusively identified.

On the basis of major-ion concentrations, ground water from the perched aquifer in the vicinity of well PM-101 is of a mixed-cation (predominantly Mg-Ca) bicarbonate composition, consistent with June 1993 results from nearby well PM-103 (Fryar and Mullican, 1993). For the major cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) and Si in perched ground water, filtered, acidified concentrations were typically greater than unfiltered, acidified concentrations. This result is counterintuitive, in that filtered concentrations are commonly viewed as approximating only dissolved concentrations, whereas total concentrations include both dissolved and particulate concentrations. As noted by Puls and Powell (1992), minor amounts of metals can be contributed by leaching from filter materials. However, that explanation is confounded by the fact that concentrations of Ca^{2+}, Mg^{2+}, and Si were higher in the unfiltered distilled water blank collected at the end of the test than in the filtered blank. The possibility of leaching of filter materials (made primarily from nylon) could not be resolved by comparing results of analyses of organic carbon in filtered and unfiltered samples. In two of four samples, including the blank, total organic carbon (TOC) (unfiltered) was higher than dissolved organic carbon (DOC) (filtered).

DISCUSSION AND CONCLUSIONS

Results from pumping tests conducted in monitor wells located at the 11-14 pond significantly increase our understanding of the hydrogeology of perched aquifers at the Pantex Plant. The mean T and K values calculated for all four wells based on delayed yield analyses were 488 ± 250 ft^2 d^{-1} and 33.8 ± 17.9 ft d^{-1} (45.3 ± 23.2 m^2 d^{-1} and 10.3 ± 5.4 m d^{-1}), respectively. These values represent the mean T and K of the wells using the different analytical techniques described. Therefore, further use of these hydraulic parameters must be represented as a mean value and not an actual measured value.

The values for T and K from the 11-14 pond pumping are considerably higher than those previously reported (Bureau of Economic Geology, 1992, and Engineering-Science, Inc., 1992, for example). These higher values may be due to any one or a combination of the following factors. First, this may simply be an area of higher T and K due to the presence of relatively cleaner sands and gravels in comparison to wells tested previously. Second, the higher discharge and longer duration of stress to the aquifer allows for a larger portion of the aquifer, and hence, more heterogeneities impacting flow, to be tested in comparison to slug tests and single well tests using low-discharge sample pumps. This is especially true with respect to slug tests where the radius of influence probably is restricted to the gravel pack and thus the zone tested is the gravel pack and not the aquifer. Third, in previous tests, the influence of barometric pressure fluctuations has not been factored into the analysis. Fourth, the sensitivity of the analysis based on variations in possible B_e has not been evaluated. Clearly, the ideal situation would include long-term water-level and barometric-pressure data from each of the wells tested so that well-specific values for B_e could be used with each correction.

Additional insight into the hydrogeologic complexity of perched aquifers in the Pantex Plant area, even on a very local scale such as with these pumping tests, can be obtained with either delayed yield or boundary condition analysis. These four monitoring wells are all located within a small area and yet hydraulic properties such as T range over an order of magnitude. It may be inferred that this range in T over the small area tested would at least suggest the presence of significant heterogeneities within the perched aquifer at this site.

The presence of such heterogeneities would not necessarily be inconsistent with the minimal changes in ground-water composition during pumping. Because the volume of aquifer influenced by pumping is larger than that from which water is actually withdrawn, and because water is preferentially drawn from more permeable units, water from outlying or less permeable regions of the perched aquifer may not have been sampled.

Application of Pumping Test Results to Remediation Alternatives

If these pumping test results are representative of those from perched aquifers throughout the Pantex Plant area, then the potential for successful remediation by pump and treat efforts is questionable. To work effectively, pump and treat systems must be located in areas where the saturated materials are relatively homogeneous, which is questionable, as indicated by the presence of gravels, sands, and silts in varying thicknesses. The problem would stem from the inability to drain low permeability intervals due to preferential flow through relatively higher permeability zones. Therefore, the feasibility of pump and treat technologies as a successful remediation strategy should be evaluated on the basis of numerous additional multiwell pumping tests for which hydraulic properties can be determined.

At least locally, the results from this pumping test allow for a better calculation of ground-water velocity than has previously been reported. Using the mean K for the four wells of 33.8 ft d^{-1} (10.3 m d^{-1}) (based on delayed yield analysis), with a local hydrologic gradient of 0.0063 (based on the mean gradient determined from three point solutions for the four wells) and an effective porosity of 0.25 (based on geophysical log response in OM-105), a ground-water velocity in the 11-14 pond area of 0.85 ft d^{-1} (0.26 m d^{-1}) can be calculated.

