PNL-8070
UC-403

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F. A. Spane, Jr.

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Prepared for the U.S. Department of Energy
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Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

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PNL-8070

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401. FTS 626-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

PNL--8070

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ABSTRACT

Slug interference testing may be a useful technique for characterizing the hydraulic properties of high conductivity formations where problems associated with disposal of contaminated ground water make pumping tests undesirable. The suitability of the slug interference method for characterizing the unconfined aquifer at the Hanford Site was evaluated in a two-phase investigation.

The first phase consisted of an analytical assessment. Slug interference responses were predicted over the range of conditions expected for the aquifer. Results of the analytical assessment showed that the test can be used for characterizing formations with hydraulic conductivities up to 10^4 ft/d if the observation well is located within 100 ft of the stress well. This is a higher conductivity range than is possible with single well slug tests. The effects of partial penetration, delayed-yield and aquifer anisotropy on expected test results were also evaluated and possible analytical corrections are presented.

The field test evaluation was conducted at a site with two observation wells and a stress well. Results verified the analytical evaluation and gave reasonable values of hydraulic conductivity and storativity. Test design considerations that optimize the observed response are discussed.

SUMMARY

A two-phase investigation was performed to evaluate the applicability of slug interference testing to hydraulically characterize the unconfined aquifer under Hanford Site conditions. The two-phase study included an initial analytical assessment to examine predicted areal slug interference responses over a wide-range of Hanford Site conditions. This was followed by a field test evaluation of the proposed test technique.

Initial results of the analytical assessment and field evaluation for utilizing the test method to support hydraulic characterization investigations on the Hanford Site are encouraging. It would appear to be particularly attractive for providing hydraulic characterization in contaminated areas where the use of standard hydrologic characterization methods (e.g., pumping tests) may not be possible (i.e., due to disposal problems created by the production of contaminated ground water). The evaluation indicates that the slug interference test method can be utilized to provide hydraulic characterization of the unconfined aquifer on the Hanford Site over a range of test conditions that exceeds those of single-well slug tests. High hydraulic conductivity sections (i.e., up to 10^4 ft/d) of the unconfined aquifer can be successfully characterized using this test method if the point of observation of the slug interference (i.e., the observation well location) is located within 100 ft of the point of stress (i.e., the stress well location).

Salient findings of the analytical assessment of slug interference testing with respect to aquifer/test conditions and ranges of hydrogeologic properties representative of the unconfined aquifer at the Hanford Site are outlined below:

Aquifer/Test Conditions

1. Slug interference tests are expected to provide valid characterization information for test intervals that exhibit confined and semi-confined conditions, and for unconfined aquifers that display test responses that are reflective of time-drawdown behavior that is not significantly influenced by delayed-yield (i.e., vertical flow/leakage) effects.

2. Slug interference tests would not be expected to provide valid hydraulic characterization results for small test intervals at the water-table surface. This is due to conditions imposed by the presence of a free-surface boundary, and the damping effect imposed by the water table.

3. To be successfully analyzed with the existing analytical methods (i.e., the computer program presented in Novakowski, 1990), the slug peak or central slug interference "hump" should not be significantly affected by delayed-yield test behavior.

4. The presence of delayed-yield behavior can be discerned by converting the observed slug test data to an equivalent head response that would be predicted for a constant-rate pumping test. Conversion of slug test response data to equivalent head values associated with constant-rate tests can be accomplished following the transformation procedure described in Peres, et al. (1989). The presence of delayed-yield behavior can then be assessed using pressure derivative analysis of the equivalent head response.

5. The effects of partial penetration cause distortion of the radial flow/equipotential pattern that would normally develop during testing within a homogeneous, isotropic aquifer surrounding a fully penetrating stress well. Partial penetration effects cause additional drawdown to occur within the surrounding screened depth interval section of the aquifer, and less drawdown to occur within the non-screened aquifer section.

6. Deviations induced by partial penetration are more significant near the stress well and diminish with distance. Flow patterns during testing are essentially radial for observation well distances ≥ 1.5 times the aquifer thickness; and for practical purposes equations based on fully penetrating stress wells (e.g., Theis equation) provide sufficiently accurate results for observation well distances as small as the aquifer thickness (i.e., $r/b \geq 1$).

7. The effects of vertical anisotropy tend to amplify the drawdown deviations caused by partial penetration. Because of the presence of stratification that is evident to some degree in most sediments, vertical anisotropy would be expected to influence test results obtained within sedimentary aquifers.

8. For a given distance, r, from a partially penetrating stress well, the effects of anisotropy would be the same as that at the distance $r(K_z/K_h)^{1/2}$ within an equivalent isotropic aquifer; where K_z = vertical hydraulic conductivity, and K_h = horizontal hydraulic conductivity. The effects of vertical anisotropy, then, can be accounted for using this relationship, if the ratio of vertical to horizontal conductivity is known or can be estimated for the test formation.

9. To be successfully analyzed with the existing analytical methods (i.e., the computer program presented in Novakowski, 1990), the slug peak or central slug interference "hump" should not be significantly affected by the effects of partial penetration and vertical anisotropy.

10. For observation well distances within a radial distance less than an aquifer thickness away from the stress well (i.e., $r/b < 1$), effects for partial penetration can be accounted for following procedures outlined in Weeks (1969). The effects of vertical anisotropy can also be accounted for (if known) given the relationship presented in Hantush (1961).

Hydrogeologic Property Effects

1. Slug interference tests can be successfully conducted for test intervals with transmissivities ranging up to 10^5 ft²/d. This represents a significant extension of single-well slug test capabilities, which are limited to transmissivities of less than approximately 10^3 ft²/d,

2. High transmissivity test formations are associated with fast slug interference test responses monitored at adjacent observation wells, while lower test interval transmissivities are associated with lagged interference responses.

3. Test formation storativity is the principal hydrogeologic parameter controlling the amplitude of the slug interference response monitored at adjacent points of observation. Because of this dependence, slug interference tests are far superior to single-well slug tests for estimating test formation storativity.

4. Slug interference responses diminish rapidly with distance from the stress well location. However, for the hydrogeologic conditions considered representative for the Hanford Site, discernable slug interference responses should be observable to distances up to 100 ft from the stress well.

5. Wellbore storage at the stress well exerts a significant influence on the amplitude of the slug interference response that propogates through the surrounding test formation. Larger wellbore storage conditions (i.e., greater well casing diameters) cause larger areal slug interference responses. Conversely, larger observation well wellbore storage conditions cause slug interference responses to be lagged and attenuated from predicted responses where observation wellbore storage is negligible.

   To maximize slug interference test responses, therefore, efforts should be made to increase wellbore storage conditions at the stress well and to reduce wellbore storage at observation wells (e.g., through use of downhole packers, etc.).

Results of the field test evaluation were also encouraging and indicate that analyzable slug interference responses were obtained at two nearby observation wells. The monitoring zones of the two observation wells are located approximately 48 and 49 ft, respectively, from the stress well test interval. Slug interference-derived transmissivity estimates obtained for the unconfined aquifer between the stress well and observation wells provided estimates ranging between 145 to 310 ft^2/d; which, based on an aquifer thickness of 52 ft, provides an estimate range of equivalent hydraulic conductivity between 2.8 ft/d and 6.0 ft/d for the aquifer between the stress and observation well locations. This hydraulic conductivity range compares favorably with single-well slug test analysis results obtained at the stress well (i.e., equivalent hydraulic conductivity ranging between 2.3 ft/d and 5.7 ft/d) during interference testing, which was representative of the screened interval test section. Less correspondence is exhibited, however, with previously conducted low-stress, single-well slug tests estimates that were obtained at the observation well locations (i.e., between 0.4 ft/d and 1.0 ft/d, and between 1.4 ft/d and 2.8 ft/d for wells 699-43-41E and -43-41F, respectively). The reason for the lower correspondence in property estimates for the previously conducted single-well slug test is not known; however, it may be related to the significantly smaller range of investigation attributed to the low stress level (approximately 1/10 that utilized during the slug interference test), which was imposed at the observation wells during the previous tests.

Storativity estimates obtained from slug interference test analysis for the observation wells provided similar results ranging between 2.9×10^{-3} and 4.4×10^{-3}. These estimated storativity values suggest semi-confined conditions, but are also within the elastic response range commonly exhibited by unconfined aquifers (e.g., Gambolati 1976; Neuman 1974, 1979).

ACKNOWLEDGMENTS

A number of people collaborated in the conduct of the field slug interference test. In particular, important contributions were made by P. D. Thorne of Pacific Northwest Laboratory (PNL) and R. L. Jones of Westinghouse Hanford Company (WHC). Numerous individuals also provided technical peer review comments of the test analysis results including: C. D. Delaney, R. L. Jackson, and A. G. Law all of WHC, and P. D. Thorne of PNL. The editorial review and guidance provided by W. R. Gorst of PNL are also acknowledged.

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FIGURES

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1.0 INTRODUCTION

Pacific Northwest Laboratory (PNL), in cooperation with Westinghouse Hanford Company, provided hydrologic testing support for a hydraulic characterization investigation that was conducted in the vicinity of the B-Pond facility. Specific PNL work tasks included the design, conduct, and evaluation of a developmental slug interference test method that was conducted as part of hydraulic characterization activities for the newly constructed well 699-43-41G test facility. Results of the field test evaluation were utilized by PNL in its assessment of the applicability of slug interference testing under Hanford Site conditions.

Current RCRA and CERCLA hydrologic characterization studies on the Hanford Site have, in some cases, been restricted by existing site conditions, e.g., contaminated ground water, purge-water disposal problems, high formation permeabilities, etc. The presence of contaminated ground water and, in some locations, areas of extremely high transmissivity (e.g., 200 East Area) greatly diminishes the ability of standard hydraulic test methods to hydrologically characterize subsurface materials. A need clearly exists to develop new test methods and/or to modify currently used techniques, to improve ongoing and future hydraulic characterization investigations on the Hanford Site. Of particular interest are test methods that can be performed rapidly, and that minimize the removal of large quantities of water (i.e., tests that minimize purge-water disposal problems).

One test method that appears to hold particular promise is slug interference testing. This test technique requires a two-well installation: a stress well and an observation well. The general test procedure requires an instantaneous head increase or decrease be initiated at the stress well, and the associated formation response be monitored at the neighboring observation well. Analysis of the monitored pressure response at the observation well provides estimates of the formation transmissivity and storativity. It should be noted that because of the high transmissivity of the unconfined aquifer over much of the Hanford Site, estimates of hydraulic properties commonly can not be obtained solely from stress well (i.e., single well) slug test results.

Slug interference testing has been utilized infrequently in the past, with its use primarily limited to hydraulically characterizing confined formations having low storativities, i.e., between 10^{-4} and 10^{-6} (e.g., Novakowski, 1989). The objective of this study is to evaluate the applicability of slug interference testing for hydraulically characterizing formations under unconfined or semi-confined conditions (i.e., between 10^{-4} and 10^{-1}). The study consists of two major elements: an analytical assessment that evaluates the sensitivity of slug interference responses to a range of hydrogeologic and site geometric conditions, which are representative of the unconfined aquifer on the Hanford Site; and a field test evaluation at a selected site that examines aspects of performing a slug interference test and compares analysis results obtained with previously conducted hydraulic characterization tests.

The analytical assessment element includes the generation of computer-derived, theoretical responses to slug interference tests for a wide-range of hydrogeologic conditions for which this technique may be viable for hydraulic characterization investigations at the Hanford Site. The parameters evaluated include transmissivity, storativity, distance between stress and observation wells, and magnitude of slug stress levels. Results of the computer analysis are included in the report, as well as

- a set of type curve graphs that demonstrate the range of applicability for the test method under Hanford Site conditions,
- a set of type curve graphs that can be used for the design of slug interference tests, and
- a list of recommendations that relate to test method and equipment considerations for performing slug interference tests.

The field test evaluation element of the study consists of assessing the performance of conducting a slug interference test at a previously characterized, multiple-well facility on the Hanford Site. Principal components of this study element include assessing aspects of conducting field slug interference tests, developing procedures for test data reduction and analysis, and the comparison of slug interference analysis results with previously conducted hydraulic characterization tests.

2.0 GENERAL TEST DESCRIPTION

Most simply described, the slug interference test technique requires a two-well installation: a stress well and an observation well. The general test procedure requires a head increase or decrease be initiated at the stress well, and the associated formation response (i.e., the slug interference) be monitored at the neighboring observation well. Analysis of the monitored pressure response at the observation well provides estimates of formation transmissivity and storativity.

Figure 2.1 shows well completion, geometric relationships, and test equipment installations for two different dual-well test system configurations that may be used for conducting slug interference tests at the Hanford Site. The test system configurations shown include locations where the water table is above (Figure 2.1a) or within (Figure 2.1b) the screened interval.

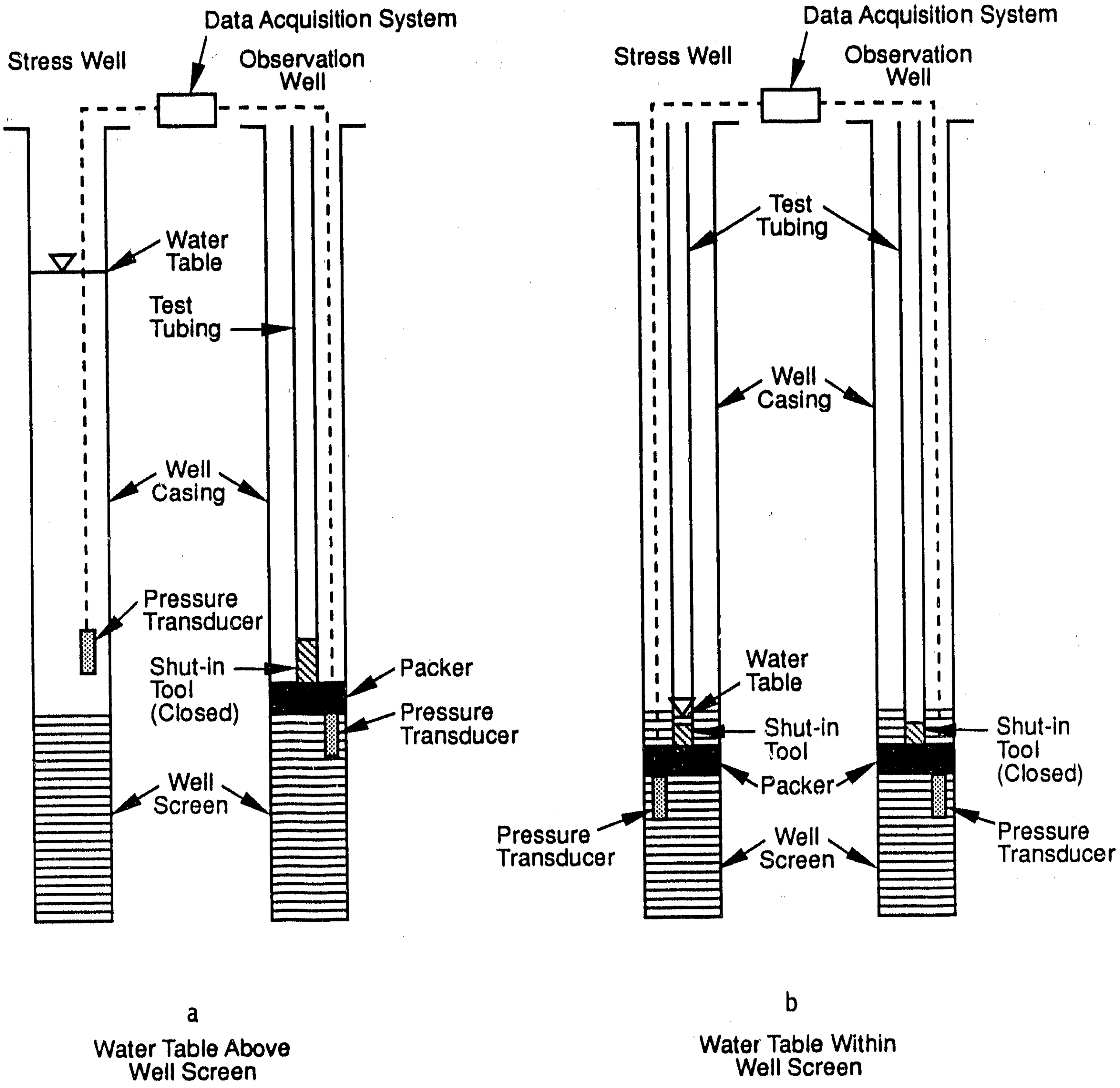

FIGURE 2.1. Well Completion, Geometric Relationships, and Test Equipment Details for Two, Dual-Well Test System Configurations a) Water Table Above Well Screen b) Water Table Within Well Screen

3.0 ANALYTICAL ASSESSMENT

3.1 TEST THEORY

The analytical solution for a slug test response for a stress well with a finite radius within an aquifer containing a semi-compressible fluid, was first presented in Cooper et al. (1967). In their article, type curves were presented that related dimensionless head response, H_D, versus the dimensionless time parameter, β, for various values of the dimensionless storage parameter, α, at the stress well location; where:

$$H_D = H/H_o \tag{1}$$

$$\beta = Tt/r_c^2 \tag{2}$$

$$\alpha = r_w^2 S/r_c^2 \tag{3}$$

where H = observed head at time t, minus pre-test static head level in well

H_o = instantaneous head change applied to well

T = transmissivity of test interval

t = test time

r_c = radius of well casing in the interval over which head change takes place

r_w = effective radius of well within test interval

S = storativity of test interval

The type curves can be used to match slug test response data at the stress well to solve for transmissivity (T) and storativity (S) using Equations (2) and (3), respectively. The Cooper et al. (1967) analytical solution in theory is strictly valid only for a fully penetrating well in a confined aquifer. Their solution, however, yields acceptable results for partially penetrating wells and unconfined aquifer tests provided that the saturated thickness of the unconfined aquifer does not change significantly (Walter and Thompson 1982) and radial flow conditions exist (i.e., no significant vertical flow components). While these conditions may be violated to some degree at the stress well, they should be acceptable at nearby points of observation.

Novakowski (1990) presented a FORTRAN program that can generate slug interference test type curves based on the analytical solutions and boundary conditions presented in Cooper et al. (1967). As stated in Novakowski (1990), the analytical solutions included in the program are given in the Laplace domain and are numerically inverted to generate data for the type curves. A modified version of the program was utilized to assess the applicability of slug interference testing for hydraulic characterization studies on the Hanford Site. The original program was modified to allow increased density of generated type-curve data points, to extend the dimensionless head lower limit, and to provide additional test description information in the computer file output. A detailed description of the original program and its use is contained in Novakowski (1990).

To assess its validity, the modified program version was utilized and compared with slug test type-curve examples presented in Cooper et al. (1967) for the stress well and Ramey et al. (1975) for slug interference responses. The test comparisons are presented in Appendix A. As indicated, the modified Novakowski (1990) program produced test results that were in close agreement with the aforementioned published type-curve data (i.e., within 3 or 4 significant decimal places for dimensionless head, H_D).

3.2 APPLICABILITY OF TEST METHOD UNDER HANFORD SITE CONDITIONS

To assess the applicability of the slug interference test method under Hanford Site conditions, a set of hydraulic property and geometric relationships were assumed. Table 3.1 lists the assumed parameter ranges used in the assessment. The range for hydraulic conductivity was selected from reported values in Gephart et al. (1979) and DOE (1988) for the more permeable sections of the unconfined aquifer at the Hanford Site. The range for storativity was obtained from multiple-well pumping test results for various stratigraphic formations of the unconfined aquifer (e.g., Hanford, middle Ringold, basal Ringold, etc.) as reported in DOE (1988).

TABLE 3.1. Parameter Ranges Used for Assessing the Applicability of Slug Interference Tests Under Hanford Site Conditions

Parameter	Range
Transmissivity (T)	10^3 to 10^5 ft²/d
Hydraulic Conductivity (K)	10^2 to 10^4 ft/d
Storativity (S)	10^{-1} to 10^{-4}
Test Interval Thickness (b)	10 ft
Stress Well Radius (r_w)	4 in.
Stress Well Casing Radius (r_o)	2 in.
Observation Well Distances (R)	10, 25, 50, 100 ft
Hydraulic Stress Level (H_o)	25 ft
Hydraulic Head Detection Limit	0.025 ft ($H_D = 0.001$)
Test Time Detection Limit	1 sec

Test interval thickness, well diameter, and well casing diameter values were taken from common well completion design specifications of RCRA and CERCLA programs. Observation well distance values were arbitrarily selected, but are considered representative of several cluster monitoring well facilities on the Hanford Site. The hydraulic stress level of 25 ft was selected for the test evaluation as the minimum, practical slug stress level to be used during slug interference testing. For higher stress levels, proportionally higher interference responses would be exhibited. Hydraulic head and test time detection limits were arbitrarily selected, but are consistent with test equipment and data acquisition systems utilized for hydraulic characterization studies on the Hanford Site.

Results of the sensitivity analyses for various specified parameter values, using a modified version of the Novakowski program, are presented in the Subsections 3.2.3 through 3.2.6.

3.2.1 Hanford Site Unconfined Aquifer

The unconfined aquifer on the Hanford Site consists of glaciofluvial deposits of the Hanford formation (informal designation) and/or fluvial and lacustrine deposits of the Ringold Formation. Hydraulic conductivities for the two formations comprising the unconfined aquifer vary considerably across the Site. Units of the overlying Hanford formation usually exhibit higher hydraulic conductivity values, which range between 10^2 and 10^4 ft/d, while members of the underlying Ringold Formation range between 10^{-1} and 10^3 ft/d (Gephart et al. 1979). Over a large part of the Hanford Site, the Hanford formation lies above the water table. However because of its inherently higher permeability, it represents a significant hydrogeologic unit for the transport of contaminated ground water within the unconfined aquifer in those regions where it is saturated (e.g., in the 200 East Area).

As suggested by the wide-range in hydraulic conductivity values, the unconfined aquifer is heterogeneous in nature and generally consists of alternating layers of sands, gravels, silts and clays. The presence of silts and clays within the aquifer (especially within the Ringold Formation) can cause ground-water conditions to be locally semi-confined in nature. For these reasons, storativity values obtained from multiple-well pumping tests for the unconfined aquifer are reported to range between 2×10^{-4} to 2×10^{-1} (DOE 1988).

The program (Novakowski 1990) used to assess the applicability of slug interference testing in this report (as well as other analytical methods based on the Theis equation, e.g., Cooper et al. 1967), was developed specifically for confined aquifer conditions. The primary difference in how an unconfined aquifer (i.e., in comparison to a confined aquifer) responds during testing is related to the manner ground water is released from the aquifer to the well, and the fact that the upper flow boundary (i.e., water table) is not fixed as is the case in the confined aquifer situation.

For confined aquifers, ground water is released from elastic storage and by compression of the aquifer matrix, while for unconfined aquifers ground water is produced from both elastic storage and by gravity drainage from the lowering water-table surface (see also Section 3.2.4). As test time increases the elastic storage, S_e, response becomes less important within the unconfined aquifer, with ground-water production being controlled largely by its specific yield, S_y. The early elastic storage response within an unconfined aquifer during early test times is well documented (e.g., Gambolati 1976; Neuman 1974, 1979).

The fact that unconfined aquifers produce ground water from two sources of storage and that the water table is not fixed during testing, causes unconfined aquifer pumping tests to depart from that predicted by the Theis equation. Walton (1960) states that unconfined aquifer constant rate pumping tests are characterized by the presence of three distinct segments on a time-drawdown curve. In the first segment, the aquifer reacts as would a confined aquifer, with ground water produced through the expansion of water and compaction of the aquifer matrix. Drawdowns during this segment follow that predicted using the Theis equation, with storativity equal to only its elastic storage component (S_e). During the second segment of the drawdown curve, the rate of drawdown decreases as gravity drainage (i.e., vertical ground-water flow components) become important within the aquifer. Gravity drainage (also referred to as delayed yield) within the unconfined aquifer causes the time-drawdown curve to deviate significantly from that predicted by the Theis equation, since the gravity drainage/vertical ground-water flow components "reflect the presence of recharge in the vicinity of the pumped well". During the third segment gravity drainage effects become insignificant and radial flow conditions are once again predominant within the aquifer. Drawdowns during this segment once again follow that predicted using the Theis equation, with storativity equal to its combined elastic storage component, S_e, and specific yield, S_y.

The influence and duration of the first two segments of the time-drawdown curve are reported by Neuman (1972) to be largely controlled by the parameter $\sigma = (S_e\ b)/S_y$; where b equals the aquifer thickness. The smaller the value of σ, the more pronounced the effects of gravity drainage (i.e., the second segment), become. As σ approaches 0, the first segment disappears leaving only the second and third segments of the curve. Conversely, as σ

approaches infinity, the second segment vanishes and the third segment becomes coincident with the first segment of the time-drawdown curve.

This characteristic unconfined aquifer test behavior displayed during constant-rate pumping tests is shown in Figure 3.1 for observation well, time-drawdown data presented in Lohman (1972). Also shown are predicted Theis type curve responses that were generated using the modified Novakowski (1990) program, based on aquifer property estimates and geometric relationship information also provided in Lohman (1972). Figure 3.1 clearly depicts the three-segment time-drawdown pattern previously discussed, and indicates that early- (first segment) and late-time (third segment) behavior can be adequately described when S_e and S_y are used, respectively, with the Theis equation.

Distance-drawdown responses within an unconfined aquifer during a constant-rate pumping test can also be "visualized" in terms of the three-segmented response pattern described above. Gambolati (1976) states that at any time during testing, three cylindrical regions around the stress well can be recognized within the aquifer. Within the inner region, flow is dominated by radial flow conditions for which the Theis solution is valid using a storativity value equal to $S_e + S_y$. In the middle region, ground-water flow components are both horizontal and vertical (i.e., the delayed-yield flow region), for which the Theis solution is not valid. In the outer region, ground-water flow is predominantly radial with the Theis solution valid using a storativity value equal to its elastic storage component (S_e).

The cylindrical, vertical boundaries separating the three "idealized" regions propagate laterally with time away from the stress well location. At the beginning of the test, however, the boundaries are coincident at the well location, with only the third region (i.e., radial flow with storativity equal to S_e) existing and surrounding the well. Gambolati (1976) concludes that an unconfined aquifer responds like an artesian (confined aquifer) at the beginning of the test, and at any time during the test there exists an outer region surrounding the stress well that reacts elastically like an artesian aquifer.

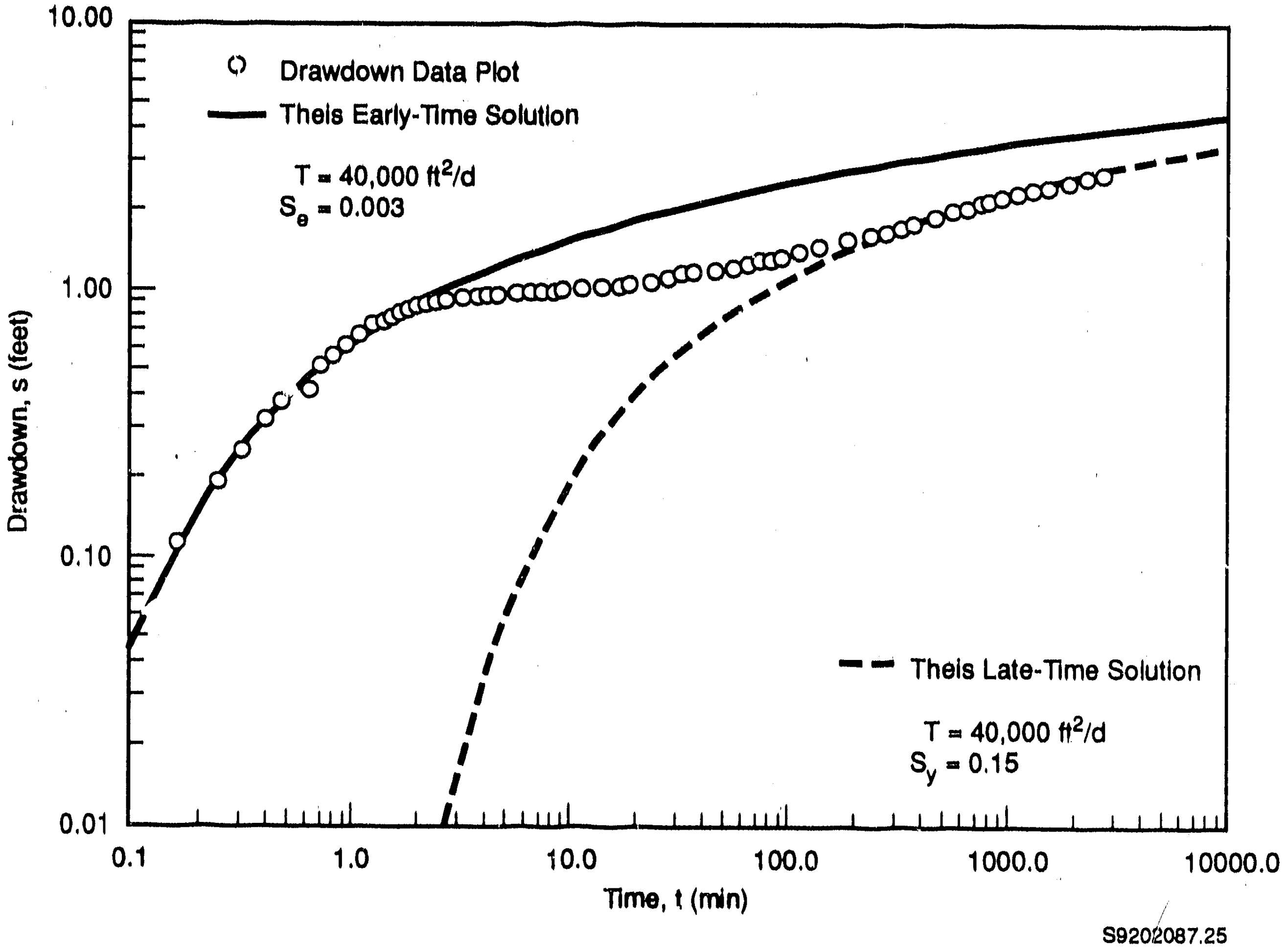

FIGURE 3.1. Characteristic Time-Drawdown Behavior for Unconfined Aquifer Conditions, During a Constant-Rate Pumping Test. (Test data taken from Lohman 1972).

