DRAFT

HYDROGEOLOGIC TESTING PLAN

FOR SHALLOW HYDRO NEST TEST WELLS,

DEAF SMITH COUNTY SITE, TEXAS

DRAFT REPORT HAS NOT BEEN REVIEWED BY DOE

TOPICAL REPORT

JANUARY 1987

S. S. PAPADOPULOS & ASSOCIATES, INC.

CONSULTING GROUND-WATER HYDROLOGISTS

DISCLAIMER

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TECHNICAL STATUS

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By

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ABSTRACT

To characterize the hydraulic parameters of shallow formations at the proposed Deaf Smith County, Texas repository site, test wells will be installed at shallow hydro nests to conduct hydrogeologic tests. The wells will penetrate the Ogallala, Dockum, Dewey Lake, Alibates, Salado, Yates, Upper and Lower Seven Rivers and Queen/Grayburg Formations.

To develop a hydrogeologic testing plan for the shallow hydro nests, the response of each formation to potential testing procedures was evaluated using design values and an assumed range for hydraulic parameters. These evaluations indicate that the horizontal properties of the Ogallala, a sandy zone of the Dockum, the Lower Seven Rivers and possibly the Alibates and Queen/Grayburg can be determined by pump tests. Standard or shut-in slug tests must be conducted in the remaining formations. Tests of very long duration would be required to determine the vertical properties of less permeable formations. Numerical modeling of the local hydrogeology may be a preferable alternative for determining vertical properties.

Based on these results, a hydrogeologic testing plan was developed. The plan recommends the installation of nineteen wells at six hydro nests, the testing of the Ogallala at three nests and the testing of the remaining formations at all six nests. Six-day pumping tests are recommended for the Ogallala. Testing of other formations is to proceed from the bottom up, with two-day pumping tests at the more permeable formations and shut-in or standard slug tests at the less permeable formations. After testing, wells are to be completed as dual monitoring wells to provide data for numerical modeling. Methods of test data analysis are discussed and illustrated with examples.

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CONVERSION FACTORS

U.S. customary units have been used in this report. Factors for converting U.S. customary units to metric units are presented below.

U.S. Customary Units	Multiply by	Metric Units
Length		
inches (in)	25.40	millimeters (mm)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (Km)
Area		
square feet (ft^2)	0.09290	square meters (m^2)
square miles (mi^2)	2.589	square kilometers (Km^2)
Volume		
cubic feet (ft^3)	0.02832	cubic meters (m^3)
gallons (gal)	3.785	liters (L)
stock tank barrels (STB)	159.0	liters (L)
Discharge Rate		
cubic feet per day (ft^3/d)	0.02832	cubic meters per day (m^3/d)
gallons per minute (gpm)	0.06309	liters per second (L/s)
stock tank barrels per day (STB/d)	159.0	liters per day (L/d)
Hydraulic Conductivity		
feet per day (ft/d)	0.3048	meters per day (m/d)
gallons per day per square foot (gpd/ft^2)	0.04075	meters per day (m/d)
Transmissivity		
feet squared per day (ft^2/d)	0.09290	meters squared per day (m^2/d)
gallons per day per foot (gpd/ft)	0.01242	meters squared per day (m^2/d)

1.0 INTRODUCTION

1.1 BACKGROUND

The United States plans to develop and begin operating the first geologic repository for high-level radioactive wastes by the end of this century. Under the selection process established by the Nuclear Waste Policy Act of 1982, the U.S. Department of Energy (DOE) identified nine potentially acceptable sites and prepared draft Environmental Assessments (EAs) for these sites. Based on the information and evaluations contained in the draft EAs, DOE nominated five of the sites as suitable for site characterization, issued final EAs on these sites, and recommended three for presidential approval. The Deaf Smith County Site in Texas is one of the three sites approved by the President for site characterization as a potential first geologic repository.

The site covers a nine square mile area in the north-central part of Deaf Smith County in the Southern High Plains of the Texas Panhandle (Figure 1-1). The terrain at the site area is nearly flat, gently sloping toward the southeast. Geologically, the site lies within the Palo Duro Basin. The basement materials in the Palo Duro Basin consist of igneous and metamorphic rocks; the basement is overlain by a 10,000 to 11,000 feet thick sequence of sedimentary rocks and evaporites (DOE, 1986). The proposed host rock for the repository is a 160-foot thick sequence of bedded salt within the Lower San Andres Formation, specifically, the Lower San Andres Unit 4 salt, which lies at a depth of about 2,500 feet below the site.

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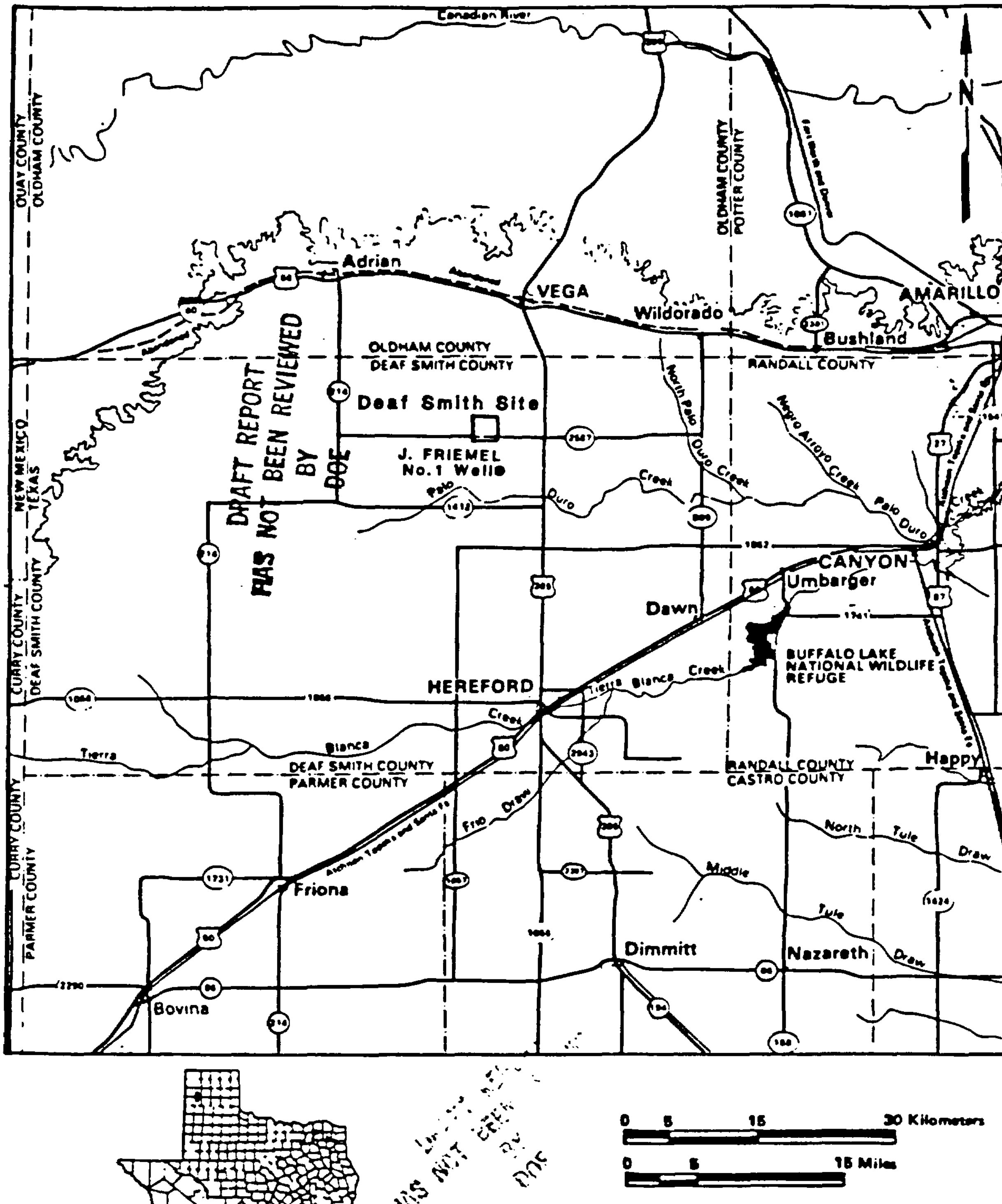
Proposed site characterization activities (DOE, 1986) comprise geotechnical field studies, the construction of two exploratory shafts and



Source : Enviromental Assessment, Deaf Smith County Site, Texas, USDOE, May, 1986, Figure 2 (Well location added)

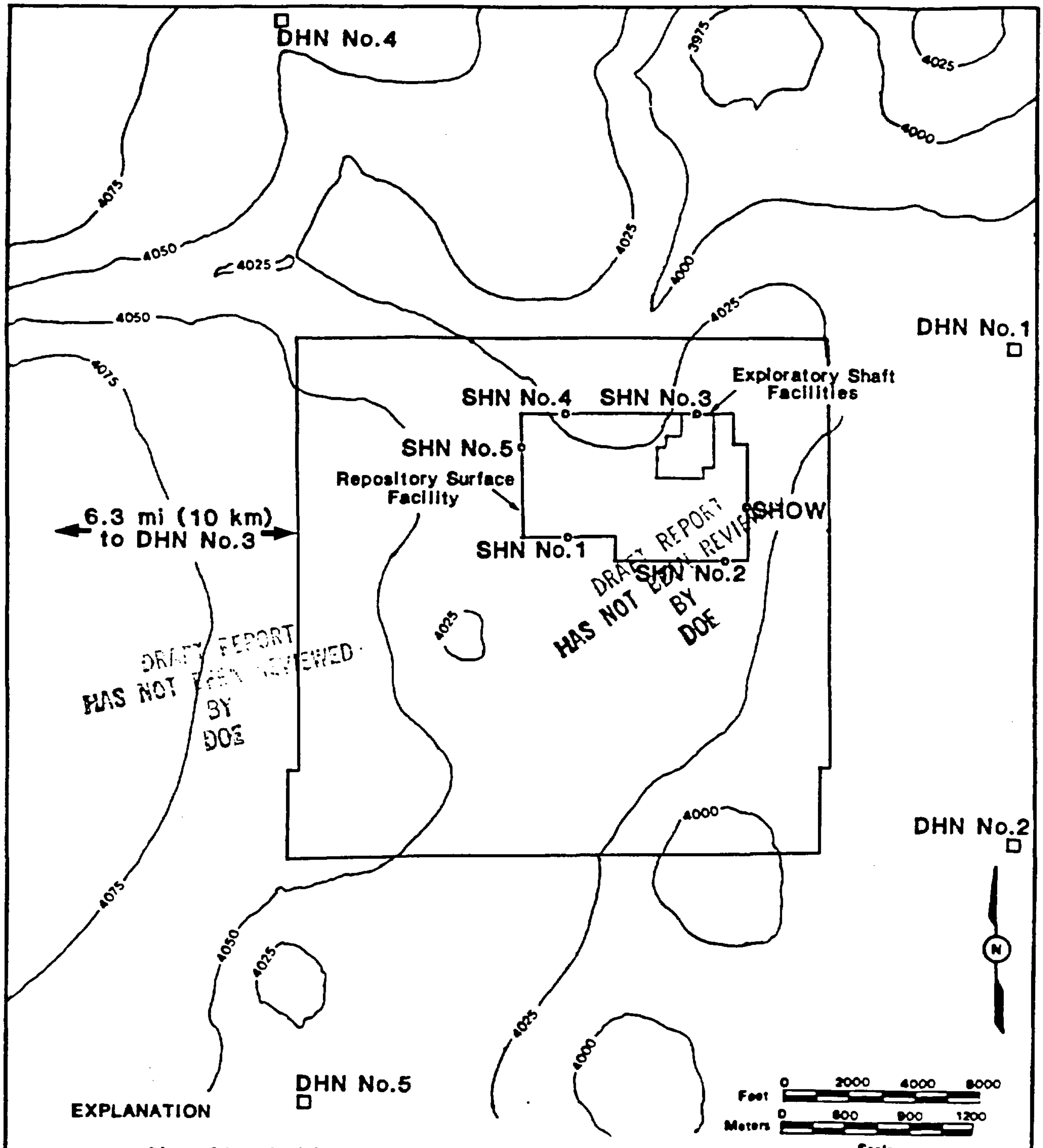
Proposed Repository Site
Deaf Smith County, Texas

Figure 1-1

associated facilities and other environmental and socioeconomic studies. The geotechnical field studies include the installation of 15 deep and 16 shallow test wells to characterize the hydraulic properties of water-bearing formations below and above the repository horizon. As proposed in the EA (DOE, 1986) the deep test wells are to be installed in five clusters of three wells each, referred to as "Deep Hydro Nests". Fifteen of the shallow test wells are also to be installed in five clusters of three wells, referred to as "Shallow Hydro Nests", with the sixteenth well installed as a single observation well. The proposed locations of these shallow and deep test wells are shown on Figure 1-2.