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Table 1. Completion information from the four monitoring wells at the 11-14 wastewater discharge pond. All wells have a borehole radius of 9 inches. Static water-level measurements are made from the top of casing.

Monitoring well ID	Total depth (ft)	Vertical well deviation (ft)	Reference elevation (ft above MSL)	Initial static water level on 4/29/92 (ft)	Static water level on 10/31/94 (ft)	Static water level on 11/4/94 (ft)
PM-101	290	0.48	3548.60	276.28	275.81	275.68
PM-102	294	0.12	3548.33	275.75	275.29	275.14
PM-103	287	0.18	3548.44	275.78	275.30	275.16
PM-104	288	0.05	3548.83	276.19	275.30	275.58

Table 2. Results from analysis (Engineering-Science, Inc., 1992) and reanalysis (this report) of recovery data collected in 11-14 monitoring wells during facility closure investigations. To provide consistent results, the saturated thickness reported in Engineering-Science, Inc. (1992) was used during reanalysis. Saturated thicknesses reported for the current study were used in all calculations of K presented in table 4.

Monitoring well ID	Pumping duration (sec)	Discharge rate (ft^3/s)	Maximum drawdown (ft)	Saturated thickness reported (ft), previous study (this study)	T (K) ft^2/d (ft/d) (previous study*)	T (K) ft^2/d (ft/d), reanalysis
PM-101	4800	0.0031	1.21	14.19 (14.76)	243 (17.1)	362 (24.5)
PM-102	3700	0.0035	0.60	11.05 (14.21)	250 (22.6)	133 (9.35)
PM-103	3600	0.0041	0.89	13.24 (14.20)	147 (11.1)	207 (14.6)
PM-104	4440	0.0028	0.35	14.00 (15.20)	286 (20.4)	385 (25.3)

•Engineering-Science, Inc. (1992)

Table 3. Barometric efficiencies calculated for perched aquifer monitoring wells at the Pantex Plant.

Well ID	Mean barometric efficiency
PM-19	1.08
PM-20	0.90
PM-38	0.73
PM-45	1.12
Mean for all wells	0.96

Captions

Figure 1. Map showing location of 11-14 monitoring wells used during pumping tests.

Figure 2. Atmospheric-pressure fluctuations recorded at the Amarillo International Airport (located approximately 10 mi [16 km] southwest of pumping test site) and corresponding uncorrected water-level fluctuations in PM-103 during the 11-14 pond pumping tests.

Figure 3. (a) Discharge rates monitored by the Sensus mechanical flow meter (flow meter no. 1) and (b) discharge measurements recorded by the two different models of Signet digital flow meters (flow meter nos. 2 and 3).

Figure 4. Water-level response in PM-101 illustrating (a) uncorrected drawdown data used with the Boulton method used for analysis of early phase, (b) corrected drawdown data used with the Boulton method for analysis of late phase, (c) corrected drawdown data used with the Jacob method, and (d) recovery data used with the Theis recovery method.

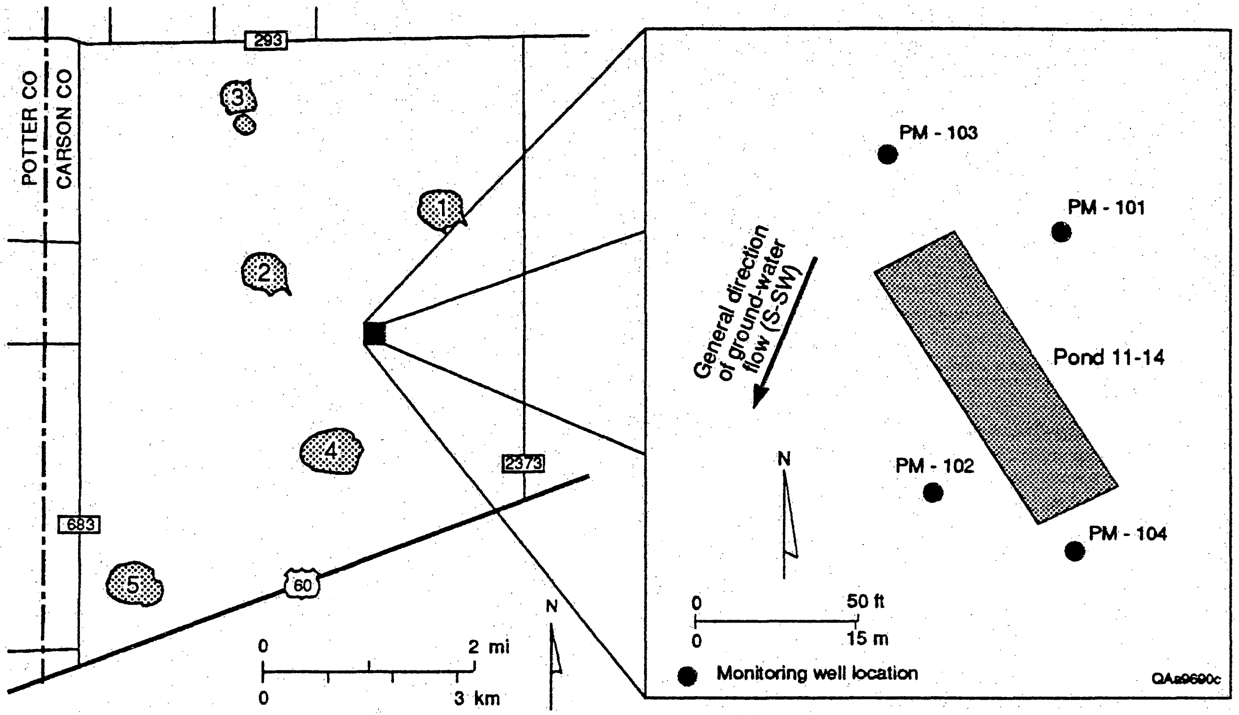
Figure 5. Water-level response in PM-102 illustrating (a) uncorrected drawdown and recovery data and barometric pressure fluctuations throughout week of testing, (b) corrected drawdown data used with the Boulton method, (c) corrected drawdown data used with the Jacob method, and (d) recovery data used with the Theis recovery method.