On the basis of the preceding discussion, slug interference tests are expected to provide valid characterization information for test intervals that exhibit confined and semi-confined conditions, and for unconfined aquifers that display test responses that are reflective of time-drawdown behavior that is not significantly influenced by delayed-yield (i.e., gravity flow/vertical flow components) effects. Slug interference tests, however, would not be expected to provide valid hydraulic characterization results for small test intervals at the water-table surface. This is due to conditions imposed by the presence of a free-surface boundary, and the damping effect imposed by the water table.

To be successfully analyzed with existing analytical methods (i.e., the computer program presented in Novakowski, 1990), the slug peak or central slug interference "hump" should not be significantly affected by delayed-yield test behavior. The presence of delayed-yield behavior can be discerned by converting the recorded slug test data to an equivalent head response that would be observed for a constant-rate pumping test. Conversion of slug test response data to equivalent head values associated with constant rate tests can be accomplished following the transformation procedure described in Peres, et al. (1989). The presence of delayed-yield behavior can then be assessed using pressure derivative analysis of the equivalent head response. A more detailed description of the conversion procedure and use of pressure derivative diagnostic methods is presented later in Section 4.4.

3.2.2 Partial Penetration and Vertical Anisotropy

The theoretical basis for the program presented in Novakowski (1990) assumes that the stress and observation wells completely penetrate a homogeneous and isotropic aquifer. The program, therefore, cannot be rigorously used to analyze test results having conditions of partial well penetration and vertical anisotropy (i.e., the ratio of vertical to horizontal hydraulic conductivity). These conditions can exert discernable effects and cause departure of test responses from those based on fully penetrating wells within homogeneous, isotropic aquifers.

The effects of partial penetration cause distortion of the radial flow/ equipotential pattern that would normally develop during testing within a homogeneous, isotropic aquifer surrounding a fully penetrating stress well. To illustrate its effect, Figure 3.2 shows the areal deviation in drawdown equipotential lines and flow lines that develop during a constant rate pumping test for a stress well that penetrates the lower 30 percent of a confined aquifer. As shown, partial penetration effects cause additional drawdown to occur within the surrounding screened depth interval section of the aquifer, and less drawdown to occur within the non-screened aquifer section, i.e., the

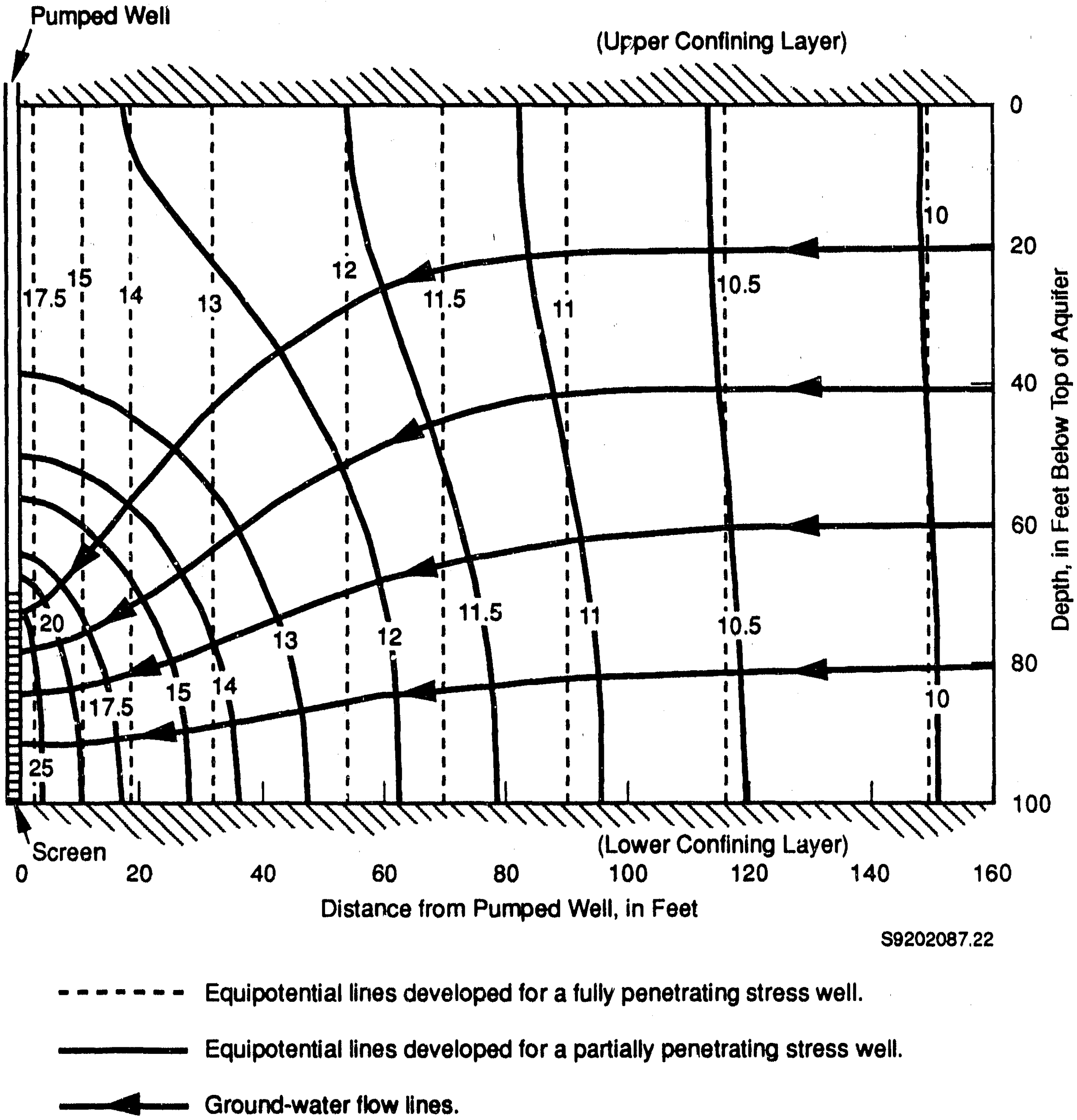

FIGURE 3.2. Affects of a Partially Penetrating Pumping Well Completed in the Lower 30 Percent of a Confined Aquifer. (Adapted from Weeks 1969).

upper 70 percent of the aquifer. Deviations induced by partial penetration are more significant near the stress well and diminish with distance. Hantush

(1961) states that the flow pattern during testing is essentially radial for observation well distances ≥ 1.5 times the aquifer thickness; and for practical purposes equations based on fully penetrating stress wells (e.g., Theis equation) provide sufficiently accurate results for observation well distances as small as the aquifer thickness (i.e., $r/b = 1$). This is provided that $u < 0.1\ (r/b)^2$; where $u = (r^2\ S)/4(T\ t)$.

For observation wells located within a ratio distance of $r/b \leq 1.5$, the effects of partial penetration during tests can be accounted for following techniques presented by Weeks (1964, 1969), which are based on relationships originally presented in Hantush (1961). The correction methods were developed for constant-rate pumping tests, however, they are assumed to be applicable for slug interference test response as described in Cooper et al. (1967) and Novakowski (1990); since these methods are based on the Theis equation.

Weeks (1969) states that the effects of vertical anisotropy also tend to amplify the drawdown deviations caused by partial penetration. Because of the presence of stratification that is evident to some degree in most sediments, vertical anisotropy would be expected to influence test results obtained within sedimentary aquifers. Neuman (1972) also reports that for most sedimentary unconfined aquifers, where the vertical anisotropy ratio is less than 1 (i.e., $K_z/K_h < 1$), the effects of elastic storage and delayed yield (i.e., gravity drainage, as discussed in Section 3.2.1) are accentuated during the aquifer test response.

Hantush (1964) reports that at a given distance, r, from a partially penetrating stress well, the effects of anisotropy would be the same as that at the distance $r(K_z/K_h)^{1/2}$ within an equivalent isotropic aquifer; where K_z = vertical hydraulic conductivity, and K_h = horizontal hydraulic conductivity. The effects of vertical anisotropy, then, can be accounted for using this relationship, if the ratio of vertical to horizontal conductivity is known or can be estimated for the test formation.

On the basis of the preceding discussion, slug interference tests can provide valid characterization information for test intervals that have partially penetrating stress wells and exhibit anisotropic behavior. This is provided that corrections are applied to observation wells within a radial distance less than an aquifer thickness (i.e., r/b < 1) away from the stress well (following procedures provided in Weeks 1964, 1969), and the vertical anisotropy within the aquifer is known and corrected for using the relationship presented in Hantush (1964).

3.2.3 Transmissivity

Figure 3.3 shows the predicted response of a slug test at the stress well for transmissivities (T) ranging between 10^3 to 10^5 ft²/d (Note: T = Kb; where K = 10^2 to 10^4 ft/day and b = 10 ft). As indicated, only slug test responses for transmissivities below 10^4 can be discerned at the stress well for a storativity value of 10^{-3} (i.e., assuming a 1 s detection limit). This corroborates the upper limit reported by Lohman (1972) for slug testing (i.e., single-well tests) of approximately 7,000 ft²/d. However, because of adverse borehole conditions (e.g., turbulent flow, etc.) and data recording

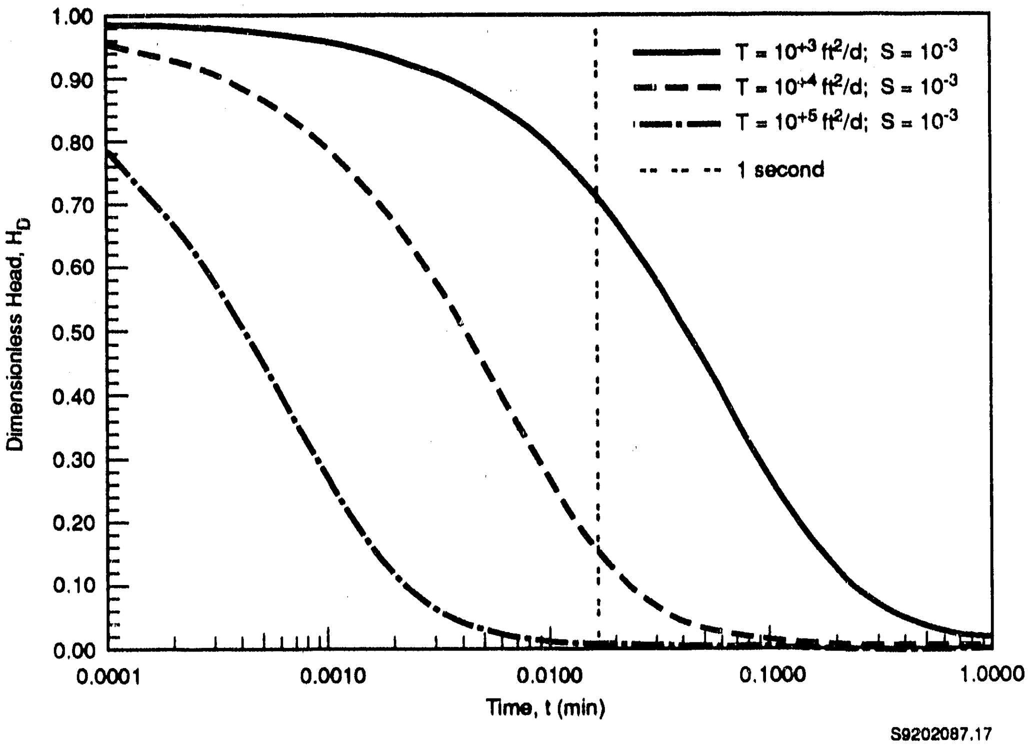

FIGURE 3.3. Predicted Slug Test Response at the Stress Well for a Transmissivity Range 10^3 to 10^5 ft²/d, and a Storativity of 10^{-3}

requirements imposed by higher transmissivity formations, a practical upper range for slug testing at single wells is about 10^3 ft^2/d.

While analyzable slug test responses at the stress well are limited to test formations with transmissivities of 10^3 ft^2/d or less, Figure 3.4 indicates that slug interference responses for transmissivities of 10^5 ft^2/d or less are readily discernible at a distance of 10 ft from the stress well location. As indicated in the figure, for a given observation point location, transmissivity has no effect on the magnitude of test response, but does exert a strong influence on the predicted slug interference response time, causing the interference response to shift horizontally on the plot. High test zone transmissivities are associated with fast test responses, while lower test interval transmissivities are associated with lagged interference responses.

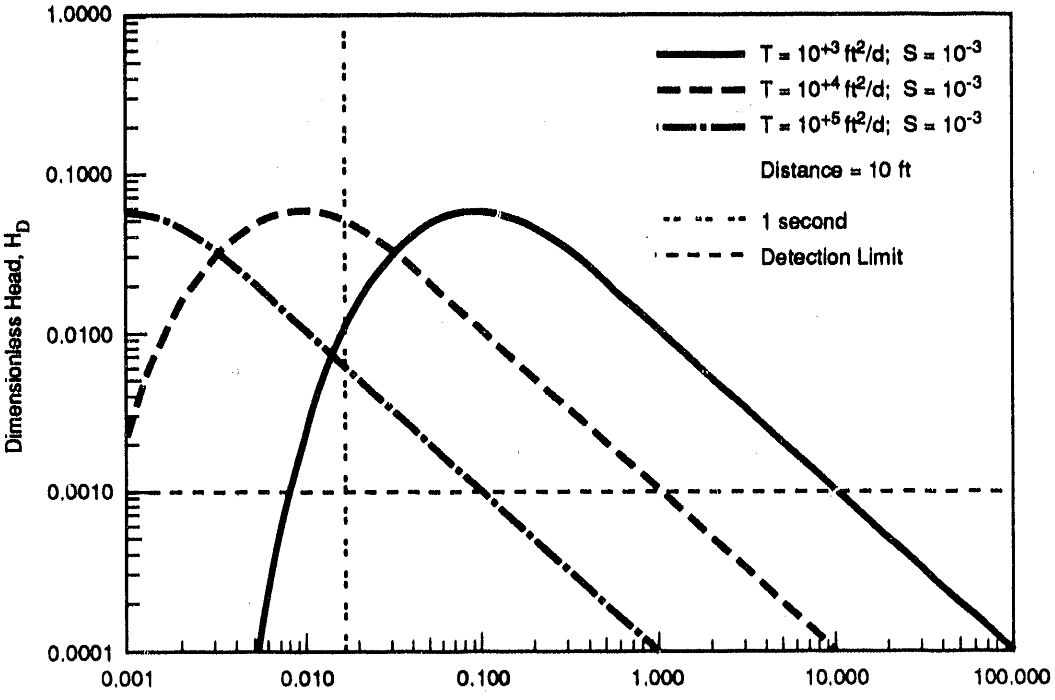

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FIGURE 3.4. Predicted Slug Interference Response at a Radial Distance of 10 ft from the Stress Well, for a Transmissivity Range 10^3 to 10^5 ft^2/d and a Storativity of 10^{-3}

3.2.4 Storativity

Storativity, S, is a dimensionless hydrologic parameter that indicates the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in head. For confined aquifers the storativity is primarily related to the compressibility of the aquifer matrix and elasticity of the contained ground water. Because compressibility and elasticity values for aquifer materials and water, respectively, are inherently small, storativities for confined aquifers are low and generally range between 10^{-5} and 10^{-3} (Heath 1983). In contrast, storativities for unconfined aquifers consist of two components; an elastic component, S_e, (as described previously for confined aquifers) and the specific yield, S_y. Because of the small value associated with the elastic storage component, long-term production of ground water from unconfined aquifers is primarily determined by its specific yield, which is reported to usually range between 0.1 and 0.3 (Heath 1983). The effect of the elastic storage component on unconfined aquifer response, however, is reported to play an important role in test response within unconfined aquifers and must be accounted for (e.g., Gambolati 1976; Neuman 1974, 1979).

Previously reported slug interference tests have been limited primarily to tests conducted in confined aquifers and/or fractured rock formations, with storativity values $\leq 10^{-4}$. These conditions are not representative of hydrologic conditions for the unconfined aquifer at the Hanford Site. In this section the affects of higher formation storativity, which are more representative of reported unconfined aquifer conditions at the Hanford Site (i.e., between 10^{-1} and 10^{-4}) are examined; both for the stress and observation well locations.

Figure 3.5 shows the predicted response of a slug test at the <u>stress well</u> for a transmissivity of 10^3 ft²/d for various values of storativity (S), ranging from 10^{-1} to 10^{-4}. As indicated in the figure, type-curve responses for storativity values 10^{-2} and less are very similar in shape. This similarity in type-curve shape prompted Cooper et al. (1967) to conclude that:

> "... because the matching of the data plot to the type curves depends on the shapes of the type curves, which differ only slightly when α differs by an order of magnitude, a determination of S by this method has questionable reliability."

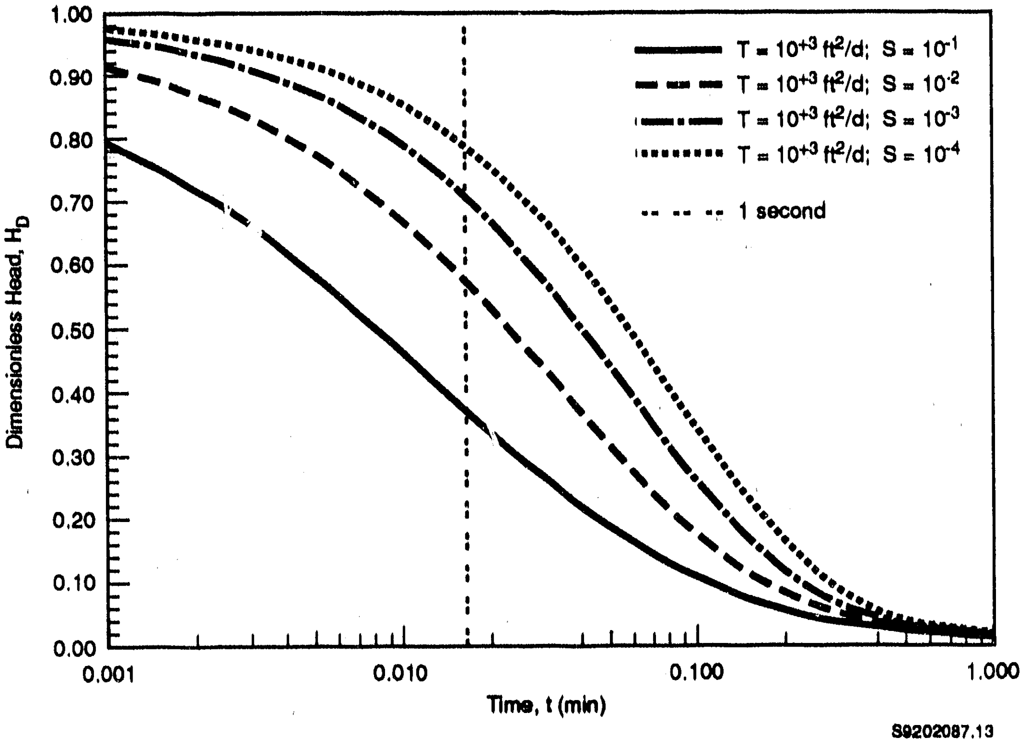

FIGURE 3.5. Predicted Slug Test Response at the Stress Well for a Storativity Range 10^{-1} to 10^{-4}, and a Transmissivity of 10^3 ft²/d

The ambiguity in determining the storativity is greatly reduced, however, when a slug interference test is observed in a nearby observation well. Figure 3.6 shows the predicted slug test response at a radial distance of 10 ft from the stress well, for a storativity range of 10^{-1} to 10^{-4} and a transmissivity of 10^3 ft²/d. In contrast to the slug response at the stress well, the shape of the slug interference response (i.e., the amplitude of the slug response) at the observation well is strongly influenced by the storativity of the aquifer. For this reason, slug interference testing can be utilized to obtain a more precise estimate of storativity for the interval tested.

3.2.5 Radial Distance

Figure 3.7 shows the predicted maximum slug interference test response as a function of radial distance from the stress well location: for a storativity, S, range 10^{-1} to 10^{-4}, and a wellbore radius, r_w, of 0.3333 ft. As

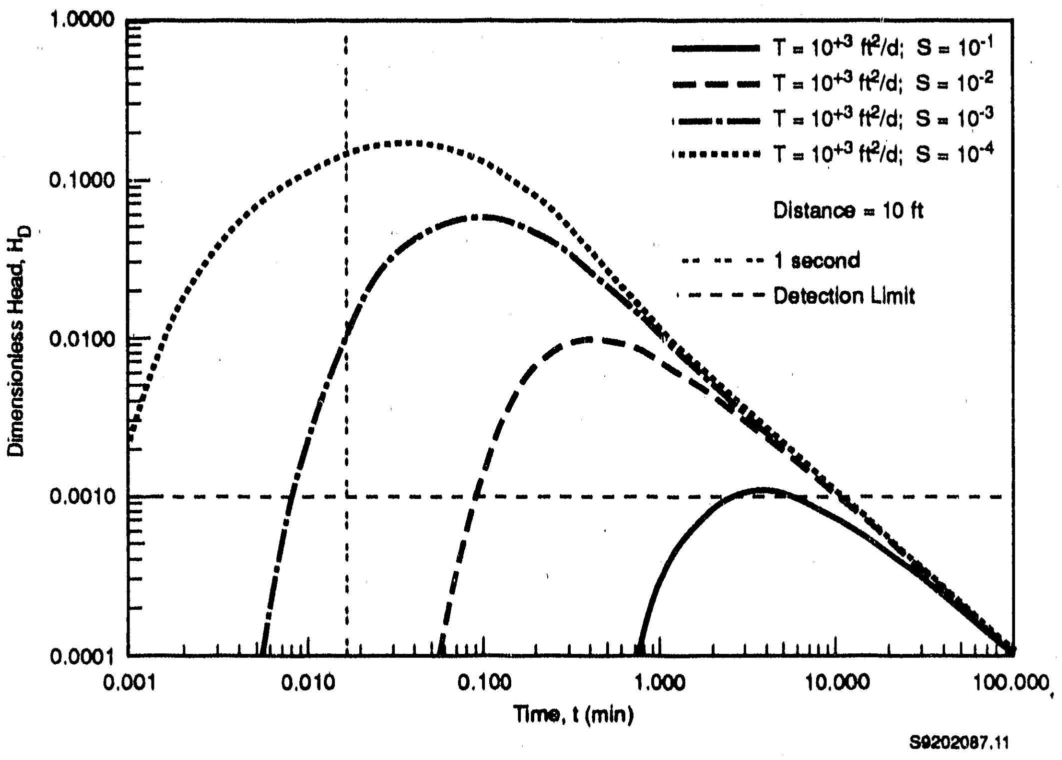

FIGURE 3.6. Predicted Slug Interference Response at a Radial Distance of 10 ft from the Stress Well, for a Storativity Range 10^{-1} to 10^{-4} and a Transmissivity of 10^3 ft²/d

expected, the figure shows that the ability to detect a response is enhanced the closer the observation well is located to the stress well and the lower the storativity value is of the geologic material. Information presented in the figure also indicates that for the storativity range considered to be representative of most unconfined aquifer conditions on the Hanford Site (i.e., 10^{-2} to 10^{-3}), that discernable slug interference responses should be observable to maximum distances of between 30 to 100 ft surrounding the stress well.

It should be restated here that transmissivity of the test formation does not influence the slug amplitude observable with distance from the point of stress application. Transmissivity does, however, (as discussed in Section 3.2.3) control how rapidly the slug response propagates away from stress well.