Other potential configurations for the shallow hydro nest test wells (Figure 1-3) have been proposed by Stone & Webster Engineering Corporation (SWEC, 1985a), which is responsible for managing the geotechnical field studies under a contract with DOE's Program Manager, the Battelle Memorial Institute (BMI), Office of Nuclear Waste Isolation (ONWI). Also, in the EA, the shallow hydro nest test wells are proposed for characterizing freshwater aquifers that occur in the uppermost Ogallala Formation and the underlying Dockum Group. However, present plans (SWEC, 1985a) are to extend these wells to the top of the Upper San Andres Formation, as shown on Figures 1-4 and 1-5.

Other geohydrologic activities at the site will include the installation of six wells in the vicinity of the two exploratory shafts to monitor the impacts of shaft construction on the shallow freshwater aquifers and 30 wells to monitor the impacts of other exploratory shaft facility structures (DOE, 1986). An additional 100 monitoring wells will be installed if the site is selected for development as a repository.



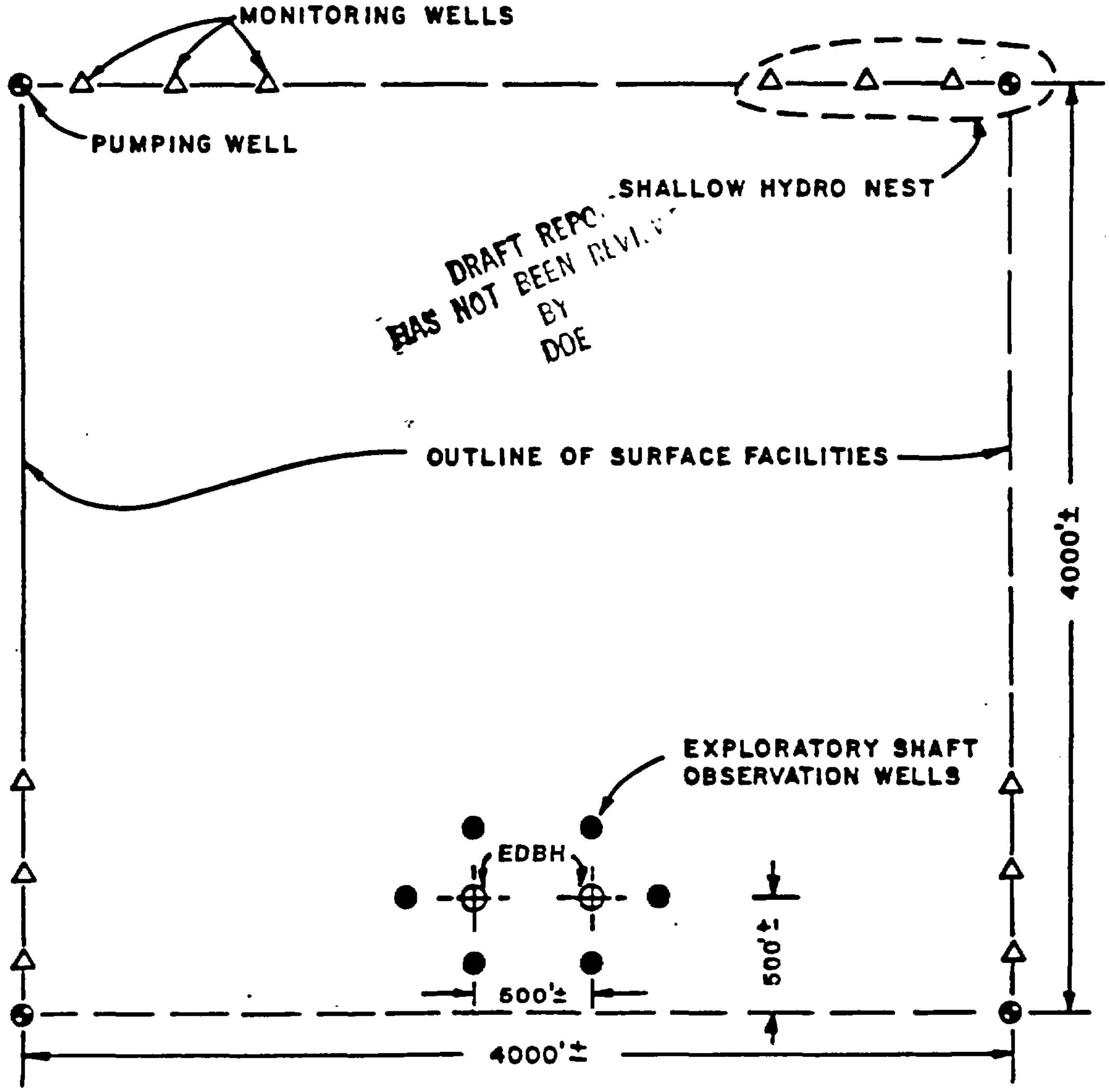
EXPLANATION

—4025— Line of equal altitude of land surface, in feet above MSL
• SHN Shallow Hydro Nests
∘ SHOW Shallow Observation Well
□ DHN Deep Hydro Nests

Adapted from : Enviromental Assessment, Deaf Smith County Site, Texas, USDOE, May 1986, Figure 4-2

Proposed Location of Shallow and Deep Hydro Nests

Figure 1-2

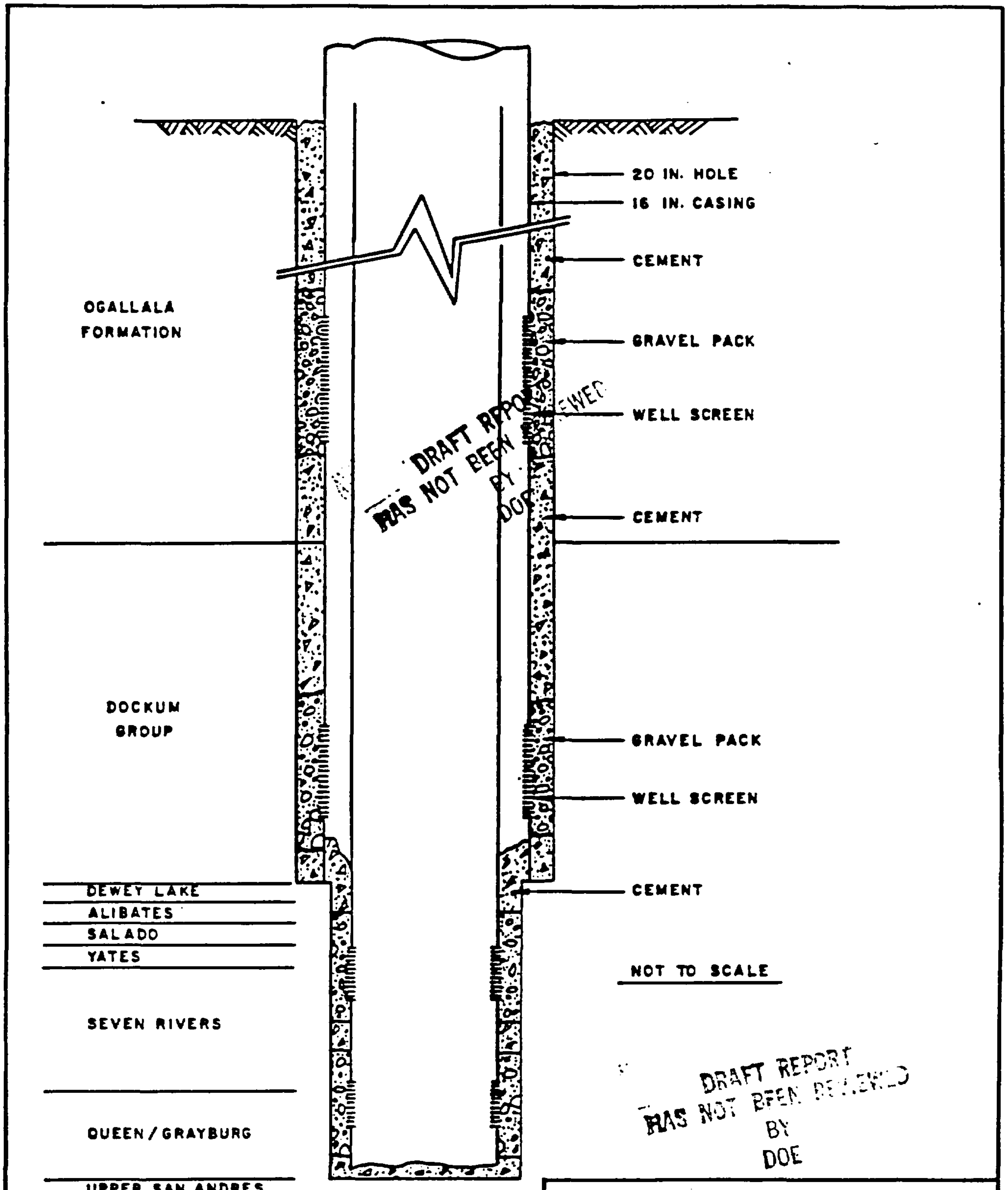


NOTE: SPACING OF MONITORING WELLS (Δ) IS NOT TO SCALE

Source : SWEC, 1985a, AP 13697-34-0, Attachment 1b-0

Potential Sites of Shallow Hydro Nests Proposed by SWEC

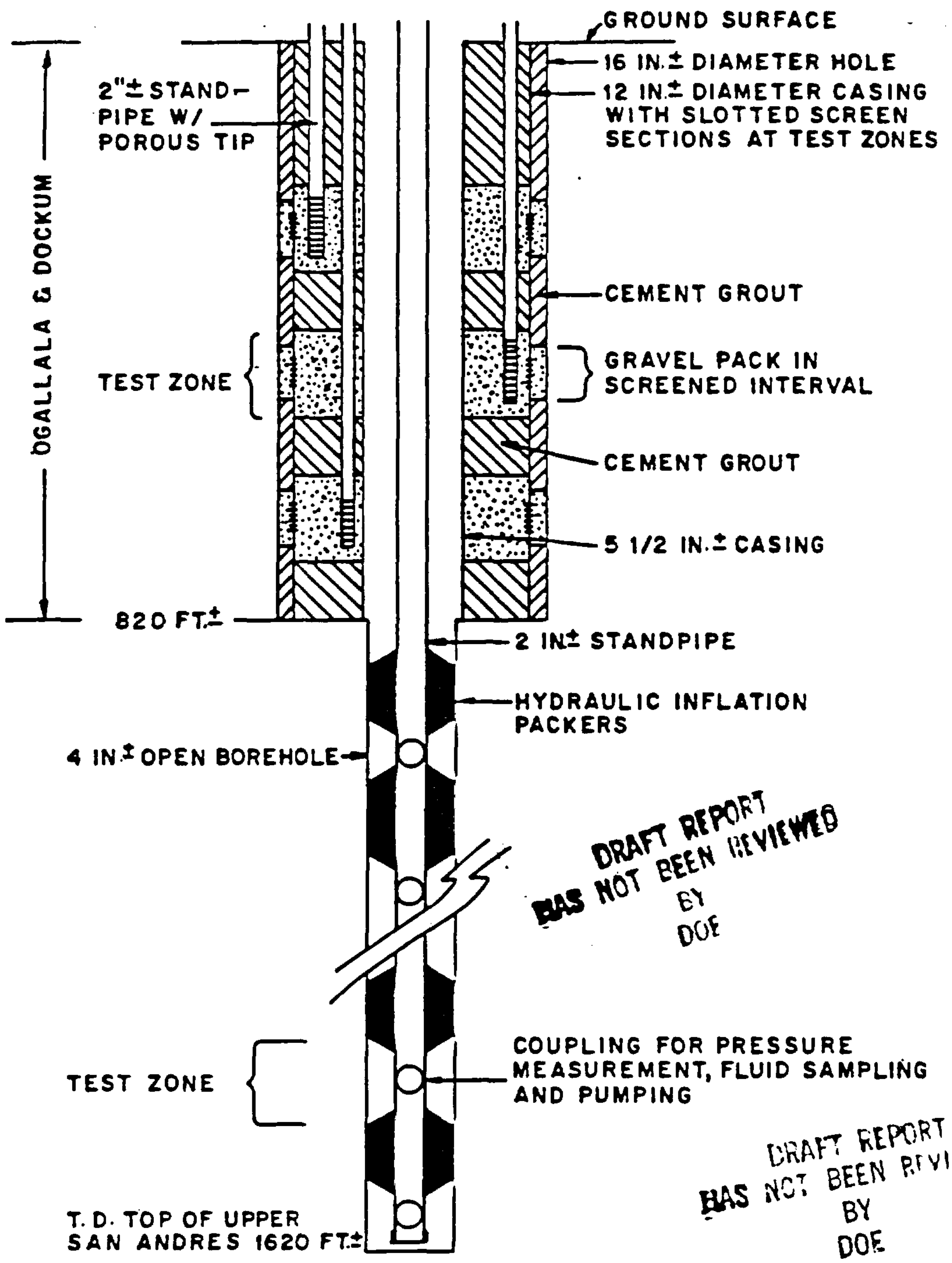
Figure 1-3



Source : SWEC, 1985a, AP 13697-34-0,
Attachment 6-0

Shallow Hydro Nest
Schematic of Pumping Well
Proposed by SWEC

Figure 1-4



Source : SWEC, 1985a, AP 13697-34-0, Attachment 6a-0

Shallow Hydro Nest Schematic of Monitoring Well Proposed by SWEC

Figure 1-5

A hydrogeologic testing plan for the six exploratory shaft monitoring wells was developed by S. S. Papadopulos & Associates, Inc. (SSP&A) and presented in an earlier report (Papadopulos, 1986). This report presents a plan for the hydrogeologic testing of the shallow hydro nest test wells. The testing of the deep hydro nest test wells will be the subject of a subsequent report.