Figure 6. Water-level response in PM-103 illustrating (a) corrected drawdown data used with the Boulton method, (b) corrected drawdown data used with the Jacob method, and (c) recovery data used with the Theis recovery method.

Figure 7. Water-level response in PM-104 illustrating (a) uncorrected drawdown and recovery data and barometric pressure fluctuations throughout week of testing, (b) corrected drawdown data used with the Boulton method, (c) corrected drawdown data used with the Jacob method, and (d) recovery data used with the Theis recovery method.

Figure 8. Plot of pH and temperature of waters produced from PM-101 during the pumping test.

Figure 9. Plot of observed Eh of waters produced from PM-101 during the pumping test.



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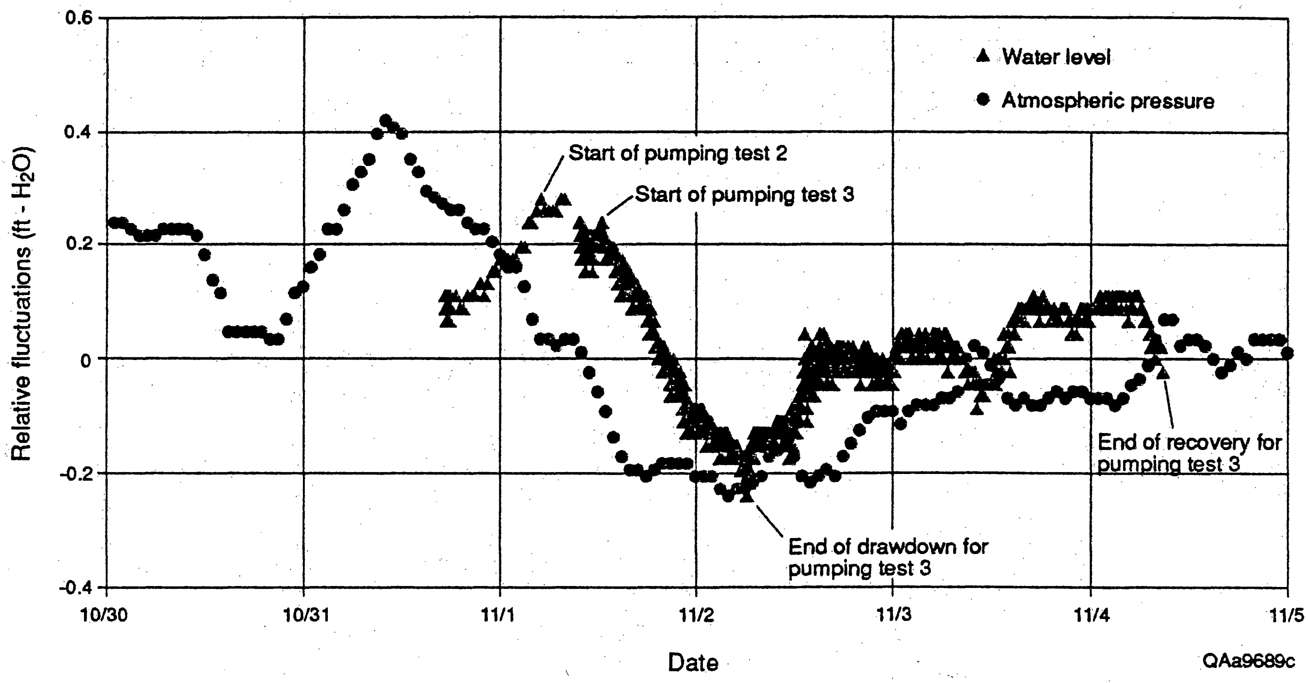