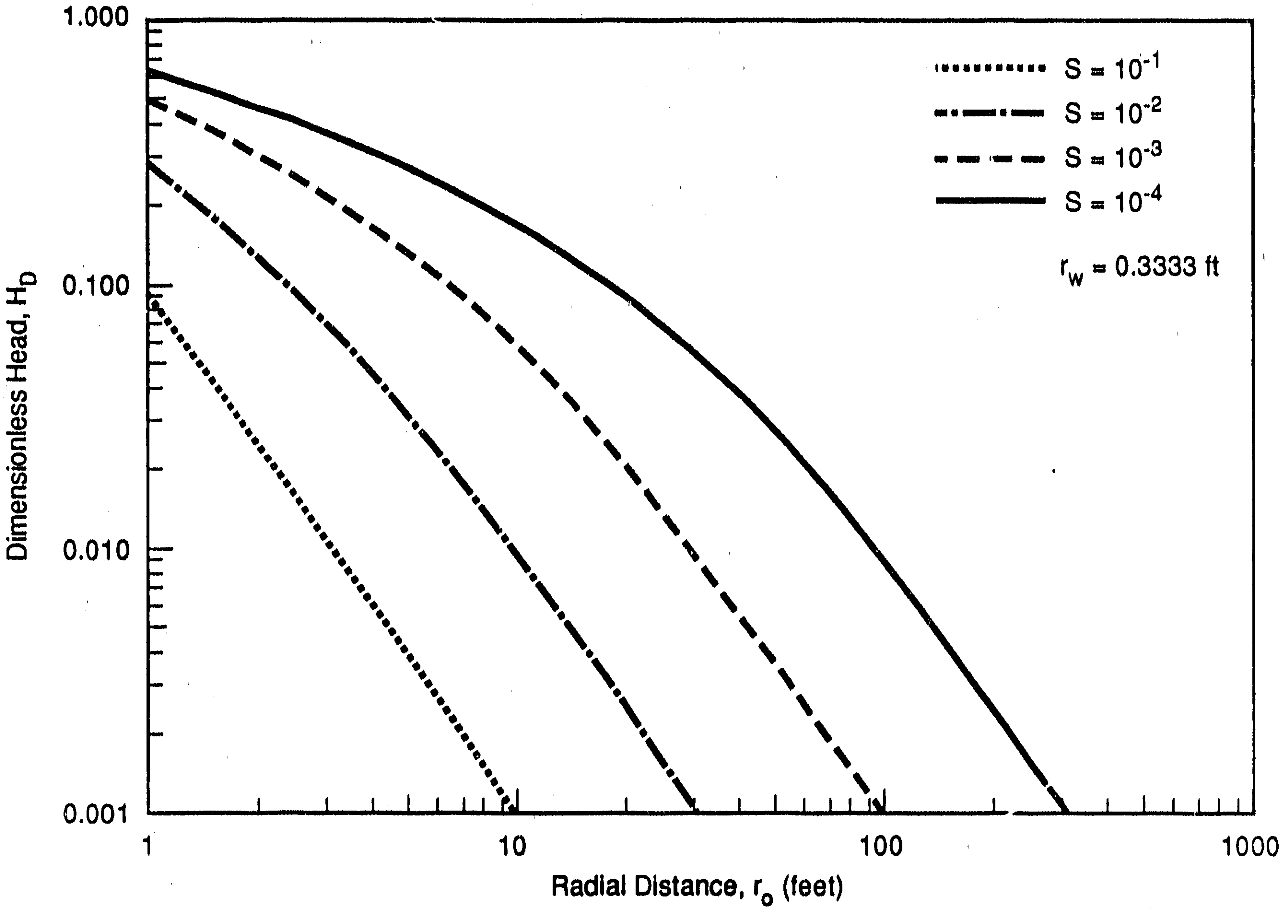

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FIGURE 3.7. Predicted Maximum Slug Interference Response as a Function of Radial Distance from the Stress Well Location, for Storativity Values, S, 10^{-1} to 10^{-4}

3.2.6 Observation Wellbore Storage

The previous discussion assumes that the wellbore storage of the observation well, C_{Do}, is negligible in comparison to that of the stress well, C_{Ds} (i.e., $C_{Do} \leq 0.1C_{Ds}$). Significant observation wellbore storage tends to cause the well response to be lagged (i.e., delayed) and attenuated from the predicted response, which assumes C_{Do} is negligible. This effect is shown diagrammatically in Figure 3.8. As indicated by Novakowski (1989), the shape of the curves for C_{Do} equal to C_{Ds} are more "peaked and distinctive" in comparison to the curves where C_{Do} is negligible. Figure 3.8 also indicates,

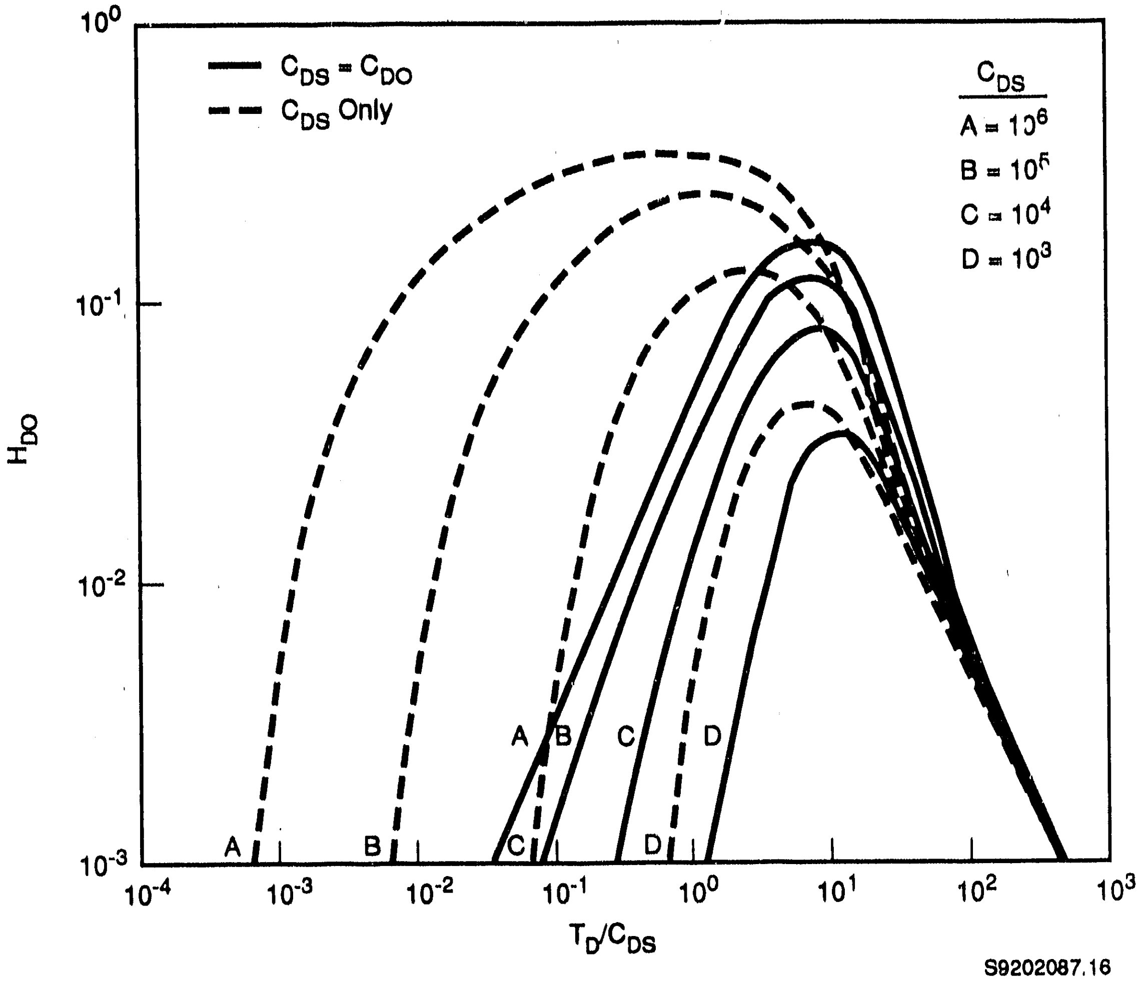


FIGURE 3.8. Comparison of Predicted Slug Interference Response for a Family C_{Ds} Type Curves, for the Case Where $C_{Do} << C_{Ds}$ and $C_{Do} = C_{Ds}$. (Adapted from Novakowski 1989).

however, that the difference in response curves diminishes appreciably as the wellbore storage value at the stress well, C_{Ds}, decreases. This suggests that only minor differences in predicted and observed responses would be expected for the wellbore storage values considered in this study (i.e., $C_{Ds} \approx 1$ to 10^3).

Novakowski (1989) presents a graphical method for analyzing slug interference responses for the case where wellbore storage at the observation well is not important (i.e., $C_{Do} << C_{Ds}$), as well as significant (i.e., $C_{Do} = C_{Ds}$).

The reader is instructed to consult Novakowski (1989) for a detailed description of the analysis procedure. It should noted that Novakowski's graphical method could not be used to analyze results of the field test evaluation presented in Section 4.4, because the graphical type curve relationships did not cover conditions that existed for the test.

3.3 TEST METHOD CONSIDERATIONS

3.3.1 Test Design

To serve as guidance for the design of field slug interference tests, a set of type-curve plots are presented in this report section. The test design type curves are expressed in dimensionless parameters to provide a broader means of application. To facilitate their use, the following definitions for the dimensionless parameters are provided:

Dimensionless Radial Distance

$$R_D = r_o/r_w \tag{4}$$

Dimensionless Time

$$T_D = (T\ t)/(S\ r_w^2) \tag{5}$$

Dimensionless Wellbore Storage

$$C_D = C_s/(2\pi\ r_w^2\ S) \tag{6}$$

where,

$$C_s = \pi\ r_c^2 \tag{7}$$

Dimensionless Head, H_D, is defined in Equation (1), and for minimum detection limit assessment was arbitrarily selected to be equal to 0.001.

Figure 3.9 shows the predicted maximum dimensionless head response with radial distance away from the stress well for the range of wellbore storage

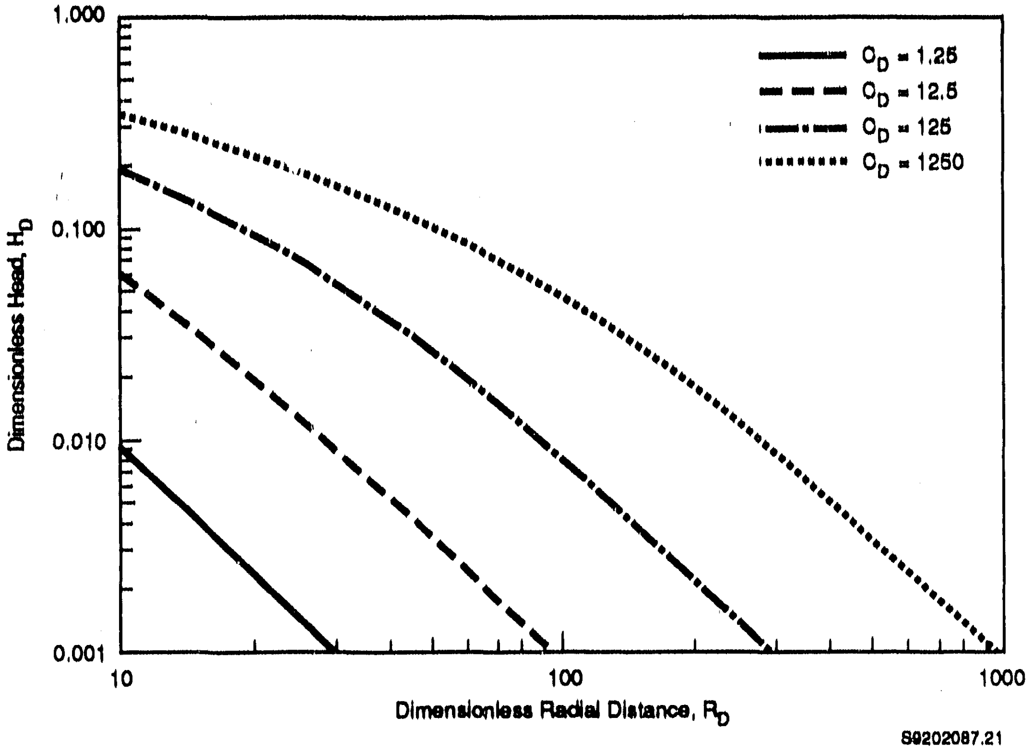


FIGURE 3.9. H_D Versus R_D Type Curves for C_D Values: 1.25, 12.5, 125, and 1250

constants considered in this study (i.e., C_D = 1.25 to 1250 for S = 10^{-1} to 10^{-4}). For the well and casing radii listed in Table 1, the wellbore storage constant range represents test interval storativity values of 10^{-1} to 10^{-4}, respectively (see Appendix A). The maximum observable response that can be expected at a prescribed observation well distance can be obtained by selecting the most representative C_D curve for the intervening test formation, and multiplying the indicated dimensionless head response by the estimated stress level to be applied at the stress well. For example: for a stress well radius of 4 in., at an observation well distance of 25 ft, a C_D type curve of 125 (i.e., a storativity of 10^{-3}) and an applied stress level of 30 ft of fluid at the stress well, a predicted observation well response of about 0.4 ft is indicated.

Figure 3.10 presents the same C_D type curves as a function of dimensionless radial distance, R_D, versus the ratio of dimensionless time, T_D, and the

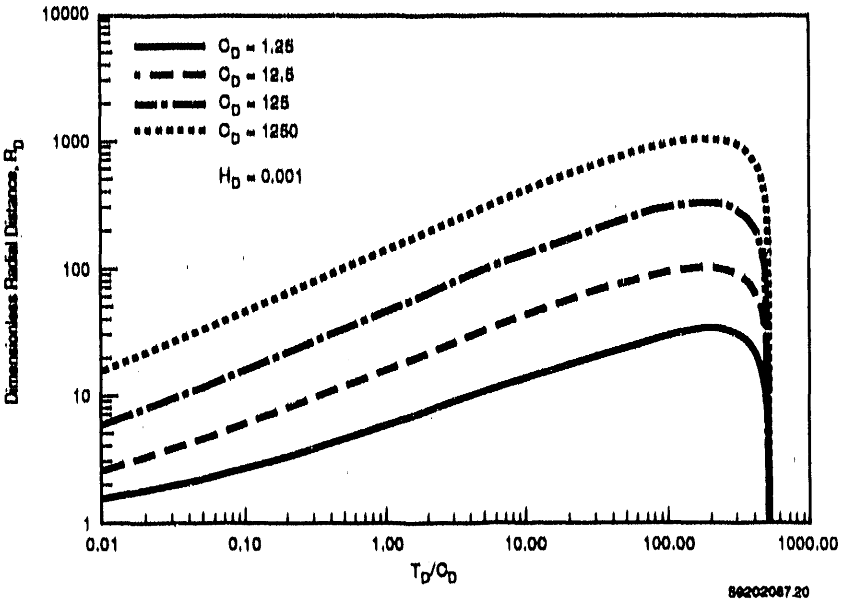


FIGURE 3.10. R_D Versus T_D/C_D Type Curves for C_D Values: 1.25, 12.5, 125, and 1250

dimensionless wellbore storage, C_D, for a minimum observable response (i.e., H_D = 0.001). Figure 3.10 can be utilized to predict the duration and the time of observation of the slug interference at the point of observation. The predicted time of observation for the slug interference response can be obtained by selecting the associated T_D/C_D value for the appropriate C_D curve and observation well distance. As indicated, each C_D curve intersects the selected R_D distance twice. The first is for the initial arrival time of the slug interference response (i.e., when it first is observable), and the second indicates the time when the slug interference response can no longer be discerned. The difference between the two times provides the duration of the slug interference response at the point of observation. Estimated times for the two points of intersection on the type curves can be obtained by multiplying the derived T_D/C_D values by the appropriate C_D curve used, and then solving for time, t, utilizing a rearranged form of the dimensionless time, T_D, equation presented in Equation (5).

As an example of using Figure 3.10, the following is provided: For a stress well radius of 4 in., a radial distance of 25 ft, and a C_D value of 125, associated T_D/C_D values of about 3.1 and 490 are indicated. This indicates T_D values of 388 and 61,250, respectively. To calculate the associated response times, a transmissivity of 1,000 ft²/d, a storativity value of 10^{-3}, and well radius of 4 in. are assumed for this example. Utilizing these parameter estimates and rearranging Equation (5) provides the following estimates: arrival time of slug interference = 4 s; termination of observable slug interference = 588 s; and, slug interference duration = 584 s.

For the purpose of describing the overall shape of the slug test response or for determining the time of the maximum observable slug interference, Figures 3.11(a) through 3.11(d) are provided for selected dimensionless radial distances of 30, 75, 150, and 300, respectively. For a stress well radius of 4 in., this is analogous to radial distances of 10, 25, 50, and 100 ft. To demonstrate their usage for determining the time of maximum slug interference, a radial distance of 25 ft ($R_D = 75$) and a $C_D = 125$ are selected. As indicated in Figure 3.11(b), based on these specified input parameters, a T_D/C_D value of 17 is obtained. Utilizing the previously cited parameter estimates for transmissivity (1,000 ft²/d), storativity (10^{-3}) and stress well radius (4 in.), and rearranging Equation (5) provides an estimate for arrival time of the maximum stress interference response of 20 s.

3.3.2 Test Method Initiation/Test Equipment

The following recommendations are provided for obtaining the optimum results in performing slug interference tests in the field:

1. To establish the response to external stresses (e.g., atmospheric pressure changes, drilling activities, etc.), it is recommended that the observation well test equipment be installed prior to initiation of drilling and/or at least one week prior to initiation of hydrologic testing activities.

2. To maximize the observed slug interference response, efforts should be made to minimize wellbore storage within the observation well. This can best be achieved by isolating the observation well test interval with a downhole straddle packer/transducer system and downhole shut-in tool device (see Figure 2.1).

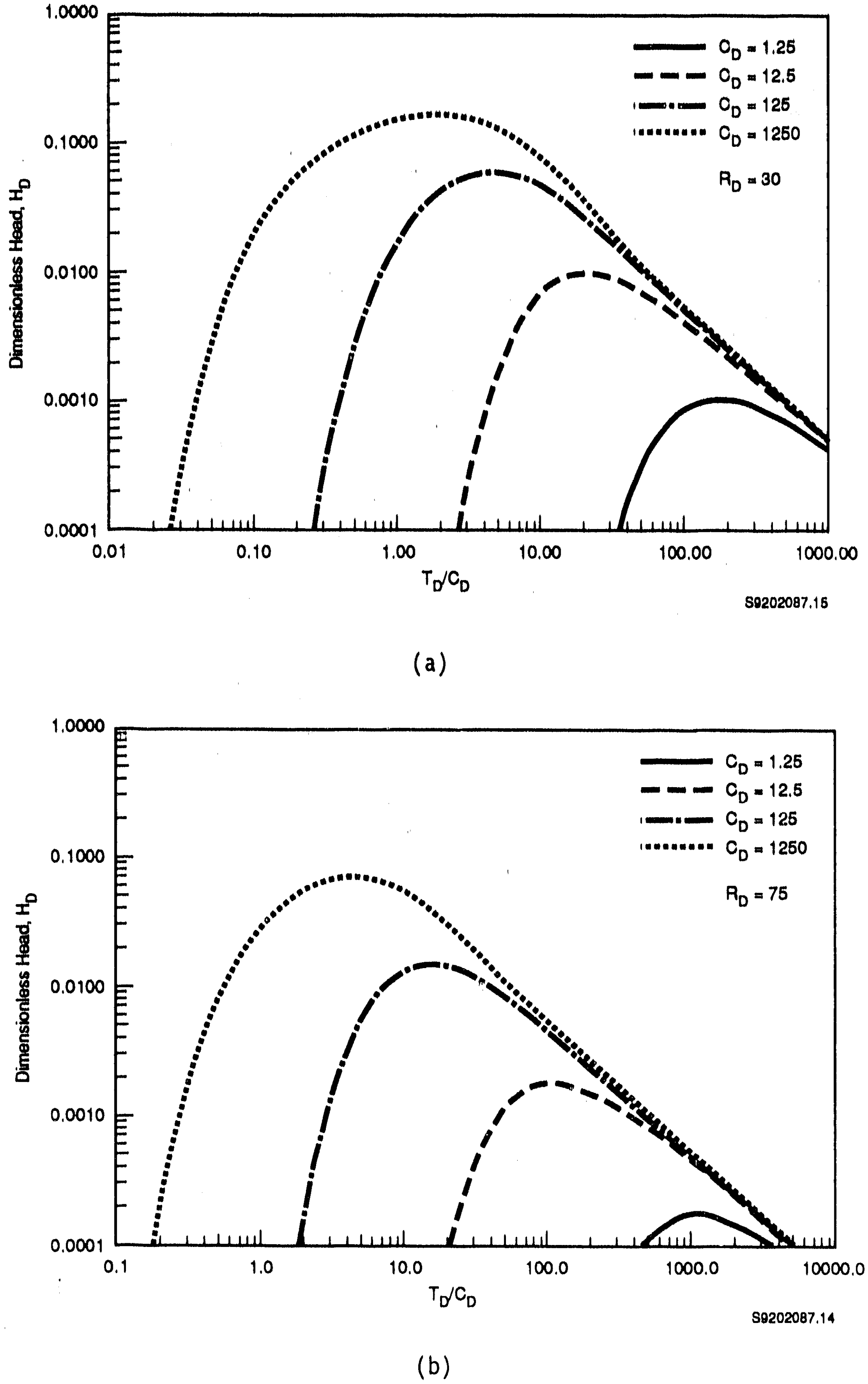
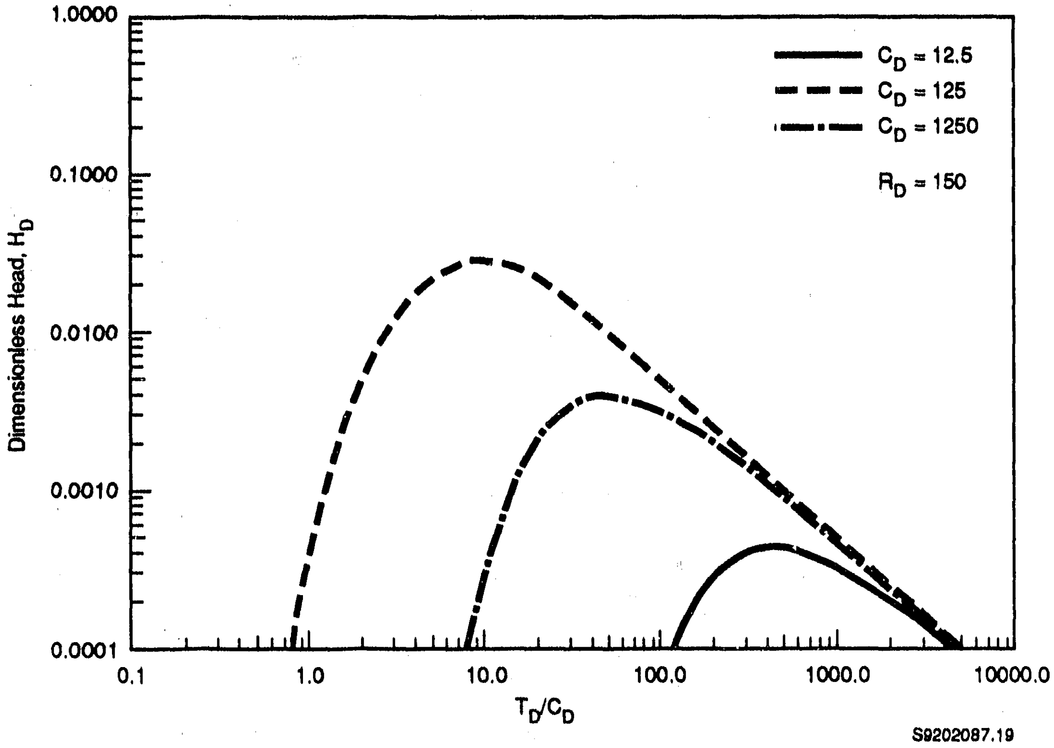
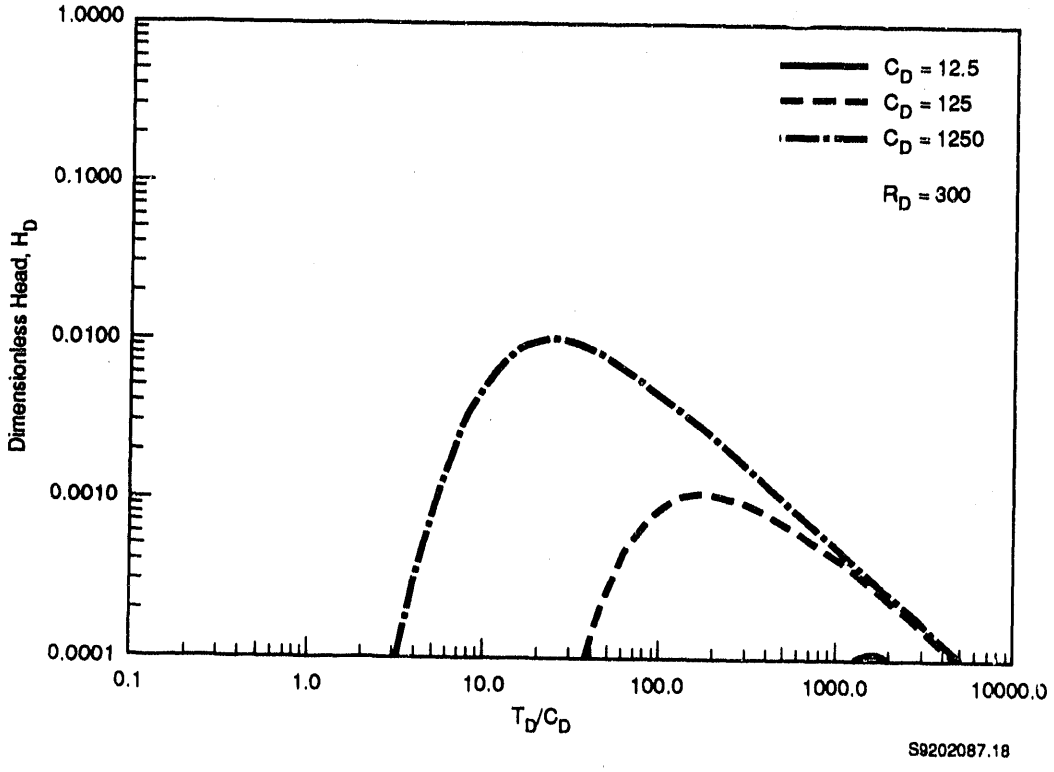


FIGURE 3.11. H_D Versus T_D/C_D Type Curves for (a) R_D = 30 and (b) R_D = 75



(c)



(d)

FIGURE 3.11. H_D Versus T_D/C_D Type Curves for (c) R_D = 150 and (d) R_D = 300

3. Wells with larger wellbore storage (i.e., larger well radii) within a well cluster site should be selected as stress well locations. No downhole equipment that would measurably decrease the wellbore storage (e.g., downhole packer system) should be employed, if possible, within the stress well.

4. High resolution pressure detection equipment and a fast data acquisition system installed at the observation well will enhance the detection of the slug interference response.

5. Stress levels equal to or greater than 25 ft of water (i.e., above or below static conditions) are recommended for propagating the slug test response from the stress well site.

6. For stress wells with static fluid columns that are 25 ft or greater above the screened interval (see Figure 2.1a), slug withdrawal tests are recommended. Water columns within the well can be lowered by increasing the air pressure in the air column space above the water column (e.g., by using regulated compressed air bottles). Care should be exercised not to lower the water column level below the top of the screened interval. This would cause injection of air into the test formation. After a period of pressure equilibration (i.e., following air injection), the air pressure can be released, which initiates the slug withdrawal test.

7. For stress wells with static fluid columns that are within the screened interval (see Figure 2.1b), slug injection tests are recommended. For these situations a downhole packer (with preferably a 3- to 5-ft packer element) would be required to ensure that the injected water does not directly discharge into the unsaturated section exposed in the screened interval. Utilization of a downhole shut-in tool will allow the administering of a water column of prescribed height above static conditions (i.e., 25 ft or greater). Opening the shut-in tool initiates the slug injection test.

4.0 FIELD TEST EVALUATION - TEST EXAMPLE

Based on the favorable findings associated with the analytical assessment of the proposed test method (Phase 1), a field test evaluation (Phase 2) was conducted. The test site location selected had been previously hydrologically characterized. The following sections describe the field test facility, test design, test equipment utilized, test method theoretical considerations, and field test evaluation and analysis.

4.1 TEST SITE DESCRIPTION

The slug interference test facility consisted of two existing wells (699-43-41E and 699-43-41F), and a new well (699-43-41G) that was drilled during July and August 1991. The two existing wells were used as observation wells during the test evaluation. New well 699-43-41G was utilized as the stress well for inducing the slug stress that was monitored at the two nearby observation wells. Pertinent well location and construction information pertaining to the stress and observation wells is provided in Figure 4.1 and Tables 4.1 and 4.2.

Construction as-builts for observation wells 699-43-41E and 699-43-41F, and temporary test completion at well 699-43-41G during the slug interference test are shown in Figures 4.2 and 4.3, respectively.