1.2 OBJECTIVE AND SCOPE

The objective of this study is to develop a plan for conducting hydrogeologic tests in the shallow hydro nest test wells with the purpose of determining the hydraulic properties of formations overlying the San Andres Formation.

The scope of work performed to accomplish this objective included the following tasks:

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1. Review of available data on the hydrogeologic setting and the hydraulic properties of the formations overlying the San Andres;

2. Evaluation of applicable testing procedures and of expected responses to testing for a range of potential hydraulic properties;

3. Review of shallow hydro nest locations and of test well design, and development of the testing plan; and

4. Formulation of test data analysis procedures.

2.0 REVIEW OF AVAILABLE DATA

2.1 HYDROGEOLOGIC SETTING

The hydrogeologic setting of the Palo Duro Basin in the Texas Panhandle is discussed in detail by Bair (1985), Bair, O'Donnell and Picking (1985) and in the EA (DOE, 1986). A brief summary is presented below.

Three hydrostratigraphic units have been identified within the sedimentary sequence that overlies the basement rocks in the Palo Duro Basin (Figure 2-1). The uppermost hydrostratigraphic unit, referred to as HSU A, is a shallow freshwater flow system. It comprises Triassic through Quaternary formations. The principal aquifers within this unit are the saturated part of the Ogallala Formation and the Santa Rosa Sand, a sandy permeable zone of the Dockum Group. The middle hydrostratigraphic unit, referred to as HSU B, is an aquitard consisting of Permian age shale, siltstone, carbonates and evaporites. The proposed host rock for the repository, the Lower San Andres Unit 4 salt, lies within this aquitard. The lowermost hydrostratigraphic unit, HSU C, is a deep basin flow system of brine aquifers. The transmissive zones within this unit are carbonates and granite wash of the Lower Permian Wolfcamp Series and of the Pennsylvanian System.

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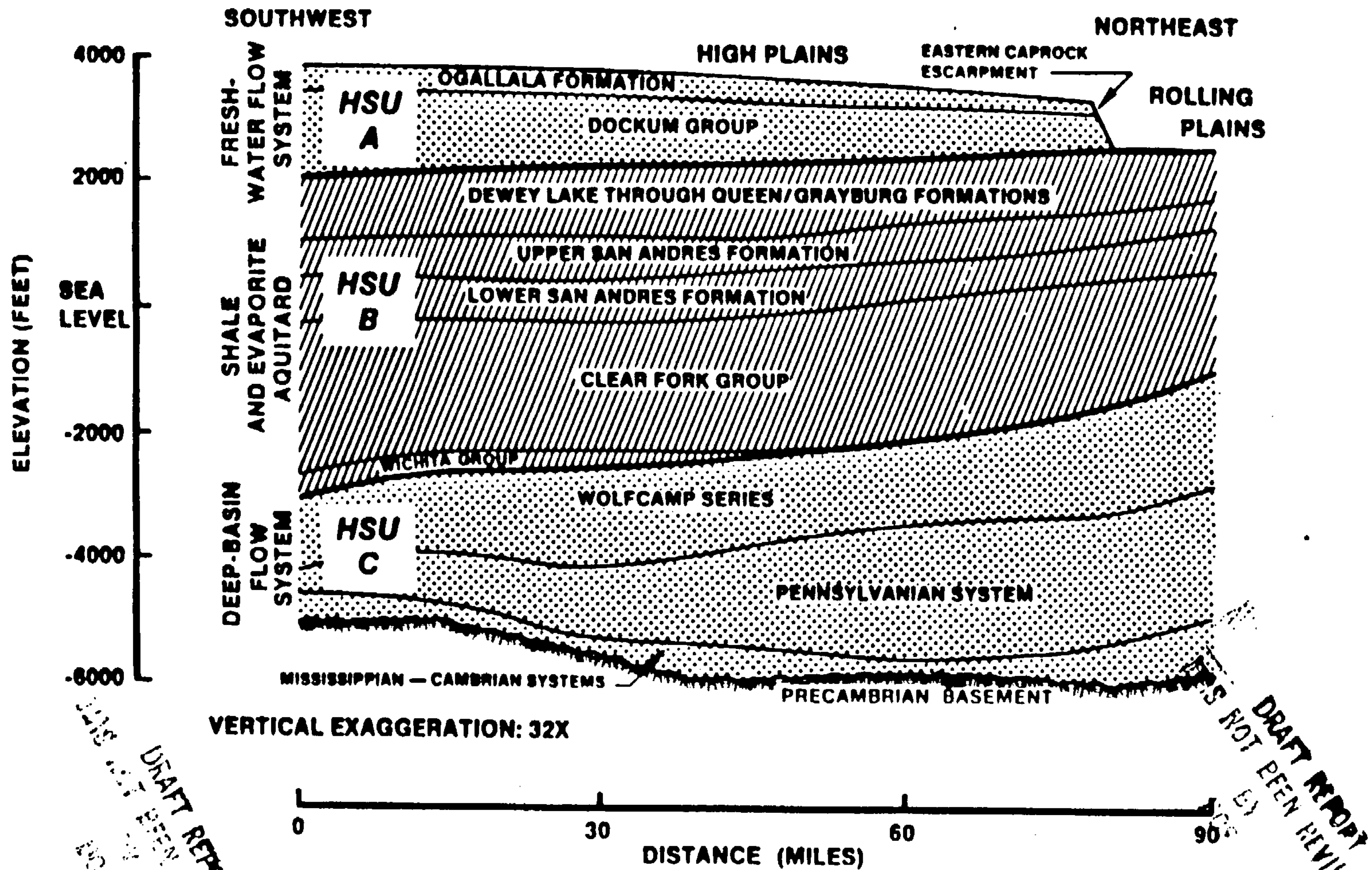
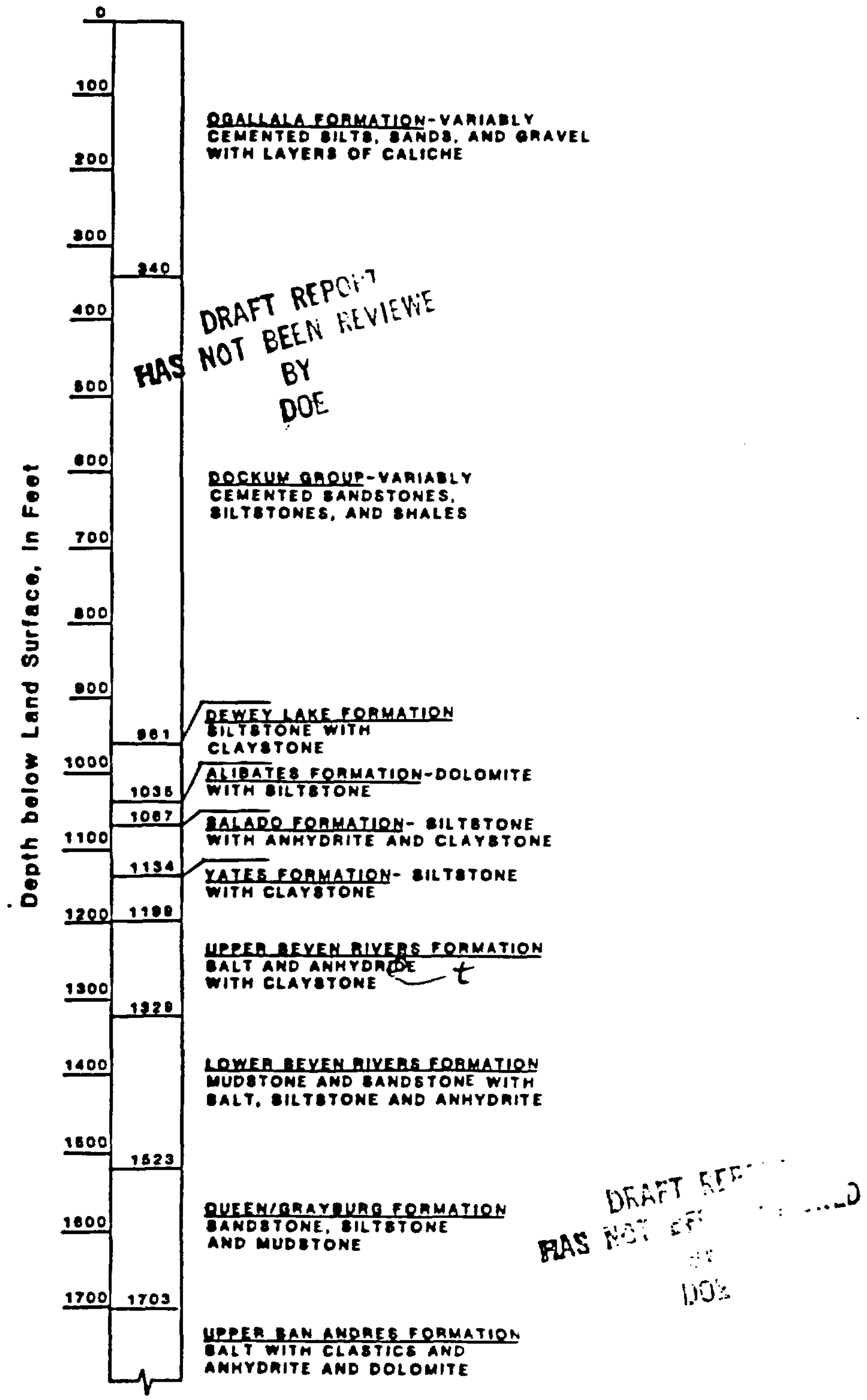
The shallow hydro nest test wells will extend to the top of the Upper San Andres Formation. That is, they will penetrate the Ogallala Formation and the Dockum Group of HSU A and the Dewey Lake, Alibates, Salado, Yates, Upper and Lower Seven Rivers and Queen/Grayburg Formations in the upper part of HSU B. The lithologic characteristics of these formations are shown on Figure 2-2. Also shown on this figure is the depth to the top of each of these formations



Source: Bair, O'Donnell and Picking, Hydrogeologic Investigations Based on Drill-Stem Test Data, Palo Duro Basin Area, Texas and New Mexico, SWEC, February 1985, BMI/ONWI-566.

Hydrostratigraphic Cross Section of the Palo Duro Basin

Figure 2-1



Lithology and Estimated Depth of Formations in Shallow Hydro Nest Test Wells

Figure 2-2

NOTE:
Based on data from DOE/SRPO, 1986, Revision 1 SRP/B-11

as estimated by the DOE Salt Repository Project Office (DOE/SRPO) for the Deaf Smith County Site (DOE/SRPO, 1986).

As stated earlier, the principal aquifers within this stratigraphic sequence are the saturated part of the Ogallala Formation and a sandy permeable zone within the Dockum Group, also referred to as the Santa Rosa Sand. Ground water within the Ogallala occurs under unconfined (water-table) conditions. The direction of ground-water flow is to the southeast with the water-table elevation ranging from about 3,800 feet above mean sea level near the northwest corner of the site to about 3,770 feet near the southeast corner (SWEC, 1984). The saturated thickness ranges from about 100 feet in the southeast to 50 feet in the northwest. A saturated thickness of 100 feet and a water table elevation of 3,793 feet are estimated by DOE/SRPO (1986) as the design values for the Deaf Smith Site.

Ground water within the sandy zone of the Dockum occurs under confined conditions. Fine-grained sediments (siltstone, claystone, and thin sandstone layers) in the upper part of the Dockum form an aquitard that separates this sandy zone from the overlying Ogallala. The potentiometric surface for the zone is at an elevation of about 3,420 feet above mean sea level (DOE/SRPO, 1986). This elevation is about 370 feet below the water table in the Ogallala, indicating downward flow from the Ogallala. The horizontal direction of ground-water flow within the sandy zone is easterly. The estimated thickness of the zone at the site is 93 feet, extending from a depth of 682 feet to 775 feet (DOE/SRPO, 1986).

The underlying Dewey Lake through Queen/Grayburg Formations have a very low permeability and are not a source of water for any use (DOE, 1986).

Available information on these formations is mostly lithologic and, in the vicinity of the site, limited to that obtained from deep wells drilled under DOE's Civilian Radioactive Management Program. Based on data extrapolated from the J. Friemel No. 1 well, about 5 miles southeast of the site (see Figure 1-1), the potentiometric surface of these formations is estimated to change from an elevation of 3,419 feet in Dewey Lake to an elevation of 3,392 feet in Queen/Grayburg (DOE/SRPO, 1986), giving (or with) a vertical gradient of about 0.045. The horizontal gradient within these formations is estimated to be 0.001 to the southeast (DOE/SRPO, 1986).