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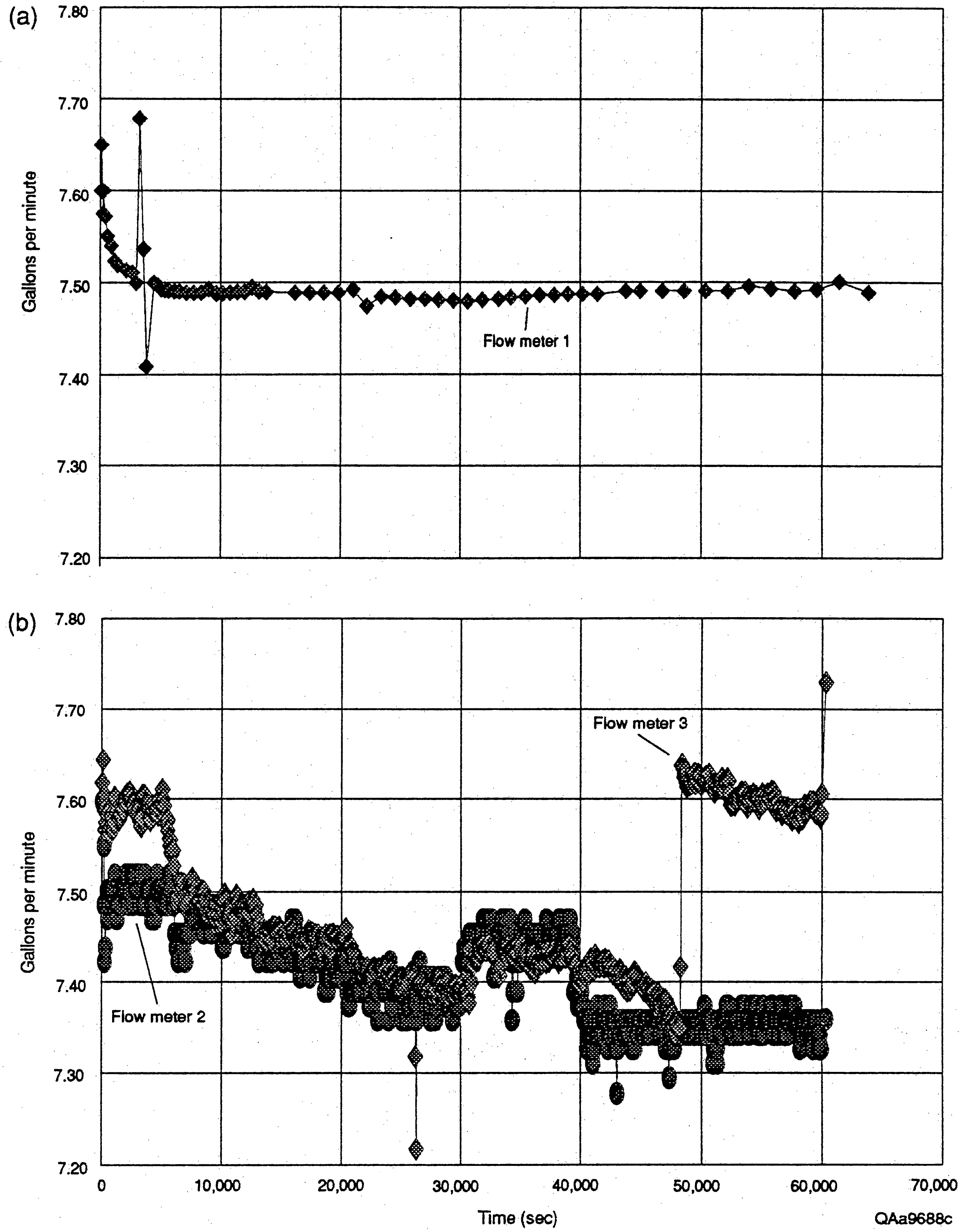