4.2 TEST EQUIPMENT

Observation Wells

Observation wells (699-43-41E and 699-43-41F) were equipped with identical downhole test equipment. The downhole installation included the following elements as shown in Figure 4.3:

- 3.5-in. - O.D., inflatable Baski packer, Model # LD200 - 3.5"6.0"2.0-STD-30-EFA10,
- Seling Corporation single pressure probe (containing a 0 - 200 psia Paroscientific quartz pressure transducer),
- Packer setting cable,

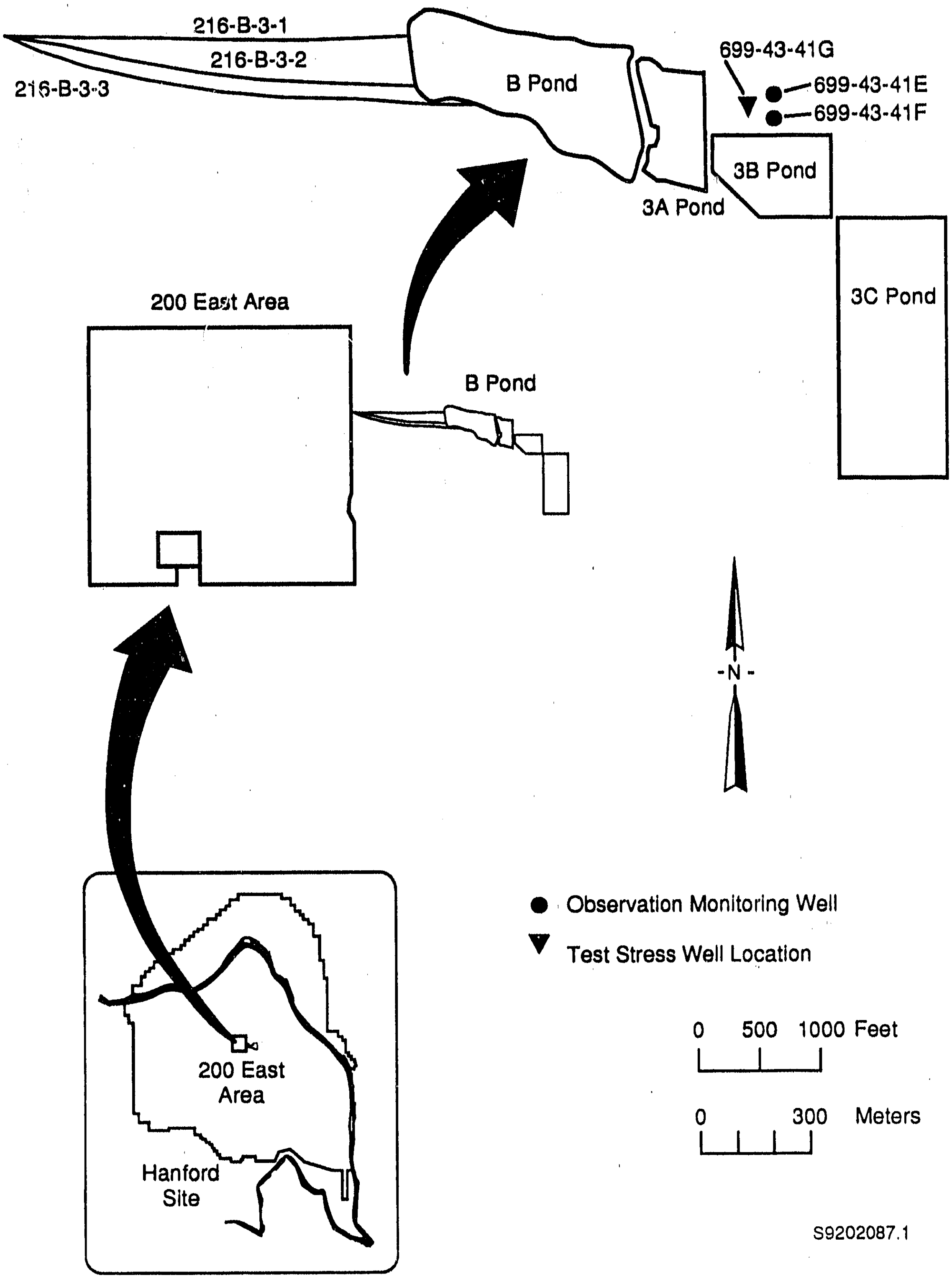


FIGURE 4.1. Location Map of Slug Interference Test Facility

TABLE 4.1. Pertinent Well Completion and Construction Information for Wells 699-43-41E, 699-43-41F, and 699-43-41G

Well Designation	Casing Diameter (in.)	Casing Depth (ft)	Screen Diameter (in.)	Screened Interval (ft)
699-43-41E[(a)]	4.0	135.5	4.0	135.5 - 146.1
699-43-41F[(a)]	4.0	165.3	4.0	165.3 - 175.9
699-43-41G[(a,b)]	10.0	162.7	8.0	162.7 - 172.8

(a) Depth interval designations for wells 699-43-41E and 699-43-41F referenced from the brass cap surface control datum; well 699-43-41G referenced from land surface.

(b) The casing and screened depth intervals indicated were valid only for the period of slug interference testing. The well was deepened and recompleted later.

TABLE 4.2. Calculated Distance Relationships Between Wells 699-43-41E, 699-43-41F, and 699-43-41G

	Hanford Site Well Coordinates		Calculated Horizontal Distance To		
Well Designation	North (ft)	West (ft)	699-43-41E (ft)	699-43-41F (ft)	699-43-41G (ft)
699-43-41E	42,994.9	40,723.0	-	50.4	47.8
699-43-41F	42,944.5	40,720.9	50.4	-	48.9
699-43-41G	42,969.0	40,763.2	47.8	48.9	-

- Packer inflation line, and
- 1/4 in. O.D., co-axial conductor cable.

The packer setting cable was used to install the inflatable packer immediately above the screened interval within each monitoring well. The packer was inflated using the packer inflation line and a surface, compressed air cylinder. Packer inflation pressures were within the manufacturer reported inflation specifications (i.e., differential pressure rating of approximately 200 psi).

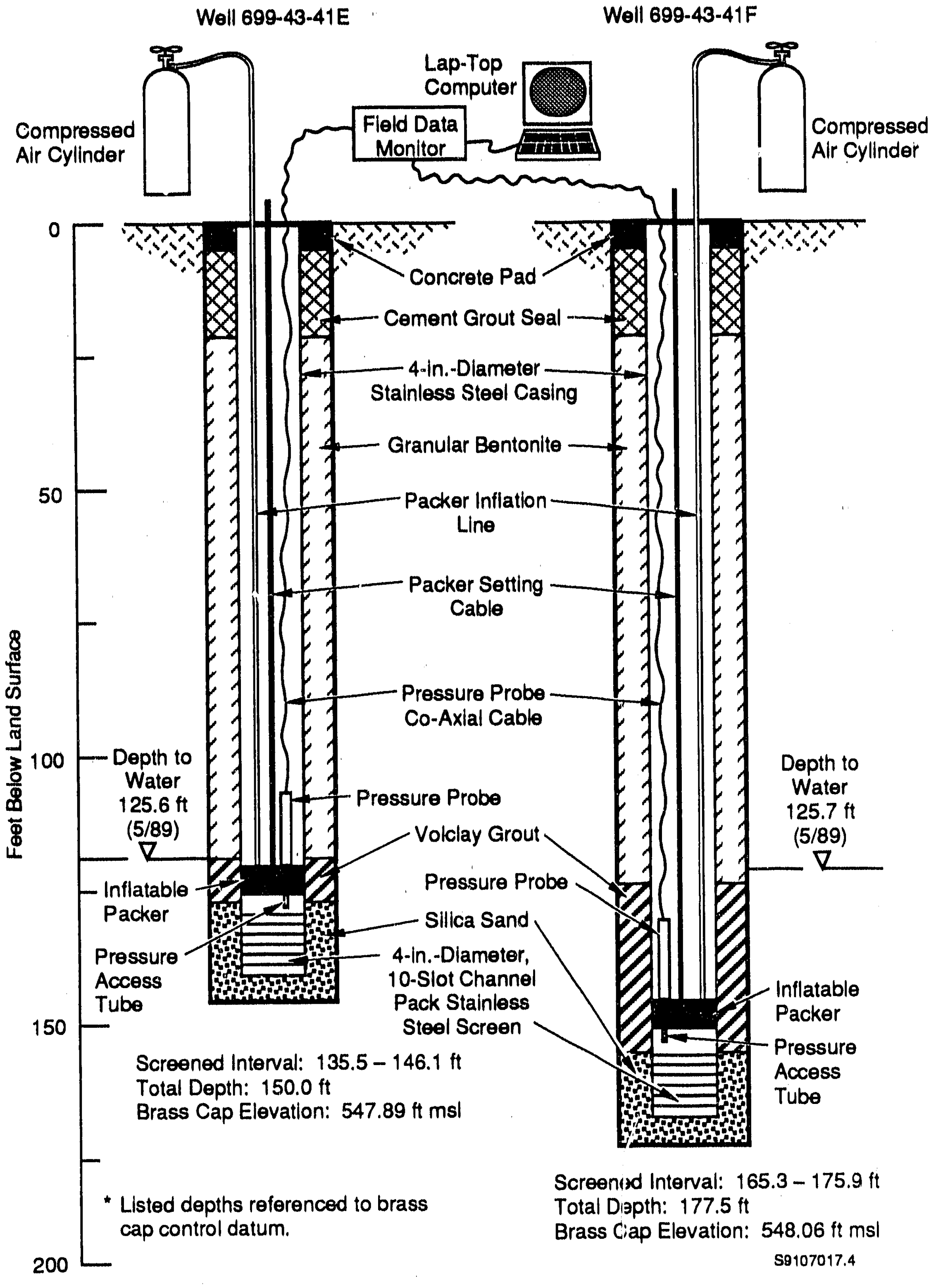


FIGURE 4.2. Construction As-Builts and Test Equipment Installations for Observation Wells 699-43-41E and 699-43-41F

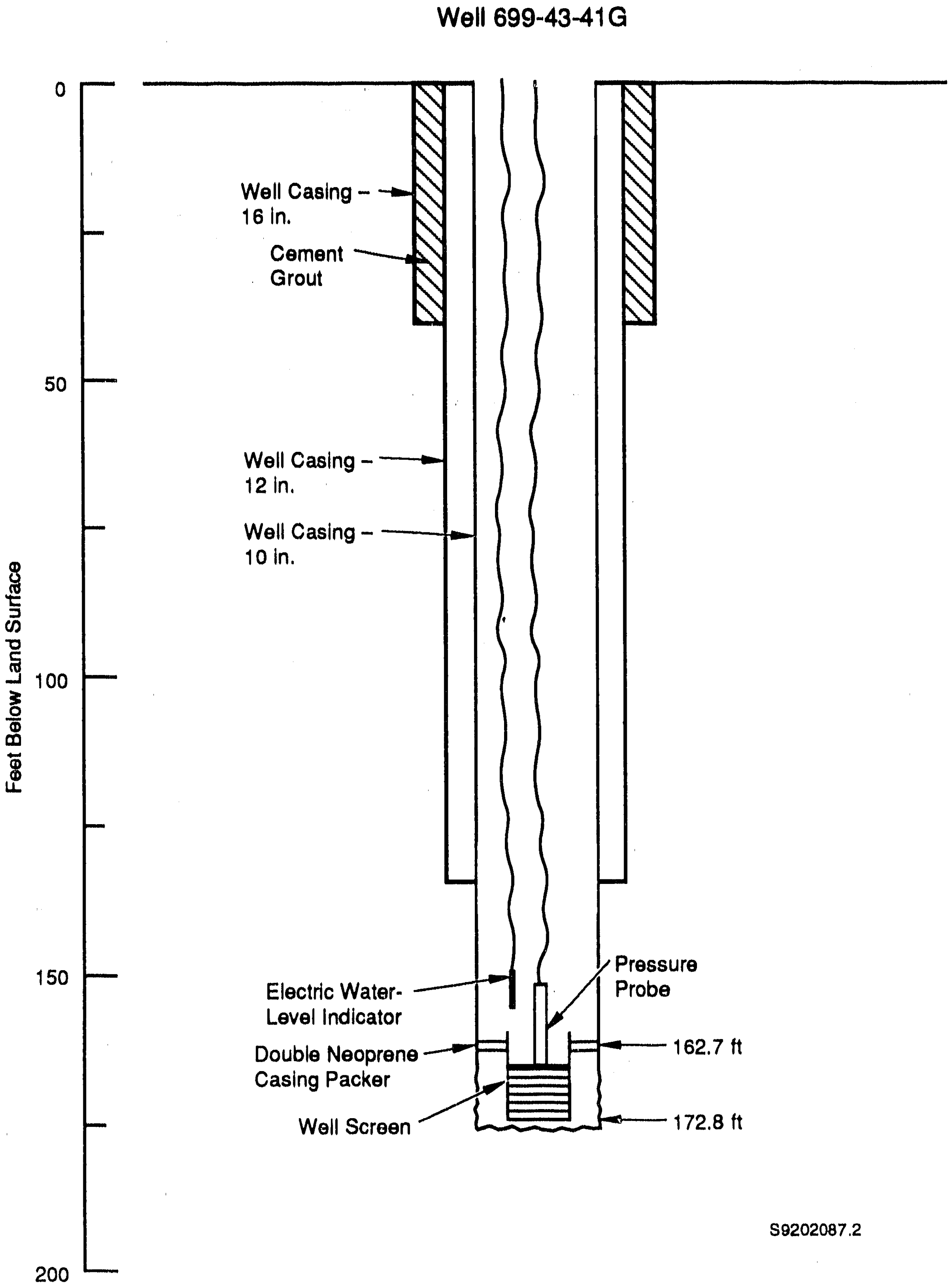


FIGURE 4.3. Temporary Well Completion and Test Equipment Installation Information for Well 699-43-41G

The Seling Corporation single pressure probe was used to sense pressure conditions below the set packer by means of a packer access-through tube that was connected to the pressure probe sensor port. Pressure readings of the pressure probe were transmitted to a surface field data monitor (Seling model # FDM 8500), using the 1/4-in.-O.D., co-axial conductor cable. Pressure readings were printed directly using the field data monitor. Originally, downhole pressures were also planned to be stored directly on a personal computer for later data retrieval and analysis. However, a lack of required compatible electronic components eliminated the possibility of direct data storage to the personal computer.

Stress Well

Upon reaching the targeted geologic horizon at well 699-43-41G, a temporary well screen assembly was installed. The well screen assembly consisted of ≈ 20-ft section of 8-in.-diameter stainless steel well screen, ≈ 5-ft blank section of stainless steel well casing, and a dual neoprene packer mounted on the top, blank section (see Figure 4.3). The dual neoprene packer served to block the direct incursion of sand and sediment during testing, i.e., from outside the well screen into the inside of the 10-in.-diameter well casing.

As in the observation wells, a Seling Corporation single pressure probe (0 to 200 psia, Paroscientific Inc. quartz transducer) was also used to measure fluid pressure responses in the stress well. The pressure probe was located immediately above the well-screened section to ensure that the probe remained submerged during all phases of slug testing. Pressure probe measurements were transmitted using the 1/4-in.-O.D., co-axial conductor cable to the same Seling Corporation field data monitor and personal computer system used to record the observation well pressure measurements.

An electric water-level indicator was also installed immediately above the well-screened section to detect when fluid levels within the stress well were depressed (i.e., by using compressed nitrogen gas) to this level. The electric water-level indicator used was of a type commonly utilized on the Hanford Site to support hydraulic characterization investigations (e.g, In-Situ Corporation, etc.).

The electric water-level indicator and pressure probe co-axial cables were conducted through an air-tight, surface wellhead assembly as shown in Figure 4.4. General components of the wellhead assembly include:

- a welded connection, attaching the wellhead assembly to the 10-in.-diameter well casing,
- four, 4-in.-diameter nipples and quick-release ball valves mounted on the side of the wellhead,
- a welded slip-on flange that provides an air-tight seal for passing cables and lines through the top of the wellhead assembly, and
- a pressure regulator and air-hose connection for administering nitrogen from a compressed nitrogen cylinder to the inside of the well casing.

4.3 TEST DESCRIPTION

The original test design called for slug interference tests to be conducted in two separate test zones in well 699-43-41G. The two test zones corresponded approximately with the screened sections monitored at the adjacent observation wells. The test zones were to be tested sequentially, after reaching the desired depths during drilling. Both observation wells are screened in a sand and gravel unit that is located immediately below a silt and clay zone that occurs within the middle Ringold Formation. As indicated in Table 4.1, well 699-43-41E is screened in the upper sand and gravel (135 to 146 ft), while well 699-43-41F is located in the lower (165 to 176 ft) sand and gravel section. Projected test depth-intervals at the test stress well 699-43-41G were expected to correspond to these screened depths. The horizontal (surface) distances between zones for the tests, based on well coordinate survey information, are provided in Table 4.2. As indicated, the horizontal distances between the wells are approximately 50 ft.

Although the original test plan called for two zones to be tested at well 699-43-41G, upon reaching the shallowest proposed test interval (i.e., approximately 135 to 145 ft, corresponding to the monitored interval at well 699-43-41E), adverse hydrogeologic conditions for conducting a slug interference test were encountered. These adverse conditions included a greater percentage of fine-grained sediments in the proposed test interval, a

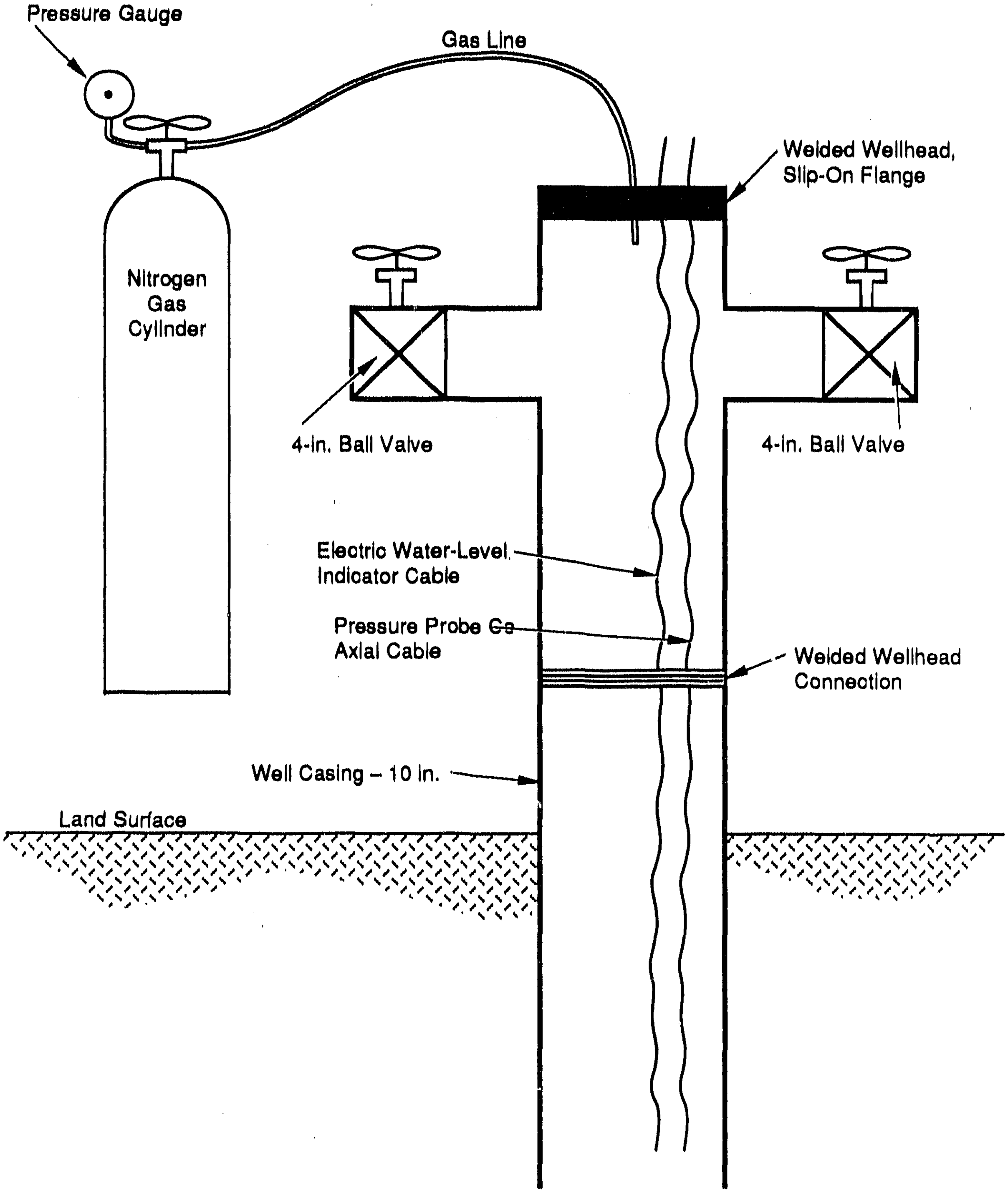


FIGURE 4.4. General Wellhead Assembly Components for Well 699-43-41G

thinner zone of saturation, and significantly lower transmissivity conditions (assumed on the basis of the large percentage of fine-grained sediments present) within the proposed test interval. Because of these encountered conditions, slug interference testing was not attempted for the shallowest proposed interval, and drilling proceeded to the second proposed test depth interval (i.e., approximately 163 to 173 ft).

The second proposed test interval was encountered on August 26, 1991. Drilling continued to a temporary completion depth of 173 ft on August 26, 1991. Following the cessation of drilling activities, test interval development by stressing and removing water from the well by repeatedly bailing the well was completed between 1030 and 1100 hours (approximately 160 to 200 gallons removed), and 1300 and 1330 hours (approximately 80 to 100 gallons removed) on August 26th. A temporary well screen assembly (as described in Section 4.2 and Figure 4.3) was installed in well 699-43-41G between 0900 and 1125 hours on August 27th. Following the installation the well screen/test interval was developed by bailing approximately 180 gallons.

To provide a preliminary indication of in situ hydraulic conditions, a low stress (approximately 2.4 ft stress displacement) slug injection and withdrawal test were conducted using a slugging rod beginning at 1317 hours, on August 27th. Results from this preliminary testing are not included in this report. Qualitative analysis of these tests, however, provided estimates of transmissivity for the stress well that were consistent with results obtained during slug interference testing (see Section 3.3.2). The well-head assembly was then attached to the 10-in. well casing and the pressure probe and electric water-level sensor installed within the well on August 28th.

Depression of the water level within well 699-43-41G using injected compressed nitrogen (following the procedure described in Section 4.3), commenced at 1132 hours on August 28th using a gas injection pressure of 15 lb/in^2. This selected injection pressure was designed to depress the water level within the stress well approximately 35 ft below the static level, which prior to gas injection was 126.56 ft below land surface. A constant gas pressure of about 15 lb/in^2 was maintained inside the well casing to equilibrate the well/test interval system during the gas injection test phase. The electric water-level sensor was also monitored during this period to ensure that gas was not injected into the screened interval. The injection of displaced water into the test interval resulted in detectable pressure changes at both observation wells. Pressures at both observation wells were allowed to equilibrate before beginning the slug withdrawal test.

The slug interference test was initiated at 0809:30 hours on August 29th, when the gas pressure within the well casing was abruptly released. The gas pressure was released in about 1 s by simultaneously opening the four, 4-in. ball valves on the surface well-head assembly. The release of gas caused ground water within the test interval to flow back inside the well casing, thus creating a slug withdrawal at the stress well. Pressure measurements were recorded at the stress well, and the slug interference response monitored at the two observation wells (i.e., 699-43-41E and 699-43-41F). Discernable interference responses to the slug test were observed at both observation wells. Analysis of the slug interference responses recorded at the two observation wells, as well as the slug response at the stress well, are presented in the following section.

4.4 TEST ANALYSIS

4.4.1 Barometric Effects

Because of the anticipated small slug interference response, plans were initiated to remove the effects of barometric pressure fluctuations from the observed slug interference record. The relationship between barometric pressure change and associated test interval pressure response has been previously described by a number of investigators for confined (e.g., Jacob 1940) and unconfined aquifers (e.g., Weeks 1979). To determine the relationship between barometric and aquifer pressure changes (i.e., barometric efficiency), pre-test interval pressures were monitored at each observation well beginning on August 5th. However, because of power supply and data acquisition system constraints, data records were discontinuous and of short-length during the pre-test period. Figure 4.5 shows test interval pressure responses for observation wells 699-43-41E and 699-43-41F, in comparison to hourly atmospheric pressure readings recorded at the Hanford meteorological station (located

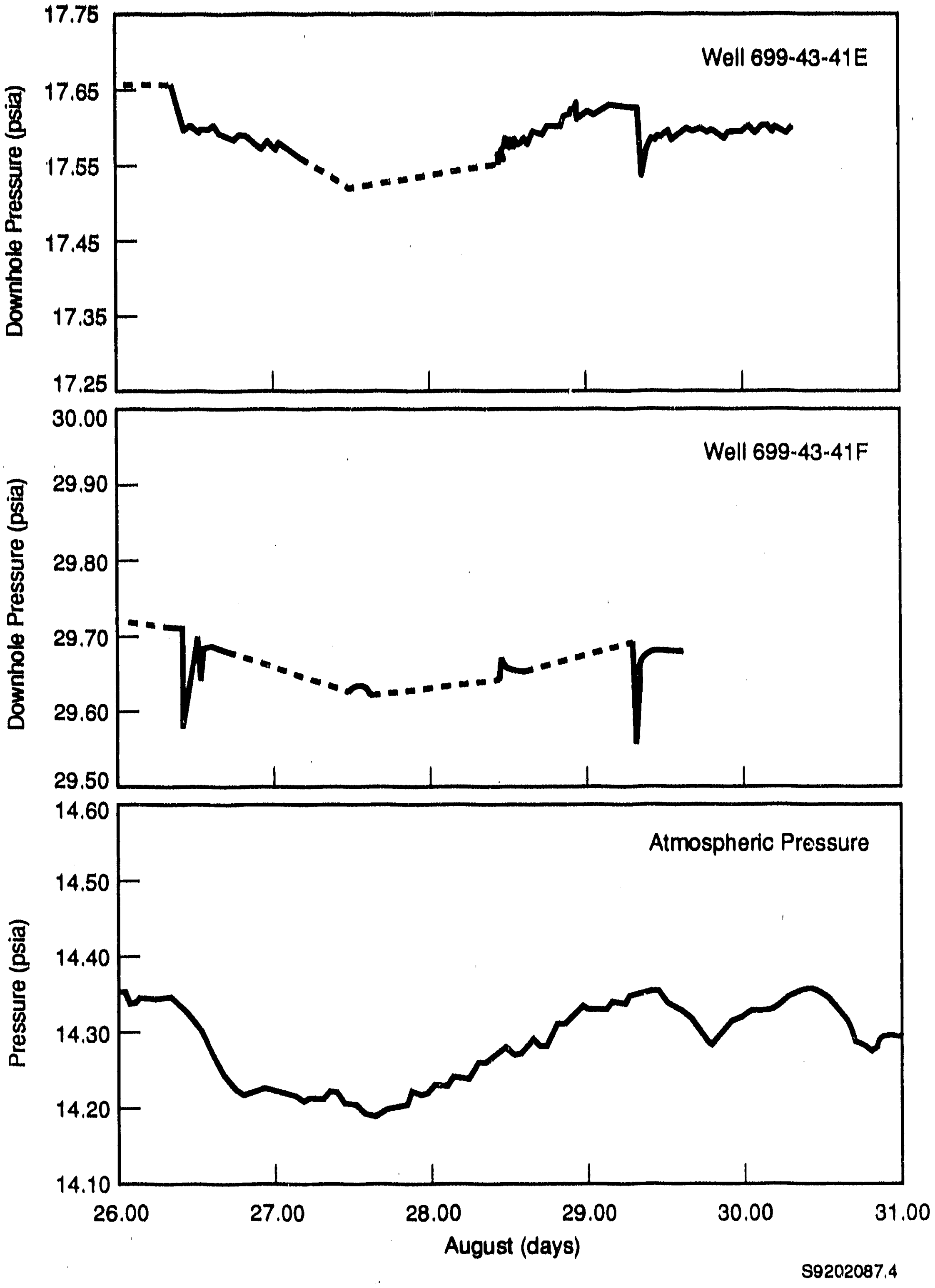


FIGURE 4.5. Comparison of Downhole Pressure Measurements for Wells 699-43-41E and 699-43-41F and Atmospheric Pressure Readings Observed During the Period August 26 to 30, 1991

approximately 5 miles from the test facility), between August 26 and 30. As indicated in Figure 4.5, considerable correspondence between test interval pressure and atmospheric pressure trend fluctuations is indicated.

To remove the effects of barometric fluctuations from the observed slug interference response recorded at wells 699-43-41E and 699-43-41F, the barometric efficiency for the test interval must be determined. The barometric efficiency of an open well/aquifer system was first defined by Jacob (1940), and can be expressed as:

$$BE = -\bar{\tau}_{fc} (\blacktriangle h_s / \blacktriangle P_o) \tag{9}$$

where τ_{fc} = average specific weight of the fluid column in the well; (lb/ft^3)

$\blacktriangle h_s$ = change in elevation of the fluid column in the well associated with atmospheric pressure change; (ft)

$\blacktriangle P_o$ = change in atmospheric pressure; (lb/ft^2)

Downhole pressure measured within an open well or in the aquifer (P_f), however, responds directly with atmospheric pressure fluctuations, but at a magnitude equal to the atmospheric pressure change minus the pressure change because of the change in the fluid column elevation within the well (Spane and Mercer 1985):

$$\blacktriangle P_f = \blacktriangle \bar{P}_o - \tau_{fc} \blacktriangle h_s \tag{10}$$

or simplifying,

$$\blacktriangle P_f = (1\text{-}BE) \blacktriangle Po \tag{11}$$

Equations 10 and 11 indicate that the change in downhole formation pressure represents only that portion of the atmospheric pressure change not borne by the test formation matrix. Therefore, high barometric efficiencies are reflective of high strength and rigid test formations, while low efficiencies indicate formations that are highly compressible (Spane and Mercer 1985).

The barometric efficiency for observation wells 699-43-41E and 699-43-41F was calculated utilizing the procedure described in Clark (1967). The Clark method is particularly applicable in calculating barometric efficiencies from test interval responses that are influenced by the presence of other extraneous trends. Briefly stated, the method requires determining the barometric efficiency from the slope of a summation plot of the incremental changes in downhole formation pressure, $\Sigma\Delta P_f$ versus the incremental change in atmospheric pressure, $\Sigma\Delta P_o$. Incremental changes in downhole formation pressure are added to the summation total when the incremental sign change is equal to that of the incremental atmospheric pressure, ΔP_o sign change for the observed incremental period (e.g., when ΔP_f and ΔP_o are both positive or negative). Conversely, incremental changes in downhole formation pressure are subtracted from the summation total when the incremental sign change is unequal to that of the incremental atmospheric pressure sign change for the observed period. In addition, no incremental change in downhole formation pressure is added to the summation total when no change in atmospheric pressure is recorded.