2.2 HYDRAULIC PARAMETERS

Available data on the hydraulic parameters of the formations to be penetrated by shallow hydro nest test wells pertain mostly to those of the Ogallala and the sandy zone of the Dockum. A discussion of the data on the hydraulic parameters of these two aquifers in the vicinity of the Deaf Smith Site was presented in an earlier SSP&A report (Papadopulos, 1986).

Based on the available data, the design values for the hydraulic conductivity and transmissivity of the Ogallala have been estimated to be (DOE/SRPO, 1986) 30 feet per day (ft/d) [224 gallons per day per square foot (gpd/ft^2)] and 3,000 feet squared per day (ft^2/d) [22,400 gallons per day per foot (gpd/ft)], respectively. A hydraulic conductivity range of 6.7 to 53 ft/d (50 to 400 gpd/ft^2), corresponding to a transmissivity range of 670 to 5,350 ft^2/d (5,000 to 40,000 gpd/ft), was used in developing a hydrogeologic testing plan for the Ogallala (Papadopulos, 1986). The specific yield was estimated to be 0.12 and to range between 0.05 and 0.20. Also, a storage coefficient of 0.0001 and a vertical-to-horizontal anisotropy ratio of 0.2 was assumed.

The design values for the hydraulic conductivity and transmissivity of the sandy zone of the Dockum are 12.6 ft/d (94 gpd/ft^2) and 1,170 ft^2/d (8,740 gpd/ft), respectively (DOE/SRPO, 1986). These values were also estimated to be the upper limits for these parameters, and lower limits of 0.13 ft/d (1 gpd/ft^2) and of 13.4 ft^2/d (100 gpd/ft), respectively, were estimated in developing a testing plan for this zone (Papadopulos, 1986). The storage coefficient was estimated to be 0.0001 with a potential range from 0.00001 to 0.001.

Hydrogeologic test data from the formations lying between the Dockum Group and the Upper San Andres Formation are available only for the Queen/Grayburg Formation. An 80-foot interval from this formation was pump-tested in the J. Friemel No.1 well (SWEC, 1985b). Data from the test were analyzed by Wilton and others (1986) and the hydraulic conductivity of the tested interval was determined to be 5.2 x 10^{-4} ft/d (3.9 x 10^{-3} gpd/ft^2).

The hydraulic conductivity of the other formations in the sequence, namely, Dewey Lake, Alibates, Salado, Yates, Upper and Lower Seven Rivers, was estimated by DOE/SRPO (1986) based on lithology and intrinsic permeabilities determined from laboratory tests of core samples or available in the literature. In these estimates the formation fluid unit weight and viscosity were assumed to be the same as those determined for samples from the Queen/Grayburg, that is, 74.29 pounds per cubic foot (lbs/ft^3) and 1.72 centipoise (cp), respectively, (Wilton and others, 1986). Similarly, estimates for the specific storage were developed by DOE/SRPO (1986) based on porosity and matrix compressibility estimates and using a formation fluid compressibility of 2.09×10^{-6} square inches per pound (psi^{-1}).

The values estimated by DOE/SRPO (1986) for hydraulic parameters pertinent to the design of hydrogeologic tests for the formations lying between the Dockum Group and the Upper San Andres Formation are summarized in Table 2-1. For the purpose of evaluating potential testing procedures, the horizontal hydraulic conductivities of these formations and, therefore, their transmissivities were assumed to range from one order of magnitude smaller than the estimated design values to one order of magnitude larger. Also, the range for specific storages and, therefore, for storage coefficients was assumed to be defined by a similar one order of magnitude variation in the values of matrix compressibilities used by DOE/SRPO (1986) to calculate the design values for these storage parameters. The resulting range for specific storages and storage coefficients were as follows:

	Specific Storage (ft^{-1})		Storage Coefficient	
Formation	Minimum	Maximum	Minimum	Maximum
Dewey Lake	2.8×10^{-7}	7.6×10^{-6}	2.1×10^{-5}	5.6×10^{-4}
Alibates	2.3×10^{-7}	2.6×10^{-6}	7.3×10^{-6}	8.5×10^{-5}
Salado	1.7×10^{-7}	2.8×10^{-6}	1.1×10^{-5}	1.9×10^{-4}
Yates	2.8×10^{-7}	4.5×10^{-6}	1.8×10^{-5}	2.9×10^{-4}
Upper Seven Rivers	1.8×10^{-7}	1.8×10^{-6}	2.4×10^{-5}	2.4×10^{-4}
Lower Seven Rivers	2.6×10^{-7}	4.3×10^{-6}	5.0×10^{-5}	8.3×10^{-4}
Queen/Grayburg	7.9×10^{-8}	1.5×10^{-6}	1.4×10^{-5}	2.8×10^{-4}

TABLE 2-1

DESIGN VALUES OF HYDRAULIC PARAMETERS

Formation	Thickness (ft)	Elevation of Potentiometric Surface (ft)	Hydraulic Conductivity: Horizontal (gpd/ft^2)	Hydraulic Conductivity: Horizontal (ft/d)*	Hydraulic Conductivity: Vertical (gpd/ft^2)	Hydraulic Conductivity: Vertical (ft/d)*	Transmissivity (gpd/ft)	Transmissivity (ft^2/d)**	Specific Storage (ft^{-1})	Storage Coefficient**
Dewey Lake	74	3,419	6.9×10^{-5}	9.2×10^{-6}	1.8×10^{-5}	2.4×10^{-6}	5.1×10^{-3}	6.8×10^{-4}	9.43×10^{-7}	7.0×10^{-5}
Alibates	32	3,417	2.3×10^{-2}	3.1×10^{-3}	2.2×10^{-4}	2.9×10^{-5}	7.4×10^{-1}	9.9×10^{-2}	4.48×10^{-7}	1.4×10^{-5}
Salado	67	3,415	6.6×10^{-5}	8.8×10^{-6}	1.7×10^{-5}	2.3×10^{-6}	4.4×10^{-3}	5.9×10^{-4}	4.05×10^{-7}	2.7×10^{-5}
Yates	65	3,413	7.0×10^{-5}	9.4×10^{-6}	1.9×10^{-5}	2.5×10^{-6}	4.6×10^{-3}	6.1×10^{-4}	6.67×10^{-7}	4.3×10^{-5}
Upper Seven Rivers	130	3,408	1.2×10^{-4}	1.6×10^{-5}	1.6×10^{-5}	2.1×10^{-6}	1.6×10^{-2}	2.1×10^{-3}	3.31×10^{-7}	4.3×10^{-5}
Lower Seven Rivers	194	3,399	2.3×10^{-2}	3.1×10^{-3}	9.7×10^{-6}	1.3×10^{-6}	4.5×10^{0}	6.0×10^{-1}	6.24×10^{-7}	1.2×10^{-4}
Queen/Grayburg	180	3,392	3.9×10^{-3}	5.2×10^{-4}	1.1×10^{-5}	1.5×10^{-6}	7.0×10^{-1}	9.4×10^{-2}	2.12×10^{-7}	3.8×10^{-5}

* Converted to ft-d units by SSP&A.

** Calculated by SSP&A from specific storage and thickness data.

Source : U.S. Department of Energy, Salt Repository Project Office, 1986, Synthetic Geotechnical Design Reference Data for the Deaf Smith Site, Revision 1, SRP/B-11, Columbus, Ohio.

3.0 EVALUATION OF POTENTIAL TESTING PROCEDURES

Procedures for the testing of the Ogallala and of the principal water-bearing zone of the Dockum were evaluated in developing the hydrogeologic testing plan for the exploratory shaft monitoring wells (Papadopulos, 1986). These evaluations indicated that within the expected range of their transmissivities, both of these aquifers can be tested using constant-rate pumping tests. Therefore, to develop a testing plan for the shallow hydro nest test wells, the evaluation of potential testing procedures was limited to the formations underlying the Dockum Group.

The potential response of these formations during different testing procedures was evaluated for three cases:

1. The design values of hydraulic conductivity and specific storage (or transmissivity and storage coefficient);

2. The assumed maximum hydraulic conductivity and minimum specific storage; and

3. The assumed minimum hydraulic conductivity and maximum specific storage.

These latter two cases envelop test responses for all potential combinations of hydraulic conductivity and specific storage (or transmissivity and storage coefficient) within the assumed range of these parameters.

3.1 CONSTANT-RATE PUMPING TESTS

Constant-rate pumping tests consist of pumping a well at a constant discharge rate and observing the drawdown (water-level decline) in the pumped well and, usually, in one or more nearby observation wells throughout the pumping period and the subsequent water-level recovery period. Data from both the pumping period and the recovery period are analyzed to determine the hydraulic properties of the tested formation. The oil industry's "drill-stem test" also falls into this category of testing. However, during this test, data are usually collected only from the pumped well and the analysis is primarily based on the recovery period data.

3.1.1 Available Drawdown and Discharge Rate

The transmissivity of the formations underlying the Dockum is very low and the specific capacity (discharge per unit drawdown) of test wells open to these formations would be also very low. However, the potentiometric surface of each of these formations is several hundred feet above the top of the formation and, thus, the drawdown available during testing would be large. To determine whether this large available drawdown could result in discharge rates that are suitable for constant-rate pumping tests, the discharge rate that can be sustained for a 24-hour period without exceeding the available drawdown of each formation was calculated.

The available drawdown for each formation was taken as being equal to the difference between the elevation of the potentiometric surface and the top of each formation, less 25 ft. This reduction by 25 ft was made to provide a safety margin against lowering the water level below the top of the formation and to account for possible well losses although, at the expected low discharge rates, well losses would most likely be negligible. The discharge rates were calculated using the Theis (1935) equation for infinite, isotropic, confined aquifers and assuming a well radius of 0.25 ft.

Table 3-1 summarizes the available drawdown, the corresponding pumping lift and the potential range of discharge rates for test wells open to any formation in the Dewey Lake through the Queen/Grayburg sequence. The minimum discharge rates correspond to the assumed minimum transmissivity and maximum storage coefficient for each formation. Conversely, the maximum discharge rates correspond to the (minimum) maximum transmissivity and (maximum) minimum storage coefficient. For the design values of the hydraulic parameters the discharge rates range from 0.0024 gpm (0.46 ft^3/d) for the Dewey Lake and Salado Formations to 2.2 gpm (420 ft^3/d) for the Lower Seven Rivers Formation.

It is apparent from these calculations that some of the formations that will be penetrated by the shallow hydro nest test wells will not yield sufficient amounts of water for conducting constant-rate pumping tests. To select the minimum discharge rate that would be suitable for constant-rate pumping tests, data from tests previously conducted in deep wells drilled under DOE's Civilian Radioactive Management Program were examined (Wilton and others, 1986). During the testing of the Queen/Grayburg Formation in well J. Friemel No. 1, the well was pumped at a rate of 3.4 stock tank barrels per day (STB/d), or 0.10 gpm (20 ft^3/d), for two pumping periods, the first for about two days and the second for about 12.5 days. During a third pumping period of about 4.5 hours the well was pumped at 6.9 STB/d (0.20 gpm or 40 ft^3/d). The lowest pumping rate used in tests conducted in Sawyer No. 1,

TABLE 3-1

POTENTIAL RANGE OF DISCHARGE RATES FOR 24-HOUR TESTS

Formation	Available Drawdown (ft)	Pumping Lift (ft)	Discharge Rate: For Design Value of Parameters (gpm)	(ft^3/d)	Estimated Range: Minimum (gpm)	(ft^3/d)	Maximum (gpm)	(ft^3/d)
Dewey Lake	322	936	0.0024	0.46	0.00090	0.17	0.015	2.9
Alibates	394	1,010	0.21	40	0.030	5.8	1.7	330
Salado	424	1,042	0.0024	0.46	0.00066	0.13	0.016	3.1
Yates	489	1,109	0.0031	0.60	0.00094	0.18	0.021	4.0
Upper Seven Rivers	549	1,174	0.010	1.9	0.0022	0.42	0.073	14
Lower Seven Rivers	670	1,304	2.2	420	0.33	64	17	3300
Queen/Grayburg	857	1,498	0.46	89	0.074	14	3.6	690

Mansfield No. 1, Zeeck No. 1, or J. Friemel No. 1 wells was 1.5 STB/d (0.04 gpm or 8 ft^3/d) during the testing of a dolomite section of the Lower San Andres Formation (Test Zone 8) in the J. Friemel No. 1 well. However, the data from this test are significantly affected by wellbore storage.

Based on this examination of discharge rates used in previous tests, a rate of 0.2 gpm (40 ft^3/d) was selected as the minimum discharge rate suitable for constant-rate pumping tests. With this criterion, and based on the sustainable discharge rates for the design values of their parameters (Table 3-1), the formation that could be pump-tested in shallow hydro nest test wells are the Alibates, Upper Seven Rivers and Queen/Grayburg Formations. Other testing procedures need to be considered for the testing of the Dewey Lake, Salado, Yates and Upper Seven Rivers Formations. Other testing procedures will also have to be considered for the Alibates and Queen/Grayburg Formations if their transmissivities are found to be near the low end of the assumed range.

