**Analysis of Pump-Spinner Test and 48-Hour Pump Test in Well NC-EWDP-19D, Near Yucca Mountain, Nevada**

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| cps | counts per second |
| gpm | gallons per minute |

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# 1.0 INTRODUCTION

From May 10 to 15, 2000, a series of spinner logging runs was conducted during static (non-pumping) and pumping conditions in well NC-EWDP-19D, along with a 48-hr. aquifer pump test. The spinner logs were run prior to pumping to quantify flow rates between screens under non-pumping conditions (crossflow), and again while pumping to evaluate zonal contributions under pumping conditions. Following the pump-spinner test, a 48-hr. aquifer pump test was performed to determine aquifer properties such as permeability and well efficiency. Additional spinner logging runs were made during the 48-hr. pump test to monitor individual zonal production rates. This report presents the results, analyses, and interpretation of the spinner logging and aquifer pump testing.

# 2.0 LOG AND TEST RESULTS

In May 2000, following the drilling, completion, and development of well NC-EWDP-19D, a series of spinner logs was run to quantify the contribution of each screened interval under non-pumping and pumping conditions. MOSDAX™ pressure sensors were placed above the submersible pump in well NC-EWDP-19D and below the water table in the nearest offset wells (the NC-EWDP-19P and the Washburn wells) to measure the pressure response to pumping. Seven intervals were completed in well NC-EWDP-19D using slotted pipe sections (commonly called “screens”) to allow flow from the aquifer into the well (Figure 1). The annulus between the pipe and the wall of the borehole was filled with gravel across the productive intervals. The productive gravel-packed intervals were separated in the annulus by bentonite grout. The depths of the screened intervals and the corresponding gravel pack depths are listed in Table 1. The purpose of these tests was to determine the hydraulic properties of the aquifers connected to the well, and to allocate those properties between the individual screened intervals using the observed changes in flow rate measured with the spinner log.

## 2.1 SPINNER LOGS

### 2.1.1 Description of Spinner Logging Procedure

On May 10, 2000, prior to pump placement and pumping, spinner logs were run at logging speeds of 30, 45, and 60 ft/min. (9.1, 13.7, and 18.3 m/min.) in well NC-EWDP-19D. The contributions of all zones (screens) were determined from these logs

On May 11, 2000, with the spinner logging tool already in the hole, the well was equipped with a Nye County submersible pump. The bottom of the pump was set at 471 ft (143.6 m) approximately 24 ft (7.3 m) above the top of Screen #2. Screen #1 could not be logged while the pump was in the well because of limited clearance between the pump and the pipe. While pumping at approximately 150 gpm (567.8 L/min.), the spinner tool was run at logging speeds of 20, 30, and 60 ft/min. (6.1, 9.1, and 18.3 m/min.). In addition, as a quality check, stationary readings were taken between each of the screened intervals.

The well was pumped for 4.5 hr., except for a 20-min. shut-in period (non-pumping time period) required to free the logging tool when it got stuck. After pumping was halted, the well was allowed to recover overnight. Following this 15-hr. recovery, an additional non-pumping logging run was made at 30 ft/min. (9.1 m/min.) to quantify crossflow prior to the start of the 48-hr. aquifer pump test.

On May 12, 2000, the 48-hr. pump test was initiated at an average rate of 156 gpm (590.5 L/min.). Spinner logging runs were made at the beginning of the 48-hr. pump test, midway through the test on May 13, 2000, and immediately prior to the end of the test on May 14, 2000.

### 2.1.2 Spinner Log Fundamentals

A spinner log is a tool designed to measure fluid velocity at various depths in a well. Spinners are relatively simple tools, consisting of a centralized logging tool with an impeller mounted on the bottom. The tool counts the number of rotations of the impeller using an optical or magnetic sensor. The counts are expressed as counts per second (cps). The counts per second are a function of the fluid velocity, the speed of the logging tool in the well, and the size and shape of the impeller. Because the logging tool only counts impeller rotations, a single stationary reading cannot distinguish between upward or downward flow, but only that flow is occurring. The raw log readings were normalized for logging speed differences and were averaged over intervals of approximately 1.5 ft (0.46 m) for analysis.

A two-pass technique involving both down and up logging runs at the same speed (Figure 2) was used to reduce potential errors due to borehole size changes, tool idiosyncrasies and other factors. As the upward fluid velocity increases at any point in the wellbore, the counts on the down run will increase while the counts on the up run will decrease, causing the two curves to diverge. To compensate for slight differences in responses, it is also desirable to record measurements in a section of the borehole where no flow is occurring. The baseline for the runs is then adjusted slightly until the two runs yield the same count rate across blank pipe with no fluid movement. In well NC-EWDP-19D, this was done below the bottom screen at 1,380 ft (420.6 m). The net counts rate was determined as half the difference in counts per second between the up and down logging runs. The fluid velocity was then computed from the spinner calibration correlation between counts per second and fluid velocity, using a velocity correction factor of 0.83 to adjust the spinner calibration measurements to field conditions (Schlumberger Limited, 1973).

The spinner tool is sensitive to fluid type, temperature, turbulence, borehole diameter, borehole size changes, and many other factors. For this reason, the spinner measurements are commonly correlated to measured flow rates in each well. Ideally, if the pump is set above all the screens, the relation between the measured counts per second and the total flow can be determined in the field. In the case of well NC-EWDP-19D, however, Screen #1 was located very close to the standing water level in the well, so that there was not sufficient distance to allow the pump to be set above Screen #1. Accordingly, the flow rate above the highest spinner readings while pumping was determined from the difference between the pumping rate and the flow produced from underlying screens. An example of this calculation is presented below. The example spinner run shown in Figure 2 is used to illustrate the analysis procedure.

The up log run counts per second readings (on the left in Figure 2) were shifted by adding 1.1 cps so that the up and down runs had the same value in the portion of the well below the bottom screen interval where no flow was occurring. Between Screen #2 and Screen #3, the difference between the up run (-30.0 cps) and the down run (60.0 cps) was 90.0 cps. Half of this value is 45.0 cps, corresponding to the flow rate in the pipe between Screens #2 and #3. From the spinner calibration tables, a spinner reading of 45.0 cps corresponded to an ideal fluid velocity of 107.3 ft/min. (32.7 m/min.). Using the 0.83 velocity correction factor, the computed average fluid velocity in the pipe was determined to be 89.0 ft/min. (27.1 m/min.). The capacity of a 7-in. (0.1778-m) outside diameter casing with a 0.317-in. (0.00805-m) wall thickness is 1.6535 gallons per ft (0.02055 $m^3$/m). The flow rate between Screens #2 and #3 of 147.2 gpm (557.2 L/min.) under pumping conditions was computed by multiplying the average fluid velocity times the pipe capacity. Based on the analysis of all the spinner logs, it was determined that Screens #1 and #2 contributed approximately 8 percent of the total flow from the well, so the estimated total flow during this logging run was 160 gpm (605.7 L/min.). This value corresponds well to measured discharge rates during the test, which averaged 156 gpm (590.5 L/min.).

### 2.1.3 Qualitative Spinner Log Interpretation

Interpretation of spinner logs requires professional judgment in addition to calculations. Numerous factors affect the readings and interpretations, including turbulence, slight variations in logging speeds, temperature, viscosity, and debris. A few of the qualitative considerations can be seen from the example spinner run shown in Figure 2:

- Because of turbulence effects in the screened interval, the most accurate readings were immediately below the screened intervals in blank pipe. The counts per second should be steady across blank intervals with no changes in pipe diameter or flow rate.

- The slope of the interpretation line or the rate in which the curves diverge provides a relative indication of permeability. The faster the change, the higher the permeability.

- Fractures show up as a step increase in counts or rate. An example is at about 955 ft (291.1 m), near the bottom of Screen #5.

- Near the bottom of Screen #3, the indicated velocity decreases. This was probably caused by fluid flowing vertically in the gravel pack outside the screen.

### 2.1.4 Spinner Log Results

The spinner log interpretations are summarized in Table 2 and Figure 3. Interpretation plots for the individual logging runs are included in Appendix A. Screens #6 and #7 exhibited negligible flow rates on the spinner logs in all cases tested, indicating they have low permeability compared to the other screened intervals.

The initial spinner runs demonstrated that significant natural crossflow occurred prior to pumping (the first column on the left in Figure 3). Most of the natural flow, totaling approximately 15 gpm (56.8 L/min.), came out of Screen #5 and entered into Screens #1 (6 gpm or 22.7 L/min.) and #3 (8 gpm or 30.3 L/min.). This information indicated Screen #5 had a higher potentiometric head than Screens #1 or #3. Screen #4 had a small amount of outflow into the well (1 gpm or 3.8 L/min.), suggesting its initial potentiometric head was slightly higher than that of Screen #3. Screen #2 had a slight inflow from the well (2 gpm or 7.6 L/min.) under natural conditions, which is consistent with a head similar to that of Screen #1.

All five main permeable zones exhibited flow into the well during the pump-spinner test (the second column from the left in Figure 3). Screen #3 contributed the greatest flow (73 gpm or 276.3 L/min.), followed by Screen #4 (45 gpm or 170.3 L/min.) and Screen #5 (26 gpm or 98.4 L/min.). Screen #2 contributed about 6 gpm (22.74 L/min.). Although it was not possible to log across Screen #1 because of the small clearance between the pump and the pipe, the indicated flow coming from that zone was small, totaling about 6 gpm (22.74 L/min.) based on the difference between the pump rate and the rate computed from the spinner log.

When pumping was nearly completed, the spinner tool was placed between Screens #2 and #3 at a depth of 550 ft (167.6 m), to observe the behavior as the pump was turned off. There was still a flow rate in the well between Screens #2 and #3 of 20.6 gpm (78.0 L/min.) after shut-in. Thus, crossflow was still occurring into the shallow zones after pumping ceased. Moreover, upward flow continued even after the well was allowed to recover overnight. An additional non-pumping logging run was then made at 30 ft/min. (9.1 m/min.) to quantify crossflow prior to the start of the 48-hr. aquifer pump test. That run, which is the center column in Figure 3, once again showed flow coming out of Screens #4 and #5, and moving into Screens #1, #2, and #3.

On May 12, 2000, the 48-hr. pump test was initiated. Well NC-EWDP-19D was pumped at an average rate of 156 gpm (590.5 L/min.) for 47.8 hr. Spinner runs were made at the beginning of the test (the fourth column from the left in Figure 3), midway through the test on May 13, 2000, and immediately prior to the end of the test on May 14, 2000 (the final column on the right in Figure 3). The flow rates from the various zones exhibited only small changes during the 48-hr. pump test, and were nearly the same as those observed in the earlier pump-spinner test.

Prior to shutting off the pump on May 14, 2000, the spinner tool was placed between Screens #3 and #4 at 699 ft (213.1 m). After shut-in , the spinner tool slowed from 24.6 cps to 0 cps before stabilizing at 7.1 cps. These data indicate the flow direction in the well reversed, from an upward flow of 80 gpm (302.8 L/min.) immediately after shut-in, to a downward flow of 23 gpm (87.1 L/min.) at later times. Hence, Screens #1, #2, and #3 appear to have experienced relatively lower drainage than Screens #4 and #5 as a result of the 48-hr. pump test.

## 2.2 PUMP TEST PRESSURE ANALYSIS

### 2.2.1 Test Procedures and Description

A 48-hr. pump test was designed for well NC-EWDP-19D to determine the transmissivity and well efficiency. Beginning May 12, 2000, the well was pumped at an average rate of 156 gpm (590.5 L/min.) for 47.8 hr. Total production during the test was 450,000 gal. (1,703,250 L) and the maximum drawdown in well NC-EWDP-19D was 18 ft (5.5 m). The pressure response to pumping was monitored in pumping well NC-EWDP-19D and in Washburn and NC-EWDP-19P observation wells. Upon cessation of pumping, pressures also were monitored during a 24-hr. recovery period.

The measured pumping rates and computed depth to water for the pump-spinner test and the 48-hr. aquifer pump test are shown in Figure 4. The rise and drop in the depth to water about two-thirds of the way through the pump-spinner tests resulted from moving the tubing that the pump was on up and down to free the logging tool when it was stuck. Pump rates were obtained using a 55 gal. (208.2 L) drum and a stopwatch. Readings were also taken using a Macrometer™ turbine flow meter. The turbine meter rates were found to be erroneously high, apparently because the meter had been placed too close to the wellhead and did not have sufficient distance from the change in flow direction for a stable flow profile to be achieved. The depth to water was determined from pressures recorded by a MOSDAX™ pressure sensor placed above the pump.

The drawdown data obtained during pumping are considered to be most useful for analysis because all five permeable intervals produced during the pumping periods. The recovery data are less suitable for analysis because the spinner logs during the recovery period indicated that significant crossflow between well screens occurred during that time. Crossflow after cessation of pumping caused the recovery trends to be artificially flattened, and application of standard analysis techniques to the recovery portion of the test would therefore yield incorrect results.

A Well Test Analysis Quality Control Checklist is included as Attachment 1 in Appendix A. This checklist documents the analysis procedure used and the results obtained.

### 2.2.2 Drawdown Analysis

After obtaining the test data and verifying quality control, the first step in the test interpretation procedure was to prepare a log-log diagnostic plot of drawdown head change versus pumping time (Figure 5). In addition to the measured response, the logarithmic derivative of the drawdown was also computed and plotted using a technique described by Horne (1997). This type of plot provides important information regarding flow regimes, including, for example:

- An initial unit slope (+1 slope) usually within the first few seconds of pumping on the drawdown and the derivative indicates wellbore storage.

- A later flat line (0 slope) in the derivative response indicates radial cylindrical flow, and the distance between the drawdown curve and the derivative curve is a measure of wellbore efficiency or skin effect.

- Multiple stable flat regions can be caused by flow barriers or multiple layers.

- A positive half slope (+½ slope) on the derivative response indicates linear flow between barriers. The distance to the barriers is determined from the time needed to reach the derivative half slope, with closer boundaries causing the half slope to develop more quickly.

- A negative half slope (-½ slope) on the derivative response is diagnostic of spherical or hemispherical flow.

Several different flow regimes are evident from inspection of the log-log plot (Figure 5) for well NC-EWDP-19D. The effects of wellbore storage and well efficiency dominated the very early time response, up to about 0.05 hr. Then, there appear to be three steps with periods of relatively stable or flat derivative response, from 0.06 to 0.25 hr., from 0.3 to 1 hr., and from 1.5 to 15 hr. These steps are inferred to result from the multiple layers that may be present. Finally, at later times, from about 10 to 48 hr., the derivative increased with a positive half slope (+½ slope), which is indicative of linear flow between barriers.