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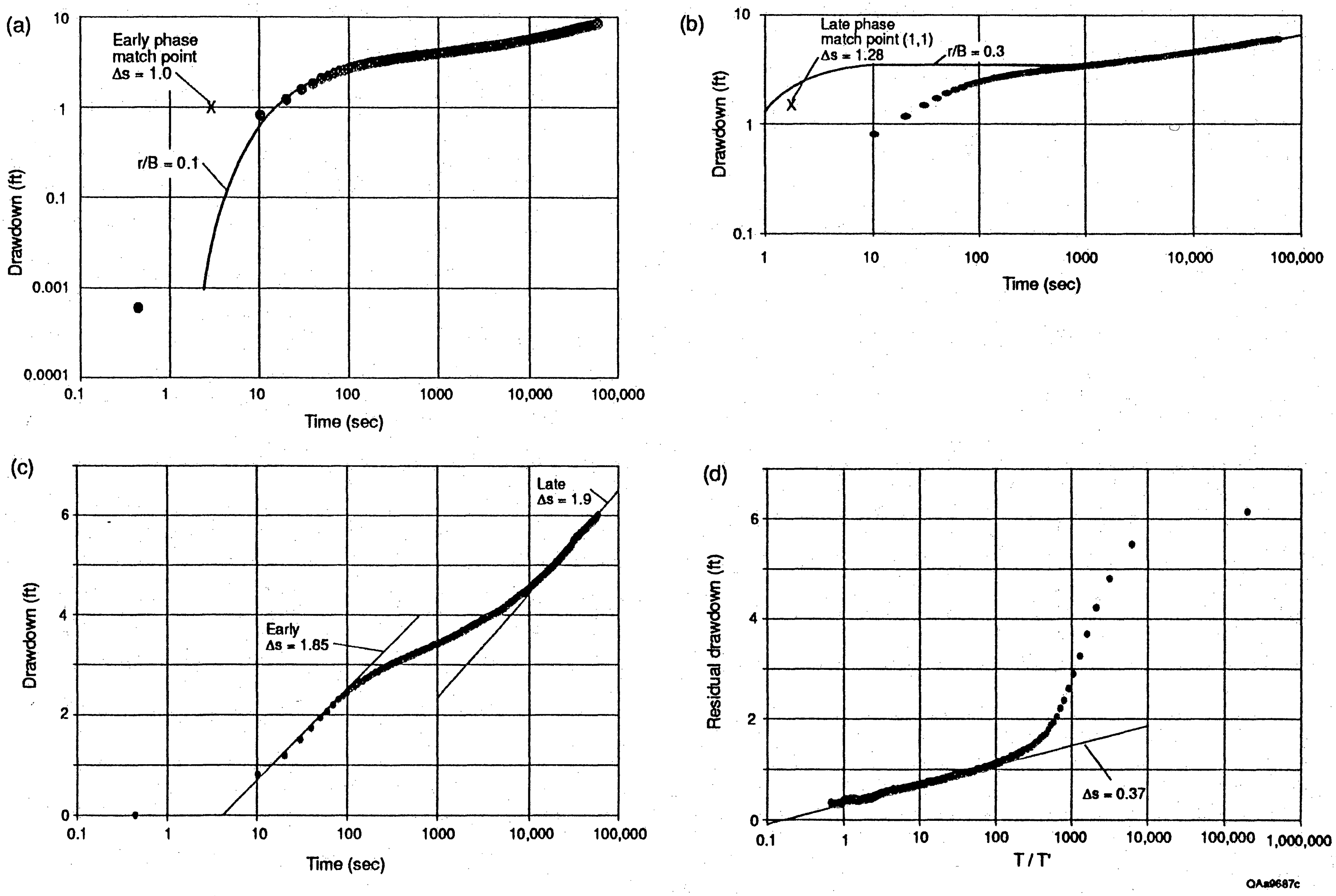