Figure 4.6 shows the combined plot of summation totals for incremental downhole formation pressure versus incremental atmospheric pressure changes as calculated using the Clark method for wells 699-43-41E and 699-43-41F for discontinuous data collected during the pre-test period (i.e., August 5 to August 28). Because of data acquisition system limitations, only a few data points are available for analysis during the pre-test period for well 699-43-41F. As shown, however, the data for well 699-43-41F plot closely to the trend exhibited for well 699-43-41E. Based on this combined analysis, a barometric efficiency of 0.382 (i.e., 38.2%) is indicated. The barometric efficiency value determined was utilized in removing the effects of barometric pressure change from the slug interference test response recorded at observation wells 699-43-41E and 699-43-41F. Results of the slug interference test analysis for the individual observation wells are presented in the following respective report sections.

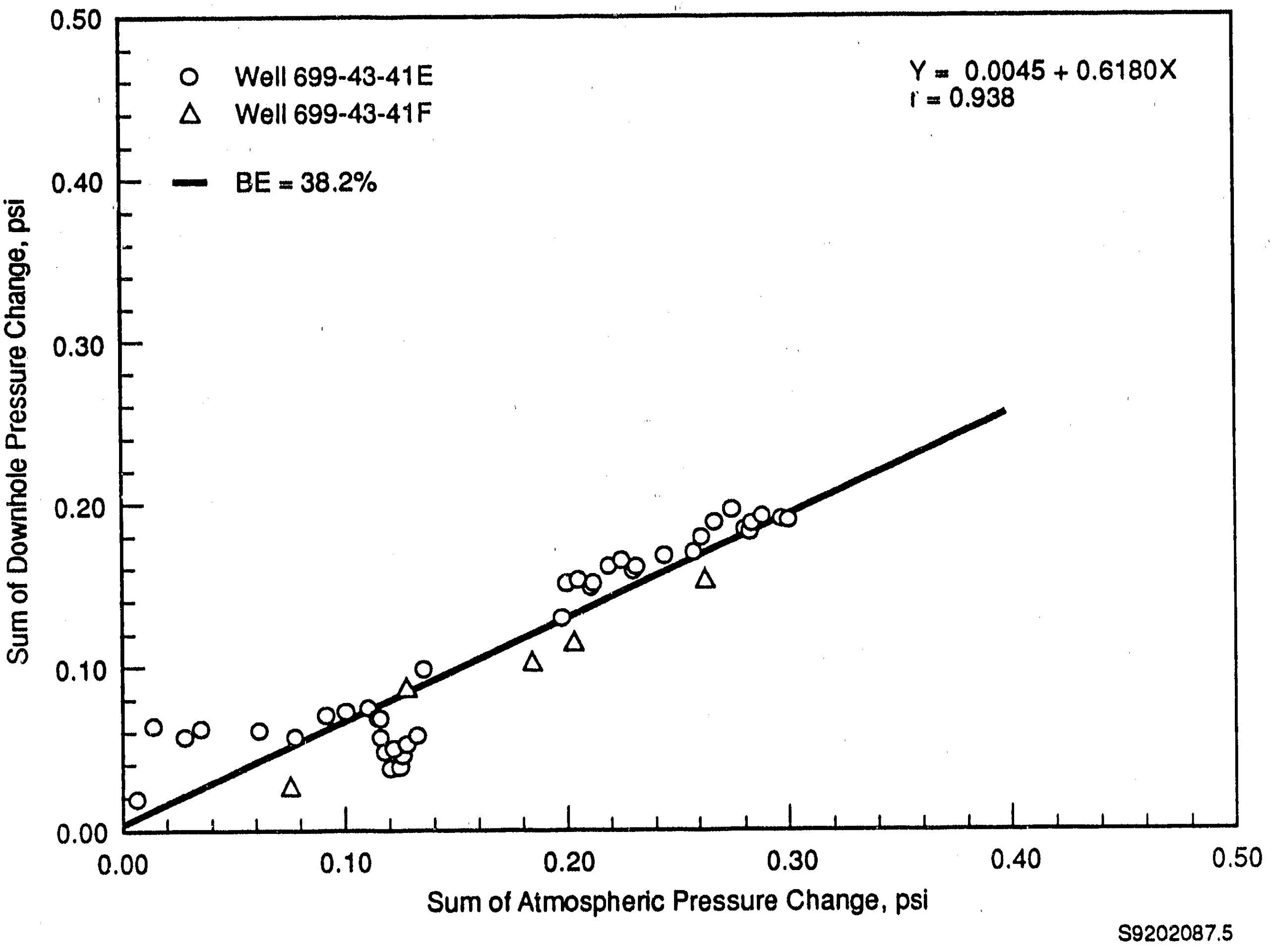


FIGURE 4.6. Barometric Efficiency Calculation for Observation Wells 699-43-41E and 699-43-41F

4.4.2 Stress Well 699-43-41G Response

The initiation of the slug interference test by the abrupt release of compressed gas within the well casing at well 699-43-41G (at 0809:30 hours on August 29th) caused ground water to flow back inside the well casing from the surrounding test interval, thus creating a slug withdrawal at the stress well. The fluid column had been depressed with compressed gas resulting in an induced stress level, H_0, of 15.15 lb/in² below the observed, pre-test downhole pressure value of 32.02 lb/in². The resulting pressure recovery was analyzed utilizing the technique described in Ostrowski and Kloska (1989), which employs the simultaneous type-curve matching of the dimensionless pressure (i.e., H/H_0) versus time and the derivative of dimensionless pressure versus time. The technique is superior to the procedure described in Cooper et al. (1967) for dimensionless pressure versus time in that the ambiguity in type-curve selection is significantly reduced.

Figure 4.7 shows the type-curve analysis of the slug withdrawal test response at the stress well using the Ostrowski and Kloska (1989) analysis procedure. As indicated, a transmissivity of approximately 60 ft²/d was calculated for the screened interval section using a type-curve match of alpha $= 10^{-6}$. Like the Cooper et al. (1967) analysis method, the Ostrowski and

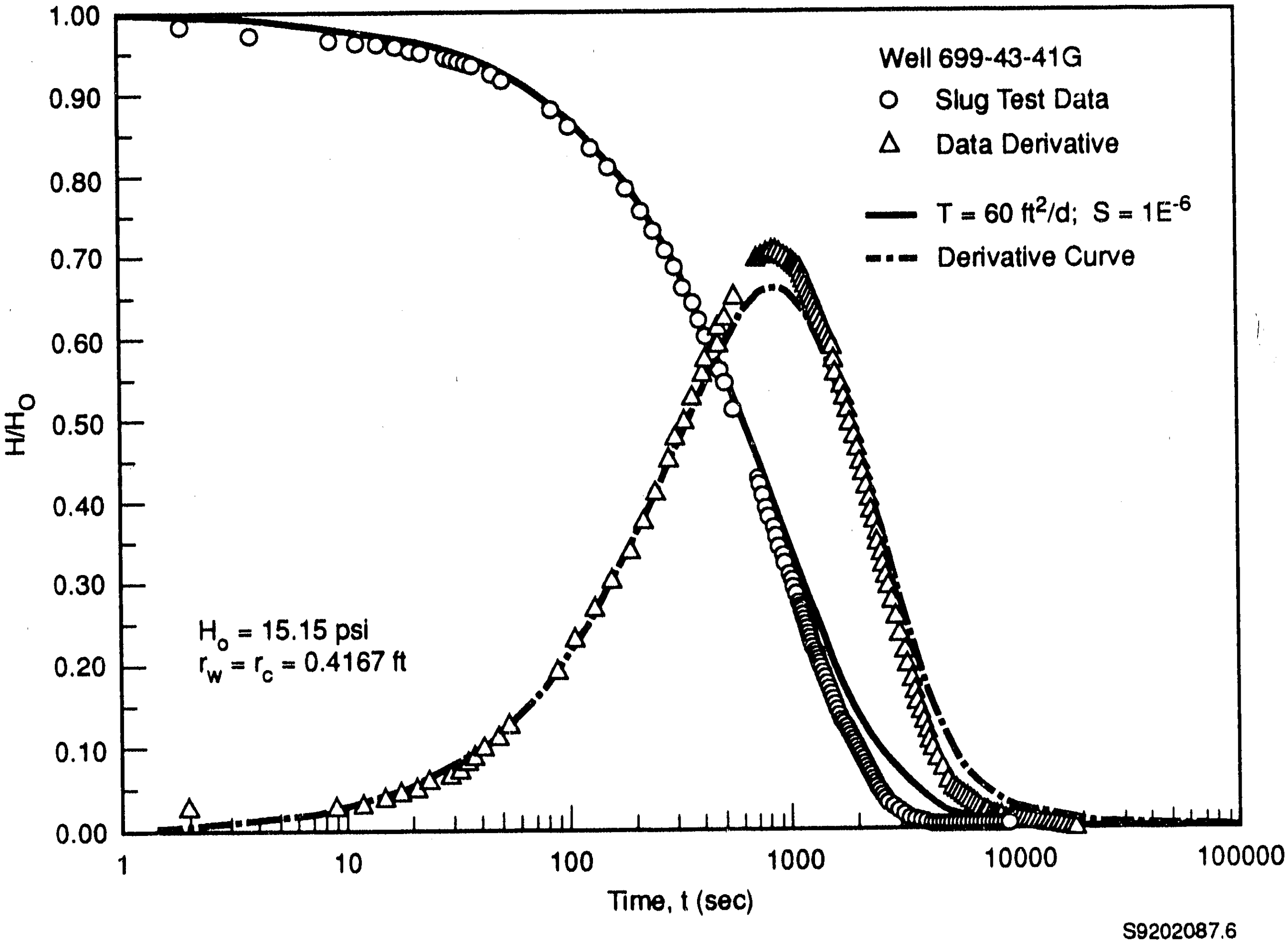


FIGURE 4.7. Slug Test Analysis for Stress Well 699-43-41G Using the Ostrowski and Kloska (1989) Analysis Method

Kloska (1989) technique is strictly valid only for fully penetrating wells. However, as indicated by Cooper et al. (1967) few wells completely penetrate an aquifer, and for wells partially penetrating stratified aquifers (where vertical hydraulic conductivities are commonly less than horizontal hydraulic conductivities) it can be assumed that two dimensional flow conditions exist during the test. For these situations, " ... the determined value of transmissivity (T) would represent approximately the transmissivity of the part of that part of the aquifer in which the well is screened..." (Cooper et al., 1967). Based on a well screen length of 10.6 ft, an equivalent hydraulic conductivity for the test section of 5.7 ft/d is indicated.

Additional examination of Figure 4.7 indicates a departure of the slug test data (i.e., after 600 s) from that predicted by the type curve. This can be indicative of non-radial flow conditions induced by vertical flow components or leaky aquifer behavior within the zone of influence for the test. Slug test head data and its derivative versus time (as shown in Figure 4.7), however, cannot be used diagnostically to identify the presence of non-radial flow behavior. This is in contrast to constant-rate pumping tests, which have been shown to display specific pressure derivative patterns for various ground-water flow conditions (e.g., Bourdet et al. 1983; Ehlig-Economides 1988).

Figure 4.8 shows the pattern of dimensionless pressure, P_D, and the dimensionless pressure derivative, P_D', during a constant-rate test for a stress well with no storage (Theis type curve) and for various wellbore storage conditions. As indicated in the figure, wellbore storage produces a characteristic "hump" pattern in the pressure derivative plot, which increases in amplitude and duration as the associated dimensionless wellbore storage value, C_D, increases. Radial flow conditions are indicated when the pressure derivative becomes horizontal (i.e., when $P_D' = 0.5$). For the examples shown, radial flow conditions are established for test times with T_D/C_D values greater than about 1000.

The presence of non-radial flow conditions caused by vertical flow or leaky aquifer behavior, is denoted on a pressure derivative plot by a diagnostic response pattern that significantly deviates below the horizontal

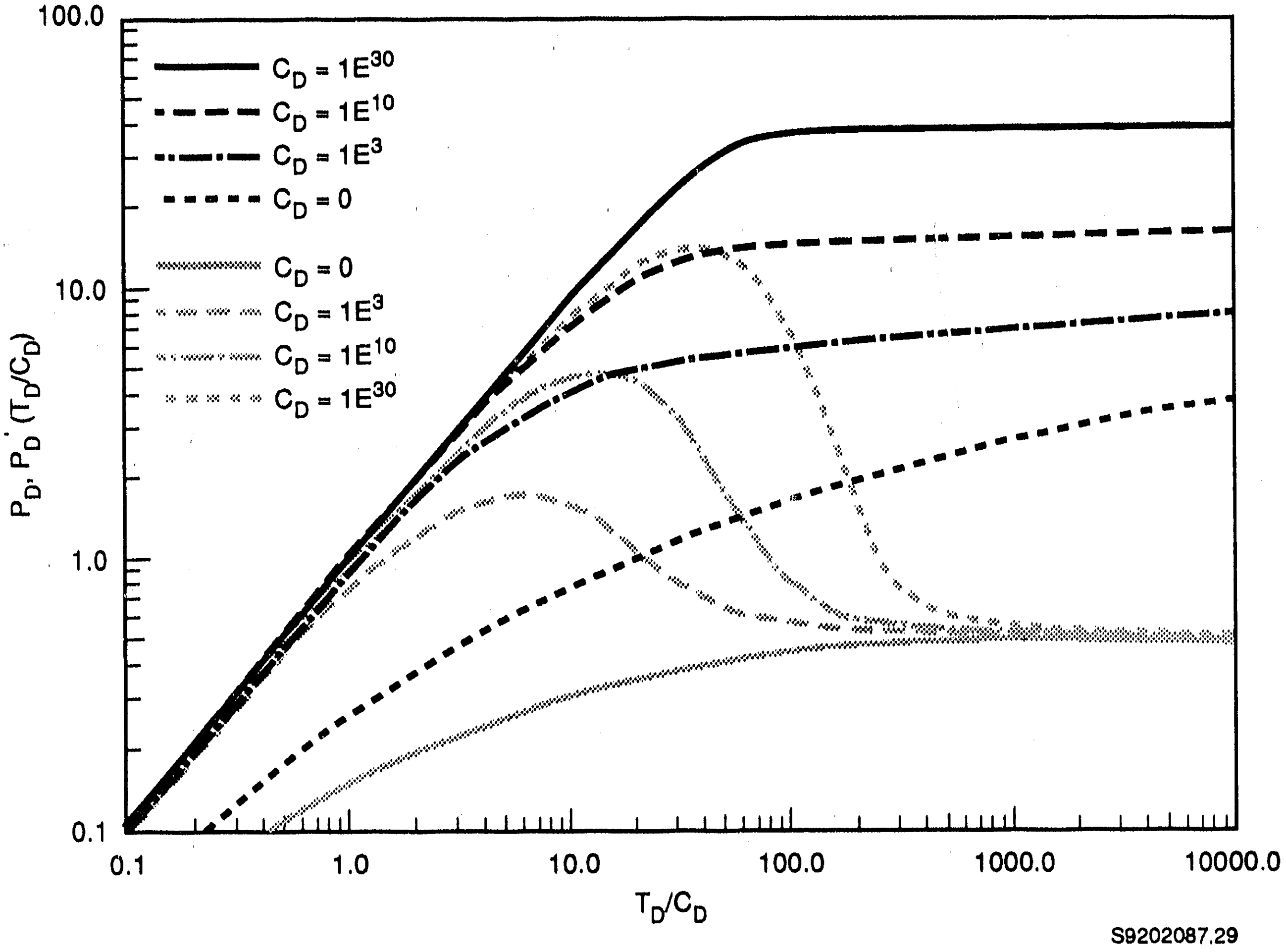


FIGURE 4.8. Dimensionsless Pressure and Dimensionless Pressure Derivative Type Curves for Constant-Rate Pumping Tests. (After Bourdet et al. 1983).

radial flow-line region of the graph (i.e., $P_D' = 0.5$). In comparison, vertical flow or leaky aquifer behavior is less obvious on a simple dimensionless pressure change plot, with its presence only suggested by a subtle deviation below the pressure change plot.

To verify the presence of non-radial flow conditions, leakage, boundaries, etc., slug test data must be first converted to an equivalent head response that would be obtained during a constant-rate pumping test, and then converted to equivalent head derivatives. Conversion of slug test response data to equivalent head and head derivative values associated with a constant-rate test can be accomplished following the transformation procedure described in Peres et al. (1989). The presence of non-radial flow conditions attributable to vertical flow or leaky aquifer behavior can then be diagnostically assessed using pressure derivative analysis plots of the form shown in Figure 4.8.

Figure 4.9 shows the results of transforming slug test data collected at well 699-43-41G to its equivalent head and derivative form for a constant-rate

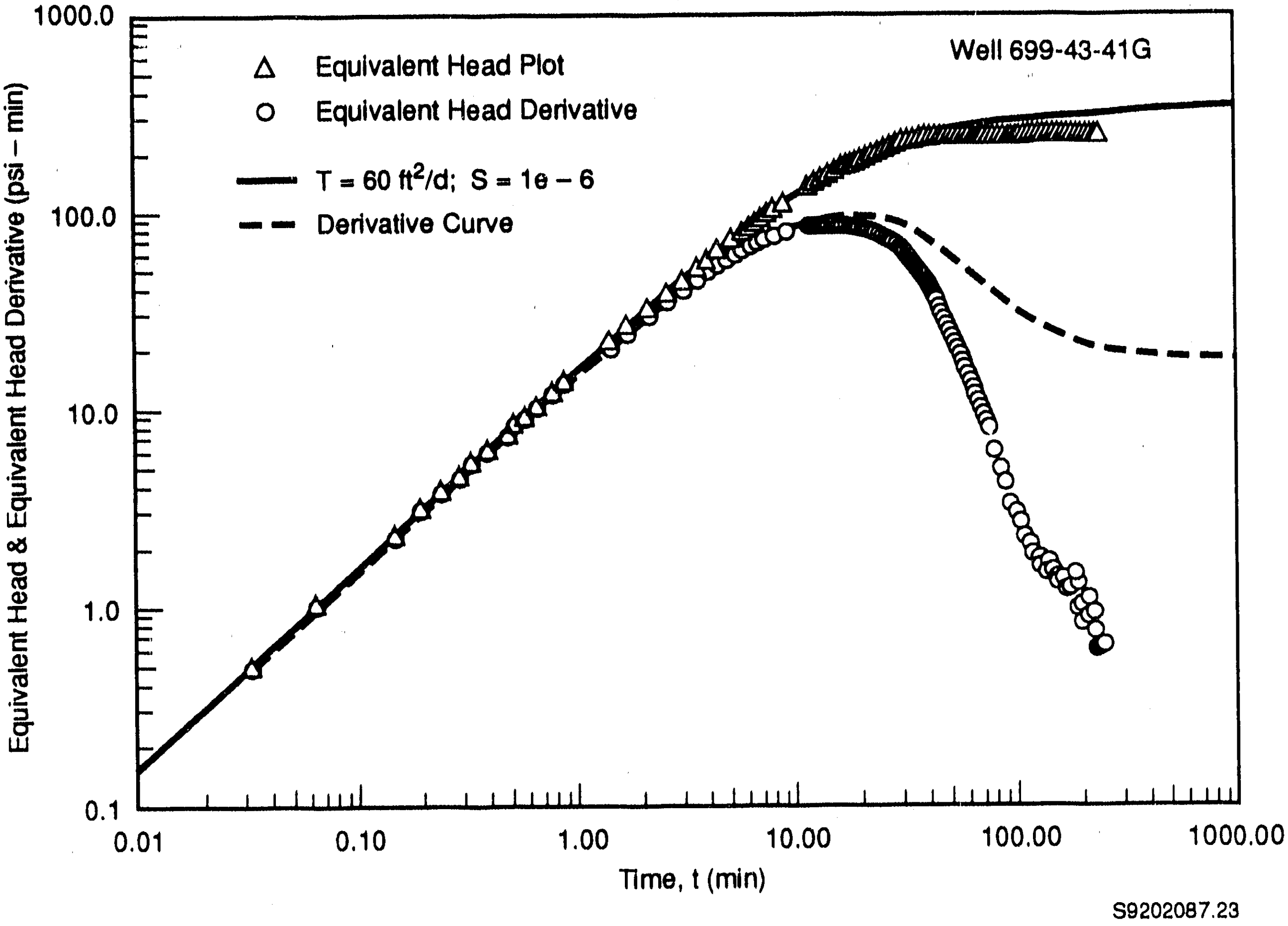


FIGURE 4.9. Diagnostic Analysis of Equivalent Head and Equivalent Head Derivative Plot Data for Slug Test Conducted at Well 699-43-41G

test. Also shown is the predicted equivalent head and head derivative type-curve response based on the previously obtained slug test analysis results for transmissivity (i.e., $T = 60\ ft^2/d$) and storativity ($S = 10^{-6}$) as indicated in Figure 4.7. The equivalent head type-curve response was calculated using the modified version of the Novakowski (1990) program, while the equivalent head derivative was determined based on the derivative algorithm described in Bourdet et al. (1989). As indicated in the figure, the equivalent head derivative response significantly deviates below the predicted derivative response after a test time of approximately 10 minutes. The deviation below the derivative type-curve region indicated for wellbore storage and radial flow confirms the presence of non-radial flow conditions that are characteristic of vertical flow/leakage behavior. Also shown in the figure is the fact that these non-radial flow conditions are only exhibited by a subtle departure from the predicted equivalent head change type curve; thereby, demonstrating the utility of pressure-derivative analysis.

The diagnostic analysis and type-curve matching results suggest that the transmissivity value of 60 ft^2/d obtained for the slug test analysis based on the Ostrowski and Kloska (1989) method (Figure 4.7) is probably a reasonable estimate of hydraulic properties for the interval tested, since it is based on type-curve matching of test data prior to establishment of significant vertical flow or leaky aquifer flow conditions (i.e., prior to test times of 10 minutes). This estimate, however, is expected to be slightly greater than actual conditions, due to the likelihood of some vertical flow or leaky aquifer behavior even during the early stages of the test.

For test analysis comparison, slug test data were also analyzed utilizing the procedure described in Bouwer and Rice (1976) and Bouwer (1989). This analysis procedure (which is based on the Thiem equation) was developed for unconfined aquifer conditions and accounts for the effects of partial penetration at the stress well. For this analysis procedure, equivalent hydraulic conductivity for the interval tested is equal to:

$$K = \frac{rc^2 \ln(Re/rw) \ln(yo/yt)}{2 L_e t} \tag{12}$$

where r_c = radius of the well casing; (ft)

r_w = radius of the well; (ft)

R_e = effective test radius; (ft)

y_o = pressure difference from static pressure at time t_o; (lb/in²)

y_t = pressure difference from static pressure at time t_t; (lb/in²)

L_e = screened test interval length; (ft)

t = test time at y_t; (sec)

where:

for $L_w = H$

$$\ln R_e/r_w = [(1.1/\ln(L_w/r_w)) + C/(\ln\{L_e/r_w\})]^{-1} \tag{13}$$

for $L_w < H$

$$\ln R_e/r_w = [(1.1/\ln(L_w/r_w)) + (A + B \ln\{(H-L_w)/r_w\}/(\ln(L_e/r_w)]^{-1} \tag{14}$$

where H = aquifer thickness; (ft)

L_w = distance from the water table to the bottom of the test section; (ft)

This analysis method is commonly used for slug tests conducted in the unconfined aquifer on the Hanford Site. Bouwer and Rice (1976) indicate that their analysis method should provide estimates of transmissivity that are of the "same order" as those calculated with the procedure of Cooper et al. (1967). Figure 4.10 shows the analysis results for the slug withdrawal test based on the Bouwer and Rice (1976) method. As indicated, a lower hydraulic conductivity value of 2.3 ft/d was obtained, which was based on the following input parameters: $H = 52$ ft (static water level to top of clay layer at 179 ft); $r_c = 0.4167$ ft; $\ln(R_e/r_w) = 2.72$ (calculated from Equation 4 and Figure 2 in Bouwer (1989) for $L_e/r_w = 24.24$); $y_o = 15.2$ lb/in²; $y_t = .053$ lb/in² (Figure 4.10); $L_e = 10.1$ ft; and, $t = 5{,}000$ s (Figure 4.10).

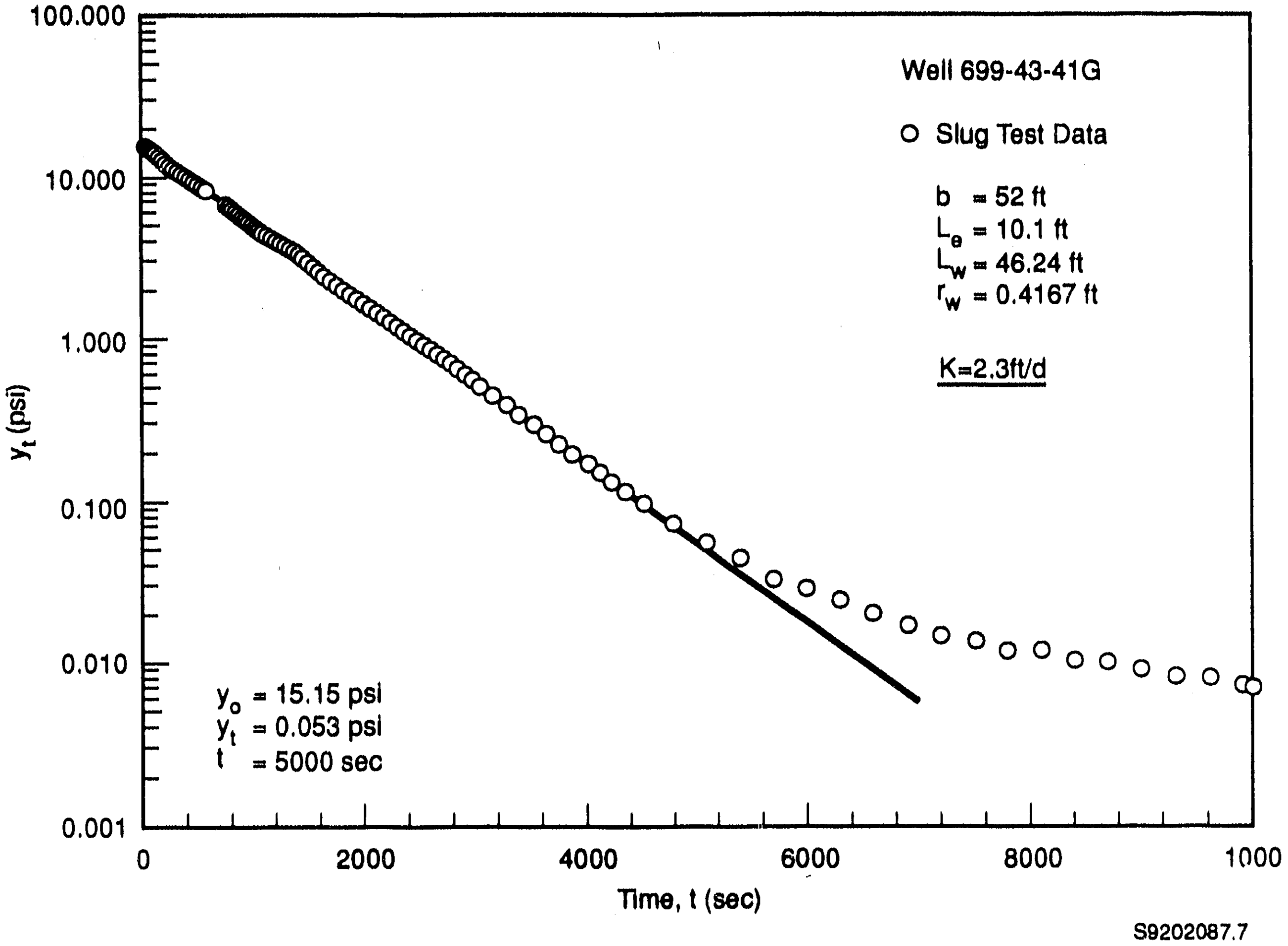


FIGURE 4.10. Slug Test Analysis for Stress Well 699-43-41G Using the Bouwer and Rice (1976) Analysis Method

The Bouwer and Rice (1976) method is based on the Thiem steady-state solution, which does not account for aquifer elastic storage during testing. In addition, the dimensionless parameters A, B, and C that are used in the analysis procedure [(Equations (13) and (14)] are based on empirical relationships developed from electric analog studies that relate effective test radius, R_e, with various test geometries. Because of the empirical nature of the developed relationships, Bouwer and Rice (1976) cite a relative accuracy for their technique of between 10% to 25%.