### 2.2.3 Recovery Analysis

Figure 6 shows the log-log plot for the recovery after the 48-hr. pump test, as well as the recovery following 20 hr. of pumping for the pump-spinner test. The recovery responses are complicated by crossflow between the various layers, so that quantitative analysis of the recovery periods is difficult or impossible. Furthermore, there is an indication that progressive plugging occurred during the test, because the recovery response from the 48-hr. pump test had an extra 4.4 ft (1.3 m) of head difference, compared to the short-term pump test recovery. The derivative responses for the two recovery periods are nearly identical, which indicates the same flow behavior was experienced in the reservoir during both recoveries. The late time differences in the derivative responses probably reflect different crossflow response between the two periods, possibly related to the greater production volume during the 48-hr. pump test.

### 2.2.4 Equivalent Single-Layer Analysis

The next step in the analysis was to prepare a preliminary interpretation of the test based on a conceptual model identified from reviewing the diagnostic plot (Figure 5). Well test analysts generally begin an analysis with the simplest model possible. In this case, that is an equivalent single layer model. Although the spinner logs demonstrated that five intervals are productive in well NC-EWDP-19D, Larsen (1981) showed that a multi-layer system with different initial heads could be modeled as an equivalent single-layer system as long as the aquifer properties do not vary significantly between zones. The log-log drawdown plot for well NC-EWDP-19D (Figure 5) also indicated the presence of linear flow between barriers as a positive half slope (+½ slope) in the derivative response from 10 to 48 hr. Accordingly, the initial test analysis included an equivalent single layer with two sealing barriers.

The drawdown head change and derivative response were analyzed using the SAPHIR ™ computer-assisted well test analysis program (Kappa Engineering, 1999). SAPHIR™ includes the standard methods of well test analysis, as well as hundreds of different models for the wellbore, different flow regimes, different types of boundaries, multiple layers, and other factors affecting flow. After a preliminary interpretation was selected, the test parameters were varied to determine a “best fit” using nonlinear regression techniques. The match results were examined on log-log (Figure 7), semilog (Figure 8), and Cartesian plots (Figure 9).

The best match using an equivalent single layer model with barriers was obtained with a transmissivity of about 4,000 $ft^2$/day (372 $m^2$/day), corresponding to an average permeability of 2.3 darcy (2.3 x $10^{-12}$ $m^2$) over the 485.5 ft (148.0 m) productive thickness. Parallel flow barriers are inferred to be present at about 240 ft (73.2 m) and 1,140 ft (347.5 m) from the well. The presence of flow barriers is considered probable based on the positive half slope in the derivative response, but the distance to the barriers should be considered very approximate because of uncertainties in average compressibility and other factors.

Formation damage is inferred from the difference between the drawdown (head change) and the derivative curves prior to the first zero slope region on the log-log plot (Figure 7). This damage is expressed mathematically as an apparent skin factor of +4, leading to a computed well efficiency of approximately 74 percent. The match to the head change and derivative response for the pumping period is considered good.

A good match was also obtained on the semilog plot (Figure 8). The influence of the barriers caused the head change to continuously increase, so that it was not possible to select a suitable straight line for a Cooper Jacob analysis (Cooper and Jacob, 1946).

The Cartesian plot for the single layer model (Figure 9) shows an excellent match during the 48-hr. pump test, but shows significant deviations during the pump-spinner test and recovery, and the 48-hr. pump test recovery. It was not possible to match the drawdown and the recovery response together with a single layer model.

### 2.2.5 Multi-Layer and Multi-Pressure Modeling

As indicated from the spinner log analysis, at least three distinct initial potentiometric head levels were present in the zones completed in this well. In order to evaluate the effect of multiple layers and different initial potentiometric heads, a generalized multi-layer model with barriers was developed by Questa Engineering to interpret the well NC-EWDP-19D pump test. This model allows the incorporation of different initial heads in each layer and thus accommodates the observed head differences in this test. The model derivation and assumptions are presented in Appendix B.

The model was developed to handle three layers with flow barriers (boundaries) parallel and equidistant from the wellbore. Based on the analysis of the spinner logs, Screens #1 and #2 were combined into a single equivalent layer for the multi-layer model, as were Screens #3 and #4. The contributions from Screens #6 and #7 were negligible and were not included. Individual zonal rates and pressures were estimated based on the incremental changes between the non-pumping spinner survey on May 12, 2000, and the spinner survey at the end of the 48-hr. pump test on May 14, 2000.

The multi-layer model was used to match the entire test history including the pump-spinner test, the initial recovery, the 48-hr. pump test, and the main pump test recovery. The transmissivity of each layer was assumed to be proportional to the indicated spinner flow rate for that layer, divided by the indicated difference in head between the final producing head in the 48-hr. pump test and the initial depth to water assumed for each layer.

The total transmissivity was computed to be 4,000 $ft^2$/day (372 $m^2$/day), which is the same value that was computed with the equivalent single layer model. The best-fit distance to the parallel boundaries was determined to be approximately 700 ft (about 213 m). The best multi-layer model match was obtained using skin factors of +2 in all zones. As previously noted, the single-layer model drawdown analysis indicated a skin of +4. Based on these modeling runs, approximately half of the apparent skin factor appears to be associated with the multi-layer effects.

A Cartesian plot comparing the model-derived depth to water with the measured depth to water is shown in Figure 10. The match is generally better than the single-layer model match, except for the later portion of the 48-hr. pump test. During that time, there was actually a greater drawdown than computed from the model, totaling approximately 2 ft of head difference. This increase in drawdown from about 1.3 to 2.8 days into the test is attributed to progressive partial plugging of one or more of the shallow screens by lost circulation material remaining from drilling.

A semilog plot comparing the model response to the measured data is shown in Figure 11. While the model matches the early radial drawdown data (1 to 5 hr.), it deviates above the curve for the remainder of the pump test. This difference is attributed to progressive partial plugging of one or more of the shallow screens by lost circulation material remaining from drilling.

The computed results for each layer are summarized in Table 3. These results are strongly dependent on the assumed allocation of transmissivity between the different layers, and on the assumption that the skin factor or well efficiency is the same in each layer. If these assumptions are not correct, then the allocated transmissivity for each zone will be in error. Subsequent testing or monitoring of individual zones should lead to better allocation of the transmissivity, and a more accurate overall analysis.

## 2.3 INTERFERENCE ANALYSIS

The Washburn and NC-EWDP-19P wells were instrumented with MOSDAX™ pressure sensors for interference analysis purposes. The data from both wells was unsuitable for analysis.

The Washburn well is located more than 1 mi. (1,610 m) away and showed no apparent change as a result of the well NC-EWDP-19D pump tests (Figure 12).

Well NC-EWDP-19P is located 81.8 ft (24.9 m) north of well NC-EWDP-19D, and is completed with a single screen and with a gravel pack from 356 to 475 ft (108.5 to 144.8 m), corresponding to the uppermost screen in well NC-EWDP-19D (411 to 431 ft or 125.3 to 131.4 m). Figure 13 shows the depth to water and barometric pressure at NC-EWDP-19P during the well NC-EWDP-19D testing. The depth to water and barometric pressure scales were selected so that changes in the water level resulting from barometric changes could be easily identified. The water level in well NC-EWDP-19P closely followed fluctuations in barometric pressure. Well NC-EWDP-19P responded almost instantly to the well NC-EWDP-19D pumping, but the magnitude of the response did not increase significantly as the test went on, therefore the response does not appear to be useful for analysis.

## 2.4 SUMMARY OF OBSERVATIONS BY INTERVAL

The following comments are based on various observations made over the course of the evaluation.

**Screen #1**–This screen appeared to have the lowest potentiometric head of all the productive zones in the well. It was not possible to obtain spinner data for this zone while pumping, but it appears to have contributed only a few percent of the total flow. Sustainable production rates from Screen #1 will probably be 10 gpm (37.9 L/min.) or less, because of the small head drawdown available in this interval.

**Screen #2**–Comments for Screen #2 are similar to comments for Screen #1. Screen #2 probably has similar permeability to Screen #1, based on water flow rate measurements taken while drilling.

**Screen #3**–Screen #3 had the highest permeability in the alluvial interval (Screens #1 to #4). The initial non-pumping spinner log indicated the zonal pressure was essentially balanced with the wellbore pressure. The interval was a major flow contributor during pumping, but spinner measurements taken on May 12, 2000, indicated inflow into the zone following shut-in. The sustained production rate from Screen #3 during the 48-hr. pump test was about 75 gpm (283.9 L/min.).

**Screen #4**–Screen #4 had good permeability, but exhibited greater head drop while pumping than Screen #3, based on spinner measurements at shut-in of the 48-hr. aquifer pump test. Spinner measurements taken on May 10, 2000, indicate there may be crossflow within different portions of the Screen #4 interval. Screen #4 had an initial potentiometric head similar to that of Screen #3. The sustained production rate from Screen #4 during the 48-hr. pump test was about 40 gpm (151.4 L/min.).

**Screen #5**–This zone may have a much greater proportion of the total transmissibility than indicated from the pump test, because of possible large positive skin due to poor connection between the wellbore and a known fracture/lost circulation zone at approximately 955 ft (291.1 m). With the highest potentiometric head of all zones in well NC-EWDP-19D, Screen #5 contributed positive production during all logging runs. The production rate from Screen #5 during the 48-hr. pump test was about 25 gpm (94.6 L/min.). It should be capable of sustaining greater production rates if it is isolated, because it could then be drawn down more than the other zones, and because a significant portion of its flow may have been crossflowing into other zones during the pump tests.

## 3.0 CONCLUSIONS

Spinner logs run under static (non-pumping) conditions in well NC-EWDP-19D were used to measure natural crossflow between screens. Additional spinner logs were run to evaluate individual zonal contributions while pumping. Screen #3 contributed the greatest flow (73 gpm or 276.3 L/min.), followed by Screen #4 (45 gpm or 170.2 L/min.), Screen #5 (26 gpm or 98.4 L/min.), and Screen #2 (6 gpm or 22.7 L/min.). It was not possible to log across Screen #1 while pumping, because of the small clearance between the pump and the pipe, but the indicated flow from that zone was estimated to be about 6 gpm (22.7 L/min.). No flow was observed from Screens #6 or #7.

A 48-hr. aquifer pump test was conducted to determine aquifer properties. Analysis of the tests was complicated by the presence of seven completion intervals and at least three different potentiometric head levels within the various zones completed. The test history was analyzed using an equivalent single-layer system, and also with a generalized multi-layer, multi-head model with barriers. The total transmissivity of the aquifers connected to Screens #1 through #5 in well NC-EWDP-19D well is 4,000 $ft^2$/day (372 $m^2$/day) based on analysis of the pump-spinner test and the 48-hr. pump test. This corresponds to an average permeability of 2.3 darcy ($2.3 \times 10^{-12}$ $m^2$) over the 485.5 ft (148.0 m) productive thickness. The permeability in well NC-EWDP-19D is lower than that observed in many of the other Early Warning Drilling Program wells.

Parallel flow barriers are inferred to be present at about 240 ft (73.2 m) and 1,140 ft (347.5 m) from the well using an equivalent single-layer model. Using a multi-layer model, parallel flow barriers are estimated to be approximately 700 ft (about 213 m) from the well. The estimated distance to the barriers should be considered very approximate because of uncertainties in average compressibility and other factors.

Heads were monitored in two offset wells to measure potential interference. While the influence of the pump testing was observed in the NC-EWDP-19P wellbore 81.8 ft (24.9 m) away, the data were not suitable for determining aquifer properties. No response was detected at the Washburn well, 6,300 ft (1,920 m) away.

The general test methodology and logging equipment are applicable for use on future wells.

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# FIGURES

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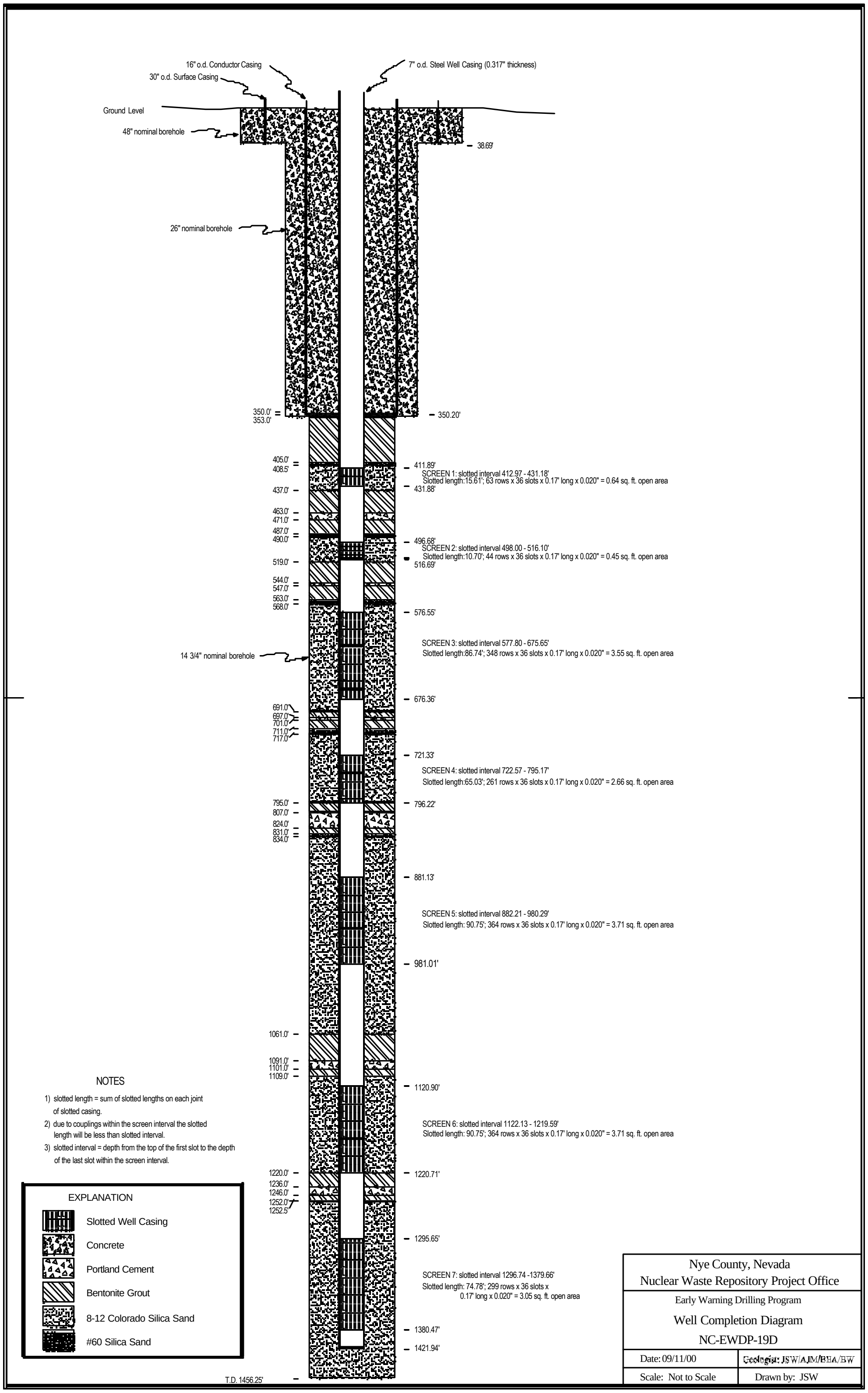