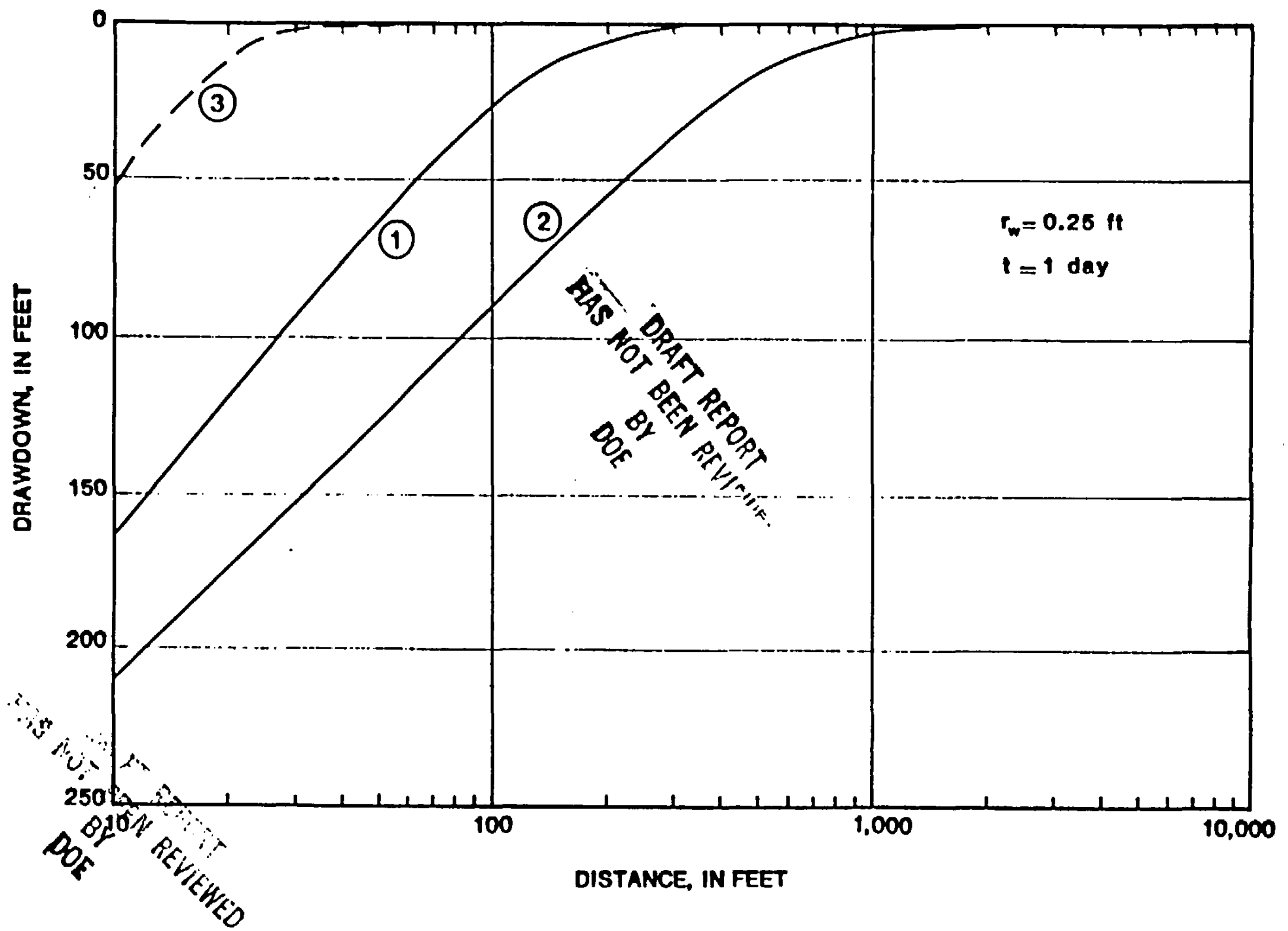
3.1.2 Drawdown in Observation Wells

As presently planned, the shallow hydro nests will consist of one pumped well and three observation wells (SWEC, 1985a). To determine the distances from the pumped well at which observation wells should be placed in order to provide adequate data during a pumping test, an evaluation was made of the drawdowns that would occur at different distances from the pumped well. This evaluation was made for the Alibates, Lower Seven Rivers and Queen/Grayburg Formations which were identified in the previous section as potential candidates for constant-rate pumping tests.

Calculations based on the design value of vertical hydraulic conductivity for adjacent formations (see Table 2-1) indicated that vertical leakage would not have a significant effect on the drawdown within the pumped formation except for pumping periods of 50 days or more. Therefore, the Theis (1935) equation was also used for the calculation of drawdown at different distances from the pumped well.

Figures 3-1, 3-2, and 3-3 show the expected drawdown after one day of pumping at different distances from the pumped well in the Alibates, Lower Seven Rivers and Queen/Grayburg Formations, respectively. The figures show the drawdown for the design values of the transmissivity and storage coefficient as well as for the assumed maximum and minimum values of these parameters. Although the discharge rates corresponding to the low transmissivity cases for the Alibates and the Queen/Grayburg Formations are less than 0.2 gpm (40 ft^3/d), the drawdowns for these cases are also shown, as dashed curves, on Figures 3-1 and 3-3 to indicate the range of drawdowns that would be expected within the assumed range of the hydraulic parameters.

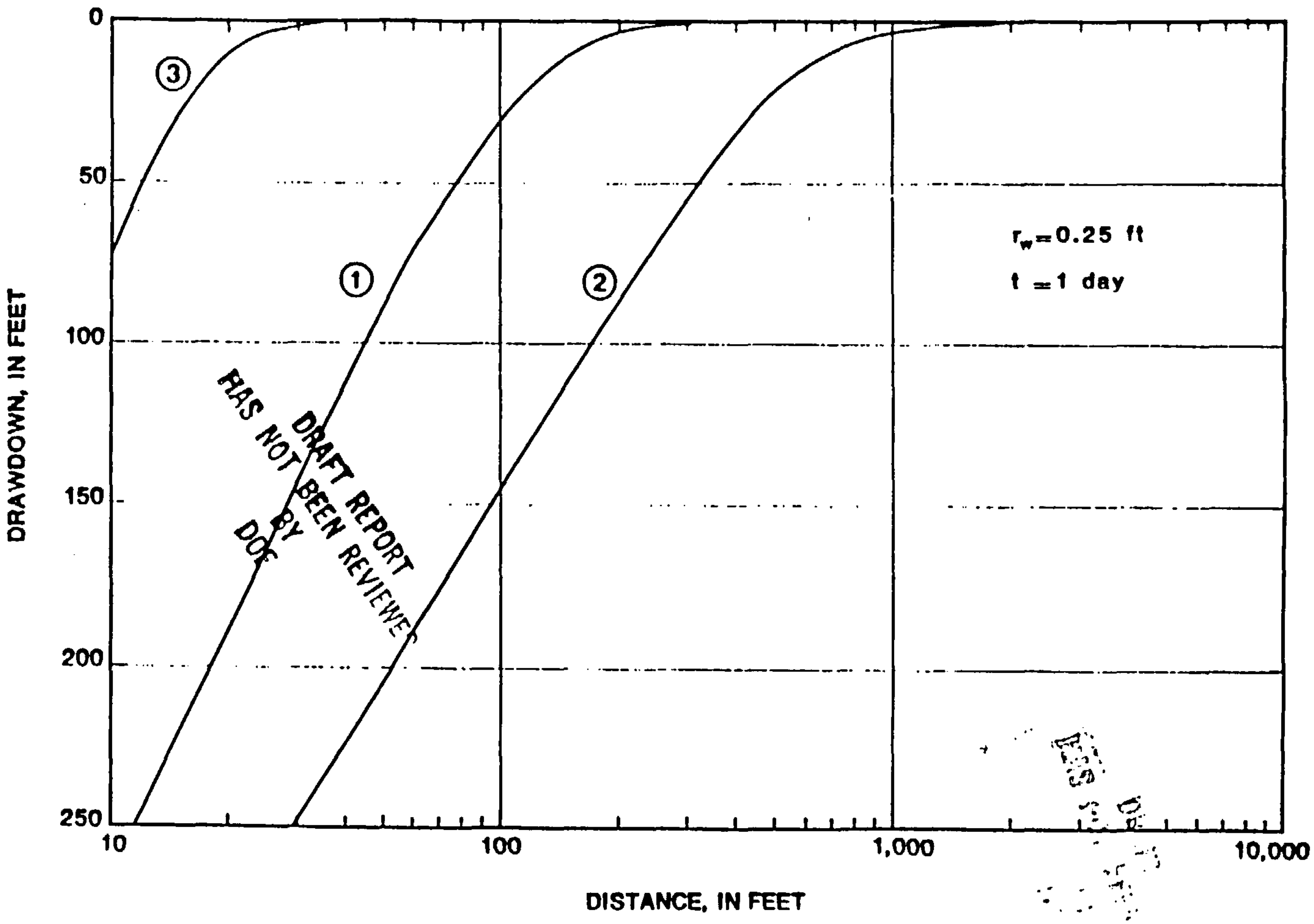
These results indicate that, for the design values of hydraulic parameters, drawdowns would propagate to distances of about 300 feet in the Alibates and Lower Seven Rivers Formations (Figures 3-1 and 3-2) and to about 200 feet in the Queen/Grayburg (Figure 3-3). However, drawdowns beyond a distance of about 150 feet are relatively small. Thus, to observe a significant drawdown during pumping tests observation wells should be placed at distances of less than 150 feet from the pumped well. If the transmissivities are near the low end of their assumed range, observation wells would be required at distances as small as 20 feet.



① T = 0.099 ft^2/d S = 1.4×10^{-5} Q = 0.21 gpm
② T = 0.99 ft^2/d S = 7.3×10^{-6} Q = 1.7 gpm
③ T = 0.0099 ft^2/d S = 8.5×10^{-5} Q = 0.030 gpm

Alibates
Expected Change in Drawdown with Distance from Pumped Well

Figure 3-1



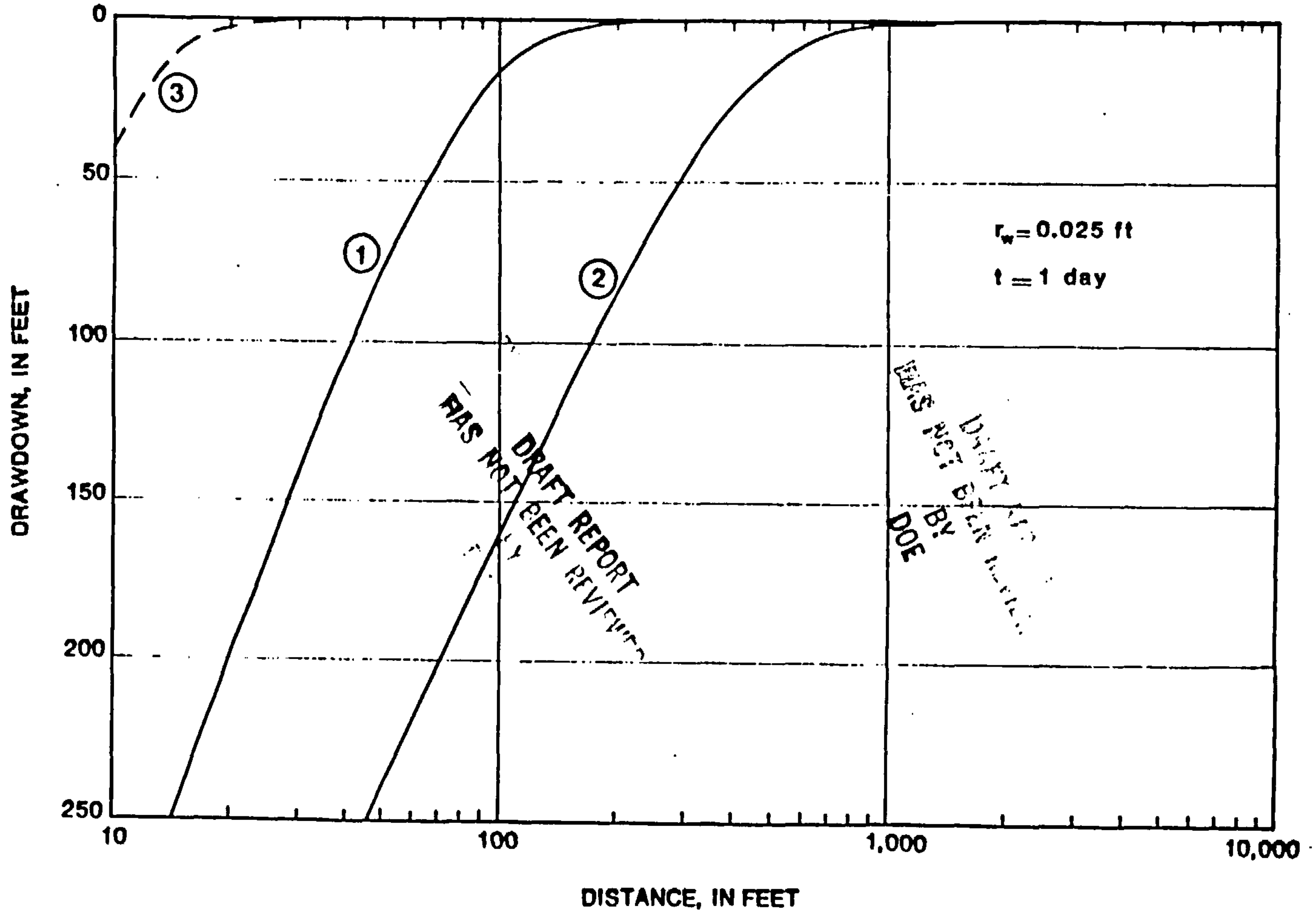
① T = 0.60 ft²/d   S = 1.2×10^{-4} Q = 2.2 gpm