Because of various limitations that were briefly described for both slug test analysis methods (i.e., Ostrowski and Kloska 1989; Bouwer and Rice 1976), no preferred or "best-estimate" of equivalent hydraulic conductivity is assigned for this test. The transmissivity estimates obtained for each analysis method are provided as a range for comparison with slug interference test results. As a consequence, an assigned equivalent hydraulic conductivity range between 2.3 ft/d and 5.7 ft/d is provided from analysis of the slug withdrawal test conducted at well 699-43-41G.

4.4.3 Observation Well 699-43-41E Response

The slug withdrawal test at well 699-43-41G caused a maximum slug interference pressure response of 0.093 lb/in^2 at observation well 699-43-41E. The maximum response was recorded approximately 1,800 seconds after slug initiation. Figure 4.11 shows the slug interference response, both for corrected and uncorrected for barometric pressure changes during the test. As indicated, considerable improvement in the late-time data profile was obtained by removing the effects of atmospheric pressure fluctuation. Examination of Figure 4.11 indicates that the slug pressure "hump" or "wave" was first detected at approximately 300 s, with residual effects of the slug interference still manifested in the observation well response up to 20,000 s.

Figure 4.12 shows the slug interference test analysis for barometric corrected data collected at observation well 699-43-41E. Type curves shown were generated using a modified version of the Novakowski code described in Section 3.0 and an observation well distance of 48 ft (horizontal distance separating the stress and observation wells). For comparison purposes, the sensitivity of the analysis to different values of storativity and transmissivity are shown in Figures 4.12a and 4.12b, respectively. As indicated, the best fit for the observed slug interference response at observation well 699-43-41E is obtained using a transmissivity value of 145 ft^2/d and a storativity value of 4.4×10^{-3}. The transmissivity and storativity values obtained from the analysis are mainly reflective of aquifer conditions from the stress well to the point of observation. Based on an aquifer thickness of 52 ft, an equivalent hydraulic conductivity value of 2.8 ft/d is indicated for

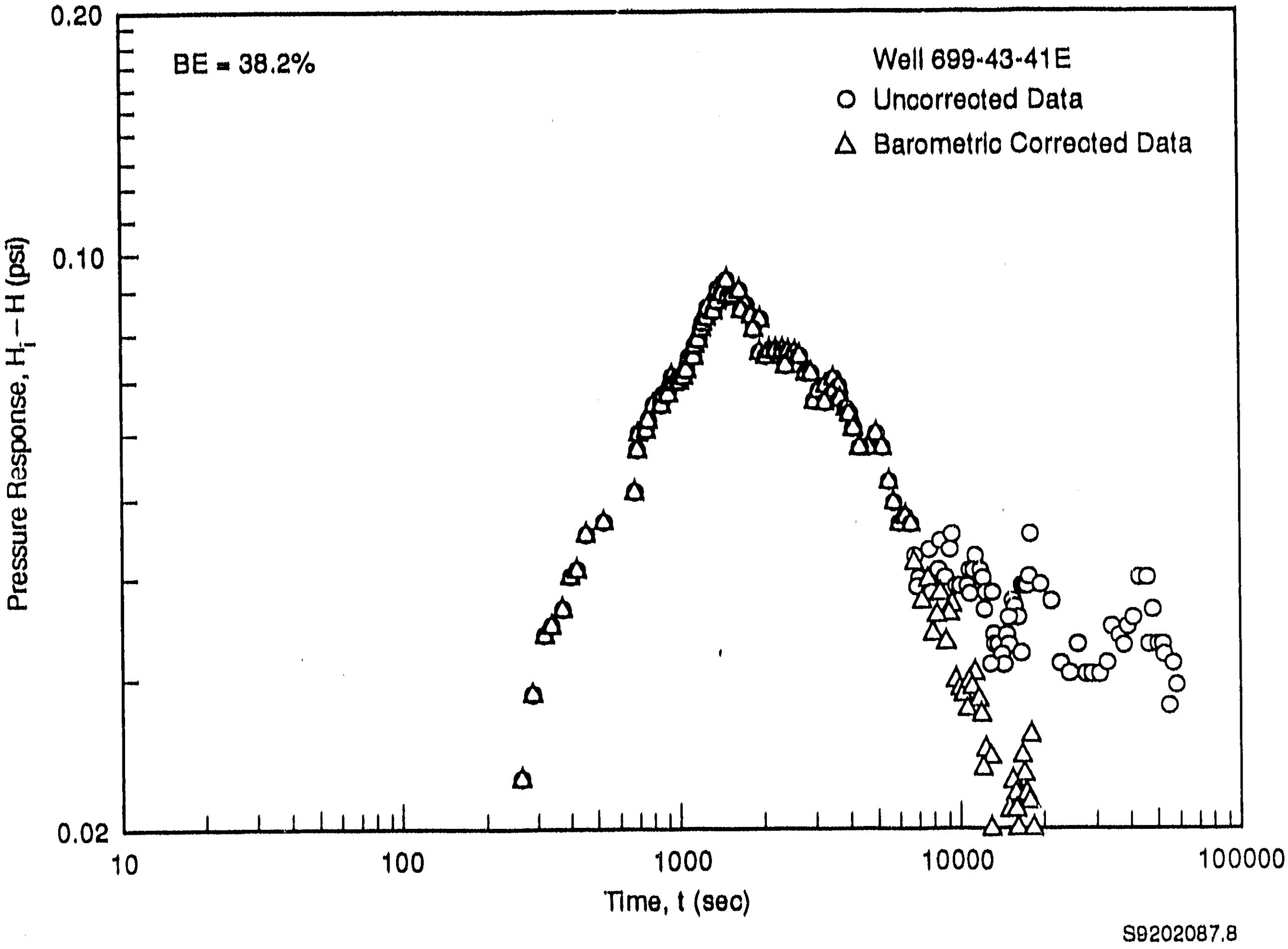


FIGURE 4.11. Slug Interference Response Data Recorded at Observation Well 699-43-41E

the intervening geologic materials. This estimate value falls within the lower range obtained at well 699-43-41G for the lower aquifer section tested, which is based on single-well slug test analysis.

Analysis of the slug interference response observed at well 699-43-41E, using the computer program presented in Novakowski (1990), assumes that the slug peak or central slug interference "hump" (which is the focus of analysis procedure) is not significantly affected by delayed-yield (i.e., vertical flow/leakage) test behavior (see Section 3.2.1). The presence of delayed-yield behavior can be discerned by converting the observed slug test data to

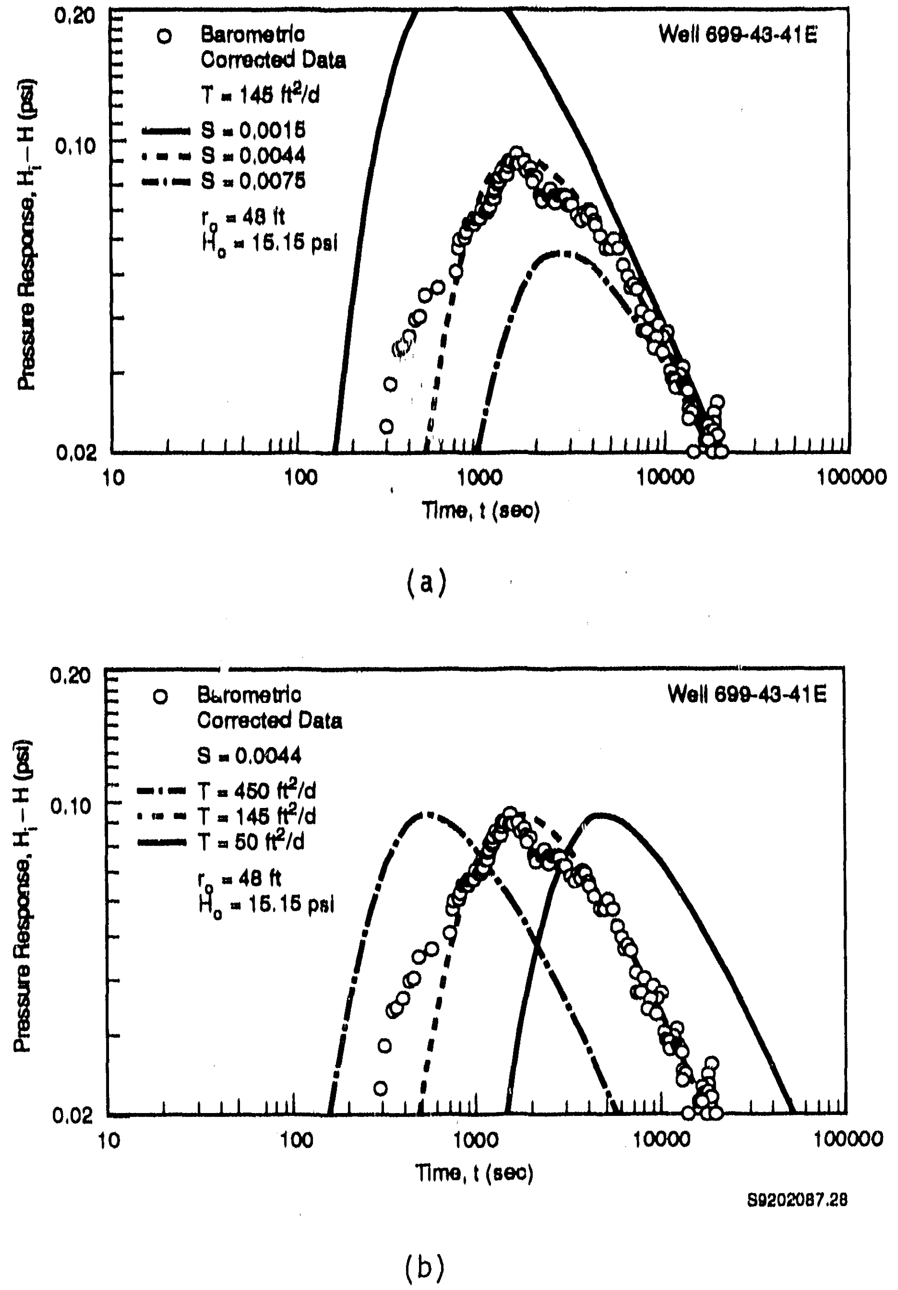


FIGURE 4.12. Slug Interference Test Analysis for Well 699-43-41E Showing: a) Effect of Varying Storativity, and b) Effect of Varying Transmissivity

equivalent head and equivalent head derivative values for a constant-rate pumping test. Conversion of slug test response data for well 699-43-41E to equivalent head and head derivative values followed the procedure described in Section 4.4.2 for analyzing test results obtained at well 699-43-41G. The presence of delayed-yield behavior was then assessed using pressure derivative analysis of the equivalent head response as also described in Section 4.4.2.

Figure 4.13 shows the results of transforming slug test data collected at well 699-43-41E to its equivalent head and derivative form for a constant-rate test. Also shown is the predicted equivalent head and head derivative type-curve response based on the previously obtained slug interference test analysis results for transmissivity (i.e., T = 145 ft^2/d) and storativity (S = 4.4 x 10^{-3}) as indicated in Figure 4.12. The equivalent head type-curve

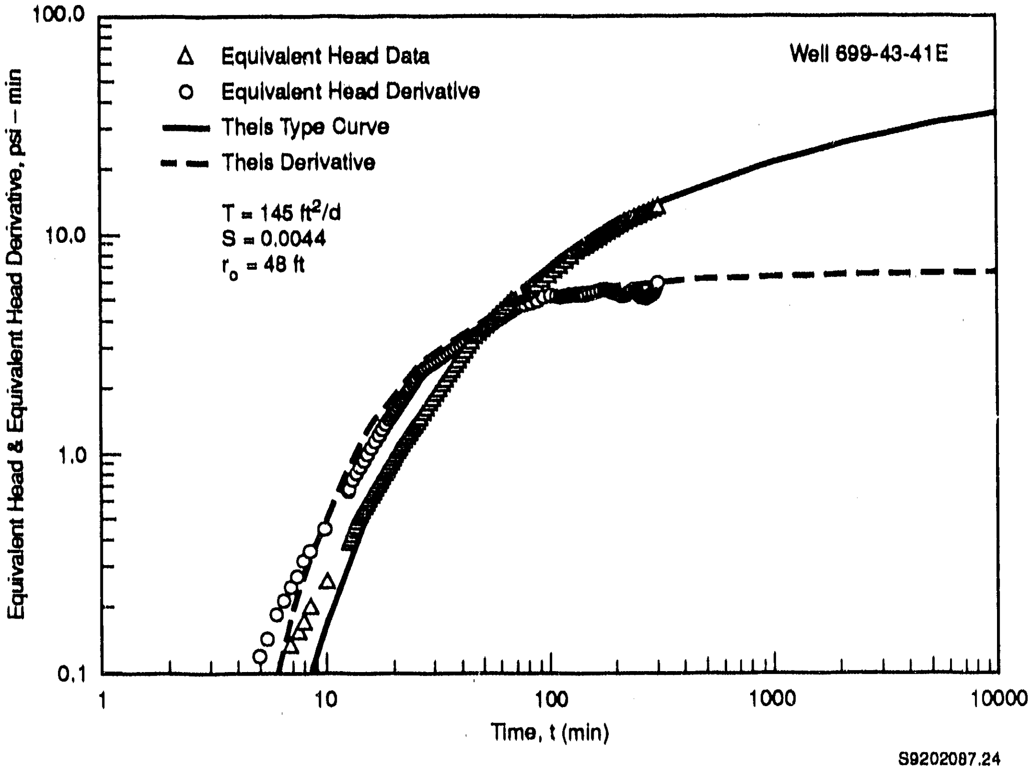


FIGURE 4.13. Diagnostic Analysis of Equivalent Head and Equivalent Head Derivative Plot Data for Slug Interference Test Observed at Well 699-43-41E

response was calculated using the modified version of the Novakowski (1990) program, while the equivalent head derivative was determined based on the derivative algorithm described in Bourdet et al. (1989). As indicated in the figure, the equivalent head and head derivative response closely match the response predicted by the type curve. Diagnostic analysis of the derivative response pattern indicates that no significant delayed-yield effects were evident in the observed test data. This suggests that the transmissivity of 145 ft^2/d and storativity of 4.4×10^{-3} obtained from the slug interference analysis are reasonable estimate of hydraulic properties for the intervening aquifer materials.

4.4.4 Observation Well 699-43-41F Response

The slug withdrawal test at well 699-43-41G caused a maximum slug interference pressure response of 0.14 lb/in^2 at observation well 699-43-41F. The maximum response was recorded approximately 650 s after slug initiation. Figure 4.14 shows the slug interference response, both corrected and uncorrected for barometric pressure changes during the test. In contrast to data obtained for observation well 699-43-41E, little improvement is indicated in the data profile obtained by removing the effects of atmospheric pressure fluctuation. This is due to the fact that the observed slug interference response dissipated more rapidly, prior to the occurrence of significant atmospheric pressure fluctuations that were manifested later in the test. Examination of Figure 4.14 also indicates that the slug pressure "hump" or "wave" was first detected at approximately 75 s, with residual effects of the slug interference still evident in the observation well response up to 4,000 s. This represents an earlier detection and slug interference dissipation by a factor of 4 to 5 in comparison to that recorded at observation well 699-43-41E.

Figure 4.15 shows the slug interference test analysis for data collected at observation well 699-43-41F. As in the analysis previously described for observation well 699-43-41E, the type curves shown were generated using a modified version of the Novakowski code described in Section 3.0 and an observation well distance of 49 ft (horizontal distance between the stress well and the point of observation. For comparison purposes, the sensitivity

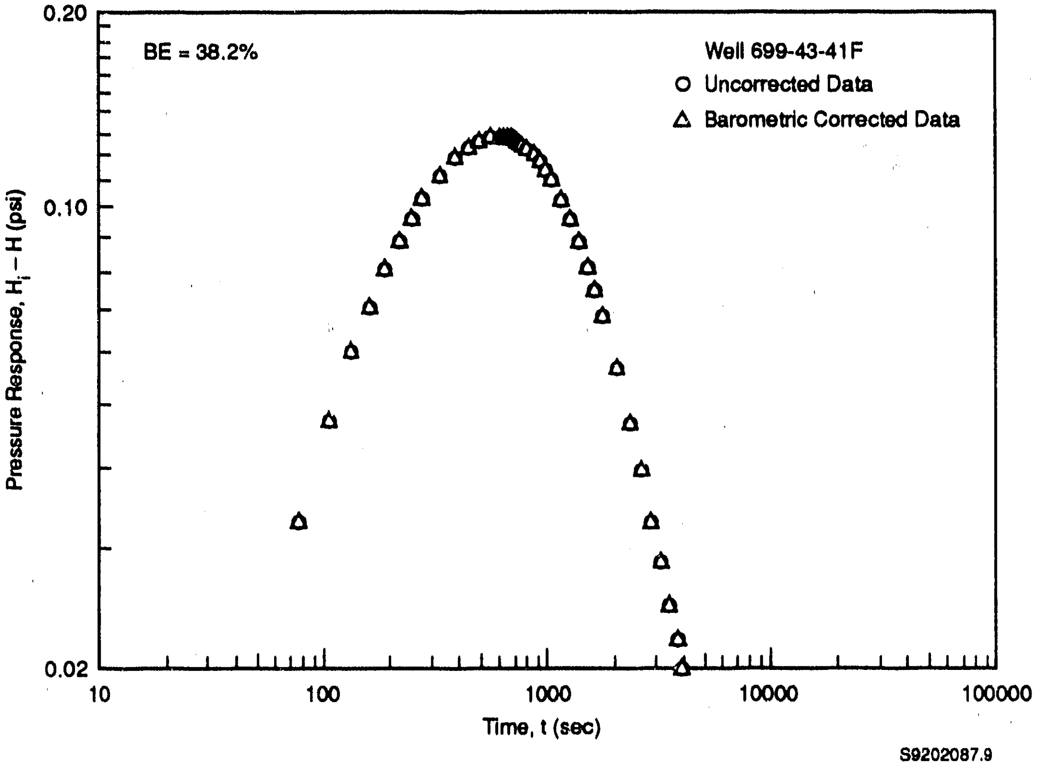


FIGURE 4.14. Slug Interference Response Data Recorded at Observation Well 699-43-41F

of the analysis to different values of storativity and transmissivity are shown in Figures 4.15a and 4.15b, respectively. As indicated, the best fit for the observed slug interference response at observation well 699-43-41F is obtained using a transmissivity value of 310 ft²/d and a storativity value of 2.9 x 10^{-3}. The transmissivity value is approximately a factor of two higher than that obtained from analysis of test data for observation well 699-43-41F. The storativity value is nearly the same as that calculated for observation well 699-43-41E and suggests semi-confined conditions, but is also within the elastic response range commonly exhibited by unconfined aquifers (e.g., Gambolati 1976; Neuman 1974, 1979). The transmissivity and storativity values obtained from the analysis are mainly reflective of aquifer conditions from the stress well to the point of observation. Based on an aquifer thickness of 52 ft, an equivalent hydraulic conductivity value of 6.0 ft/d is indicated

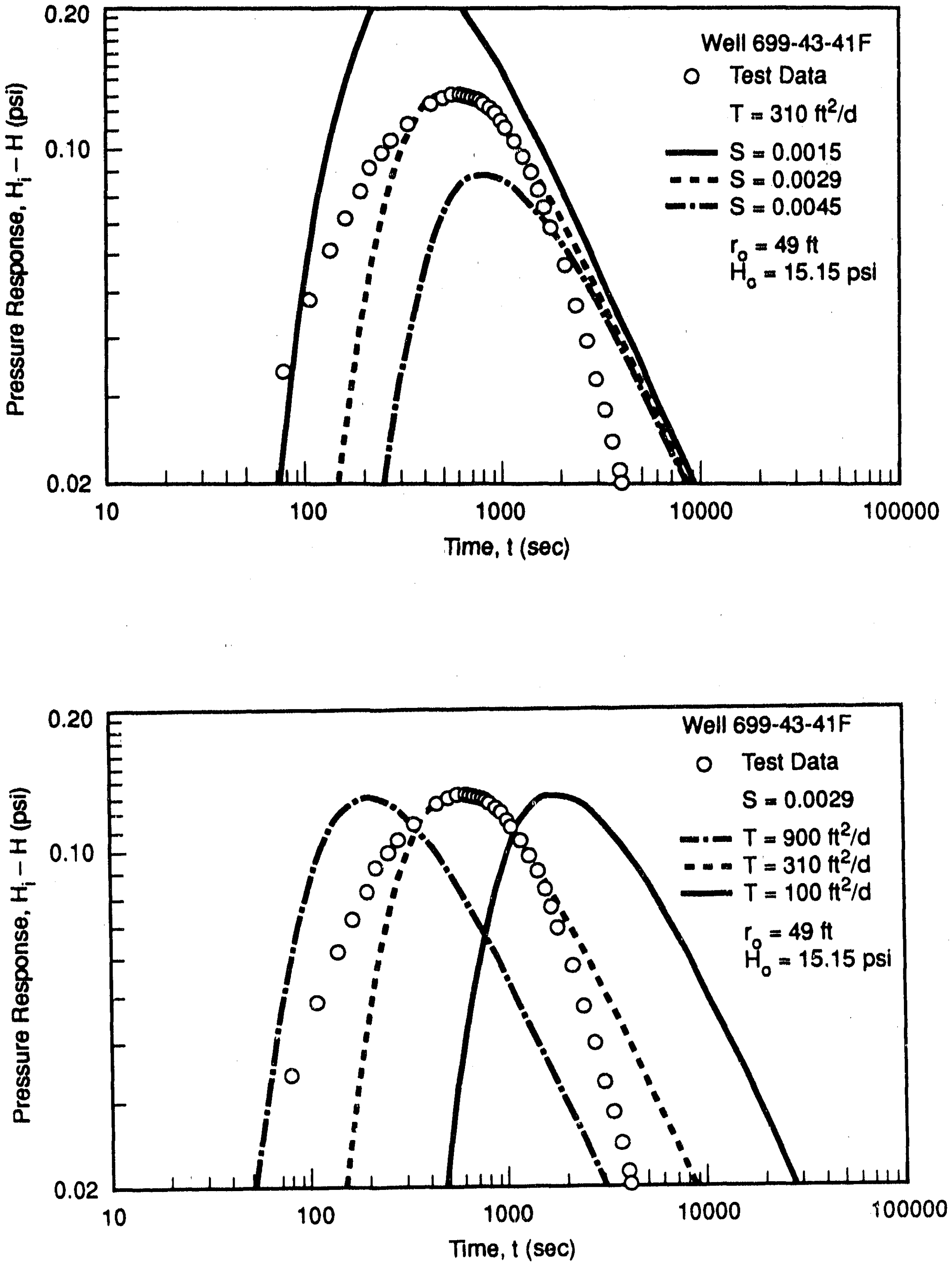


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FIGURE 4.15. Slug Interference Test Analysis for Well 699-43-41F

for the intervening geologic materials. This estimate falls near the upper range obtained at well 699-43-41G (for the lower aquifer test section), which is based on single-well slug test analysis.

It should be noted that while an appropriate fit of the central data region was obtained, early-time (buildup) and late-time data (recovery) do not precisely match the type-curve. Possible explanations for this behavior include the presence of relatively significant vertical ground-water flow/leakage conditions during testing, partial penetration effects, etc.

Analysis of the slug interference response observed at well 699-43-41F, using the computer program presented in Novakowski (1990), assumes that the slug peak or central slug interference "hump" (which is the focus of analysis procedure) is not significantly affected by delayed-yield (i.e., vertical flow/leakage) test behavior (see Section 3.2.1). The presence of delayed-yield behavior can be discerned by converting the observed slug test data to equivalent head and equivalent head derivative values for a constant-rate pumping test. Conversion of slug test response data for well 699-43-41F to equivalent head and head derivative values followed the procedure described in Section 4.4.3 for analyzing test results obtained at well 699-43-41E. The presence of delayed-yield behavior was then assessed using pressure derivative analysis of the equivalent head response as described in Section 4.4.2.

Figure 4.16 shows the results of transforming slug test data collected at well 699-43-41F to its equivalent head and derivative form for a constant-rate test. Also shown is the predicted equivalent head and head derivative type-curve response based on the previously obtained slug interference test analysis results for transmissivity (i.e., $T = 310$ ft^2/d) and storativity ($S = 2.9 \times 10^{-3}$) as indicated in Figure 27. The equivalent head type-curve response was calculated using the modified version of the Novakowski (1990) program, while the equivalent head derivative was determined based on the derivative algorithm described in Bourdet et al. (1989). As indicated in the figure, the equivalent head derivative response significantly deviates below the predicted derivative response after a test time of approximately 30 minutes. The deviation below the derivative of the Theis type-curve confirms the presence of non-radial flow conditions that are characteristic of

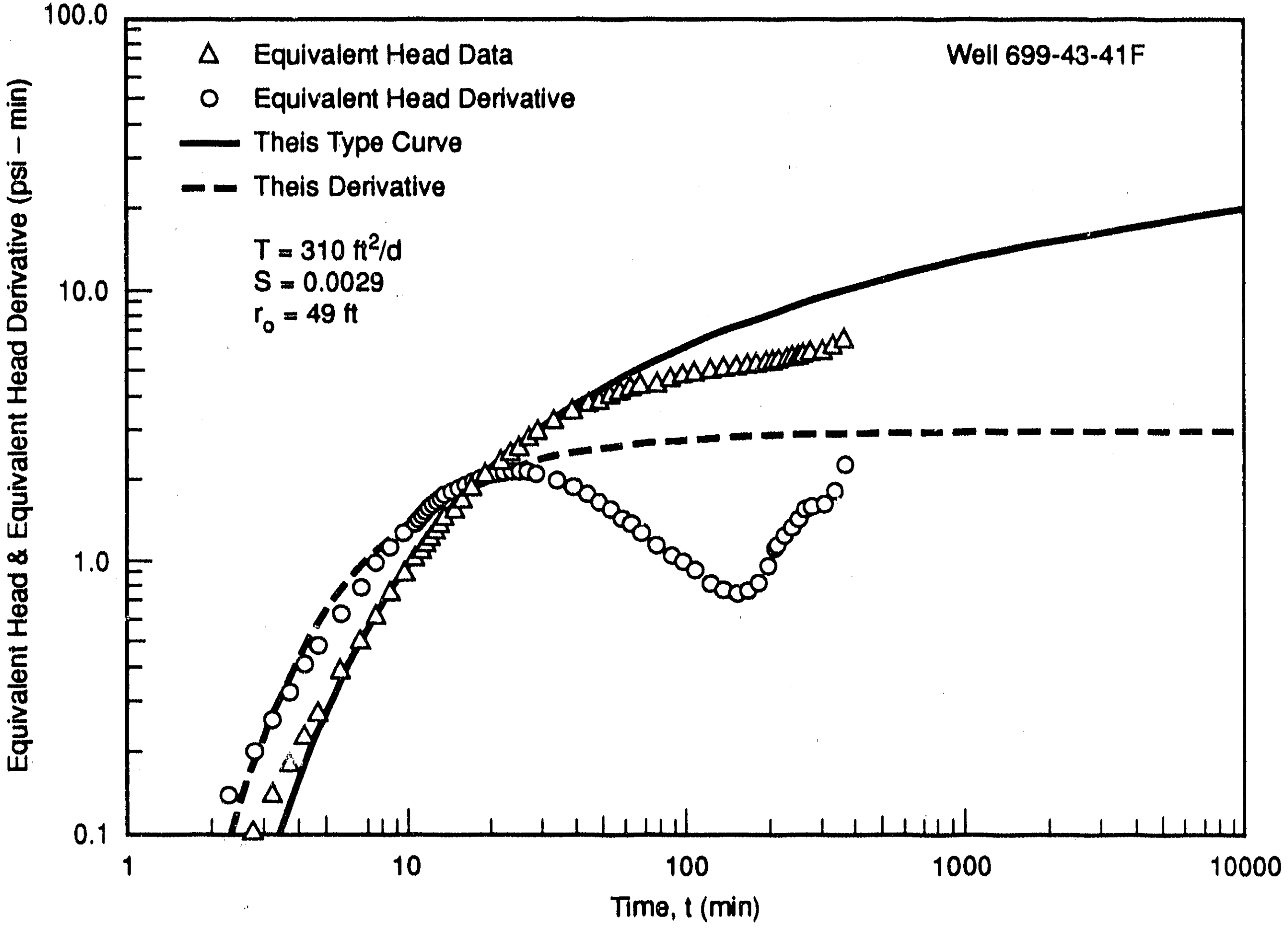

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FIGURE 4.16. Diagnostic Analysis of Equivalent Head and Equivalent Head Derivative Plot Data for Slug Interference Test Observed at Well 699-43-41F

delayed yield (i.e., vertical flow/leakage) behavior. The leakage or delayed yield conditions are also evident in the figure by the deviation below the Theis equivalent head type curve.