NOTE: o.d. = outer diameter

**Figure 1**
**Completion Diagram for Well NC-EWDP-19D**

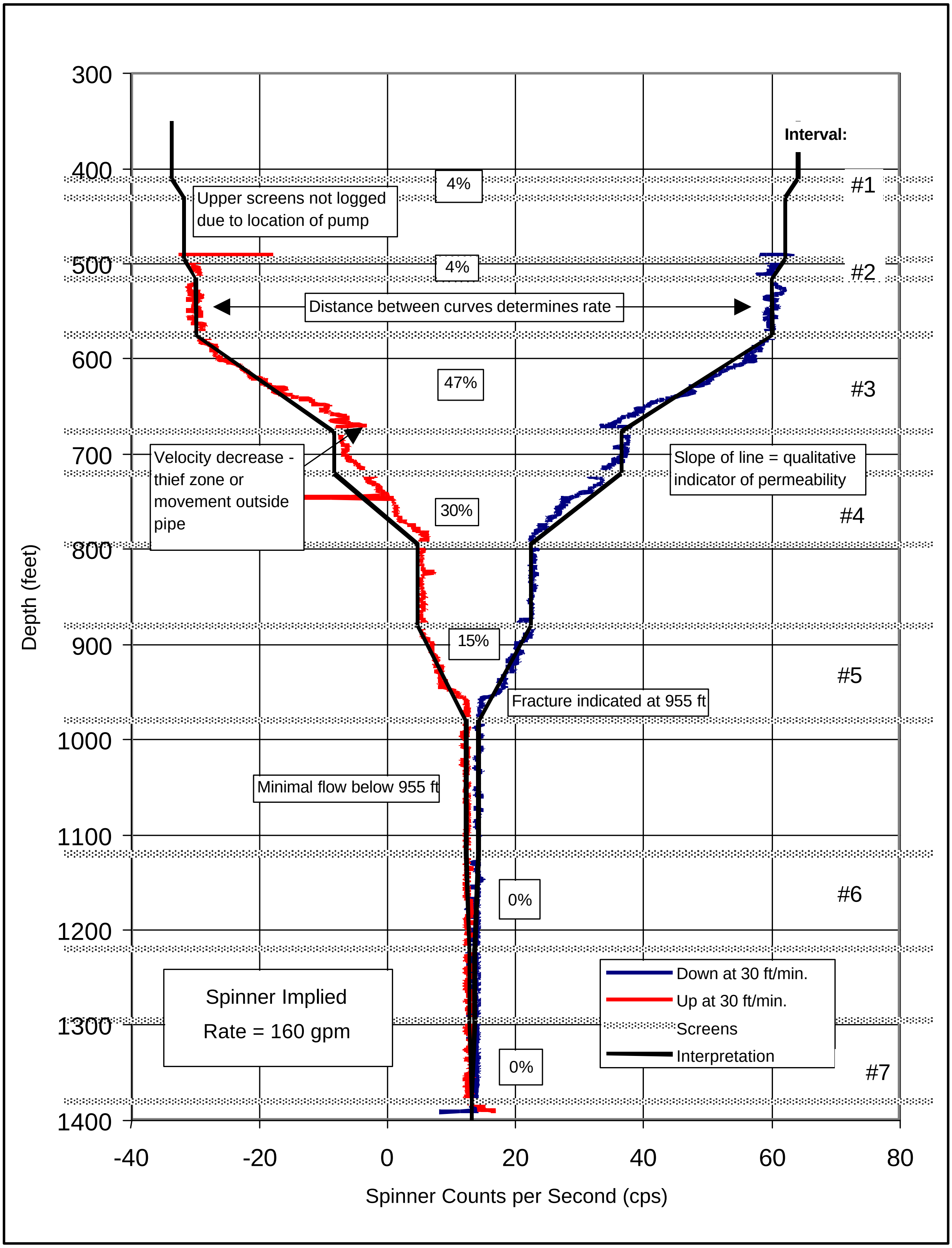


**Figure 2**
**Example Spinner Run at Well NC-EWDP-19D (30 ft/min.)**

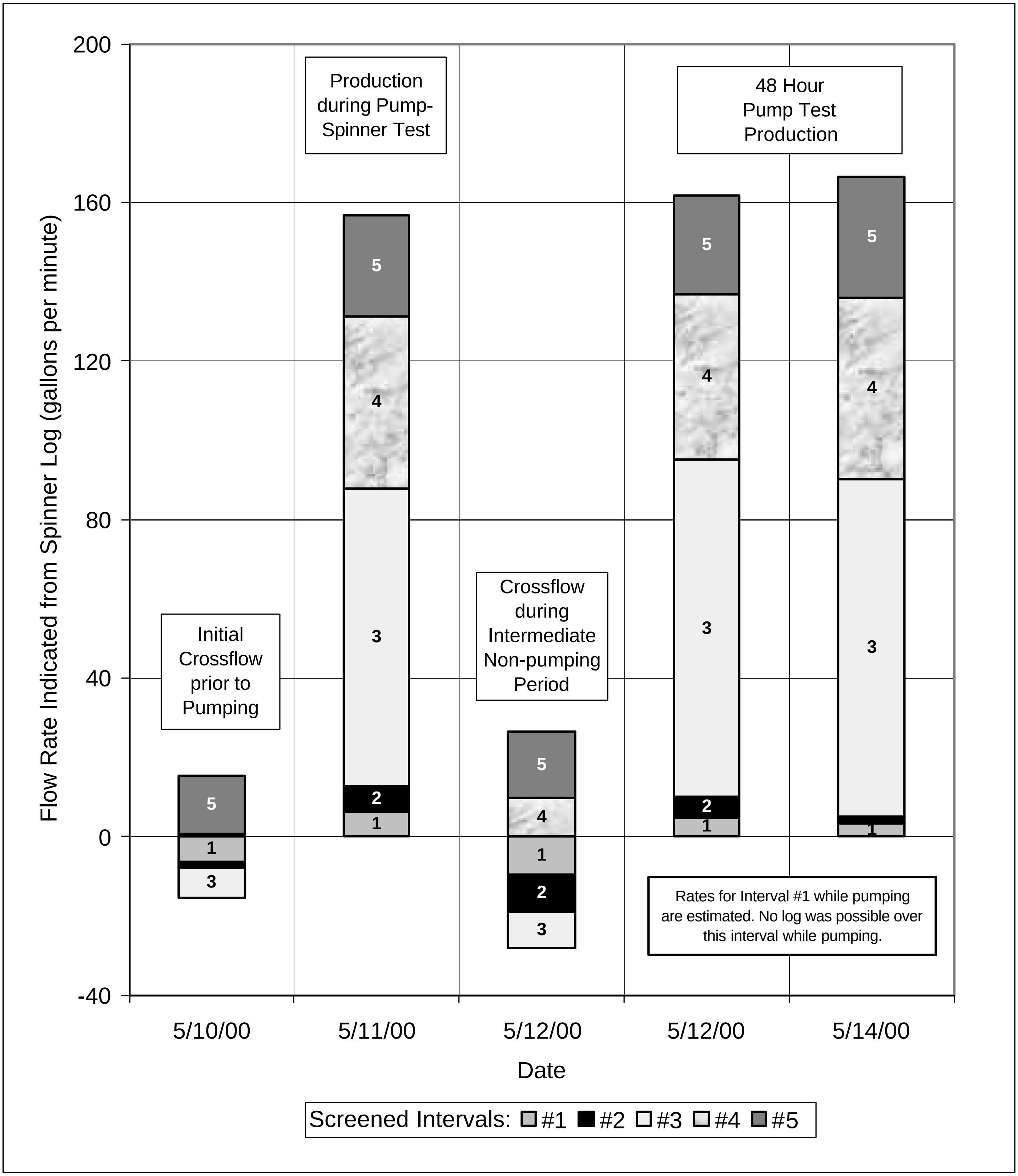


**Figure 3**
**Spinner Log Results for Well NC-EWDP-19D**

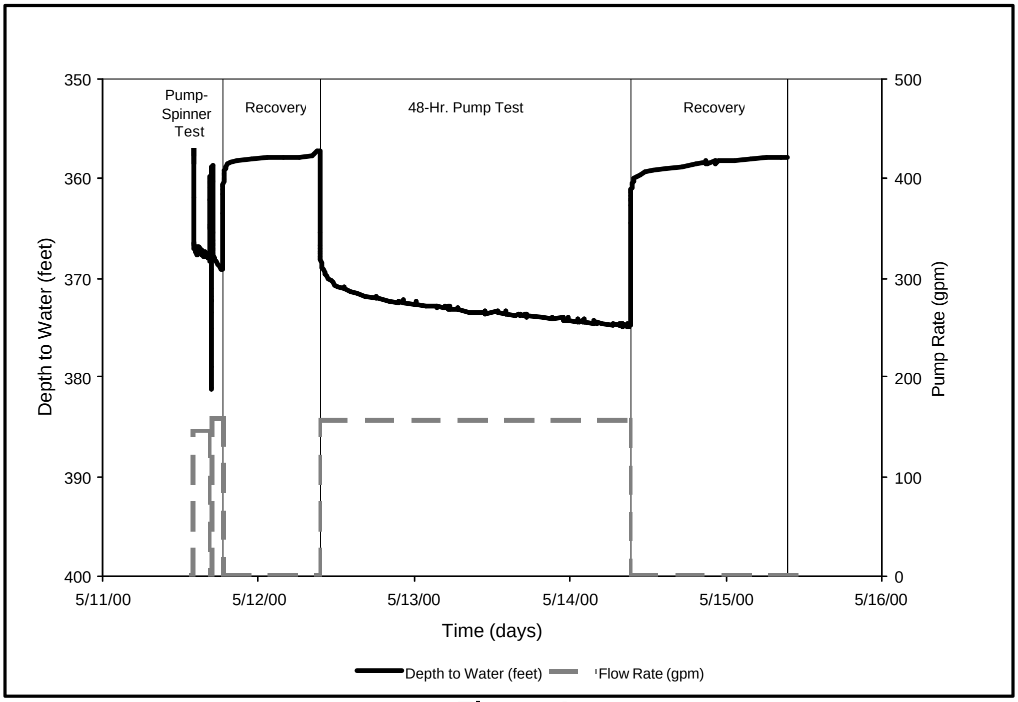


**Figure 4**
**Measured Pumping Rates and Depth to Water for the Pump-Spinner Test and the 48-Hour Pump Test**

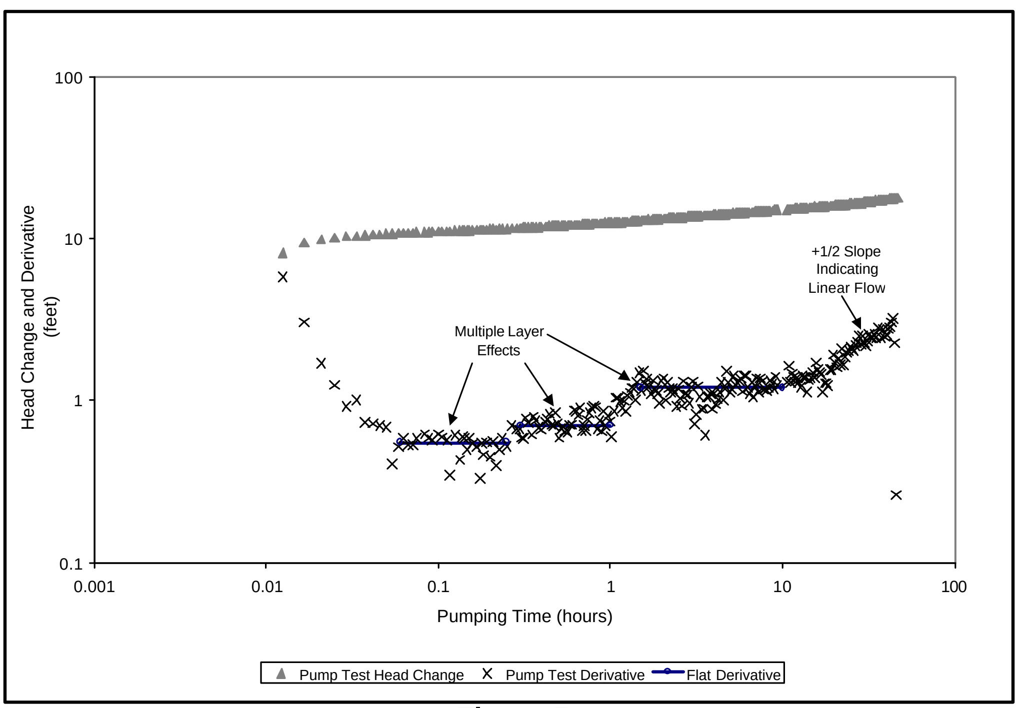


**Figure 5**
**Log-Log Diagnostic Plot of Well NC-EWDP-19D Drawdown Response**

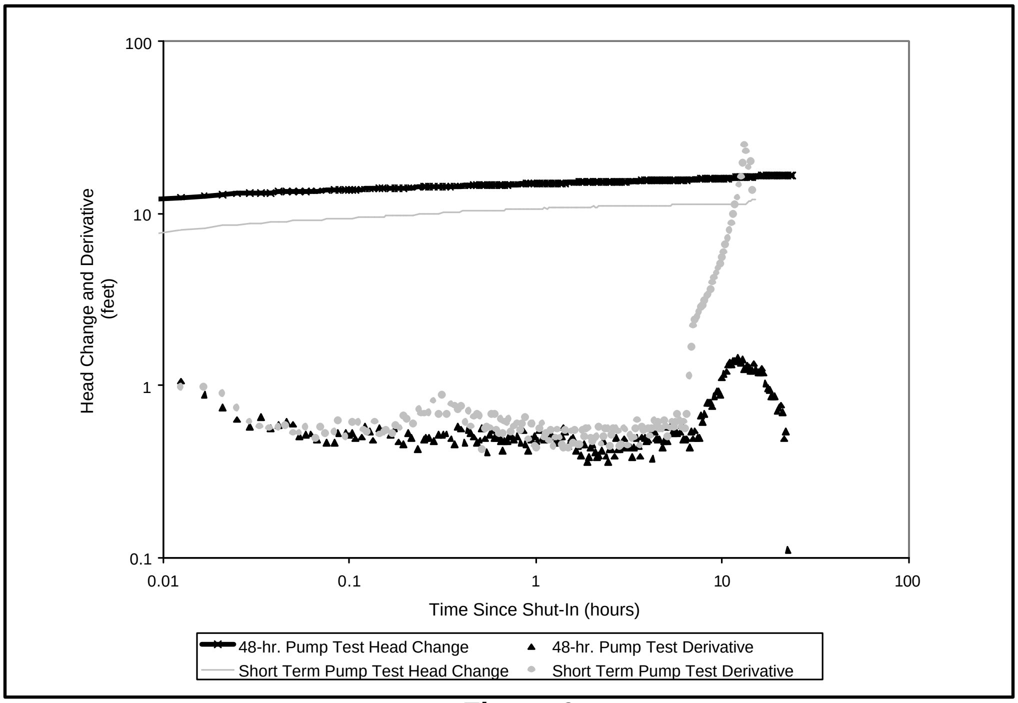