② T = 6.0 ft²/d   S = 5.0×10^{-5} Q = 17 gpm

③ T = 0.060 ft²/d   S = 8.3×10^{-4} Q = 0.33 gpm

Lower Seven Rivers
Expected Change in Drawdown with Distance from Pumped Well

Figure 3-2



① T = 0.094 ft^2/d S = 3.8×10^{-5} Q = 0.46 gpm

② T = 0.94 ft^2/d S = 1.4×10^{-5} Q = 3.6 gpm

③ T = 0.0094 ft^2/d S = 2.8×10^{-4} Q = 0.074 gpm

Queen / Grayburg
Expected Change in Drawdown with Distance from Pumped Well

Figure 3-3

3.1.3 Wellbore Storage Effects

When a well is pumped, part of the water pumped from the well is derived from water stored in the well. This wellbore storage causes the drawdowns to deviate from those predicted by the Theis (1935) equation. Wellbore storage effects are most significant during the early period of pumping when the water level in the well is declining rather rapidly. As pumping progresses and the rate of water-level decline decreases, wellbore storage effects also decrease and eventually become negligible. Papadopulos and Cooper (1967) give the following criterion for this early period during which wellbore storage effects are significant:

$$t < 250 r_c^2 / T \tag{3-1}$$

where t = time since pumping started;

r_c = the radius of the well casing ~~the~~ within the interval of water-level decline; and

T = the transmissivity of the pumped formation.

As this criterion indicates, for a given casing radius, the duration of this early period is inversely proportional to the transmissivity. In formations of high transmissivity wellbore storage effects disappear within a few minutes or even a few seconds after the beginning of pumping. Conversely, in formations of low transmissivity these effects may last for a long period of time.

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Calculations based on the above criterion, a casing radius of 0.25 ft and the design values of transmissivity indicate that the duration of the period during which wellbore storage effects are significant would be about 160 days for the Alibates and the Queen/Grayburg Formations and about 25 days for the Lower Seven Rivers Formation. Thus, although equations that account for wellbore storage are available (Papadopulos and Cooper, 1967; Papadopulos, 1967), the determination of the hydraulic properties of these formations would require unreasonably long testing periods unless procedures are used that minimize wellbore storage effects.

Such a procedure would be to conduct the tests under shut-in conditions. That is, the interval to be tested could be isolated from communication with water stored in the wellbore above the tested interval by packers or other means. Under these conditions, wellbore storage effects are reduced to those caused by water derived from the expansion of the water stored within the isolated interval. Bredehoeft and Papadopulos (1980) show that the effects of this type of wellbore storage are equivalent to substituting the following expression for r_c^2 (the square of the casing radius):

$$\gamma_w c_w V_w \ / \ \pi \qquad (3\text{-}2)$$

where V_w = the volume of the isolated interval;

c_w = the compressibility of the water within the isolated interval; and

γ_w = the unit weight of the water within the isolated interval.

Neuzil (1982) correctly points out that instead of the compressibility of the water c_w, the aggregate compressibility of the isolated interval, which includes the effects of the deformation of the casing and of other equipment or tubing that may be present in the isolated interval, should be used in the above expression. This aggregate compressibility can be determined only in the field. Therefore, the compressibility of water will continue to be used in the evaluations presented in this report.

If the thickness of the isolated interval is equal to the formation thickness b, then the volume of the isolated interval is equal to

$$V_w = \pi r_c^2 b \qquad (3\text{-}3)$$

and expression (3-2) becomes

$$\gamma_w c_w r_c^2 b \qquad (3\text{-}4)$$

Substituting the expression given by (3-4) for r_c^2 in the wellbore storage criterion (3-1), the criterion for wellbore storage effects during shut-in tests becomes

$$t < 250 \;\; \gamma_w c_w r_c^2 b/T \qquad (3\text{-}5)$$

or, since the transmissivity is equal to the product of the hydraulic conductivity K and the thickness b

$$t < 250 \;\; \gamma_w c_w r_c^2/K \qquad (3\text{-}6)$$

Using this criterion, the fluid compressibility and unit weight used by DOE/SRPO (1986) in estimating storage coefficients, and the design values of hydraulic conductivity, the duration of wellbore storage effects for shut-in tests is calculated to be about 8 minutes for the Alibates and Lower Seven Rivers Formations and about 50 minutes for the Queen/Grayburg Formation.

3.2 OTHER TESTING PROCEDURES

As indicated in Section 3.1.1, procedures other than the constant-rate pumping test need to be considered for the testing of the Dewey Lake, Salado, Yates and Upper Seven Rivers Formations and, possibly, of the Alibates Queen/Grayburg Formations. Available procedures for the testing of formations of low hydraulic conductivity are the ~~following~~ falling or rising head test, more commonly known as "slug" tests. Slug tests consist of artificially causing an instantaneous change in the hydraulic head within the test well and observing the rate at which the head recovers to pre-test static conditions.

The standard slug test (Ferris and Knowles, 1954; Ferris and others, 1962; Cooper and others, 1967; Papadopulos and others, 1973) is conducted in an open well and the instantaneous head change is caused by raising or dropping the water level in the well, either through the sudden pumping or injection of a known volume of water, or by the sudden insertion or extraction of a piece of pipe or other displacement device of known volume. The modified, or shut-in, slug test (Bredehoeft and Papadopulos, 1980; Neuzil, 1982) is conducted by isolating the test interval in the well by packers or other means and causing an instantaneous pressure change by suddenly introducing or removing a known volume of water into or from the isolated interval. An evaluation of the potential response of the above cited formations to these types of tests is presented below.

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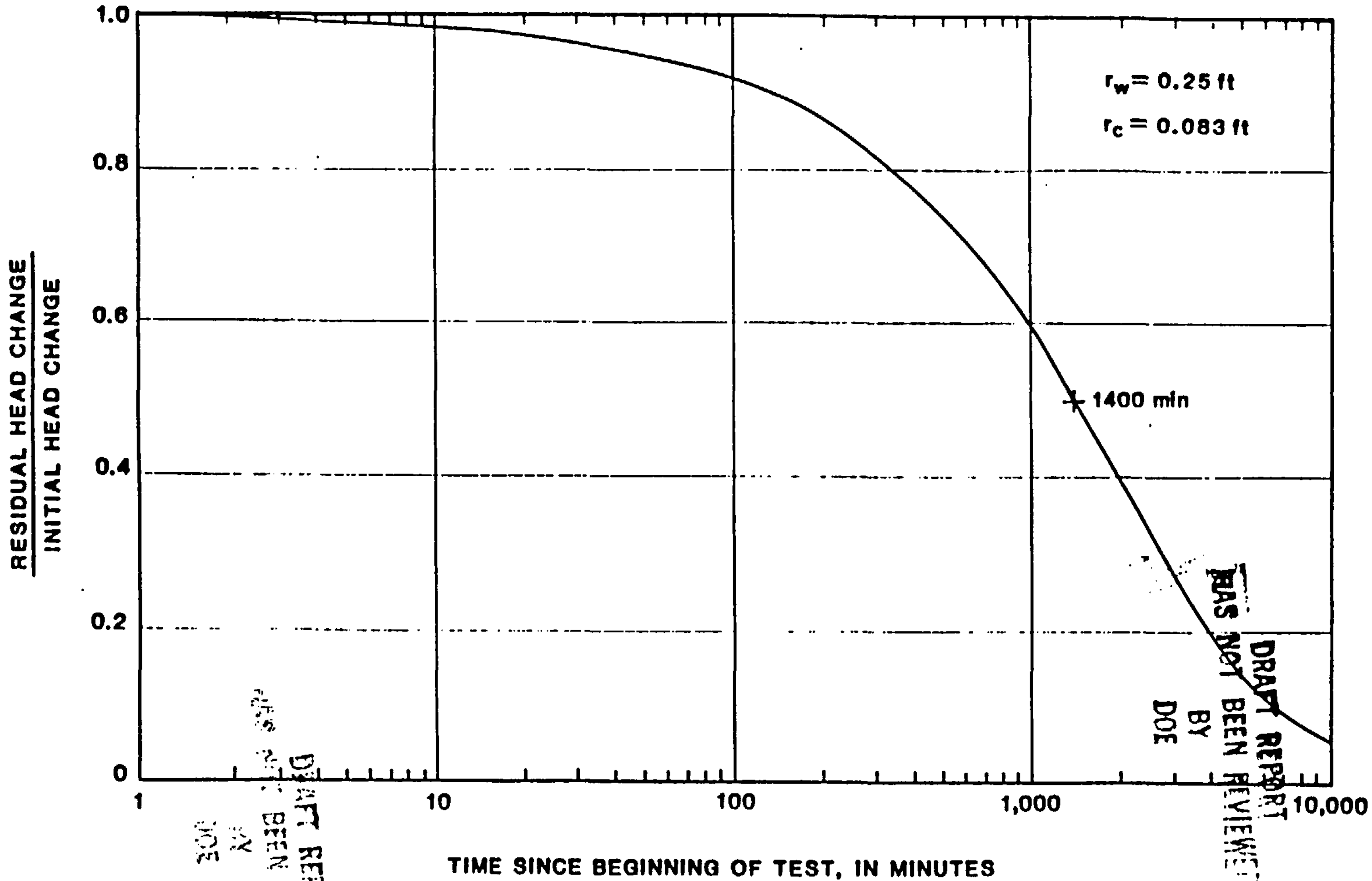
3.2.1 Standard Slug Tests

Ideally, during a slug test the water level should be observed until it fully recovers to the pre-test water level. However, in formations of very low transmissivity this may not be possible as the rate of water-level recovery would be very slow and unreasonably long periods would be required for full recovery. Nevertheless, to provide adequate data for analysis the test must be conducted until at least a 50 percent recovery occurs.

For a given transmissivity, the rate of water-level recovery during a slug test depends on the volume of water that flows into or out of the formation per unit water-level change in the well. Hence, the rate of water-level recovery can be accelerated by reducing this volume. This can be accomplished by installing a packer and tubing of a diameter smaller than that of the well casing and conducting the test within the tubing.

In the evaluations presented below, it was assumed that the test well has a radius of 0.25 ft and that the test is conducted within tubing with a radius of 0.083 ft. Also, for formations having estimated transmissivities and storage coefficients that are not significantly different from each other, a single response curve was calculated using average values of transmissivity and storage coefficient.

Figure 3-4 shows the expected response of the Alibates or of the Queen/Grayburg Formation to a standard slug test. The response is for the low transmissivity, high storage coefficient case which, as established previously, would not permit constant-rate pump testing. Also shown on this figure is the time at which a 50 percent recovery of the water level is expected to occur. It is apparent from this evaluation that a test of one to two days' duration would provide adequate data for analysis.