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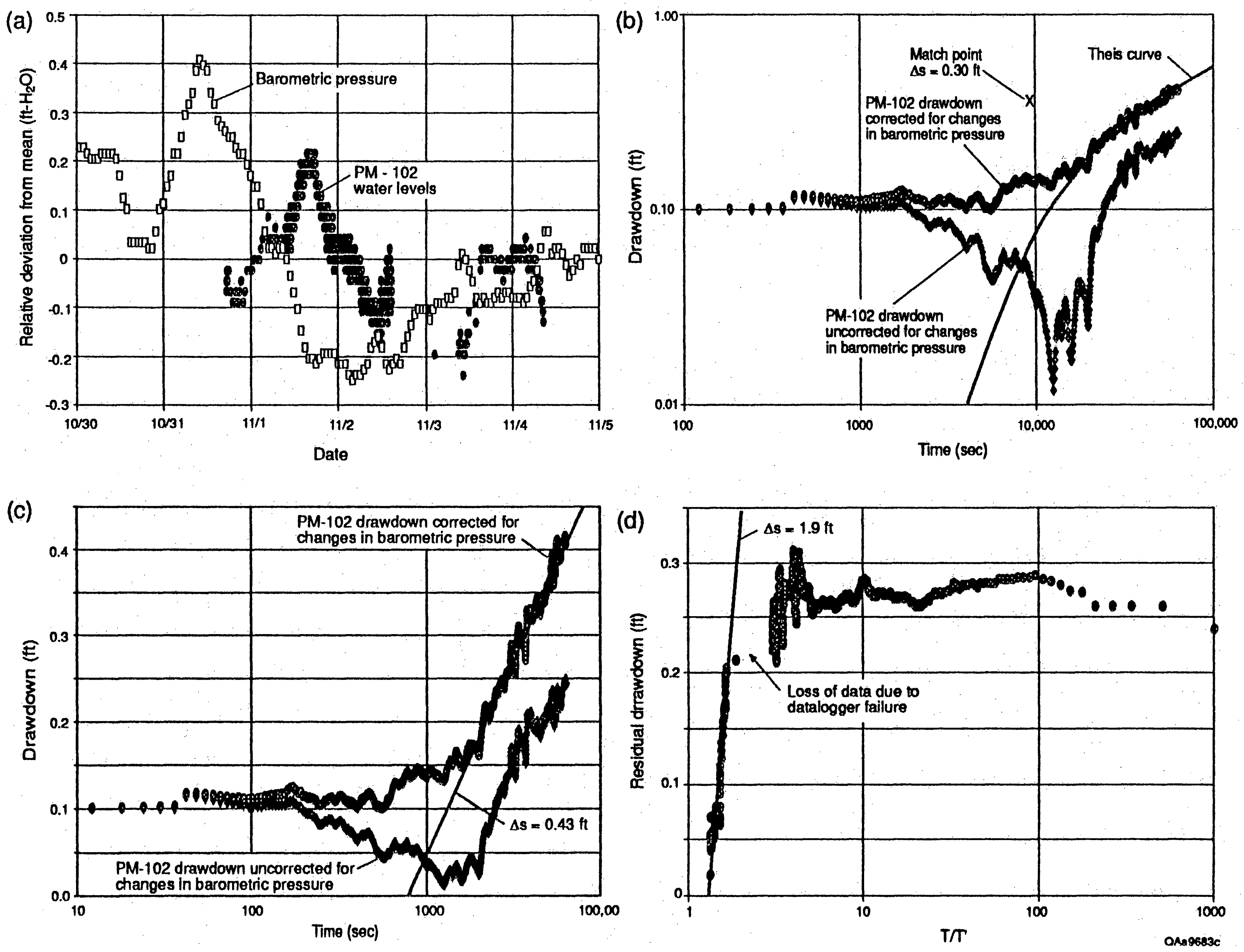


Figure 5. Water-level response in PM-102 illustrating (a) uncorrected drawdown and recovery data and barometric pressure fluctuations throughout week of testing, (b) corrected drawdown data used with the Boulton method, (c) corrected drawdown data used with the Jacob method, and (d) recovery data used with the Theis recovery method.