**Figure 6**
**Comparison of Well NC-EWDP-19D Recovery Response for Two Recovery Periods**

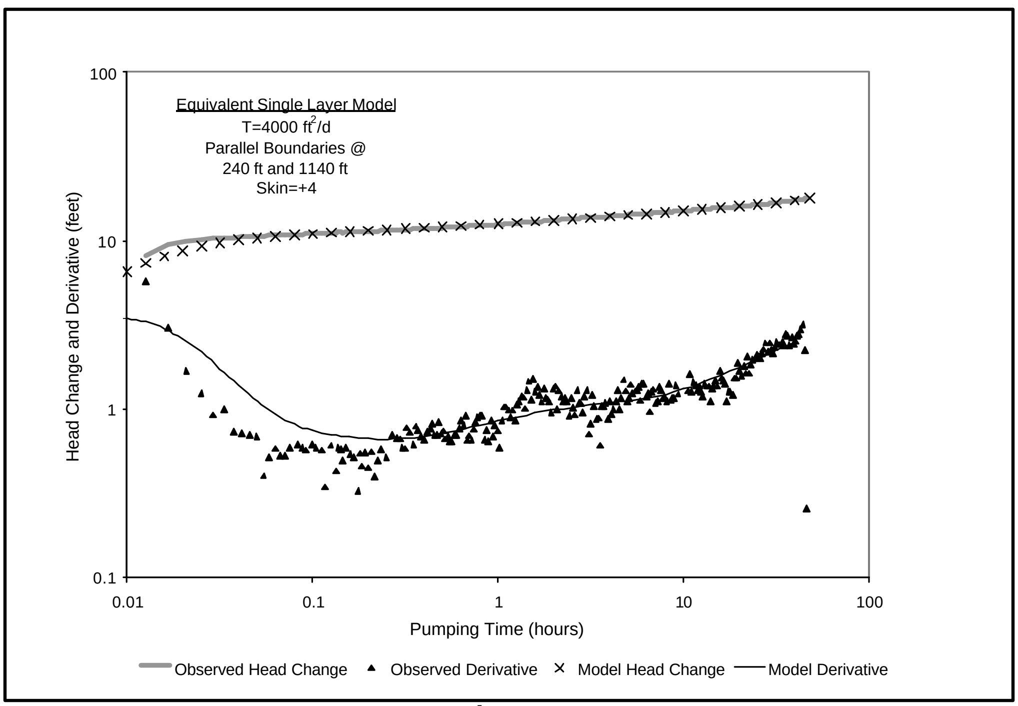


**Figure 7**
**Log-Log Plot Comparing the Equivalent Single-Layer Model to Actual Data**

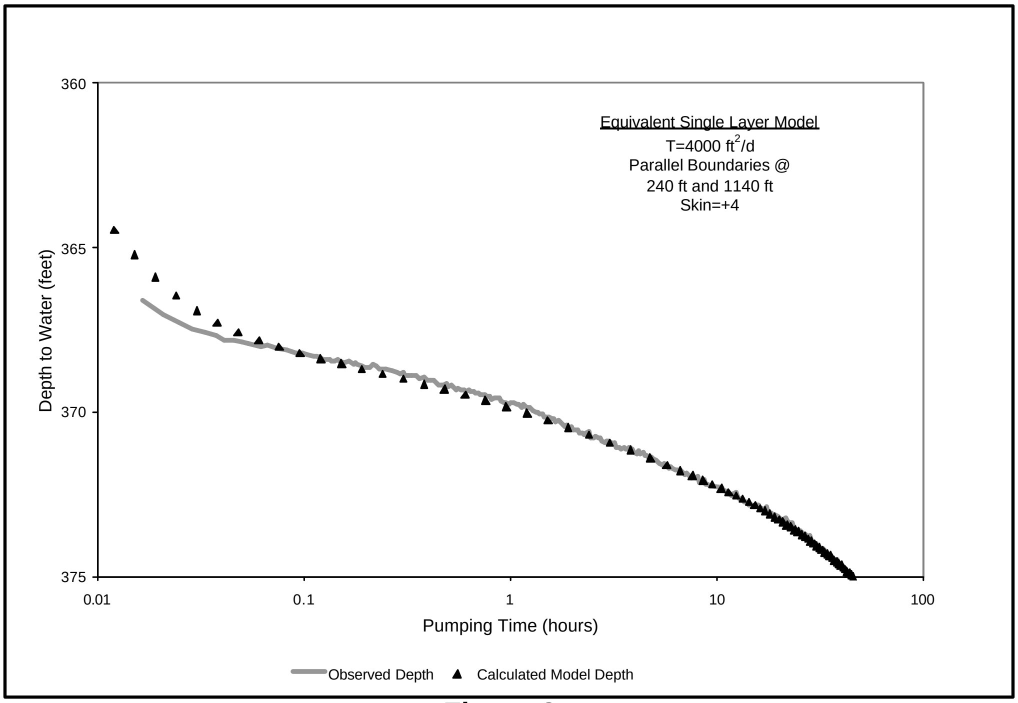


**Figure 8**
**Semilog Plot Comparing the Equivalent Single-Layer Model to Actual Data**

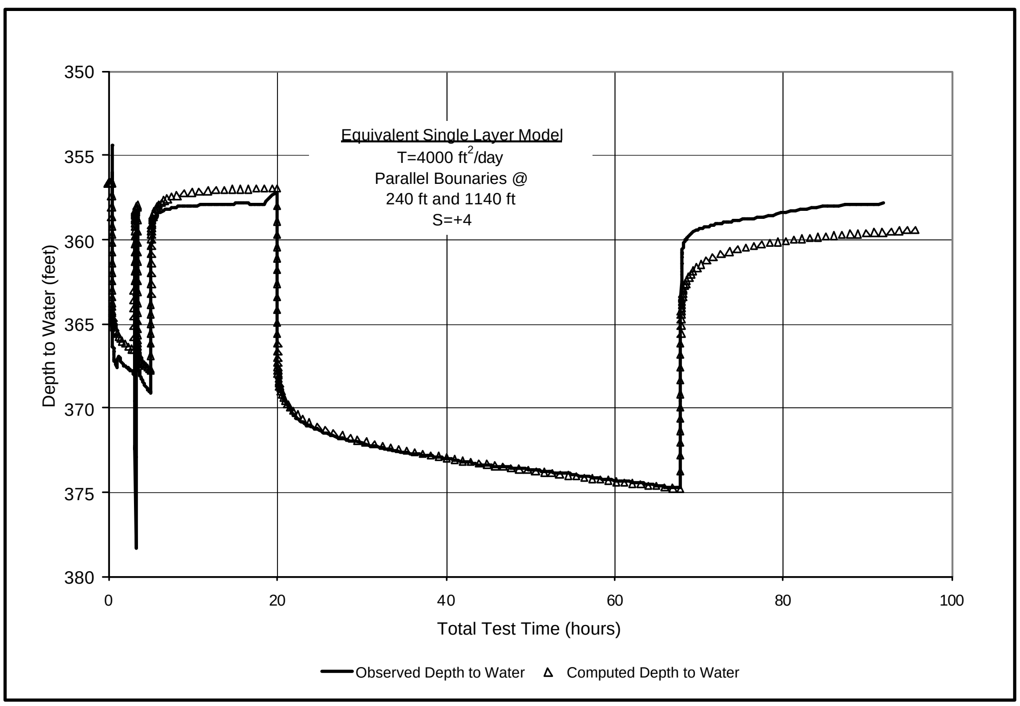


**Figure 9**
**Cartesian Plot Comparing the Equivalent Single-Layer Model to Actual Data**

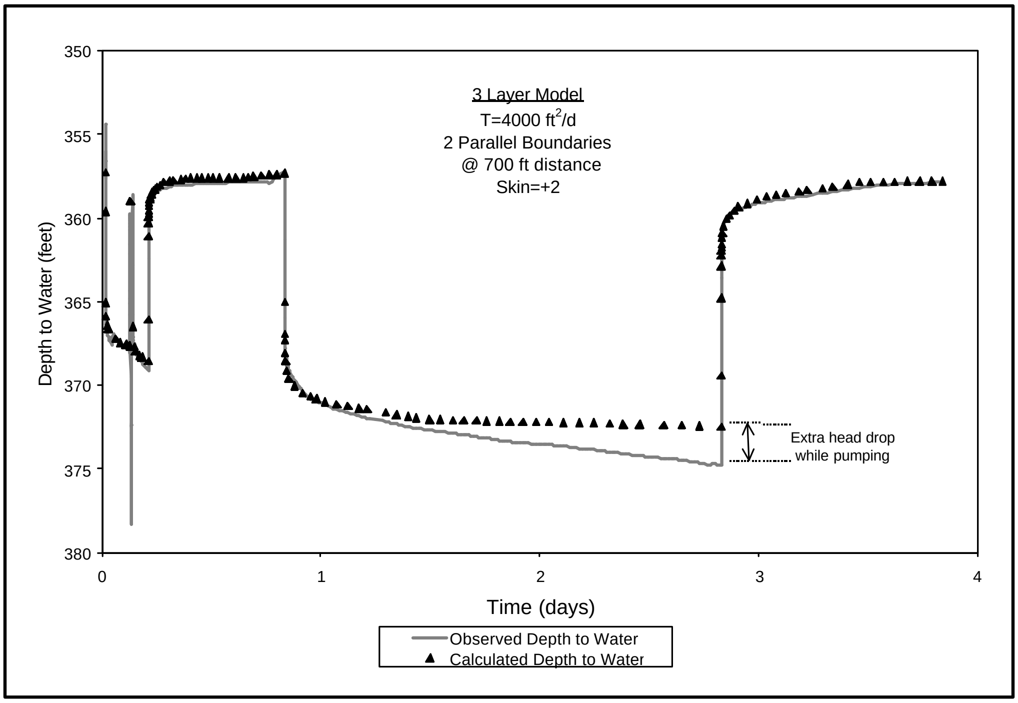


**Figure 10**
**A Comparison between Measured Depth to Water and Results Computed using the Multi-Layer, Multi-Pressure Model**