T = 9.6 × 10^{-3} ft^2/d S = 1.8 × 10^{-3}

Alibates or Queen/Grayburg Expected Response to Standard Slug Test

Figure 3-4

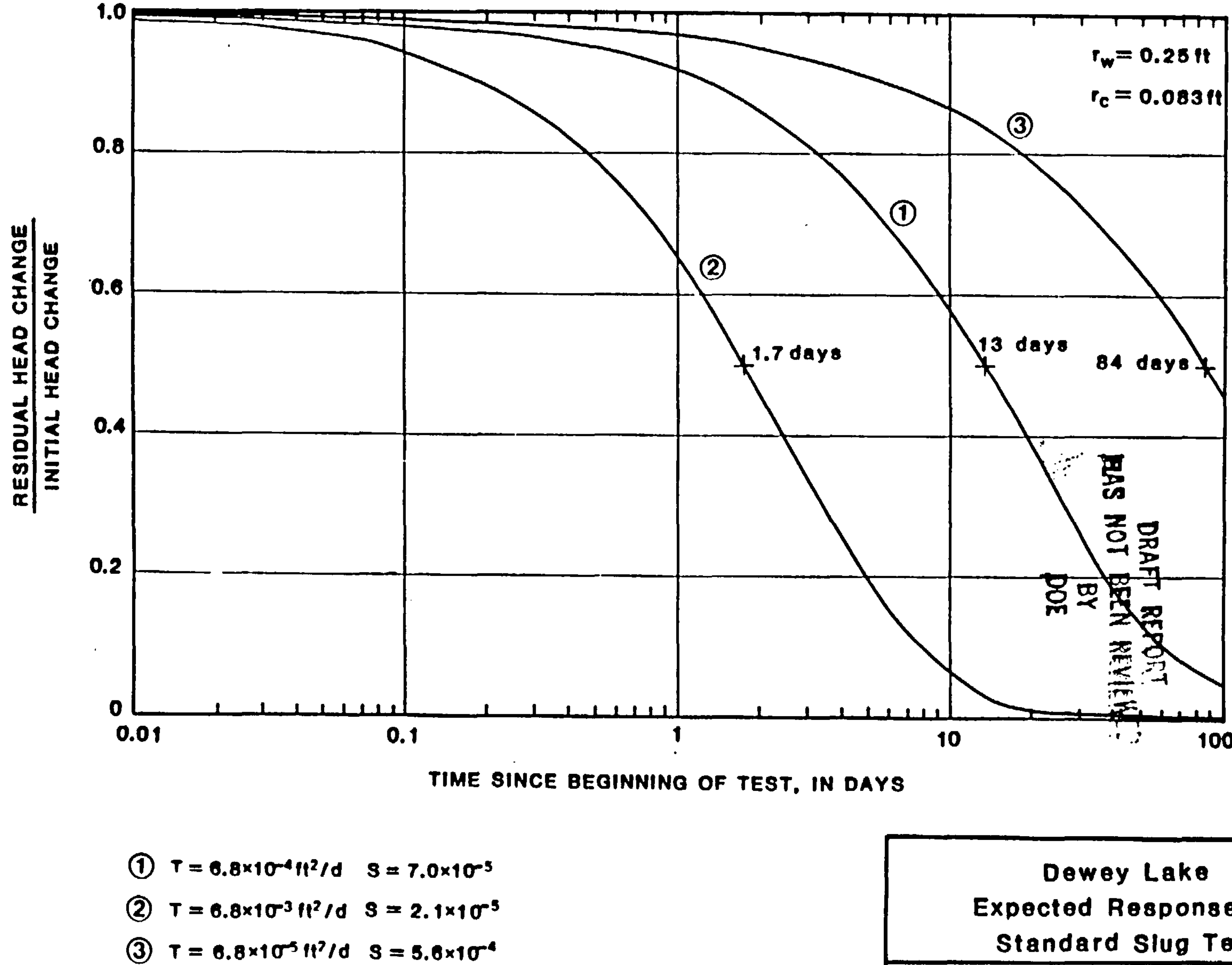
Figure 3-5 shows the expected response of the Dewey Lake Formation to a standard slug test, Figure 3-6 that of the Salado or Yates Formation and Figure 3-7, that of the Upper Seven Rivers Formation. As indicated on these figures, for transmissivities near the high end of the range assumed for these formations, 50 percent recovery occurs within about two days or less. However, if the transmissivities are near their design values or lower, tests of about 10 to over 100 days would be required to obtain sufficient data for analysis.

For these cases, evaluations based on the shut-in slug test are made in the next section.

3.2.2 Shut-In Slug Tests

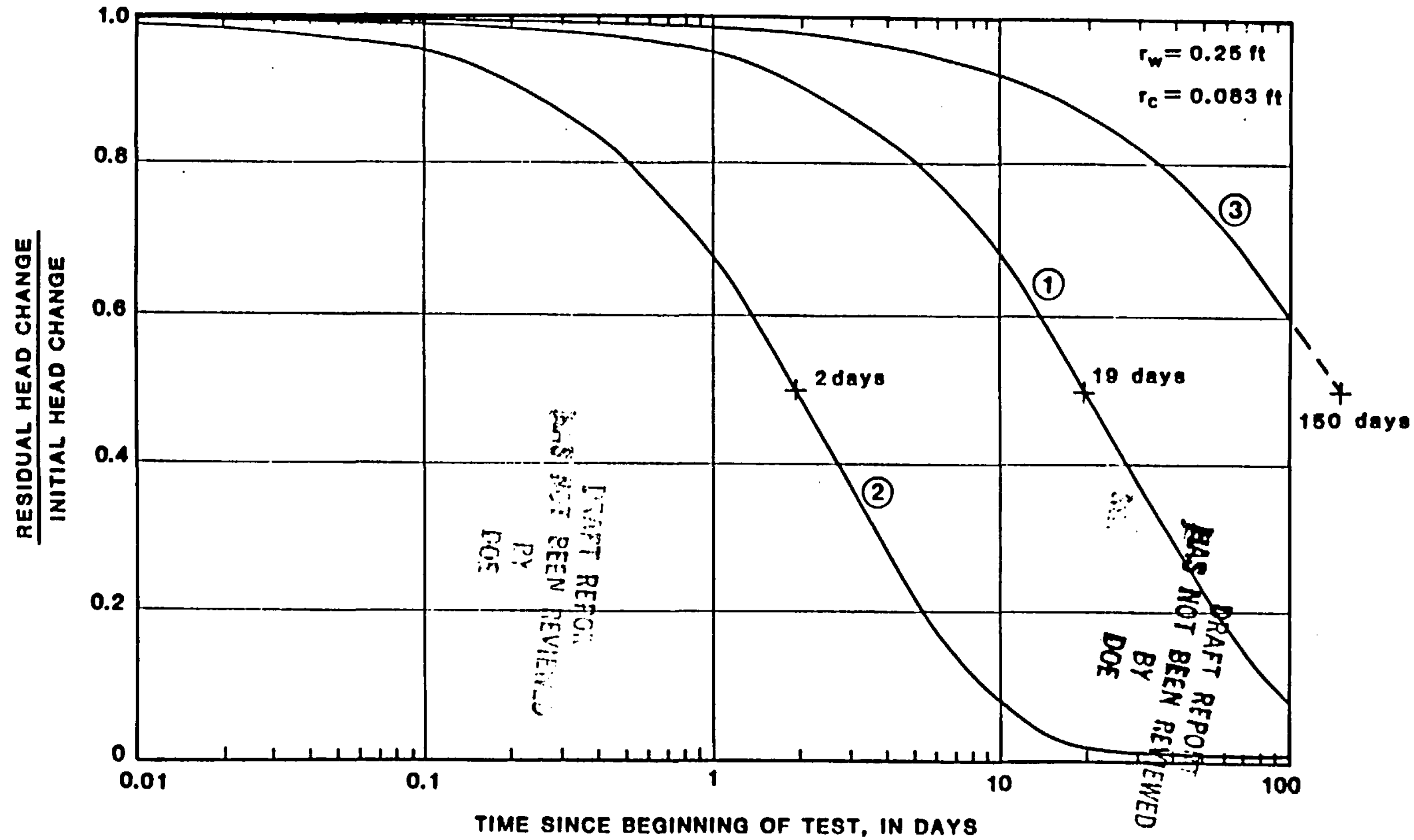
As stated earlier, the shut-in slug test is conducted by isolating the test interval and suddenly introducing into, or removing from, the isolated interval a known volume of water. The amount of water flowing into or out of the formation is that derived from the decompression or compression of the water within the isolated interval.

If the length of the isolated interval is equal to the thickness of the formation, or if the transmissivity represents a thickness of the formation equal to the length of the isolated interval, then the rate at which the pressure or hydraulic head approaches the pre-test level is dependent on the hydraulic conductivity and specific storage rather than the transmissivity and storage coefficient. Therefore, in calculating the expected responses to shut-in tests, formations having similar hydraulic conductivity were combined and a single response curve was developed using average hydraulic conductivity



Dewey Lake
Expected Response to
Standard Slug Test

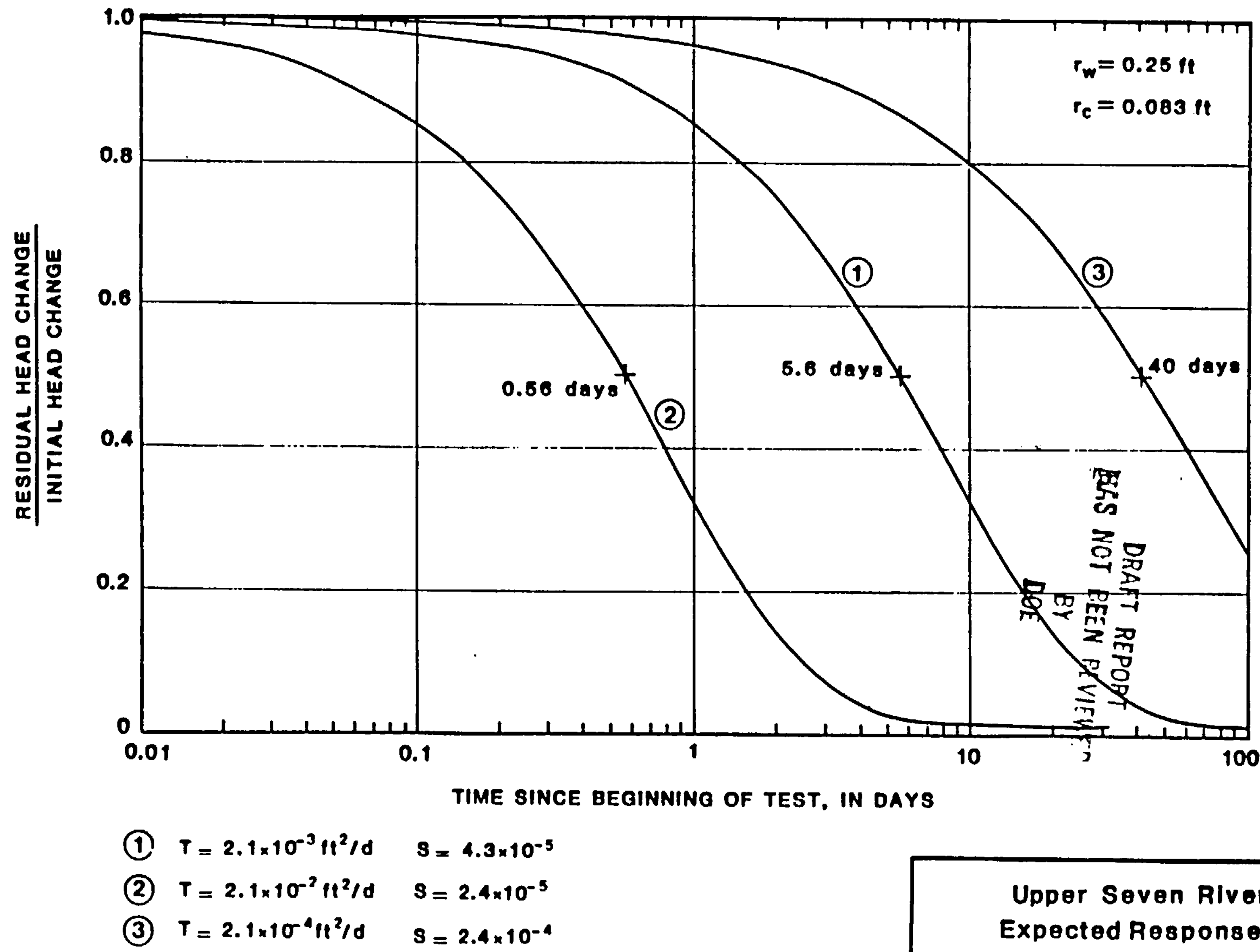
Figure 3-5



1 $T = 6.0 \times 10^{-4} ft^2/d$ $S = 3.5 \times 10^{-5}$
2 $T = 6.0 \times 10^{-3} ft^2/d$ $S = 1.5 \times 10^{-5}$
3 $T = 6.0 \times 10^{-5} ft^2/d$ $S = 2.4 \times 10^{-4}$