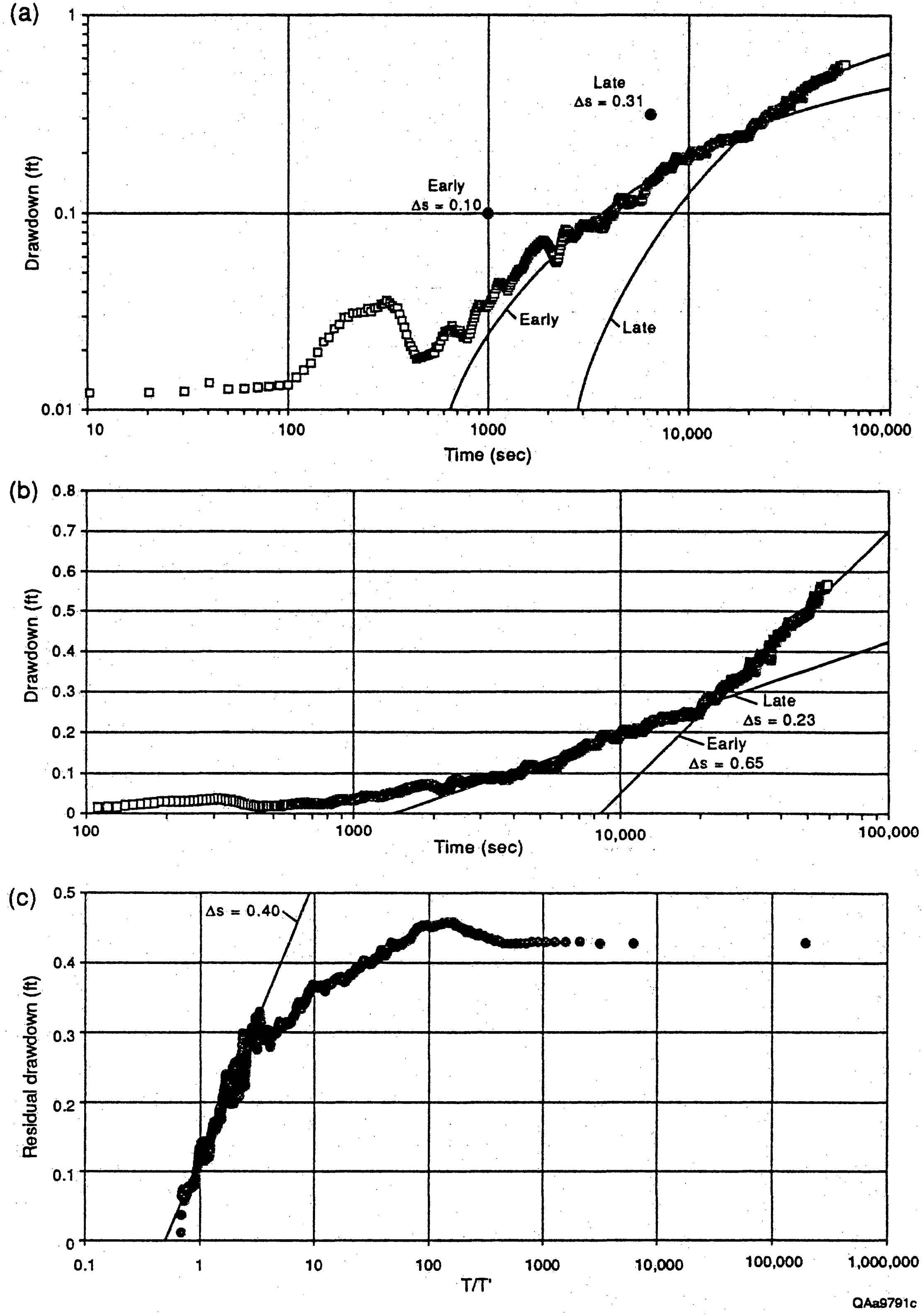


Figure 6. Water-level response in PM-103 illustrating (a) corrected drawdown data used with the Boulton method, (b) corrected drawdown data used with the Jacob method, and (c) recovery data used with the Theis recovery method.