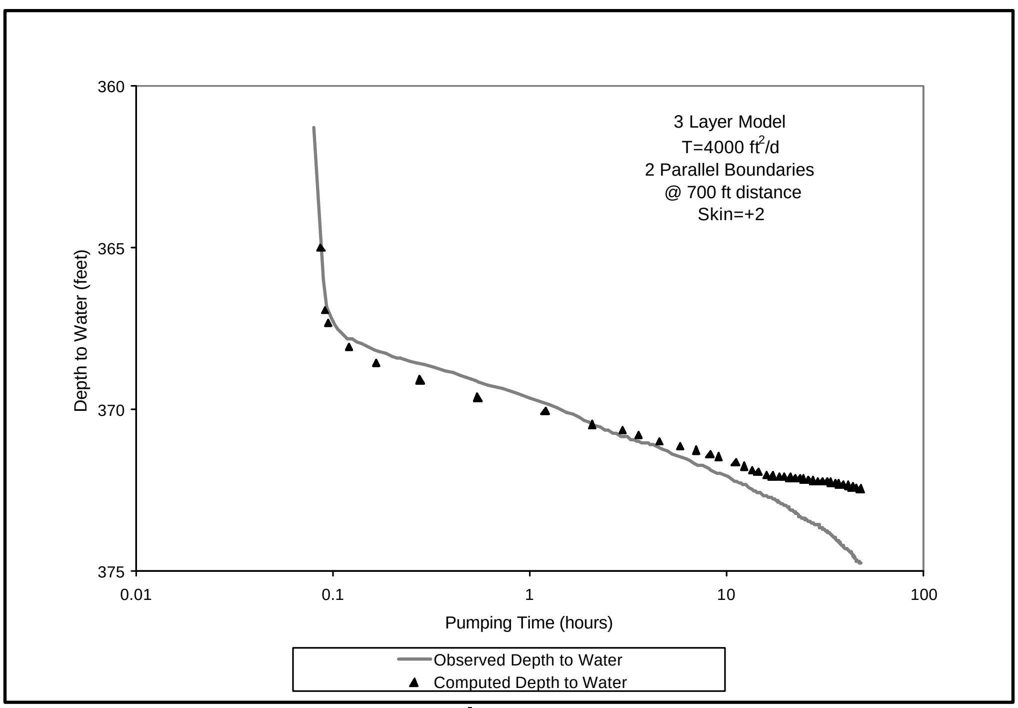


**Figure 11**
**Semilog Plot Comparing Model Response to Measured Data for the Three-Layer Model**

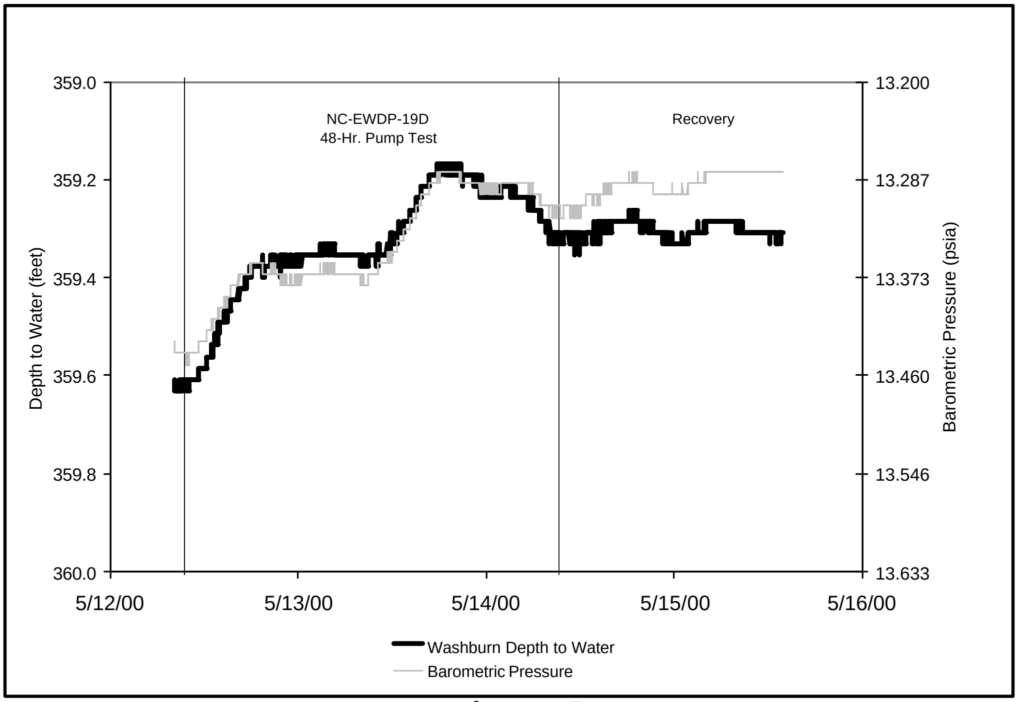


**Figure 12**
**Washburn Observation Well Response to Well NC-EWDP-19D Pump Test**

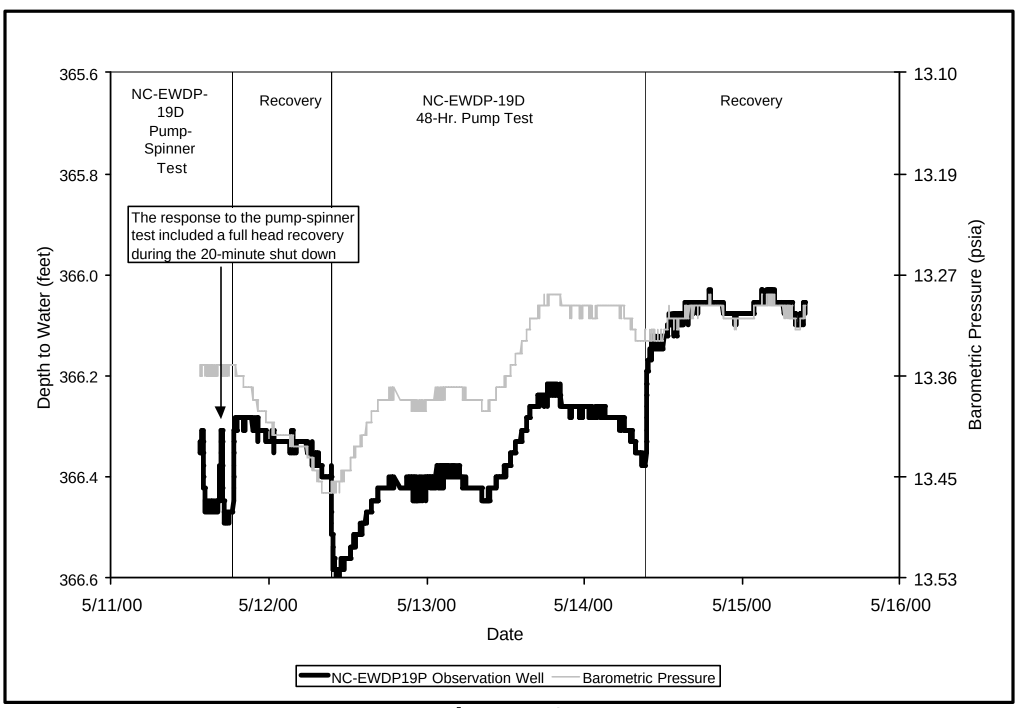


**Figure 13**
**NC-EWDP-19P Observation Well Response to Well NC-EWDP-19D Pump Test**

**TABLES**

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**Table 1**
**Completed Intervals in Well NC-EWDP-19D**

| Screen Interval Number | Screen Depths (ft) | Gravel Pack Depths (ft) | Net Thickness (ft) |
|---|---|---|---|
| 1 | 411-431 | 408.5-437 | 28.5 |
| 2 | 495-516 | 490-519 | 29 |
| 3 | 575-676 | 568-691 | 123 |
| 4 | 720-795 | 717-795 | 78 |
| 5 | 880-980 | 834-1061 | 227 |
| 6 | 1120-1220 | 1109-1220 | 111 |
| 7 | 1295-1380 | 1252-1456 | 204 |

**Table 2**
**Flow Rates Determined from Spinner Surveys**

| Screen Number | Rates Under Non-Pumping Conditions (gpm) | | | Rates During Pump-Spinner Testing (gpm) | | | | Rates Under Non-Pumping Conditions (gpm) | Rates During 48-hr. Pump Test (gpm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | May 10, 2000 | | | May 11, 2000 | | | | May 12, 2000 | May 12, 2000 | May 13, 2000 | May 14, 2000 |
| | Logging Speed | | | Logging Speed | | | | Logging Speed | Logging Speed | | |
| | 30 ft/min. | 45 ft/min. | 60 ft/min. | 0 [a] ft/min | 30 ft/min. | 60 ft/min. | 20 ft/min. | 30 ft/min. | 30 ft/min. | 30 ft/min. | 30 ft/min. |
| 1 | -6 | -7 | -6 | 7 [b] | 6 [b] | 6 [b] | 5 [b] | -10 [b] | 5 [b] | 3 [b] | 3 [b] |
| 2 | -2 | 0 | -2 | 7 [b] | 6 [b] | 6 [b] | 3 [b] | -10 [b] | 5 [b] | 3 [b] | 2 [b] |
| 3 | -8 | -7 | -7 | 78 | 73 | 75 | 85 | -9 | 85 | 85 | 85 |
| 4 | 1 | 1 | 1 | 50 | 45 | 43 | 45 | 10 | 42 | 46 | 46 |
| 5 | 15 | 13 | 14 | 25 | 26 | 26 | 27 | 17 | 25 | 29 | 30 |
| 6 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 1 | 3 | 2 | 2 |
| 7 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 1 | 2 | 2 | 2 |
| Total | 0 | 0 | 0 | 167 | 160 | 160 | 167 | 0 | 167 | 170 | 170 |

[a] Denotes stationary reading taken between intervals
[b] Estimated from rate allocation based on May 10, 2000, non-pumping conditions

**Table 3**
**Summary of Well NC-EWDP-19D Pump Test Interpretations**

| Type of Analysis | Screen Numbers | Net Thickness (ft) | Percentage of Flow Contribution based on Spinner Analysis (%) | Transmissivity ($ft^2/d$) | Permeability (darcy) | Initial Depth to Water (ft) |
|---|---|---|---|---|---|---|
| Single Layer | 1-5 | 485.5 | 100% | 4000 | 2.3 | 357 |
| Multi-Layer | 1-2 | 57.5 | 8% | 576 | 2.8 | 371 |
| | 3-4 | 201 | 76% | 3096 | 4.3 | 357 |
| | 5 | 227 | 16% | 328 | 0.4 | 339 |
| | **Total** | 485.5 | 100% | 4000 | NA | NA |

# APPENDIX A
# ANALYSIS OF SPINNER LOGS

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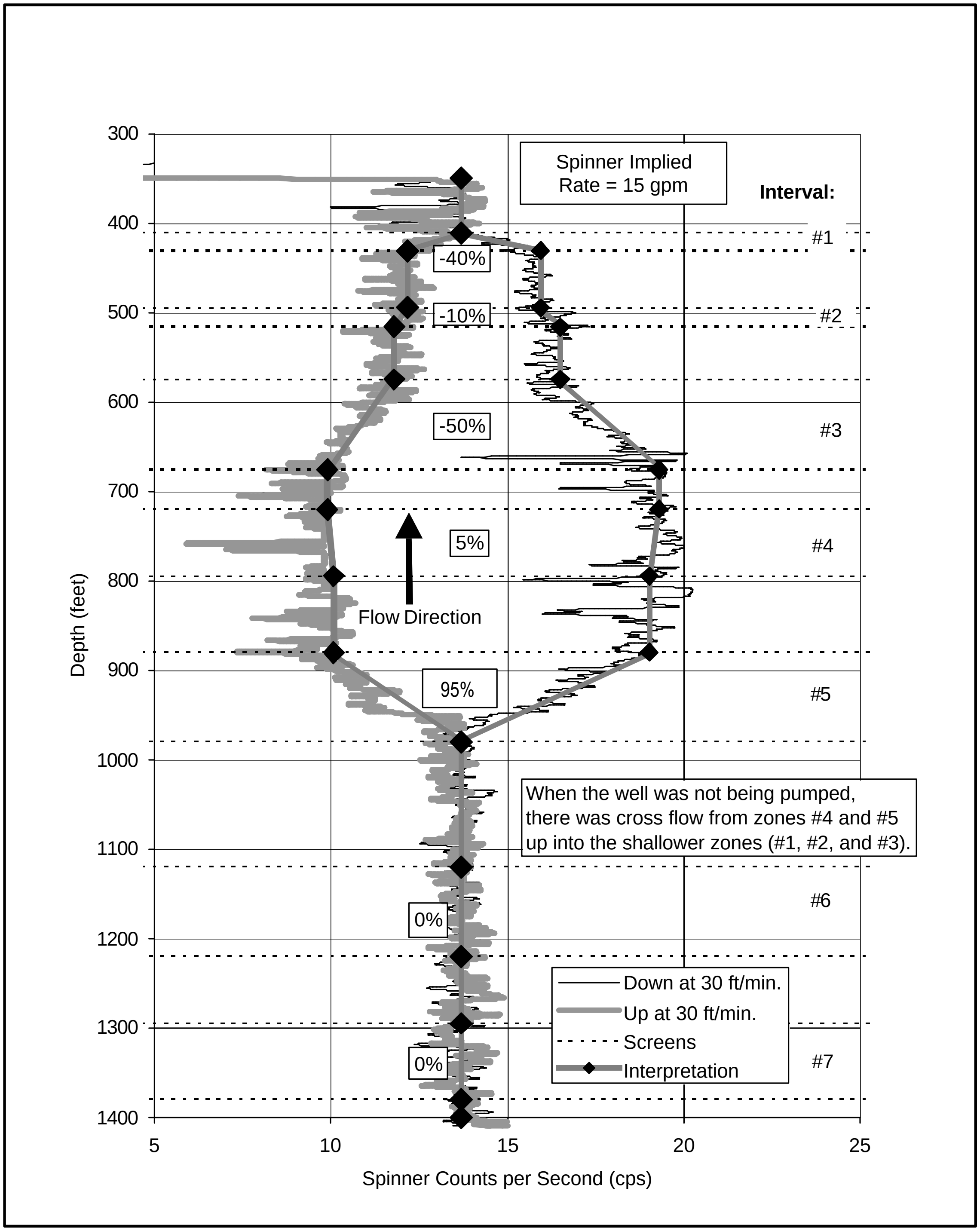