The late-time (i.e., $t > 200$ min) upward deflection of the equivalent head derivative data, back to the indicated radial flow conditions on the Theis derivative plot is interesting. The return to radial flow conditions in late-time may be related to the third-segment of unconfined aquifer response behavior which follows delayed-yield response (see Section 3.2.1). In this region, time-drawdown data follows that predicted by the Theis equation with storativity equal to its combined elastic storage component, S_e, and specific yield, S_y. Not enough data is present, however, to corroborate this observation.

The diagnostic analysis and type-curve matching results suggest that the values for transmissivity of 310 ft^2/d and storativity of 2.9×10^{-3} obtained for the slug interference test analysis are reasonable estimates of hydraulic properties for the intervening aquifer materials; since it is based on type-curve matching of test data prior to establishment of significant vertical flow or leaky aquifer flow conditions (i.e., prior to test times of 30 minutes). This estimate, however, would be expected to be slightly greater than actual conditions, due to the likelihood of some vertical flow or leaky aquifer behavior even during the early stages of the test.

5.0 CONCLUSIONS

Results of the field test evaluation indicate that analyzable slug interference responses were obtained at two nearby observation wells (699-43-41E and -43-41F) located approximately 48 and 49 ft, respectively, from the stress test well (699-43-41G) location. Slug interference analysis provided transmissivity estimates for the unconfined aquifer <u>between</u> the stress well and observation well location of 145 ft^2/d and 310 ft^2/d. Based on an aquifer thickness of 52 ft, an estimate range for equivalent hydraulic conductivity from 2.8 ft/d to 6.0 ft/d is indicated for the intervening aquifer between the stress and observation well locations. This hydraulic conductivity range compares favorably with single-well slug test analysis results obtained at the stress well (i.e., equivalent hydraulic conductivity ranging between 2.3 ft/d and 5.7 ft/d) during interference testing, which was representative of the screened interval test section. Less correspondence is exhibited for previously conducted low-stress, single-well slug tests estimates that were obtained at the observation well locations (i.e., between 0.4 ft/d and 1.0 ft/d, and between 1.4 ft/d and 2.8 ft/d obtained for wells 699-43-41E and -43-41F, respectively), which are discussed in Appendix C. The reason for the lower correspondence with results obtained from the previously conducted single-well (observation well) slug tests is not known; however, it may be related to the considerably smaller range of investigation attributed to the low stress level (approximately 1/10 that utilized during the slug interference test), which was imposed at the observation wells during the previously conducted single-well tests.

Storativity estimates obtained from slug interference test analysis for the observation wells provided similar results ranging between 2.9×10^{-3} and 4.4×10^{-3}. These estimated storativity values suggest semi-confined conditions, but are also within the elastic response range commonly exhibited by unconfined aquifers (e.g., Gambolati 1976; Neuman 1974, 1979).

Other salient conclusions that are pertinent for slug interference test analysis are provided below:

1. For observation wells displaying a long-duration and low amplitude response, the recorded slug interference data can be significantly improved for type-curve analysis by removing the effects of other extraneous stress factors, such as barometric fluctuations during testing.

2. The central slug interference test data "hump" should be the focus for analysis using the program presented in Novakowski (1990). The analysis method assumes that no vertical/leakage flow conditions are significant within this focusing region of the slug test data set.

3. The presence of non-radial flow conditions (i.e., vertical/leakage flow) within regions of the data set, which are not valid using Theis equation based solutions, can be detected through use of diagnostic pressure derivative analysis. The procedure requires that the slug test data be first converted to equivalent head and head derivative data that would be obtained during a constant-rate pumping test, following the procedure described in Peres et al. (1989). The equivalent head and head derivative data can then be subjected to diagnostic analysis using available dimensionless pressure and dimensionless pressure derivative type curves (e.g., Bourdet et al. 1983, 1989).

4. Because of the favorable observation well distance versus aquifer thickness ratio (i.e., $r/b \approx 1$), no corrections for stress well partial penetration effects were applied to the observed slug interference data. It should be possible, however, to correct for partial penetration effects by following the methods presented in Weeks (1969), which would be applied to the slug test data that has been transformed to equivalent head form.

Initial results of the analytical assessment and field evaluation for applying slug interference testing as a possible hydraulic characterization method at the Hanford Site are encouraging. It would appear to be particularly attractive for providing hydraulic characterization in contaminated areas where the use of standard hydrologic characterization methods (e.g., pumping tests) may not be possible (i.e., due to disposal problems created by the production of contaminated ground water).

While the slug interference test field evaluation provided representative results for a test formation (Ringold Formation) possessing an intermediate transmissivity (i.e., 10^2 ft^2/d), the real benefit of the technique at the Hanford Site may be for characterizing higher transmissivity formations (> 10^3 ft^2/d, e.g., overlying glaciofluvial deposits) for which single-well slug test methods are not applicable.

Additional field evaluation tests are recommended to more fully assess the applicability range of slug interference testing. In particular, it is recommended that a site is selected that has already undergone detailed hydraulic characterization using standard hydraulic characterization techniques (i.e., constant-rate pumping tests). It would also be useful if additional sites be tested with test intervals that encompass the water table; since this condition is expected to attenuate and delay the slug interference signal produced at the stress well.

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APPENDIX A

COMPARISON OF NOVAKOWSKI PROGRAM-GENERATED SLUG TEST RESPONSES, WITH PUBLISHED TYPE CURVE RESPONSES AT THE STRESS WELL (COOPER ET AL. 1967) AND OBSERVATION WELL (RAMEY ET AL. 1975)

APPENDIX A

COMPARISON OF NOVAKOWSKI PROGRAM-GENERATED SLUG TEST RESPONSES, WITH PUBLISHED TYPE CURVE RESPONSES AT THE STRESS WELL (COOPER ET AL. 1967) AND OBSERVATION WELL (RAMEY ET AL. 1975)

STRESS WELL COMPARISON

For the test comparison of slug test results at the stress well, the modified Novakowski (1990) program was run to duplicate results listed in Cooper et al. (1967) for alpha, α, curves: -1, -3, and -5. As indicated from Equation (3), for situations where $r_c = r_w$, this would be analogous to storativity values of 10^{-1}, 10^{-3}, and 10^{-5}.

To use the modified Novakowski program, the selected alpha curve values were converted to dimensionless wellbore storage, C_D, values using the following relationships presented in Novakowski (1990) and Cooper et al. (1967):

$$C_D = C_s/(2\pi\ r_w^2\ S) \qquad \text{(A-1)}$$

and,

$$C_s = \pi\ r_c^2 \qquad \text{(A-2)}$$

and Equation (3),

$$\alpha = S\ (r_w^2/r_c^2)$$

Combining the above listed relationships, yields:

$$C_D = 1/2\alpha \qquad \text{(A-3)}$$

The comparison results for the selected alpha curve/dimensionless wellbore storage values, for the given beta (β) values, are presented below.

	Alpha-1		Alpha-3		Alpha-5	
Beta	Cooper et al. (1967)	Program Results	Cooper et al. (1967)	Program Results	Cooper et al. (1967)	Program Results
0.001	0.9771	0.9771	0.9969	0.9969	0.9992	0.9991
0.01	0.9238	0.9257	0.9853	0.9854	0.9942	0.9942
0.1	0.7460	0.7460	0.9183	0.9183	0.9572	0.9571
1.0	0.3117	0.3117	0.5729	0.5729	0.7080	0.7079
10.0	0.03065	0.03065	0.04821	0.04821	0.08378	0.08372
100.0	0.002577	0.002577	0.002653	0.002653	0.002725	0.002726

(Note: Beta, $\beta = (T_D/C_D)/2$

OBSERVATION WELL COMPARISON

For the test comparison of predicted slug interference test results at an observation well, the modified Novakowski (1990) program was also used to duplicate results listed in Ramey et al. (1975) for a dimensionless wellbore storage, C_D, of 1000 and for dimensionless radial distances, R_D of 2, 20, and 200 (where R_D = radial distance to the point of observation divided by the wellbore radius; r_o/r_w).

Dimensionsless Wellbore Storage Constant, CD, = 100

	RD = 2		RD = 20		RD = 200	
TD/CD	Ramey et al. (1975)	Program Results	Ramey et al. (1975)	Program Results	Ramey et al. (1975)	Program Results
0.1	0.592663	0.592661	0.000005	*	-	*
1.0	0.518490	0.518490	0.044472	0.043852	-	*
5.0	0.216084	0.216084	0.081941	0.081941	-	*
10.0	0.099411	0.099412	0.056775	0.056776	0.000001	*
50.0	0.011098	0.011098	0.010990	0.010990	0.001299	0.001240
100.0	0.005466	0.005467	0.005272	0.005272	0.001815	0.001733

Dimensionsless Wellbore Storage Constant, CD, = 1000

	RD = 2		RD = 20		RD = 200	
TD/CD	Ramey et al. (1975)	Program Results	Ramey et al. (1975)	Program Results	Ramey et al. (1975)	Program Results
0.1	0.736588	0.730589	0.052210	0.051593	-	*
1.0	0.626510	0.626512	0.207075	0.207976	0.000001	*
5.0	0.295102	0.295102	0.155703	0.155703	0.004776	0.004882
10.0	0.139691	0.139692	0.089605	0.089605	0.012811	0.012596
50.0	0.012812	0.012813	0.011998	0.011998	0.008895	0.008895
100.0	0.005627	0.005627	0.005474	0.005474	0.004785	0.004785

* The modified Novakowski program does not calculate dimensionless head responses below 0.00001.

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APPENDIX B

SLUG INTERFERENCE TEST DATA

B.1. Stress Well 699-43-41G

B.2. Observation Well 699-43-41E

B.3. Observation Well 699-43-41F

TABLE B.1. Slug Interference Test Data - Stress Well 699-43-41G

Date	Clock Time	Pressure Reading, psia
8/28/91	10:30:06	32.0100
8/28/91	10:34:50	32.0083
8/28/91	10:39:50	32.0083
8/28/91	10:44:50	32.0074
8/28/91	10:49:50	32.0074
8/28/91	10:54:50	32.0059
8/28/91	11:04:57	32.0041
8/28/91	11:09:40	32.0050
8/28/91	11:14:40	32.0050
8/28/91	11:19:40	32.0033
8/28/91	11:24:40	32.0204
8/28/91	11:29:40	32.0237
8/28/91	11:32:07	32.0219
8/28/91	11:32:24	32.0219
8/28/91	11:32:30	began pressurizing casing
8/28/91	11:32:52	32.4637
8/28/91	11:33:19	33.0412
8/28/91	11:33:52	33.6492
8/28/91	11:34:19	34.1508
8/28/91	11:34:51	34.7866
8/28/91	11:35:23	35.6176
8/28/91	11:35:51	36.7833
8/28/91	11:36:24	38.7328
8/28/91	11:37:16	42.0238
8/28/91	11:37:57	43.8191
8/28/91	11:38:58	45.8497
8/28/91	11:46:37	39.9554
8/28/91	11:47:18	39.6899
8/28/91	11:48:19	39.3423
8/28/91	11:49:20	39.0274
8/28/91	11:50:20	38.7380
8/28/91	11:51:21	38.4701
8/28/91	11:52:22	38.2226
8/28/91	11:53:18	38.5190
8/28/91	11:54:19	38.1862
8/28/91	11:55:20	37.9460
8/28/91	11:56:21	37.7287
8/28/91	11:57:22	37.5273
8/28/91	11:58:18	37.3522
8/28/91	12:00:06	37.0391
8/28/91	12:04:51	36.6868
8/28/91	12:09:51	36.4860
8/28/91	12:14:51	35.8163
8/28/91	12:19:51	35.3062
8/28/91	12:24:51	34.8868

TABLE B.1. (contd)

Date	Clock Time	Pressure Reading, psia
8/28/91	12:29:51	34.9676
8/28/91	12:34:51	34.5793
8/28/91	12:39:51	34.2658
8/28/91	12:44:51	34.0073
8/28/91	12:49:51	33.7869
8/28/91	12:54:51	33.6014
8/28/91	12:59:51	33.4398
8/28/91	13:09:15	33.1929
8/28/91	13:18:59	32.9961
8/28/91	13:28:59	32.8403
8/28/91	13:38:59	32.7227
8/28/91	13:48:59	32.6280
8/28/91	13:58:59	32.6818
8/28/91	14:08:59	32.6912
8/28/91	14:18:59	32.6000
8/28/91	14:28:59	32.5310
8/28/91	14:38:59	32.4730
8/28/91	14:48:59	32.4183
8/28/91	14:58:59	32.3699
8/28/91	15:03:16	32.3478
8/28/91	15:32:59	32.2403
8/28/91	16:02:59	32.1652
8/28/91	16:32:59	32.1166
8/28/91	17:02:59	32.0851
8/28/91	17:32:59	32.0697
8/28/91	18:02:59	32.0662
8/28/91	18:32:59	32.0714
8/28/91	19:02:59	32.0842
8/28/91	19:32:59	32.0918
8/28/91	20:02:59	32.0901
8/28/91	20:32:59	32.0927
8/28/91	21:02:59	32.0901
8/28/91	21:32:59	32.0851
8/28/91	22:02:59	32.0766
8/28/91	22:32:59	32.0654
8/28/91	23:02:59	32.0688
8/28/91	23:32:59	32.0740
8/29/91	0:02:59	32.0758
8/29/91	0:32:59	32.0749
8/29/91	1:02:59	32.0732
8/29/91	1:32:59	32.0782
8/29/91	2:02:59	32.0877
8/29/91	2:32:59	32.0851
8/29/91	3:02:59	32.0971
8/29/91	3:32:59	32.0886
8/29/91	4:02:59	32.1047

TABLE B.1. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	4:33:00	32.1116
8/28/91	12:34:51	34.5793
8/29/91	7:02:59	32.0886
8/29/91	7:32:59	32.0714
8/29/91	7:43:53	32.0654
8/29/91	7:48:37	32.0630
8/29/91	7:53:37	32.0612
8/29/91	7:58:37	32.0586
8/29/91	8:03:37	32.0586
8/29/91	8:05:58	32.0560
8/29/91	8:06:16	32.0569
8/29/91	8:06:43	32.0560
8/29/91	8:07:11	32.0560
8/29/91	8:07:43	32.0560
8/29/91	8:08:11	32.0552
8/29/91	8:08:43	32.0543
8/29/91	8:09:20	32.0534
8/29/91	8:09:27	32.0560
8/29/91	8:09:29	32.0552
8/29/91	8:09:30	31.0567
8/29/91	8:09:31	released gas pressure in stress well
8/29/91	8:09:32	16.8700
8/29/91	8:09:33	17.0190
8/29/91	8:09:35	17.1201
8/29/91	8:09:40	17.2473
8/29/91	8:09:43	17.3031
8/29/91	8:09:46	17.3527
8/29/91	8:09:49	17.4050
8/29/91	8:09:52	17.4590
8/29/91	8:09:55	17.5087
8/29/91	8:10:01	17.6019
8/29/91	8:10:04	17.6515
8/29/91	8:10:07	17.7021
8/29/91	8:10:10	17.7517
8/29/91	8:10:13	17.8014
8/29/91	8:10:20	17.9188
8/29/91	8:10:26	18.0190
8/29/91	8:11:00	18.5871
8/29/91	8:11:18	18.8880
8/29/91	8:11:45	19.3111
8/29/91	8:12:12	19.6803
8/29/91	8:12:45	20.1022
8/29/91	8:13:17	20.5166
8/29/91	8:13:44	20.8662
8/29/91	8:14:16	21.2527

TABLE B.1. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	8:14:43	21.5656
8/29/91	8:15:15	21.9231
8/29/91	8:15:43	22.2191
8/29/91	8:16:14	22.5562
8/29/91	8:16:46	22.8813
8/29/91	8:17:14	23.1500
8/29/91	8:17:46	23.4549
8/29/91	8:18:14	23.7081
8/29/91	8:19:11	24.2181
8/29/91	8:21:54	25.5401
8/29/91	8:22:12	25.6631
8/29/91	8:22:39	25.8466
8/29/91	8:23:11	26.0565
8/29/91	8:23:38	26.2303
8/29/91	8:24:10	26.4272
8/29/91	8:24:37	26.5913
8/29/91	8:25:09	26.7771
8/29/91	8:25:37	26.9319
8/29/91	8:26:09	27.1071
8/29/91	8:26:41	27.2771
8/29/91	8:27:08	27.4109
8/29/91	8:27:40	27.5724
8/29/91	8:28:07	27.7047
8/29/91	8:28:39	27.8540
8/29/91	8:29:11	27.9998
8/29/91	8:29:38	28.1190
8/29/91	8:30:10	28.2545
8/29/91	8:30:38	28.3670
8/29/91	8:31:10	28.4964
8/29/91	8:31:37	28.6019
8/29/91	8:32:09	28.7226
8/29/91	8:32:41	28.8392
8/29/91	8:33:08	28.9360
8/29/91	8:33:40	29.0441
8/29/91	8:34:07	29.1347
8/29/91	8:34:39	29.2376
8/29/91	8:35:25	29.3772
8/29/91	8:36:11	29.5141
8/29/91	8:37:07	29.6691
8/29/91	8:38:07	29.8274
8/29/91	8:39:08	29.9745
8/29/91	8:40:09	30.1130
8/29/91	8:41:10	30.2432
8/29/91	8:42:10	30.3635
8/29/91	8:43:11	30.4765
8/29/91	8:44:07	30.5739

TABLE B.1. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	8:45:08	30.6738
8/29/91	8:46:08	30.7662
8/29/91	8:47:09	30.8524
8/29/91	8:48:10	30.9337
8/29/91	8:49:10	31.0089
8/29/91	8:50:11	31.0814
8/29/91	8:51:07	31.1411
8/29/91	8:52:08	31.2035
8/29/91	8:53:09	31.2608
8/29/91	8:54:09	31.3153
8/29/91	8:55:10	31.3648
8/29/91	8:56:39	31.4315
8/29/91	8:58:24	31.5040
8/29/91	9:00:24	31.5744
8/29/91	9:02:24	31.6372
8/29/91	9:04:24	31.6919
8/29/91	9:06:24	31.7397
8/29/91	9:08:24	31.7788
8/29/91	9:10:24	31.8146
8/29/91	9:12:24	31.8445
8/29/91	9:14:24	31.8719
8/29/91	9:16:24	31.8941
8/29/91	9:18:24	31.9145
8/29/91	9:20:24	31.9316
8/29/91	9:22:24	31.9462
8/29/91	9:24:59	31.9622
8/29/91	9:29:44	31.9852
8/29/91	9:34:44	32.0015
8/29/91	9:39:44	32.0126
8/29/91	9:44:44	32.0237
8/29/91	9:49:44	32.0280
8/29/91	9:54:44	32.0321
8/29/91	9:59:44	32.0365
8/29/91	10:04:44	32.0391
8/29/91	10:09:44	32.0415
8/29/91	10:14:44	32.0423
8/29/91	10:19:44	32.0441
8/29/91	10:24:44	32.0441
8/29/91	10:29:44	32.0456
8/29/91	10:34:44	32.0458
8/29/91	10:39:44	32.0467
8/29/91	10:44:44	32.0476
8/29/91	10:49:44	32.0476
8/29/91	10:54:44	32.0484
8/29/91	10:59:44	32.0493
8/29/91	11:04:44	32.0493

TABLE B.1. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	11:09:44	32.0484
8/29/91	11:14:44	32.0493
8/29/91	11:19:44	32.0510
8/29/91	11:24:44	32.0519
8/29/91	11:29:44	32.0510
8/29/91	11:34:44	32.0519
8/29/91	11:39:44	32.0510
8/29/91	11:44:44	32.0519
8/29/91	11:49:44	32.0528
8/29/91	11:54:44	32.0534
8/29/91	11:59:44	32.0534
8/29/91	12:04:44	32.0534
8/29/91	12:09:44	32.0543
8/29/91	12:14:44	32.0510
8/29/91	12:19:44	32.0534
8/29/91	12:24:44	32.0534
8/29/91	12:29:44	32.0528
8/29/91	12:34:44	32.0519
8/29/91	12:39:44	32.0510
8/29/91	12:44:44	32.0528
8/29/91	12:49:44	32.0510
8/29/91	12:54:44	32.0493
8/29/91	12:59:44	32.0484
8/29/91	13:04:44	32.0528
8/29/91	13:09:44	32.0519
8/29/91	13:14:44	32.0543
8/29/91	13:19:44	32.0543
8/29/91	13:24:44	32.0543
8/29/91	13:28:18	32.0510
8/29/91	13:58:02	32.0528
8/29/91	14:28:02	32.0528
8/29/91	14:58:02	32.0510
8/29/91	15:28:02	32.0502
8/29/91	15:58:02	32.0484
8/29/91	16:28:02	32.0467
8/29/91	16:58:02	32.0450
8/29/91	17:28:02	32.0432
8/29/91	17:58:02	32.0415
8/29/91	18:28:02	32.0415
8/29/91	18:58:02	32.0319
8/29/91	19:28:02	32.0408
8/29/91	19:58:02	32.0415
8/29/91	20:28:02	32.0432
8/29/91	20:58:02	32.0450
8/29/91	21:28:02	32.0450
8/29/91	21:58:02	32.0450

TABLE B.1. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	22:28:02	32.0458
8/29/91	22:58:02	32.0467
8/29/91	23:28:02	32.0484
8/29/91	23:58:02	32.0476
8/30/91	0:28:02	32.0502
8/30/91	0:58:02	32.0502
8/30/91	1:28:02	32.0519
8/30/91	1:58:02	32.0510
8/30/91	2:28:02	32.0519
8/30/91	2:58:02	32.0519
8/30/91	3:28:02	32.0519
8/30/91	3:58:02	32.0552
8/30/91	4:28:02	32.0534
8/30/91	4:58:02	32.0569
8/30/91	5:28:02	32.0595
8/30/91	5:58:02	32.0604
8/30/91	6:28:03	32.0621
8/30/91	6:58:03	32.0630
8/30/91	7:28:03	32.0638

TABLE B.2. Slug Interference Test Data - Observation Well 699-43-41E

Date	Clock Time	Pressure Reading, psia	
8/28/91	10:30:13	17.5474	
8/28/91	10:34:56	17.5525	
8/28/91	10:39:56	17.5559	
8/28/91	10:44:56	17.5533	
8/28/91	10:49:56	17.5584	
8/28/91	10:54:56	17.5653	
8/28/91	11:05:03	17.5678	
8/28/91	11:09:47	17.5661	
8/28/91	11:14:47	17.5678	
8/28/91	11:19:47	17.5712	
8/28/91	11:24:47	17.5670	
8/28/91	11:29:47	17.5653	
8/28/91	11:32:14	17.5721	
8/28/91	11:32:31	17.5712	Began pressurizing casing
8/28/91	11:32:59	17.5610	
8/28/91	11:33:26	17.5567	
8/28/91	11:33:59	17.5619	
8/28/91	11:34:26	17.5593	
8/28/91	11:34:58	17.5661	
8/28/91	11:35:30	17.5627	
8/28/91	11:35:58	17.5576	
8/28/91	11:36:30	17.5584	
8/28/91	11:37:22	17.5576	
8/28/91	11:38:04	17.5593	
8/28/91	11:46:43	17.5804	
8/28/91	11:47:25	17.5746	
8/28/91	11:48:26	17.5729	
8/28/91	11:49:27	17.5787	
8/28/91	11:50:27	17.5778	
8/28/91	11:51:28	17.5729	
8/28/91	11:52:29	17.5729	
8/28/91	11:53:25	17.5695	
8/28/91	11:54:26	17.5704	
8/28/91	11:55:27	17.5687	
8/28/91	11:56:28	17.5704	
8/28/91	11:57:29	17.5704	
8/28/91	11:58:25	17.5687	
8/28/91	12:00:13	17.5695	
8/28/91	12:04:58	17.5761	
8/28/91	12:09:58	17.5695	
8/28/91	12:14:58	17.5746	
8/28/91	12:19:58	17.5687	
8/28/91	12:24:58	17.5721	
8/28/91	12:29:58	17.5729	
8/28/91	12:34:58	17.5721	

TABLE B.2. (contd)

Date	Clock Time	Pressure Reading, psia
8/28/91	12:39:58	17.5721
8/28/91	12:49:58	17.5804
8/28/91	12:44:58	17.5755
8/28/91	12:54:58	17.5729
8/28/91	12:59:58	17.5729
8/28/91	13:09:22	17.5725
8/28/91	13:19:06	17.5738
8/28/91	13:29:06	17.5746
8/28/91	13:39:06	17.5804
8/28/91	13:49:06	17.5755
8/28/91	13:59:06	17.5755
8/28/91	14:09:06	17.5770
8/28/91	14:19:06	17.5795
8/28/91	14:29:06	17.5821
8/28/91	14:39:06	17.5846
8/28/91	14:49:06	17.5838
8/28/91	14:59:06	17.5846
8/28/91	15:03:23	17.5821
8/28/91	15:33:06	17.5778
8/28/91	16:03:06	17.5880
8/28/91	16:33:06	17.5940
8/28/91	17:03:06	17.5923
8/28/91	17:33:06	17.5906
8/28/91	18:03:06	17.5931
8/28/91	18:33:06	17.5974
8/28/91	19:03:06	17.6000
8/28/91	19:33:06	17.6034
8/28/91	20:03:06	17.6025
8/28/91	20:33:06	17.6025
8/28/91	21:03:06	17.6110
8/28/91	21:33:06	17.6127
8/28/91	22:03:06	17.6195
8/28/91	22:33:06	17.6212
8/28/91	23:03:06	17.6280
8/28/91	23:33:06	17.6127
8/29/91	0:03:06	17.6153
8/29/91	0:33:06	17.6204
8/29/91	1:03:06	17.6170
8/29/91	1:33:06	17.6178
8/29/91	2:03:06	17.6195
8/29/91	2:33:06	17.6238
8/29/91	3:03:06	17.6246
8/29/91	3:33:06	17.6280
8/29/91	4:03:06	17.6287
8/29/91	7:03:06	17.6280
8/29/91	7:33:06	17.6312

TABLE B.2. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	7:44:00	17.6272
8/29/91	7:48:44	17.6272
8/29/91	7:53:44	17.6295
8/29/91	7:58:44	17.6280
8/29/91	8:03:44	17.6280
8/29/91	8:06:05	17.6280
8/29/91	8:06:23	17.6272
8/29/91	8:06:50	17.6280
8/29/91	8:07:18	17.6280
8/29/91	8:07:50	17.6238
8/29/91	8:08:18	17.6238
8/29/91	8:08:50	17.6204
8/29/91	8:11:06	17.6127
8/29/91	8:11:24	17.6127
8/29/91	8:11:52	17.6136
8/29/91	8:12:19	17.6102
8/29/91	8:12:51	17.6110
8/29/91	8:13:23	17.6085
8/29/91	8:13:50	17.6093
8/29/91	8:14:23	17.6051
8/29/91	8:14:50	17.5991
8/29/91	8:15:22	17.5940
8/29/91	8:15:49	17.5931
8/29/91	8:16:21	17.5914
8/29/91	8:16:53	17.5880
8/29/91	8:17:21	17.5872
8/29/91	8:17:53	17.5829
8/29/91	8:19:18	17.5812
8/29/91	8:22:01	17.5770
8/29/91	8:22:19	17.5704
8/29/91	8:22:46	17.5678
8/29/91	8:23:18	17.5670
8/29/91	8:23:45	17.5653
8/29/91	8:24:17	17.5627
8/29/91	8:24:44	17.5627
8/29/91	8:25:16	17.5627
8/29/91	8:25:44	17.5610
8/29/91	8:26:16	17.5610
8/29/91	8:26:48	17.5576
8/29/91	8:27:15	17.5585
8/29/91	8:27:47	17.5585
8/29/91	8:28:14	17.5576
8/29/91	8:28:46	17.5567
8/29/91	8:29:18	17.5533
8/29/91	8:29:45	17.5533
8/29/91	8:30:17	17.5508