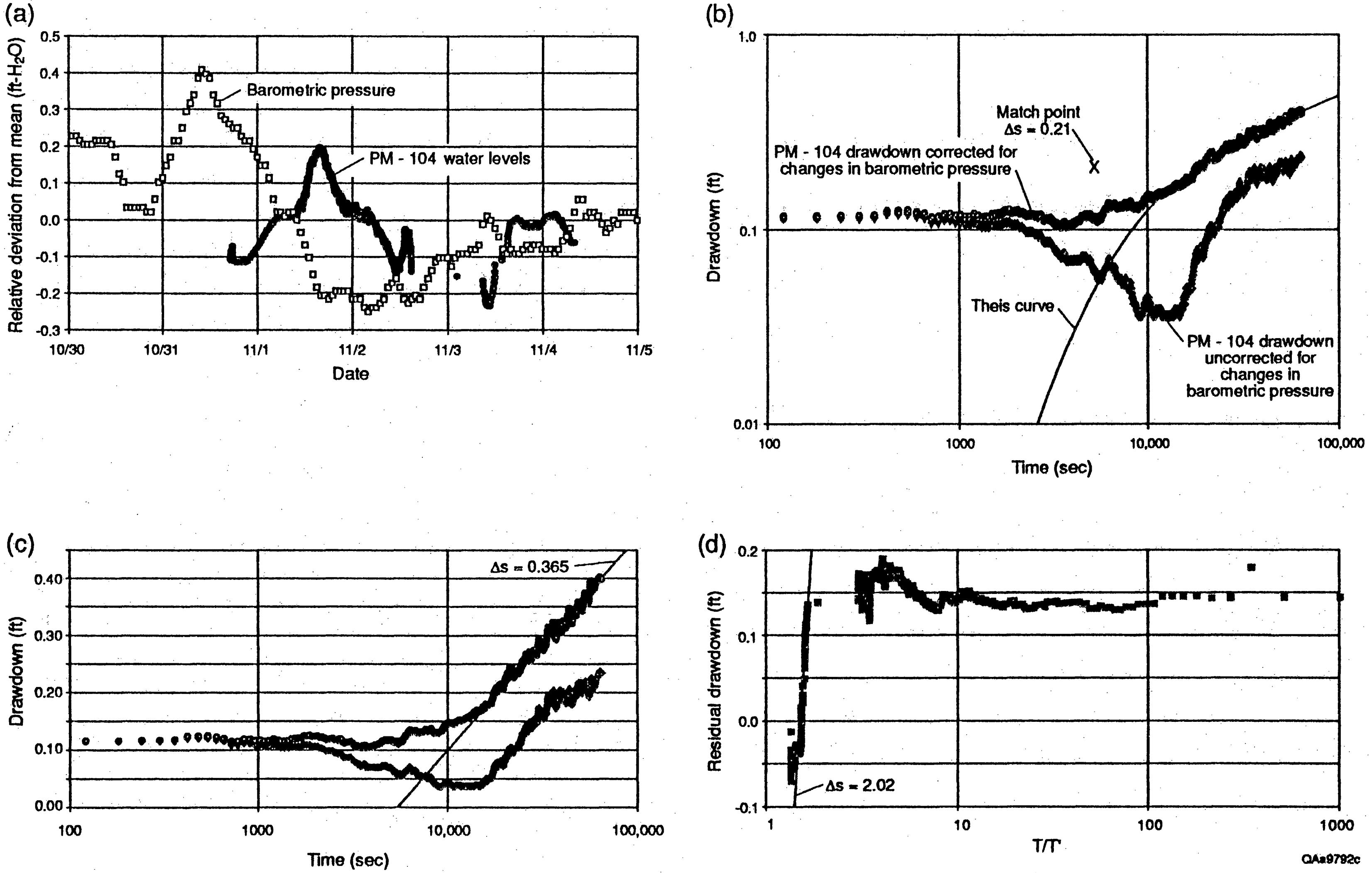
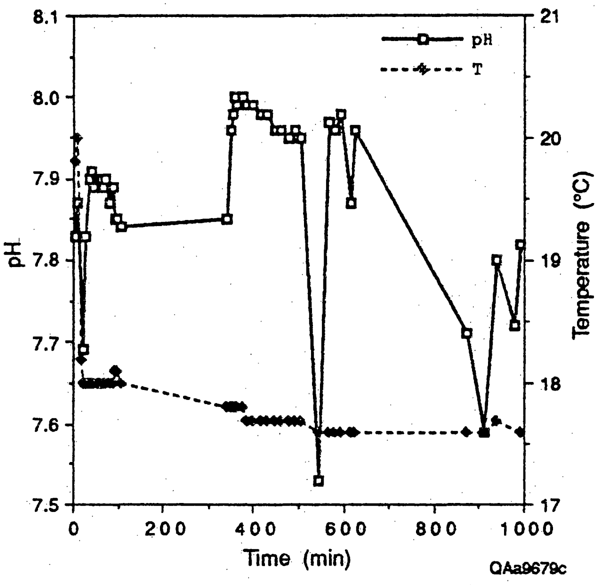


Figure 7. Water-level response in PM-104 illustrating (a) uncorrected drawdown and recovery data and barometric pressure fluctuations throughout week of testing, (b) corrected drawdown data used with the Boulton method, (c) corrected drawdown data used with the Jacob method, and (d) recovery data used with the Theis recovery method.



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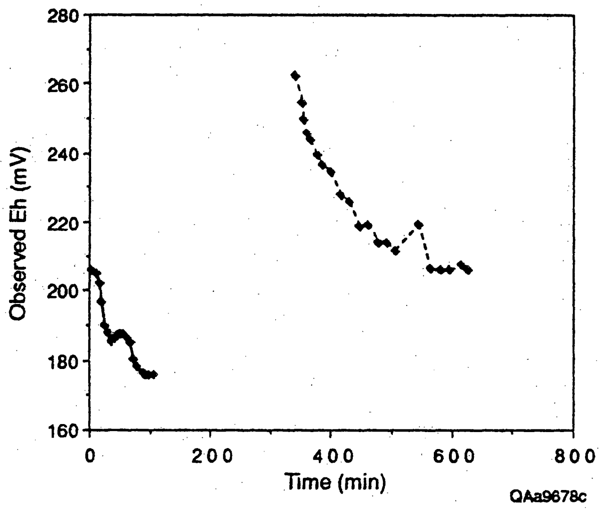

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