**Figure A1**
**Well NC-EWDP-19D Spinner Survey Cross Flow Prior to Pump/Spinner Test (30 ft/min., May 10, 2000)**

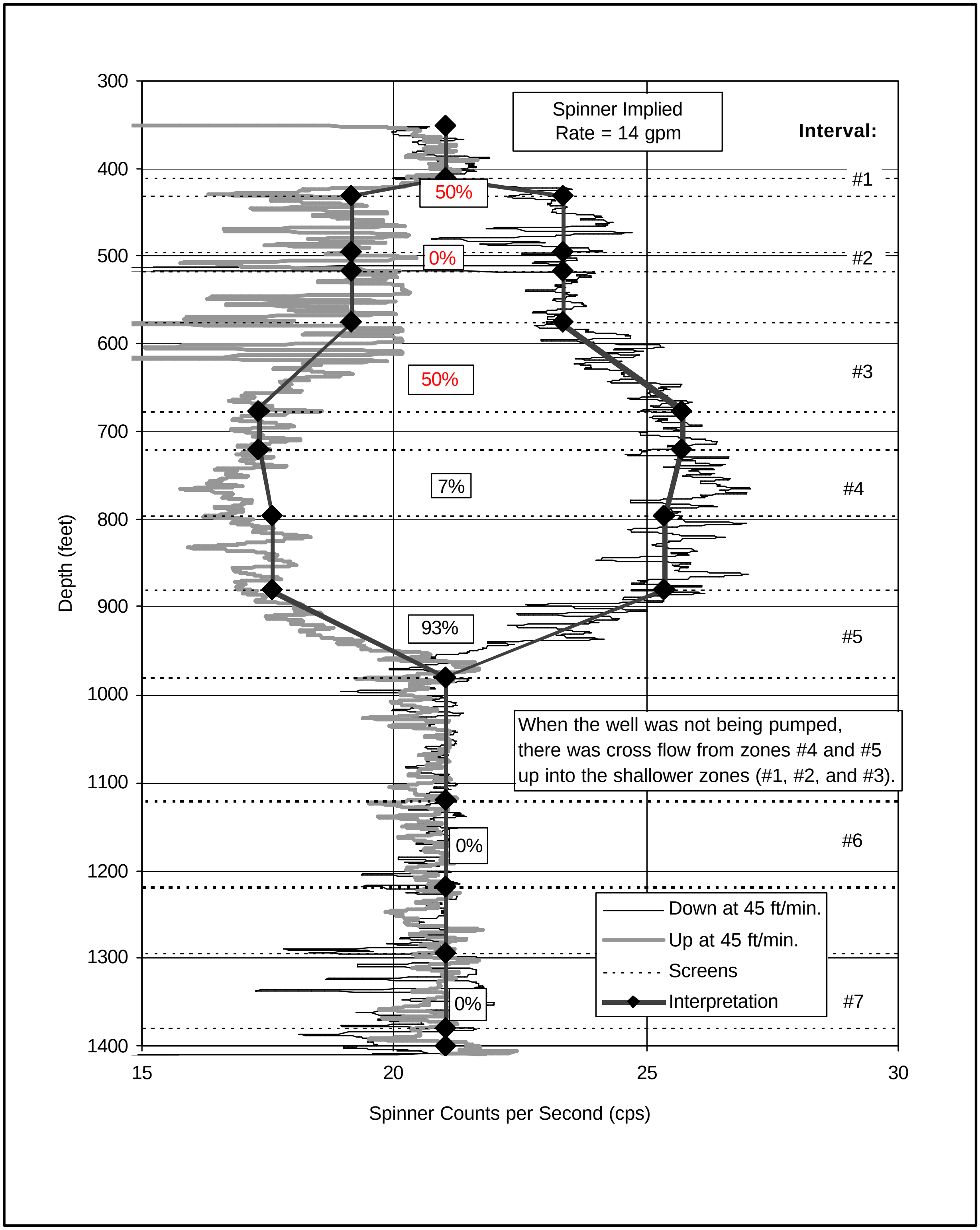


**Figure A2**
**Well NC-EWDP-19D Spinner Survey Cross Flow Prior to Pump/Spinner Test**
**(45 ft/min., May 10, 2000)**

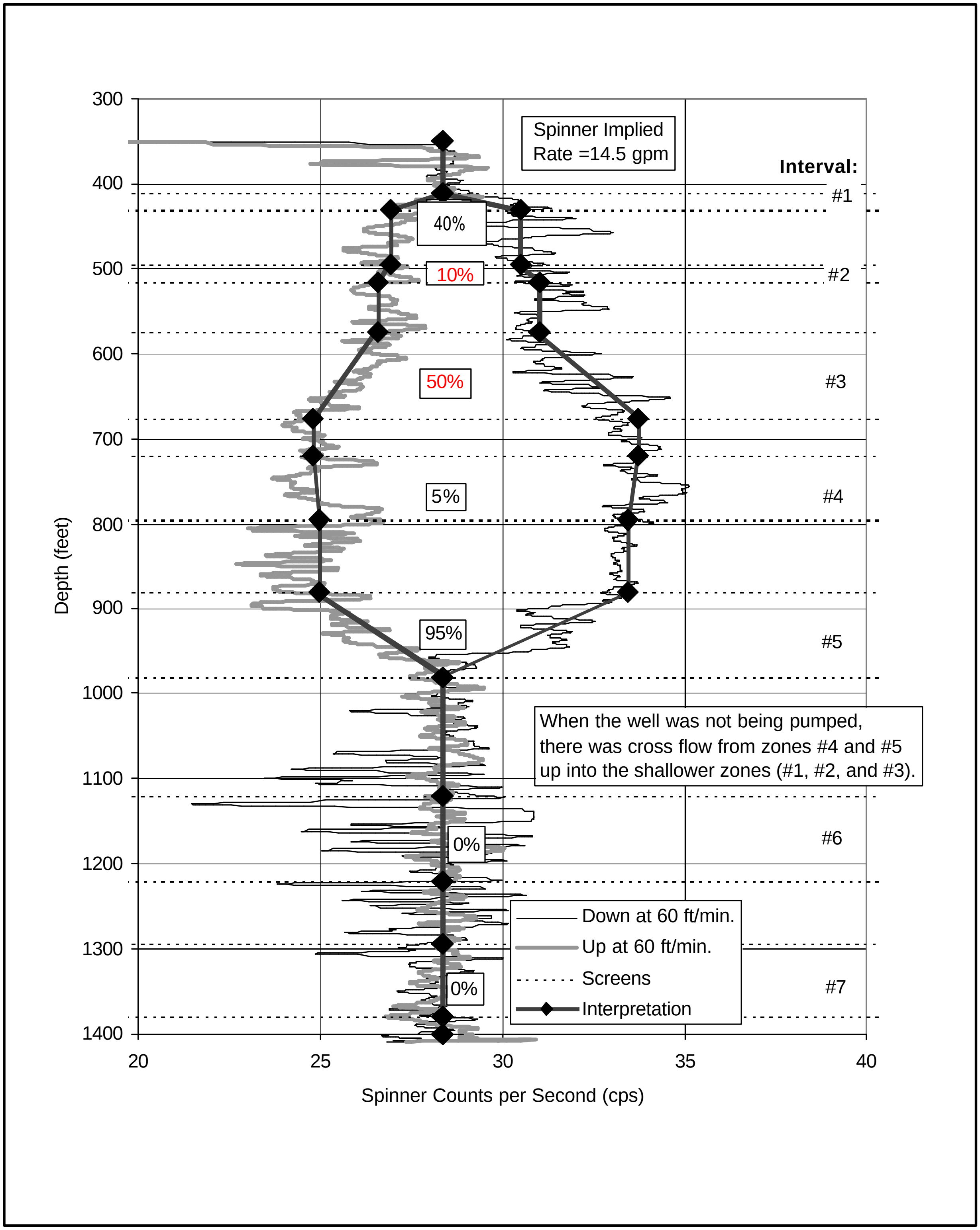


**Figure A3**
**Well NC-EWDP-19D Spinner Survey Cross Flow Prior to Pump/Spinner Test**
**(60 ft/min., May 10, 2000)**

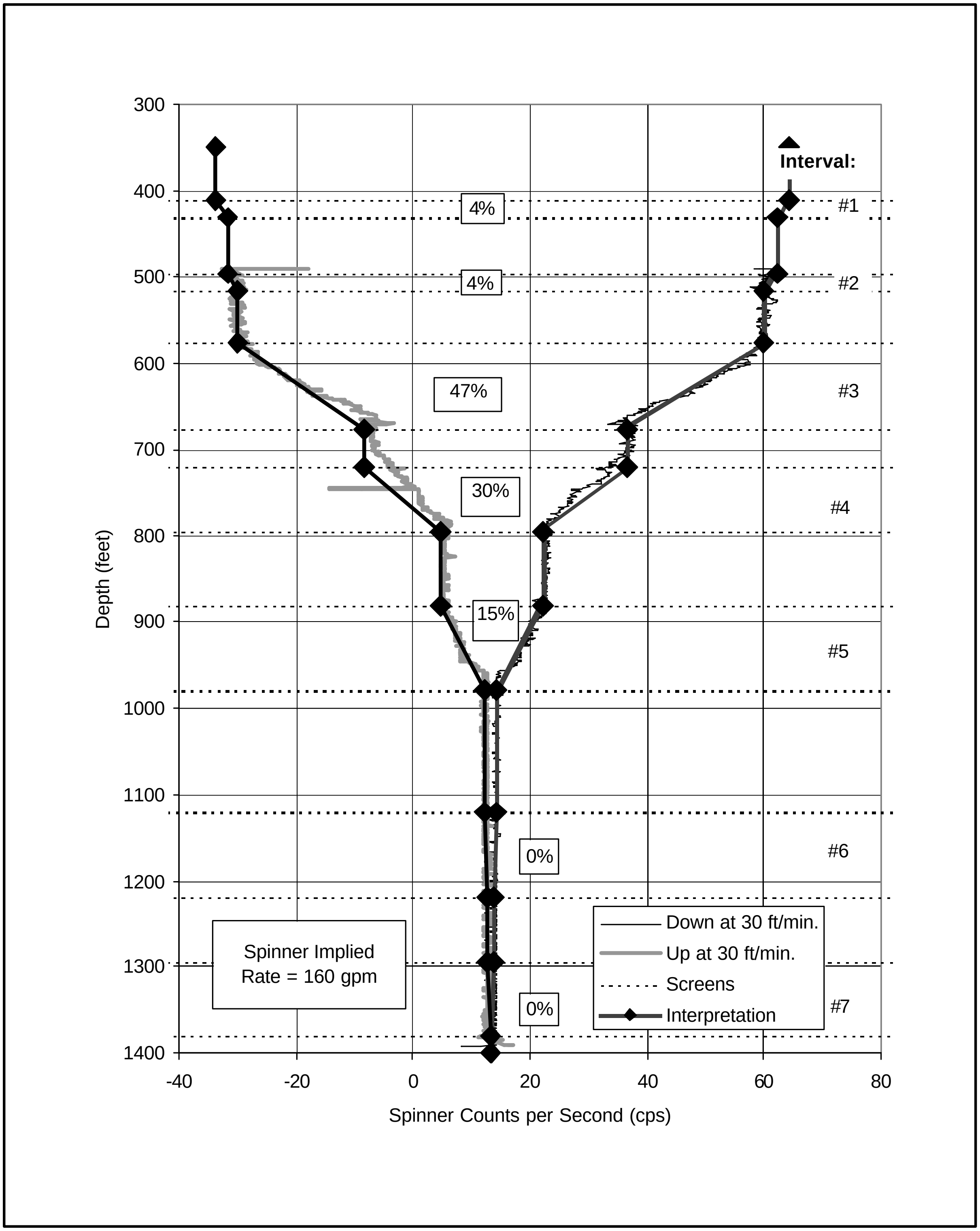


**Figure A4**
**Well NC-EWDP-19D Spinner Survey Pump/Spinner Test (30 ft/min., May 11, 2000)**

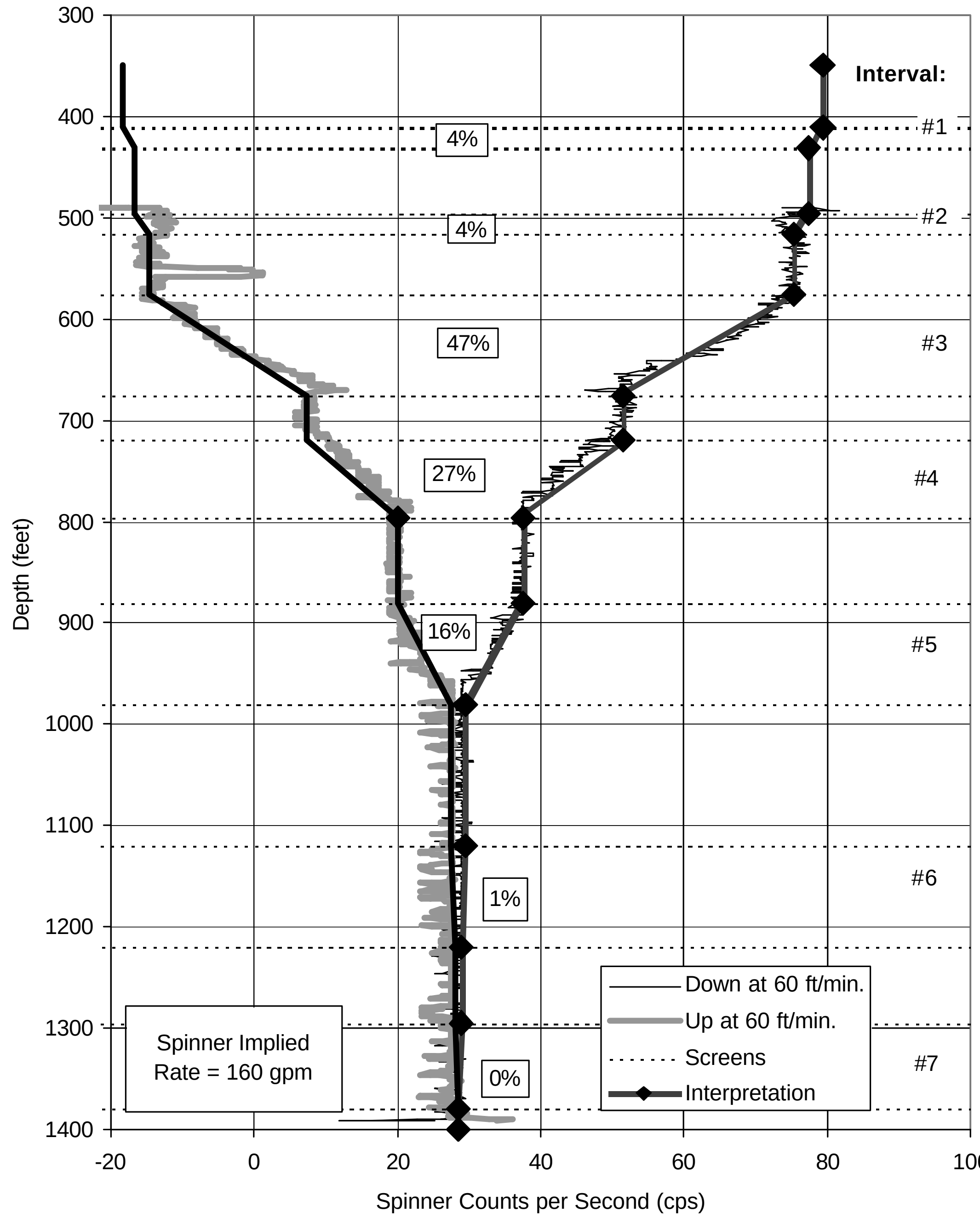


**Figure A5**
**Well NC-EWDP-19D Spinner Survey Pump/Spinner Test (60 ft/min., May 11, 2000)**

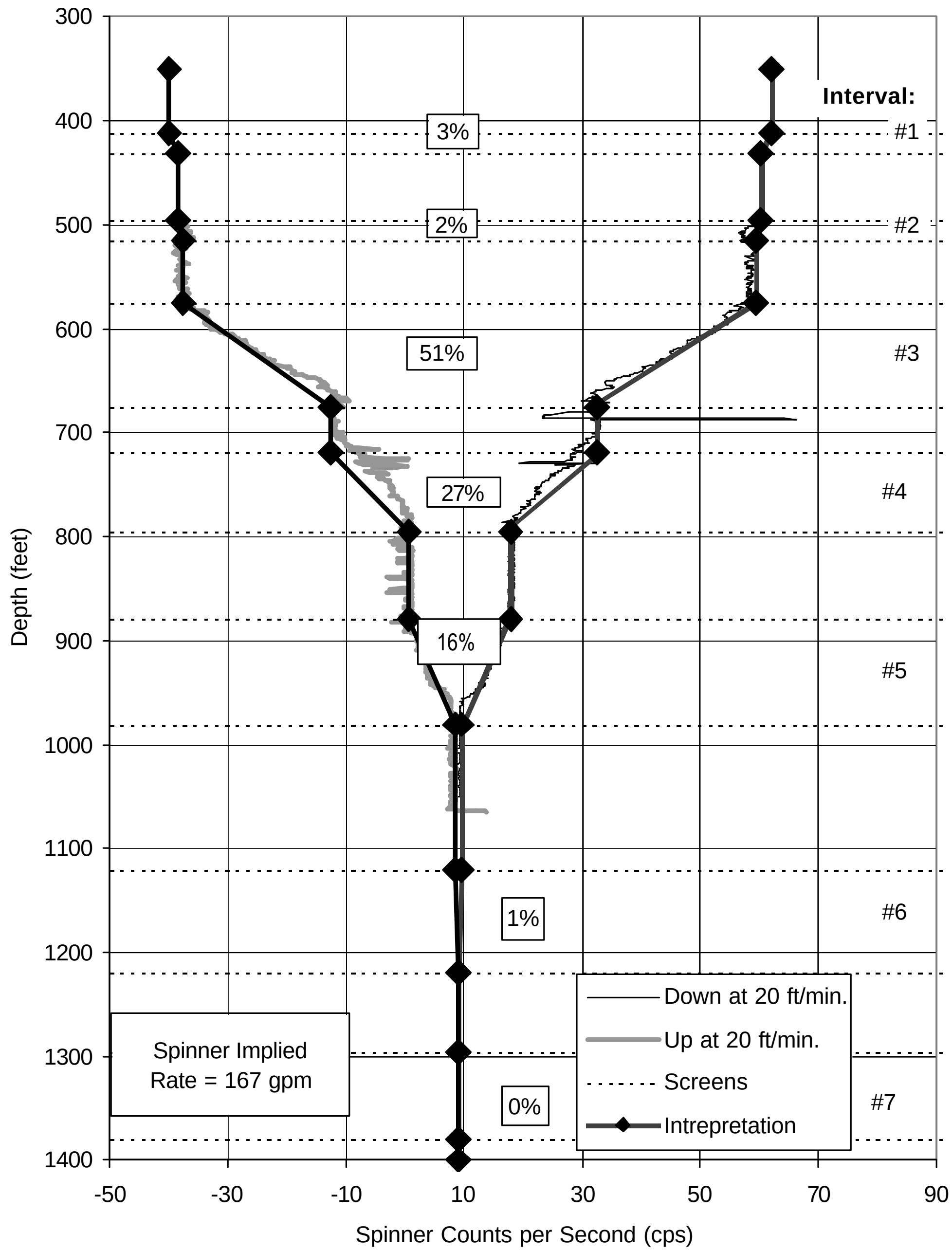


**Figure A6**
**Well NC-EWDP-19D Spinner Survey Pump/Spinner Test (20 ft/min., May 11, 2000)**

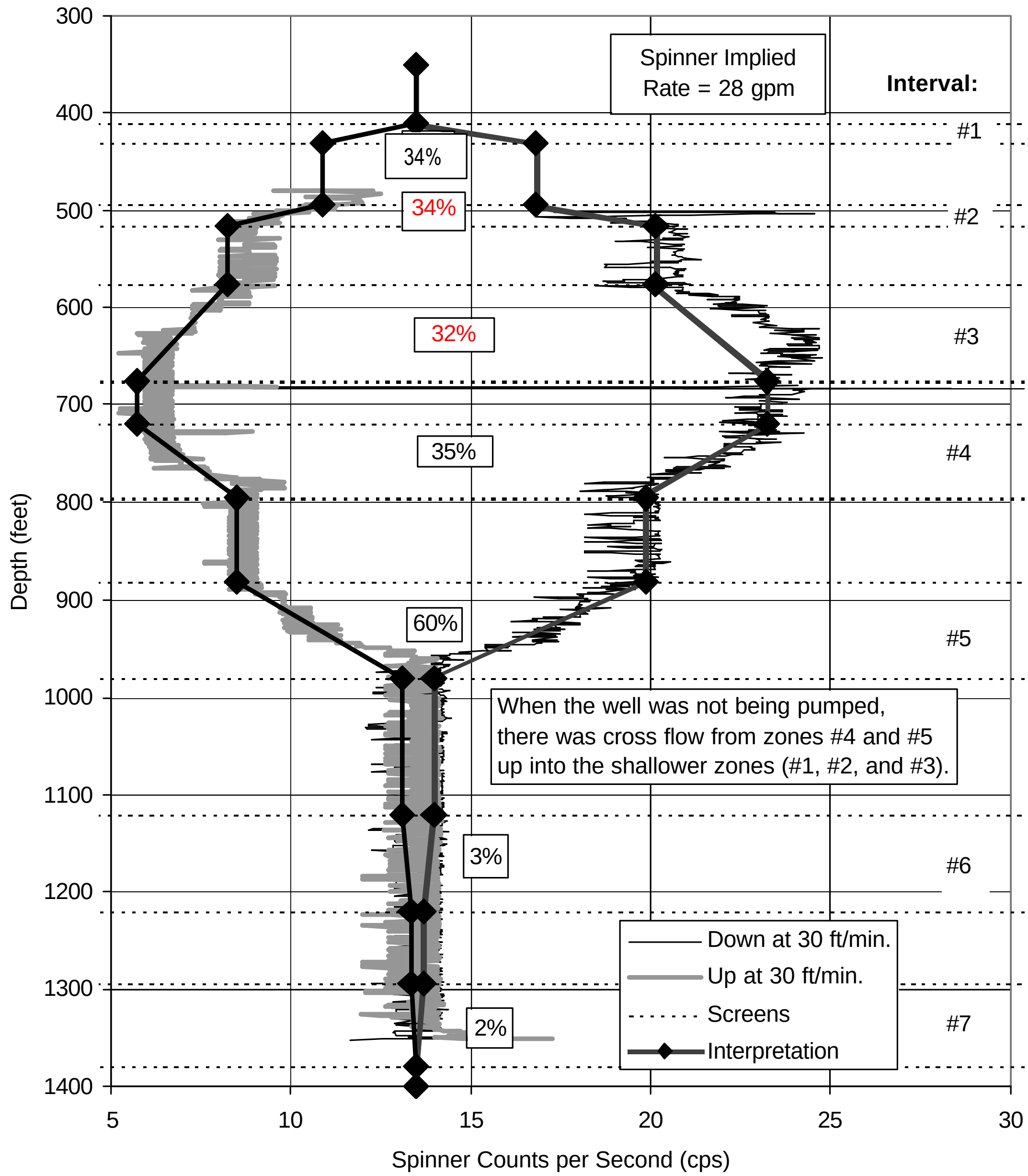


**Figure A7**
**Well NC-EWDP-19D Spinner Survey Cross Flow Prior to 48-Hour Pump Test**
**(30 ft/min., May 12, 2000)**

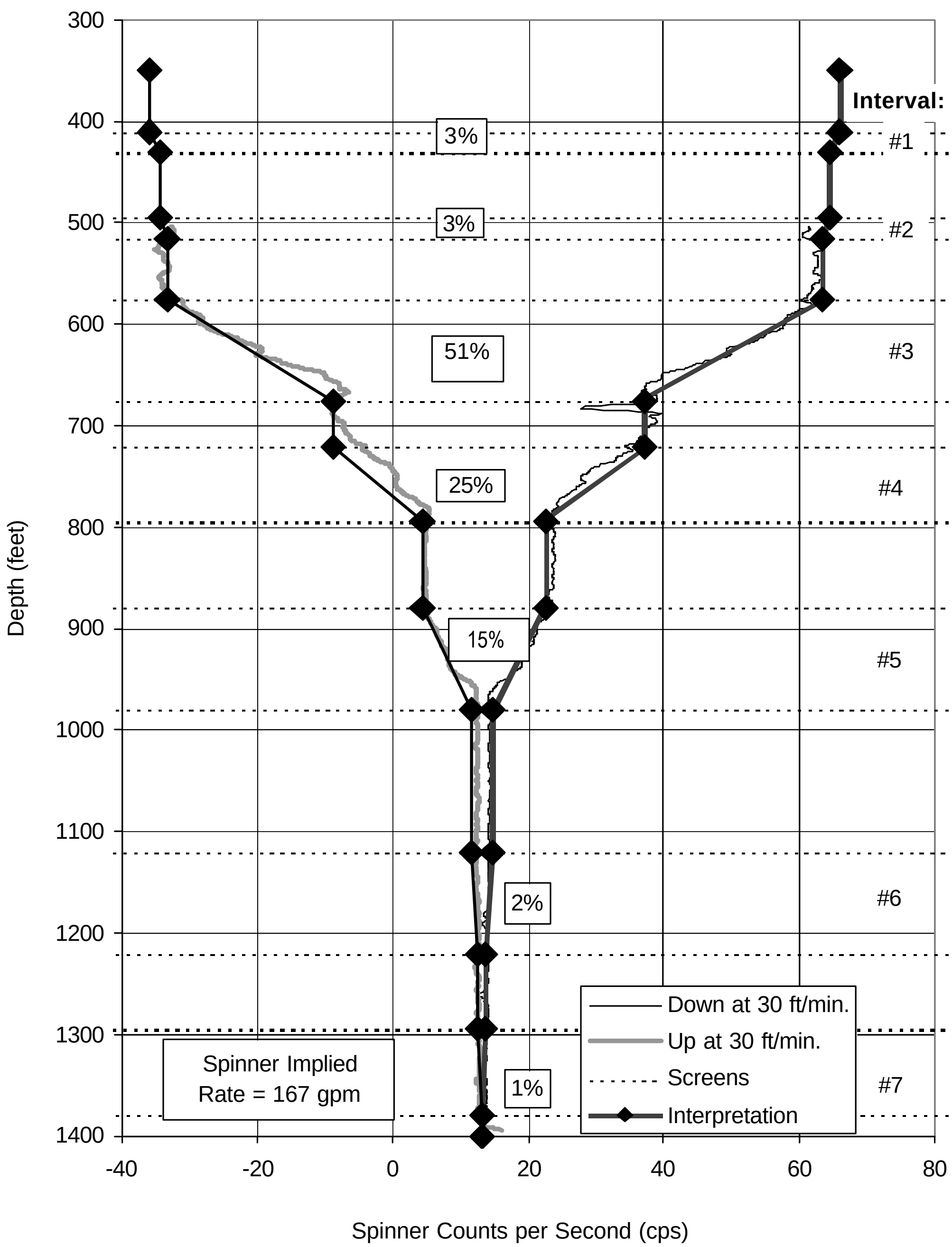


**Figure A8**
**Well NC-EWDP-19D Spinner Survey at Beginning of 48-Hour Pump Test**
**(30 ft/min., May 12, 2000)**

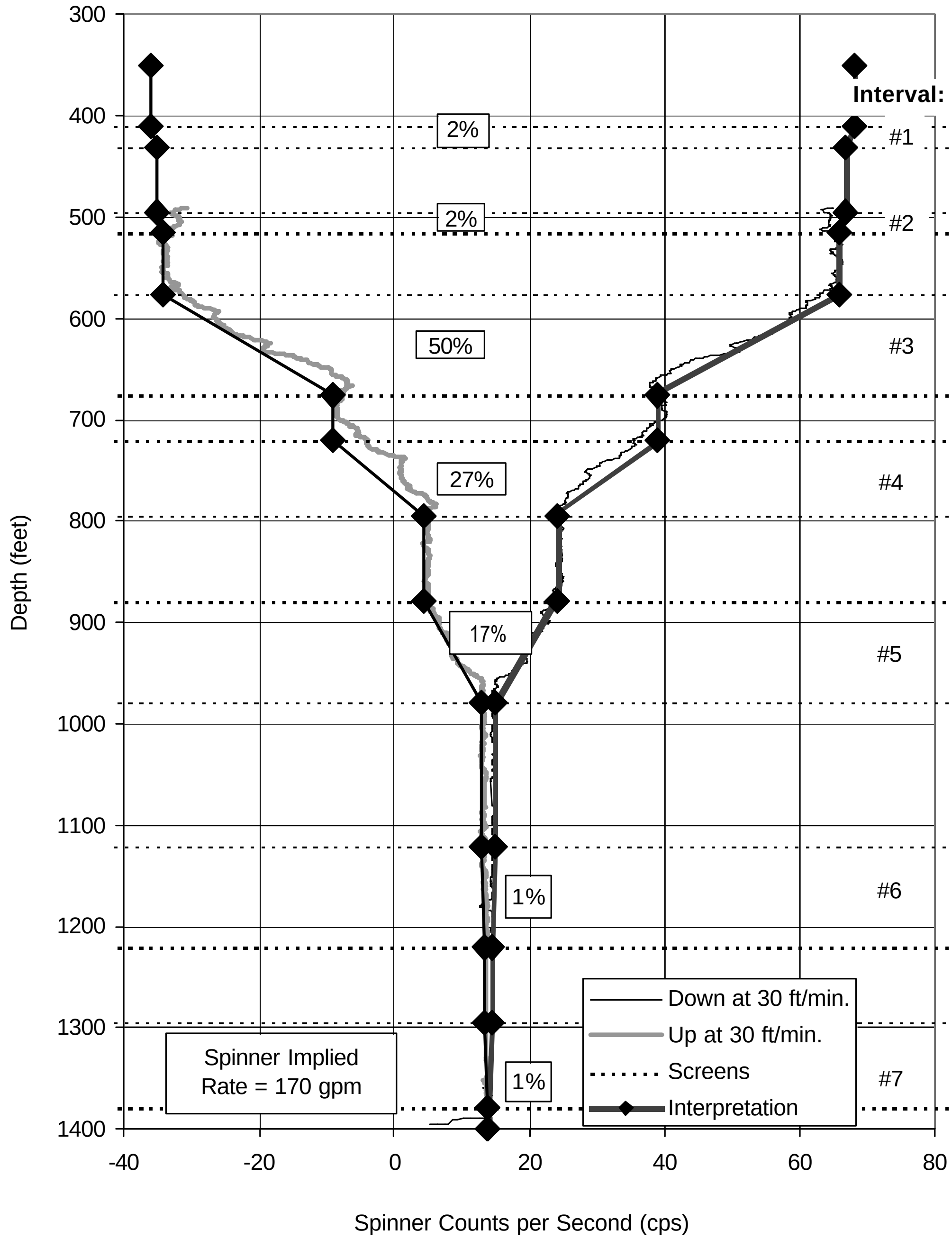


**Figure A9**
**Well NC-EWDP-19D Spinner Survey at Middle of 48-Hour Pump Test**
**(30 ft/min., May 13, 2000)**

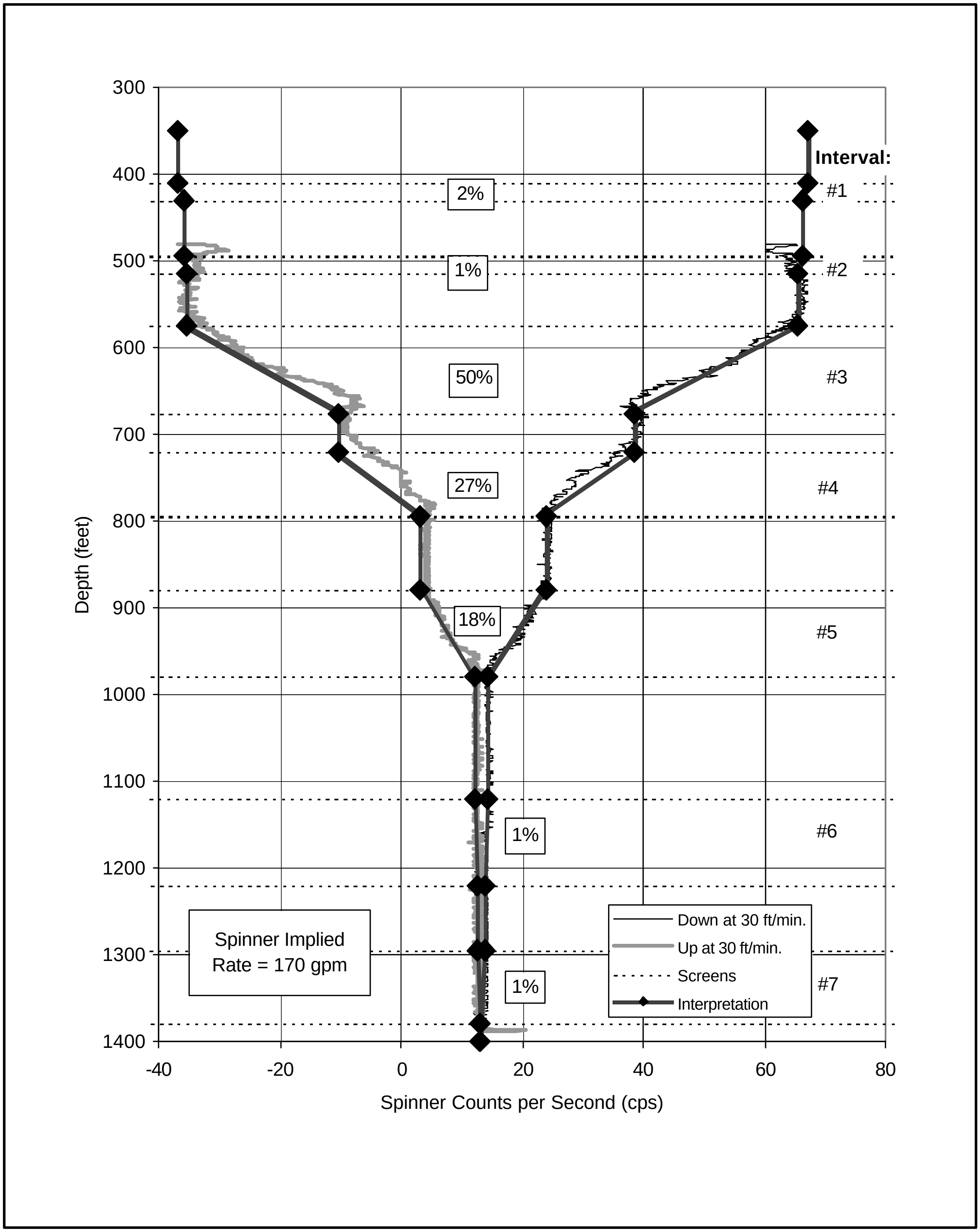


**Figure A10**
**Well NC-EWDP-19D Spinner Survey at End of 48-Hour Pump Test**
**(30 ft/min., May 14, 2000)**

## ATTACHMENT 1
## WELL TEST ANALYSIS QUALITY CONTROL CHECKLIST

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**Attachment 1**

## NYE COUNTY NUCLEAR WASTE REPOSITORY OFFICE

INDEPENDENT SCIENTIFIC INVESTIGATION
YUCCA MOUNTAIN, NEVADA

## WELL TEST ANALYSIS QUALITY CONTROL CHECKLIST

### Test Information

Borehole: EWDP #19D
Interval Tested: Entire Wellbore, 7 Intervals 411'-1380'
Test Date: May 12-15, 2000
Datum: 1.63' above GL for Fluid levels, 361.9' for Probe
Test Type: 48 hr.Pump/Spinner Survey
Observation Well(s)?: EWDP #19P, Washburn 1X
Remarks: Small response seen at 19P, No response seen at Washburn well.

### Source of Data

Pressure File: 19D_P6.CSV
Source: e-mail, J Walker w/ Nye Co.
Type of Pressure Gauge: Westbay #2323 (19D), #1807 (19P)
Units: psia & degrees C
Rate File: Hand Input
Source: Nye County Field Notebook
Type of Flow Meter: Flow Meter Totalizer, Barrel Calibration
Units: GPM, converted to BPD

### Assumptions

| | Value | Units | Source | Comments |
|---|---|---|---|---|
| Height | 485.5 | ft | Spinner Log | Productive Gravel Intervals screens 1-5 |
| Porosity | 25% | | Est | Alluvium |
| Viscosity | 0.7723 | cp | *Saphir* | Software value |
| Wellbore Radius | 0.615 | ft | est | Nominal Bit Size |
| Compressibility | 0.0648 | $psi^{-1}$ | Calculated | Unconfined =0.8/(0.433X 28.5') |
| Compressibility | $5.0 \times 10^{-5}$ | $psi^{-1}$ | Assumed | Confined - Estimated |
| Temperature | 90 | deg F | Assumed | Estimated |
| **S** -Storage Coefficient | 0.2 | ft/ft | Assumed | Unconfined (0.80 X 25%) |

### Results

**Cartesian Plot Analysis:** Attach Plot
Length of Flow: 47.85 hrs
Steady State? No
Pseudo-Steady State? No