TABLE B.2. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	8:30:45	17.5499
8/29/91	8:31:17	17.5474
8/29/91	8:31:44	17.5465
8/29/91	8:32:16	17.5448
8/29/91	8:32:48	17.5423
8/29/91	8:33:15	17.5431
8/29/91	8:33:47	17.5431
8/29/91	8:34:14	17.5406
8/29/91	8:34:46	17.5380
8/29/91	8:35:32	17.5389
8/29/91	8:36:18	17.5355
8/29/91	8:37:14	17.5389
8/29/91	8:38:14	17.5389
8/29/91	8:39:15	17.5380
8/29/91	8:40:16	17.5423
8/29/91	8:41:17	17.5414
8/29/91	8:42:17	17.5440
8/29/91	8:43:18	17.5474
8/29/91	8:44:14	17.5448
8/29/91	8:45:15	17.5525
8/29/91	8:46:15	17.5525
8/29/91	8:47:16	17.5533
8/29/91	8:48:17	17.5525
8/29/91	8:49:17	17.5525
8/29/91	8:50:18	17.5525
8/29/91	8:51:14	17.5516
8/29/91	8:52:1	17.5525
8/29/91	8:53:16	17.5550
8/29/91	8:54:16	17.5525
8/29/91	8:55:17	17.5525
8/29/91	8:56:46	17.5525
8/29/91	8:58:31	17.5533
8/29/91	9:00:31	17.5567
8/29/91	9:02:31	17.5567
8/29/91	9:04:31	17.5619
8/29/91	9:06:31	17.5602
8/29/91	9:08:31	17.5619
8/29/91	9:10:31	17.5593
8/29/91	9:12:31	17.5610
8/29/91	9:14:31	17.5585
8/29/91	9:16:31	17.5593
8/29/91	9:18:31	17.5619
8/29/91	9:20:31	17.5636
8/29/91	9:22:31	17.5644
8/29/91	9:25:06	17.5670
8/29/91	9:29:51	17.5704

TABLE B.2. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	9:34:51	17.5704
8/29/91	9:39:51	17.5678
8/29/91	9:44:51	17.5704
8/29/91	9:49:51	17.5755
8/29/91	9:54:51	17.5787
8/29/91	9:59:51	17.5812
8/29/91	10:04:51	17.5804
8/29/91	10:09:51	17.5812
8/29/91	10:14:51	17.5855
8/29/91	10:19:51	17.5889
8/29/91	10:24:51	17.5880
8/29/91	10:29:51	17.5846
8/29/91	10:34:51	17.5897
8/29/91	10:39:51	17.5872
8/29/91	10:44:51	17.5838
8/29/91	10:49:51	17.5880
8/29/91	10:54:51	17.5846
8/29/91	10:59:51	17.5829
8/29/91	11:04:51	17.5889
8/29/91	11:09:51	17.5889
8/29/91	11:14:51	17.5889
8/29/91	11:19:51	17.5897
8/29/91	11:24:51	17.5872
8/29/91	11:29:51	17.5872
8/29/91	11:34:51	17.5855
8/29/91	11:39:51	17.5872
8/29/91	11:44:51	17.5880
8/29/91	11:49:51	17.5914
8/29/91	11:54:51	17.5897
8/29/91	11:59:51	17.5897
8/29/91	12:04:51	17.5965
8/29/91	12:09:51	17.5940
8/29/91	12:14:51	17.5948
8/29/91	12:19:51	17.5948
8/29/91	12:24:51	17.5957
8/29/91	12:29:51	17.5965
8/29/91	12:34:51	17.5940
8/29/91	12:39:51	17.5948
8/29/91	12:44:51	17.5923
8/29/91	12:49:51	17.5906
8/29/91	12:54:51	17.5914
8/29/91	12:59:51	17.5923
8/29/91	13:04:51	17.5957
8/29/91	13:09:51	17.5889
8/29/91	13:14:51	17.5889
8/29/91	13:19:51	17.5889

TABLE B.2. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	13:24:51	17.5880
8/29/91	13:28:25	17.5829
8/29/91	13:58:09	17.5889
8/29/91	14:28:09	17.5906
8/29/91	14:58:09	17.5965
8/29/91	15:28:09	17.5974
8/29/91	15:58:09	17.5948
8/29/91	16:28:09	17.5974
8/29/91	16:58:09	17.5974
8/29/91	17:28:09	17.5974
8/29/91	17:58:09	17.5965
8/29/91	18:28:09	17.5931
8/29/91	18:58:09	17.5940
8/29/91	19:28:09	17.5948
8/29/91	19:58:09	17.5931
8/29/91	20:28:09	17.5923
8/29/91	20:58:09	17.5880
8/29/91	21:28:09	17.5880
8/29/91	21:58:09	17.5948
8/29/91	22:28:09	17.5914
8/29/91	22:58:09	17.5948
8/29/91	23:28:09	17.5948
8/29/91	23:58:09	17.5957
8/30/91	0:28:09	17.6000
8/30/91	0:58:09	17.5965
8/30/91	1:28:09	17.5983
8/30/91	1:58:09	17.5931
8/30/91	2:28:09	17.5940
8/30/91	2:58:09	17.5983
8/30/91	3:28:09	17.6017
8/30/91	3:58:09	17.6000
8/30/91	4:28:09	17.5948
8/30/91	4:58:09	17.5991
8/30/91	5:28:09	17.5965
8/30/91	5:58:09	17.5957
8/30/91	6:28:09	17.5957
8/30/91	6:58:09	17.5948
8/30/91	7:28:09	17.6000

TABLE B.3. Slug Interference Test Data - Observation Well 699-53-41F

Date	Clock Time	Pressure Reading, psia
8/26/91	8:46	29.7064
8/26/91	9:18	29.7048
8/26/91	9:34	29.7048
8/26/91	10:08	29.7056
8/26/91	10:27	29.7040
8/26/91	10:52	29.5749
8/26/91	11:05	29.5856
8/26/91	11:13	29.5996
8/26/91	13:00	29.6867
8/26/91	13:02	29.6892
8/26/91	13:03	29.6900
8/26/91	13:04	29.6925
8/26/91	13:05	29.6925
8/26/91	13:07	29.6933
8/26/91	13:09	29.6875
8/26/91	13:09.5	29.6834
8/26/91	13:10	29.6818
8/26/91	13:10.5	29.6801
8/26/91	13:23	29.6505
8/26/91	13:26	29.6374
8/26/91	13:33	29.6464
8/26/91	13:36	29.6555
8/26/91	13:37	29.6579
8/26/91	13:38	29.6604
8/26/91	13:39	29.6620
8/26/91	13:58	29.6785
8/26/91	14:21	29.6810
8/26/91	14:58	29.6818
8/26/91	15:38	29.6810
8/27/91	12:04	29.6218
8/27/91	12:10	29.6234
8/27/91	12:20	29.6250
8/27/91	12:30	29.6283
8/27/91	12:58	29.6292
8/27/91	13:01	29.6292
8/27/91	13:08	29.6296
8/27/91	13:16	29.6296
8/27/91	13:18	29.6300
8/27/91	13:18.5	29.6308
8/27/91	13:20	29.6312
8/27/91	13:21.5	29.6316
8/27/91	13:23	29.6329
8/27/91	13:25	29.6329
8/27/91	13:27.5	29.6324
8/27/91	13:28.5	29.6324
8/27/91	13:30	29.6320

TABLE B.3. (contd)

Date	Clock Time	Pressure Reading, psia
8/27/91	13:34	29.6316
8/27/91	13:40	29.6312
8/27/91	13:45	29.6312
8/27/91	13:50	29.6304
8/27/91	14:00	29.6308
8/27/91	14:10	29.6296
8/27/91	14:25	29.6296
8/27/91	14:35	29.6292
8/27/91	14:40	29.6279
8/27/91	14:55	29.6279
8/27/91	15:15	29.6271
8/27/91	15:19	29.6263
8/27/91	15:19.5	29.6250
8/27/91	15:20	29.6242
8/27/91	15:20.5	29.6238
8/27/91	15:21	29.6230
8/27/91	15:21.5	29.6222
8/27/91	15:22	29.6222
8/27/91	15:23	29.6213
8/27/91	15:24	29.6209
8/27/91	15:25	29.6209
8/27/91	15:26	29.6205
8/27/91	15:28	29.6189
8/27/91	15:29	29.6193
8/27/91	15:30	29.6197
8/27/91	15:32	29.6205
8/28/91	9:30:00	29.6386
8/28/91	10:34:00	29.6415
8/28/91	10:44:00	29.6403
8/28/91	10:48:00	29.6403
8/28/91	10:50:00	29.6394
8/28/91	11:08:00	29.6398
8/28/91	11:12:00	29.6394
8/28/91	11:18:00	29.6398
8/28/91	11:25:00	29.6398
8/28/91	11:32:00	29.6403
8/28/91	11:33:00	29.6403
8/28/91	11:34:00	29.6411
8/28/91	11:35:00	29.6427
8/28/91	11:36:00	29.6448
8/28/91	11:37:00	29.6472
8/28/91	11:38:00	29.6514
8/28/91	11:40:00	29.6588
8/28/91	11:42:00	29.6625
8/28/91	11:49:00	29.6678
8/28/91	11:52:00	29.6666

TABLE B.3. (contd)

Date	Clock Time	Pressure Reading, psia	
8/28/91	11:55:00	29.6657	
8/28/91	12:01:00	29.6649	
8/28/91	12:10:00	29.6616	
8/28/91	12:20:00	29.6604	
8/28/91	12:30:00	29.6592	
8/28/91	12:44:00	29.6579	
8/28/91	13:00:00	29.6559	
8/28/91	13:15:00	29.6542	
8/28/91	13:45:00	29.6522	
8/28/91	14:15:00	29.6526	
8/28/91	14:50:00	29.6501	
8/28/91	15:30:00	29.6497	
8/29/91	7:35:00	29.6879	
8/29/91	7:50:00	29.6863	
8/29/91	8:03:00	29.6851	
8/29/91	8:07:00	29.6855	
8/29/91	8:07:50	29.6859	
8/29/91	8:09:30	29.685	began slug interference test
8/29/91	8:09:50	29.6785	
8/29/91	8:10:20	29.6662	
8/29/91	8:10:50	29.6514	
8/29/91	8:11:20	29.6374	
8/29/91	8:11:50	29.6242	
8/29/91	8:12:20	29.6135	
8/29/91	8:12:50	29.6037	
8/29/91	8:13:20	29.5946	
8/29/91	8:13:50	29.5872	
8/29/91	8:14:20	29.5806	
8/29/91	8:15:20	29.5724	
8/29/91	8:16:20	29.5650	
3/29/91	8:17:20	29.5609	
8/29/91	8:18:20	29.5576	
8/29/91	8:19:20	29.5560	
8/29/91	8:20:20	29.5560	
8/29/91	8:20:50	29.5560	
8/29/91	8:21:20	29.5564	
8/29/91	8:21:50	29.5568	
8/29/91	8:22:20	29.5576	
8/29/91	8:22:50	29.5589	
8/29/91	8:23:20	29.5605	
8/29/91	8:23:50	29.5617	
8/29/91	8:24:50	29.5642	
8/29/91	8:25:50	29.5671	
8/29/91	8:26:50	29.5708	
8/29/91	8:27:50	29.5745	
8/29/91	8:29:50	29.5819	

TABLE B.3. (contd)

Date	Clock Time	Pressure Reading, psia
8/29/91	8:31:50	29.5893
8/29/91	8:33:50	29.5963
8/29/91	8:35:50	29.6037
8/29/91	8:37:50	29.6102
8/29/91	8:40:00	29.6172
8/29/91	8:45:00	29.6287
8/29/91	8:50:00	29.6390
8/29/91	8:55:00	29.6464
8/29/91	9:00:00	29.6530
8/29/91	9:05:00	29.6575
8/29/91	9:10:00	29.6616
8/29/91	9:15:00	29.6645
8/29/91	9:20:00	29.6678
8/29/91	9:30:00	29.6715
8/29/91	9:40:00	29.6731
8/29/91	9:50:00	29.6752
8/29/91	10:00:00	29.6773
8/29/91	10:15:00	29.6781
8/29/91	10:30:00	29.6797
8/29/91	10:45:00	29.6805
8/29/91	11:00:00	29.6814
8/29/91	11:15:00	29.6805
8/29/91	11:30:00	29.6797
8/29/91	11:45:00	29.6797
8/29/91	12:00:00	29.6797
8/29/91	12:15:00	29.6797
8/29/91	12:30:00	29.6789
8/29/91	12:45:00	29.6789
8/29/91	13:00:00	29.6797
8/29/91	13:30:00	29.6797
8/29/91	14:00:00	29.6781
8/29/91	14:30:00	29.6781
8/29/91	15:00:00	29.6773
8/29/91	15:15:00	29.6773

APPENDIX C

PREVIOUS SINGLE-WELL SLUG TEST ANALYSIS RESULTS

C.1 PREVIOUS SINGLE-WELL SLUG TEST ANALYSIS RESULTS - OBSERVATION WELL 699-43-41E

A low stress (H_o = 3.54 ft) slug injection test was conducted at well 699-43-41E on June 29, 1989. The slug test was initiated by rapidly submerging a slugging rod of known volume (0.326 ft^3), and recording the associated pressure recovery response to static condition with a downhole pressure transducer and surface data recording system. A detailed description of the test and listing of field test data is provided in Borghese and Goodwin (1989).

The slug injection data were analyzed using the same analytical methods (i.e., Ostrowski and Kloska (1989) and Bouwer and Rice (1976) used in analyzing the single-well test at well 699-43-41G. A brief description of the two analysis methods is provided in Section 5.4.2. Figure C-1.1 shows the type-curve analysis of the slug injection test response at well 699-43-41E using the Ostrowski and Kloska (1989) analysis procedure. Pertinent analysis information is provided in the figure. As indicated, a transmissivity of approximately 11 ft^2/d was calculated for the screened interval section using a type-curve match of alpha = 10^{-6}. Based on a well screen interval length of 10.6 ft, an equivalent hydraulic conductivity of 1.0 ft/d for the test interval is indicated.

As a means of analysis method comparison, the slug injection test results were also interpreted using the Bouwer and Rice (1976) technique. Figure C-1.2 shows the results and pertinent information used in this analysis. As indicated, a lower equivalent hydraulic conductivity value of 0.4 ft/d was obtained, which was based on the following input parameters: r_c = 0.1667 ft; r_w = 0.2675 ft (accounting for the effects of the sand-pack envelop as described in Bouwer 1989); ln (R_e/r_w) = 2.65 (calculated from Equation 4 and Figure 2 in Bouwer (1989) for L_e/r_w = 39.626); y_o = 3.54 ft; y_t = 0.707 ft (Figure C-1.2); L_e = 10.6 ft; L_w = 20.5 ft; H = 52 ft (static water level to top of clay layer at 179 ft); and, t = 20 min (Figure C-1.2).

Because of various deficiencies that were briefly described for both analysis methods in Section 5.4.2, no preferred or "best-estimate" of equivalent hydraulic conductivity are assigned for this test. The transmissivity estimates obtained for each analysis method are provided as a range for comparison with slug interference test results. As a consequence, an assigned equivalent hydraulic conductivity range between 0.4 ft/d and 1.0 ft/d is provided from analysis of the single-well test at well 699-43-41E. It should be noted that because of the low stress utilized during the slug injection test (i.e., 1/10 that used for the slug interference test), the cited range for equivalent hydraulic conductivity provided for this test is expected to be only representative of hydrogeologic conditions a short distance from the screened interval.

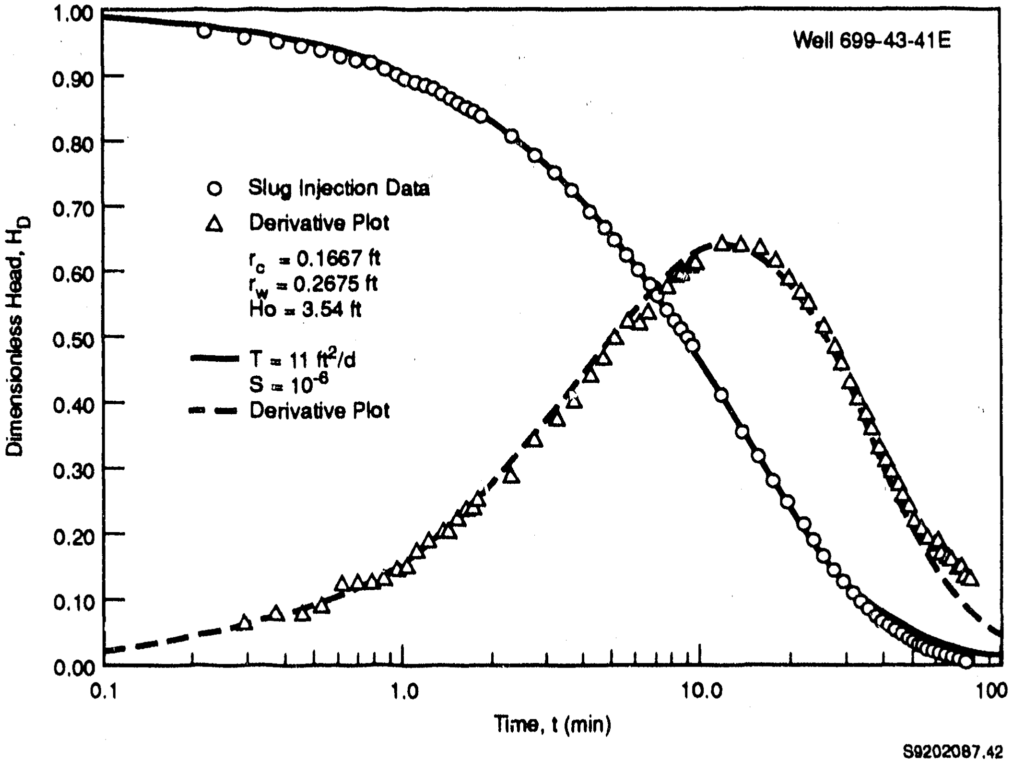

FIGURE C-1.1. Slug Test Analysis for Stress Well 699-43-41E Using the Ostrowski and Kloska (1989) Analysis Method

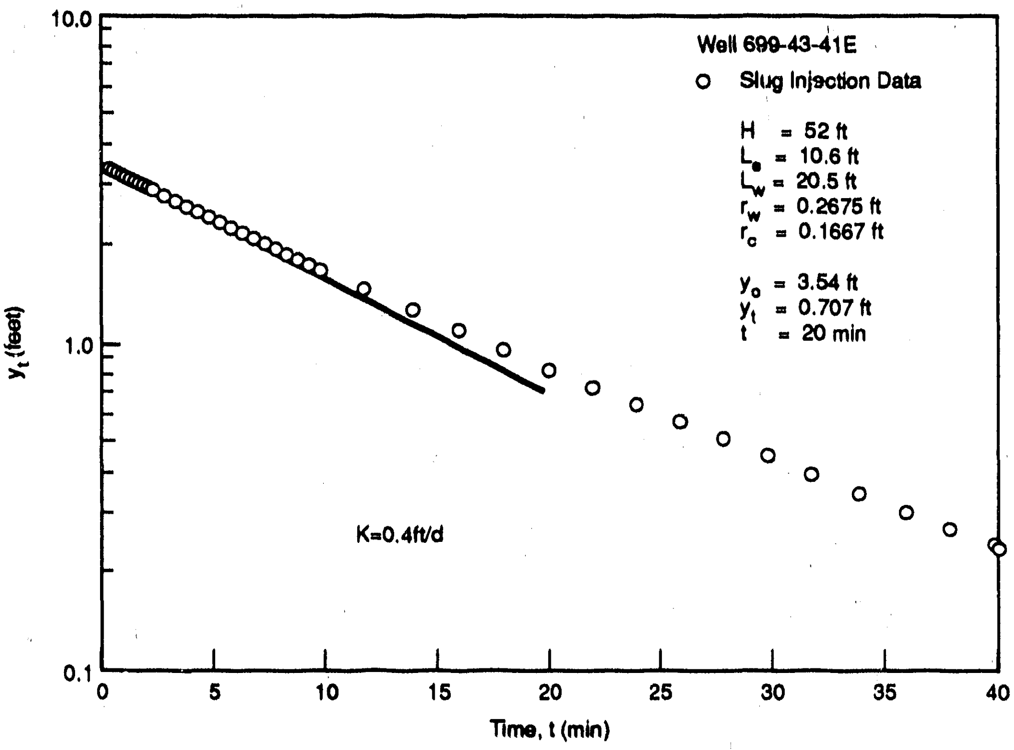

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FIGURE C-1.2. Slug Test Analysis for Stress Well 699-43-41E Using the Bouwer and Rice (1976) Analysis Method

C.2 PREVIOUS SINGLE-WELL SLUG TEST ANALYSIS RESULTS - OBSERVATION WELL 699-43-41F

A low stress (H_0 = 3.69 ft) slug injection test was conducted at well 699-43-41F on May 30, 1989. The slug test was initiated by rapidly submerging a slugging rod of known volume (0.326 ft^3), and recording the associated pressure recovery response to static condition with a downhole pressure transducer and surface data recording system. A detailed description of the test and listing of field test data is provided in Borghese and Goodwin (1989).

The slug injection data were analyzed using the same analytical methods (i.e., Ostrowski and Kloska (1989) and Bouwer and Rice (1976) used in analyzing the single-well test at well 699-43-41G. A brief description of the two analysis methods is provided in Section 5.4.2. Figure C-2.1 shows the type-curve analysis of the slug injection test response at well 699-43-41F using the Ostrowski and Kloska (1989) analysis procedure. Pertinent analysis information is provided in the figure. As indicated, a transmissivity of approximately 30 ft^2/d was calculated for the screened interval section using a type-curve match of alpha = 10^{-6}. Based on a well screen interval length of 10.6 ft, an equivalent hydraulic conductivity of 2.8 ft/d for the test interval is indicated.

As a means of analysis method comparison, the slug injection test results were also interpreted using the Bouwer and Rice (1976) technique. Figure C-2.2 shows the results and pertinent information used in this analysis. As indicated, a lower equivalent hydraulic conductivity value of 1.4 ft/d was obtained, which was based on the following input parameters: $r_c = 0.1667$ ft; $r_w = 0.2675$ ft (accounting for the effects of the sand-pack envelop as described in Bouwer, 1989); $\ln (R_e/r_w) = 3.741$ (calculated from Equation 4 and Figure 2 in Bouwer (1989) for $L_e/r_w = 39.626$); $y_o = 3.69$ ft; $y_t = 0.479$ ft (Figure C-2.2); $L_e = 10.6$ ft; $L_w = 52$ ft; $H = 52$ ft (static water level to top of clay layer at 179 ft); and, $t = 10$ min (Figure C-2.2).

Because of various deficiencies that were briefly described for both analysis methods in Section 5.4.2, no preferred or "best-estimate" of equivalent hydraulic conductivity are assigned for this test. The transmissivity estimates obtained for each analysis method are provided as a range for comparison with slug interference test results. As a consequence, an assigned equivalent hydraulic conductivity range between 1.4 ft/d and 2.8 ft/d is provided from analysis of the single-well test at well 699-43-41F. It should be noted that because of the low stress utilized during the slug injection test (i.e., 1/10 that used for the slug interference test), the cited range for equivalent hydraulic conductivity provided for this test is expected to be only representative of hydrogeologic conditions a short distance from the screened interval.

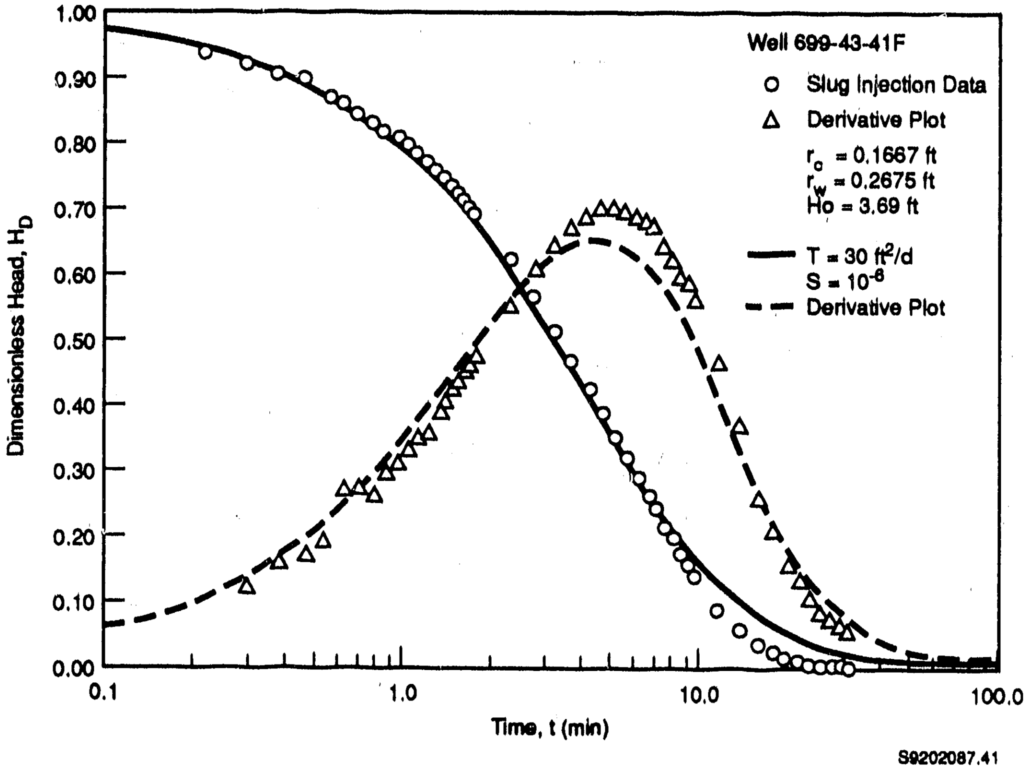

FIGURE C-2.1. Slug Test Analysis for Stress Well 699-43-41F Using the Ostrowski and Kloska (1989) Analysis Method

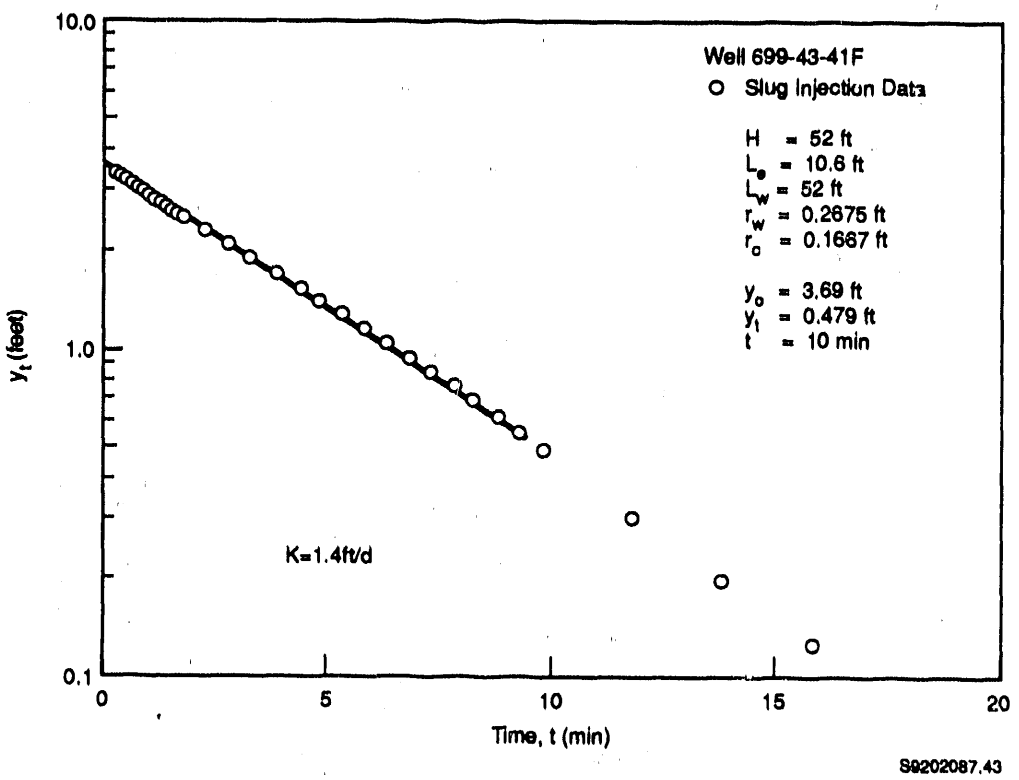

FIGURE C-2.2. Slug Test Analysis for Stress Well 699-43-41F Using the Bouwer and Rice (1976) Analysis Method

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