Remarks: Data from prior days spinner testing left attached to data file.

**Log-Log Plot Analysis:** Attach Plot
Flow Regimes Noted: (Circle Appropriate Types; Include Flow Regime Plot if Appropriate)
~~Bilinear~~ ~~Spherical~~ Other
Remarks: DD data shows linear flow or near wellbore plugging. Recovery data predominantly radial
Average properties obtained from radial flow period between 2 and 20 hrs. Boundary effects t>20

**Analysis Procedures**

Software Utilized: Kappa-Saphir File Name: 19Dmod1-8.kwt Location: SHS Laptop (Dell)
Software Utilized: Multi Zone Model File Name: 19Dlaplace shs6.xls Location: SHS Laptop (Dell)

**Result Summary (Include Units)**

**T** - Transmissivity: 30,000 gpd/ft
Initial Pressure: 59.9 psi, ( 354.4' DTW)
Permeability: 0.4-4.3 Darcy
Final Flowing Pressure: 51.0 psi, (374.8' DTW)
Skin: +4 combined, varies by zone
Extrapolated Reservoir Pressure: Varies by Zone
Effective Flow Time: 47.85 hours
Radius of Investigation: 3500' at avg. 2.3 darcy
Average Flow Rate: 156 gpm, 5355 bpd
Distance to Boundary: 700'. +/- 400'
Total Flow Volume: 450,000 gal, 10,700 bbls
Effective Storativity for Zero Skin: NA

Remarks:
Spinner survey analysis indicates at least three different static head levels present. Analysis was made using a generalized multi zone model that allows for distinct pressures and boundaries. The kh was allocated to the individual screens using the spinner log. (Assumes similar skins)

Analyzed by: Scott H Stinson, P.E.
Analysis Date: 8/18/2000

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# APPENDIX B

## ANALYSIS OF WELL TEST RESPONSE OF A MULTI-LAYER RESERVOIR WITH PARALLEL SEALING FAULTS AND DIFFERENT INITIAL HEADS

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# APPENDIX B

## ANALYSIS OF WELL TEST RESPONSE OF A MULTI-LAYER RESERVOIR WITH PARALLEL SEALING FAULTS AND DIFFERENT INITIAL HEADS

Following the methodology outlined in Sabet (1991), the relevant equation for radial flow in layer *j* for a well in an infinite reservoir is:

$$\frac{\partial^2 P_j}{\partial r^2} + \frac{1}{r}\frac{\partial P_j}{\partial r} = \frac{f_j\, m_j\, c_j}{k_j}\frac{\partial P_j}{\partial t}$$

$$\textit{Subject To}$$

$$P_j[r,0] = P_{ij}$$

$$P_j[\infty,t] = P_{ij}$$

**Equation B- 1**

The appropriate wellbore conditions are that the wellbore pressure in each layer is the same, and that the total producing rate is equal to the sum of the rates from the individual layers, plus any contribution from wellbore storage:

$$P_w[t] = P_j[r_w,t] - S_j\left(r\frac{\partial P_j}{\partial r}\right)_{r=r_w}$$

$$q[t] = \sum_j q_j[t] - C\frac{d\,P_w}{d\,t} = \sum_j 2p\left(\frac{k\,h}{m}\right)_j\left(r\frac{\partial P_j}{\partial r}\right)_{r=r_w} - C\frac{d\,P_w}{d\,t}$$

**Equation B- 2**

Take the Laplace Transform of these equations and solve for the pressure (or head) in Laplace domain. The diffusivity equation (B-1) in Laplace domain (with domain variable *z*) becomes:

$$\frac{d^2\,\overline{P_j}}{d\,r^2} + \frac{1}{r}\frac{d\,\overline{P_j}}{d\,r} = \frac{f_j\, m_j\, c_j}{k_j}\left(z\,\overline{P_j} - P_{ij}\right)$$

**Equation B- 3**

The general solution is a combination of modified Bessel Functions of order zero:

$$\overline{P_j} = \frac{1}{z}P_{ij} - A_j\, K_0\left[r\sqrt{\frac{z}{h_j}}\right] - B_j\, I_0\left[r\sqrt{\frac{z}{h_j}}\right]$$

**Equation B- 4**

The $I_0$ coefficient vanishes because the pressure is bounded at infinite distance. Using the term $a_j$, we can solve for the rate and well pressure terms as follows:

$$a_j = \frac{r_w}{\sqrt{h_j}}$$

$$\overline{q_j} = 2p\ T_j\ A_j\ a_j \sqrt{z}\, K_1\left[a_j \sqrt{z}\right]$$

$$\bar{q} = -C\left(z\,\overline{P_w} - P_{wo}\right) + \sum \overline{q_j}$$

$$\overline{P_w} = \frac{1}{z} P_{ij} - A_j\, K_0\left[a_j \sqrt{z}\right] - S_j\ A_j\ a_j \sqrt{z}\, K_1\left[a_j \sqrt{z}\right]$$

$$d_j = K_0\left[a_j \sqrt{z}\right] + S_j\ a_j \sqrt{z}\, K_1\left[a_j \sqrt{z}\right]$$

$$\overline{P_w} = \frac{1}{z} P_{ij} - A_j\, d_j$$

$$A_j = \frac{1}{d_j}\left(\frac{1}{z} P_{ij} - \overline{P_w}\right)$$

$$\bar{q} = -C\left(z\,\overline{P_w} - P_{wo}\right) + \sum 2p\ T_j\ A_j\ a_j \sqrt{z}\, K_1\left[a_j \sqrt{z}\right]$$

$$= C\,P_{wo} - C\,z\,\overline{P_w} + \sum \frac{2p\ T_j}{d_j}\left(\frac{1}{z} P_{ij} - \overline{P_w}\right) a_j \sqrt{z}\, K_1\left[a_j \sqrt{z}\right]$$

$$\overline{P_w} = \frac{C\,P_{wo} + \sum \dfrac{2p\ T_j}{d_j \sqrt{z}} P_{ij}\ a_j\ K_1\left[a_j \sqrt{z}\right] - \bar{q}}{C\,z + \sum \dfrac{2p\ T_j}{d_j} a_j \sqrt{z}\, K_1\left[a_j \sqrt{z}\right]}$$

**Equation B- 5**

In the event that parallel sealing faults are present at a distance L from the well, a series of image wells is added to the $d_j$ term to account for the flow barriers:

$$d_j = K_0\left[a_j \sqrt{z}\right] + S_j\ a_j \sqrt{z}\, K_1\left[a_j \sqrt{z}\right] + 2\sum_{m=1}^{\infty} K_0\left[m\,L\sqrt{\frac{z}{h_j}}\right]$$

**Equation B- 6**

The resulting pressure equation is numerically inverted using the Stehfest Algorithm (Stehfest, 1970).

**Nomenclature:**

| | |
|---|---|
| A | Coefficient in Laplace domain solution (see Equation B-4) |
| B | Coefficient in Laplace domain solution (see Equation B-4) |
| C | Wellbore storage constant |
| c | Total compressibility |
| h | Net thickness |
| $I_0$ | Modified Bessel Function of the First Kind, of order zero |
| $K_0$ | Modified Bessel Function of the Second Kind, of order zero |
| $K_1$ | Modified Bessel Function of the Second Kind, of order one |
| k | Formation permeability |
| L | Distance to flow barriers from well |
| m | Summation variable in Equation B-6 |
| P | Reservoir pressure or head |
| $P_i$ | Initial reservoir pressure or head |
| $P_w$ | Wellbore pressure or head |
| $P_{wo}$ | Initial wellbore pressure or head |
| q | Flow rate |
| r | Radial distance from well |
| $r_w$ | Wellbore radius |
| S | Skin factor, dimensionless |
| T | Transmissivity |
| t | Time |
| z | Laplace domain variable |
| $\alpha$ | Coefficient defined in Equation B-5 |
| $d$ | Coefficient defined in Equation B-5 or Equation B-6 |
| $\eta$ | Hydraulic diffusivity, transmissivity divided by storativity |
| $m$ | Fluid viscosity |
| $p$ | 3.14159265358979… |
| $f$ | Porosity |
| subscript j | Denotes layer number |

NOTES:

1. A bar over a variable denotes the Laplace transform of that variable.
2. Any consistent set of units may be used.

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