Salado or Yates
Expected Response to
Standard Slug Test

Figure 3-6



Upper Seven Rivers
Expected Response to
Standard Slug Test

Figure 3-7

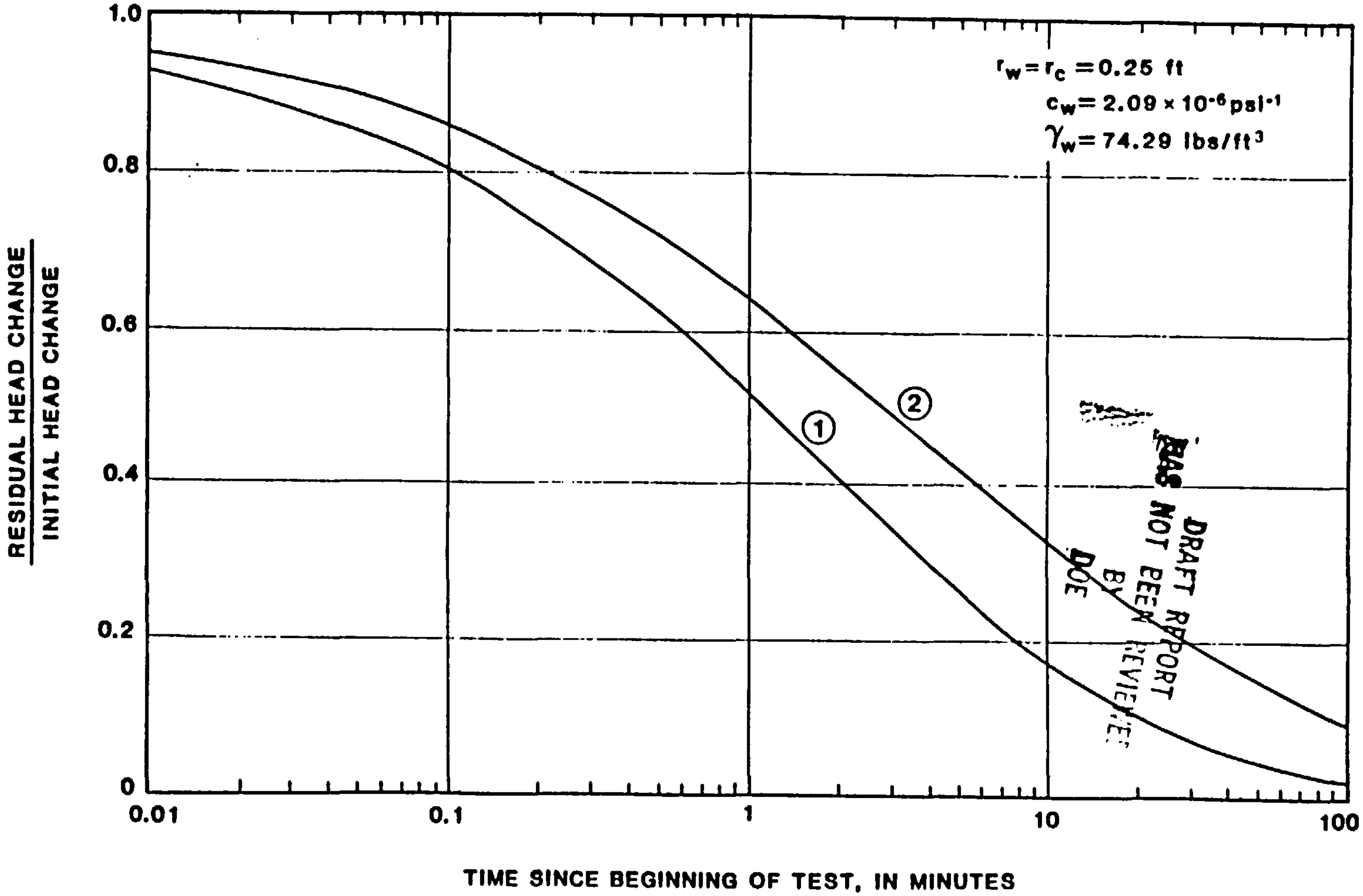
and specific storage values. A fluid compressibility of 2.09×10^{-6} psi^{-1} and a fluid unit weight of 74.29 lbs/ft^3 (DOE/SRP, 1986) were used in these calculations.

Figure 3-8 shows the expected response of the Dewey Lake, Salado or Yates Formation to a shut-in slug test and Figure 3-9 that of the Upper Seven Rivers Formation. The responses are for the design values of hydraulic conductivity and specific storage and for the minimum hydraulic conductivity and specific storage cases which, as established in the previous section, would require very long test periods if tested by the standard slug test. As shown in Figures 3-8 and 3-9, almost a full recovery to pre-test conditions would be expected to occur within a few hours of the beginning of a shut-in test in these formations.

3.2.3 Response in Observation Wells

Both the standard and the shut-in slug tests are single well tests. That is, water-level or pressure recovery data are usually collected only from the test well. To assess whether collection of data from nearby observation wells could be useful in the interpretation of the test, calculations were made of the expected response of observation wells at a distance from the test well.

An analytical solution of the response to a standard slug test at distances from the test well is given by Cooper and others (1967). However, this solution is in the form of an infinite integral for which tabular values are not available. Therefore, to develop the expected response in observation wells, a numerical radial flow model was used.

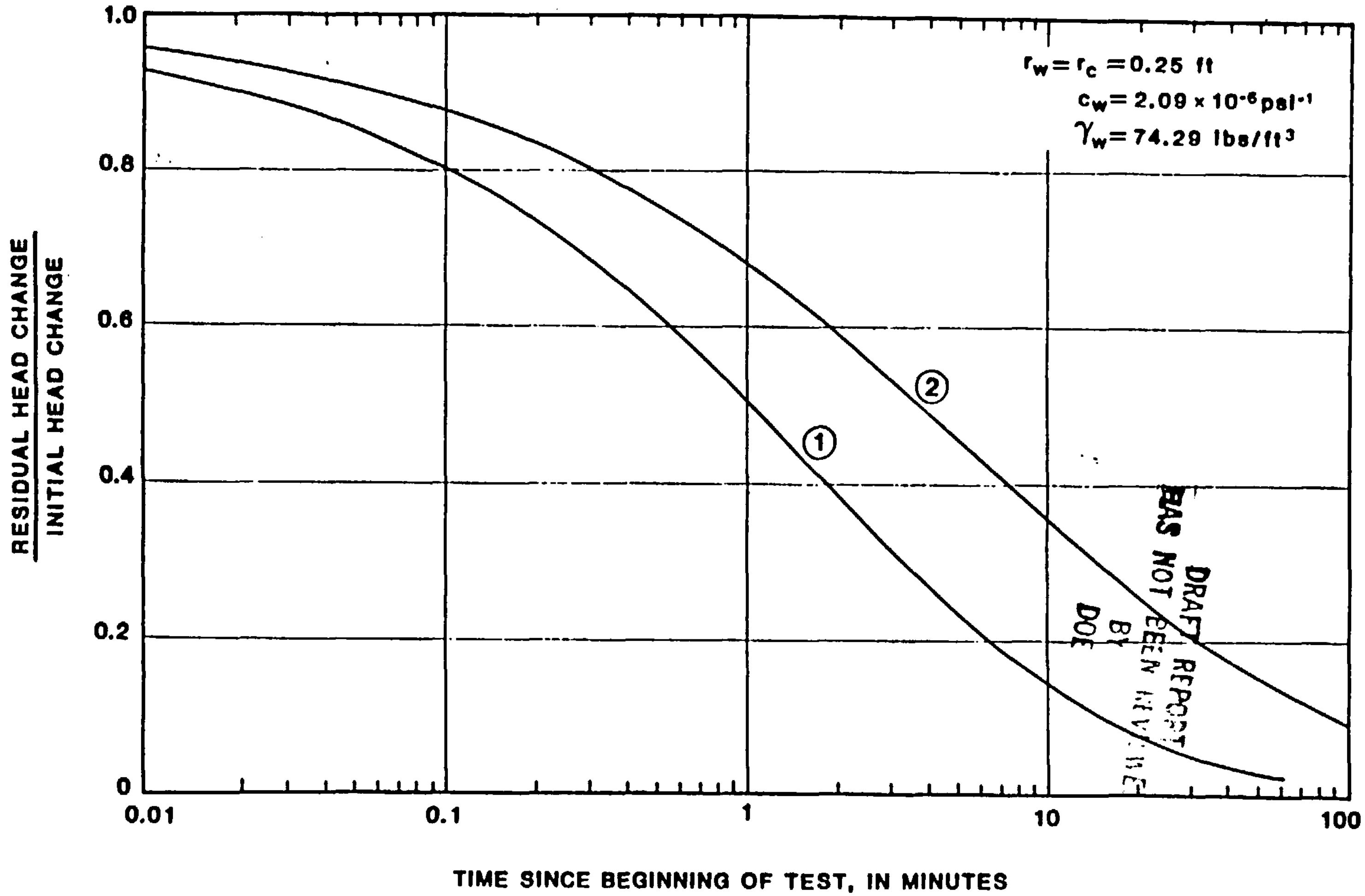


(1) K = 9.1×10^{-6} ft/d $S_s = 6.7 \times 10^{-7}$ ft^{-1}

(2) K = 9.1×10^{-7} ft/d $S_s = 5.0 \times 10^{-6}$ ft^{-1}

Dewey Lake, Salado or Yates
Expected Response to
Shut-in Slug Test

Figure 3-8



① $K = 1.6 \times 10^{-5}$ ft/d $S_s = 3.3 \times 10^{-7}$ ft^{-1}

② $K = 1.6 \times 10^{-6}$ ft/d $S_s = 1.8 \times 10^{-6}$ ft^{-1}

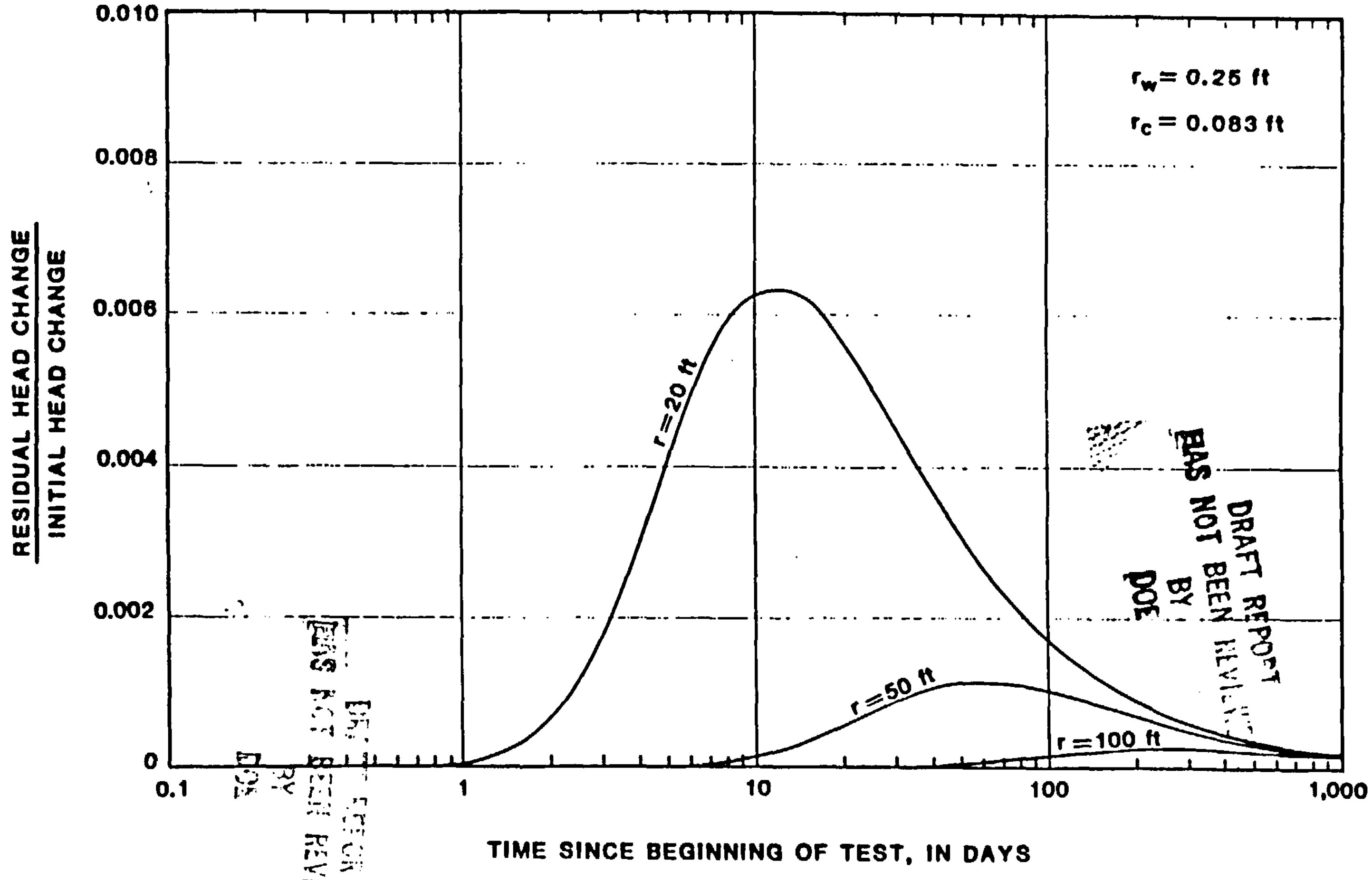
Upper Seven Rivers
Expected Response to
Shut-in Slug Test

Figure 3-9

Figure 3-10 shows the expected response in observation wells 20 ft, 50 ft and 100 ft from the test well during the testing of the Alibates Formation by the standard slug test (low transmissivity, high storage coefficient case). The nearest observation well begins responding to the test about one day after the beginning of the test and, as would be expected, it has the most pronounced response to the test. The response in this well reaches a peak at about 10 days; however, the magnitude of the peak is only 0.6 percent of the initial head change imposed at the test well. More distant wells begin to respond much later and have a much smaller peak.

Figure 3-11 shows the expected response in observation wells during the testing of the Dewey Lake Formation by the shut-in slug test (design values case). As in the case of the Alibates standard slug test response, the nearest observation well begins responding after about one day and peaks at about 10 days. The similar response times result because the Alibates and the Dewey Lake have similar hydraulic diffusivities (ratio of hydraulic conductivity to specific storage) and the propagation of head is controlled by that diffusivity. Note, however, that the magnitude of the peak for the Dewey Lake (Figure 3-11) is a hundred times smaller than that of the Alibates (Figure 3-10), or only 0.006 percent of the initial head change imposed at the test well.

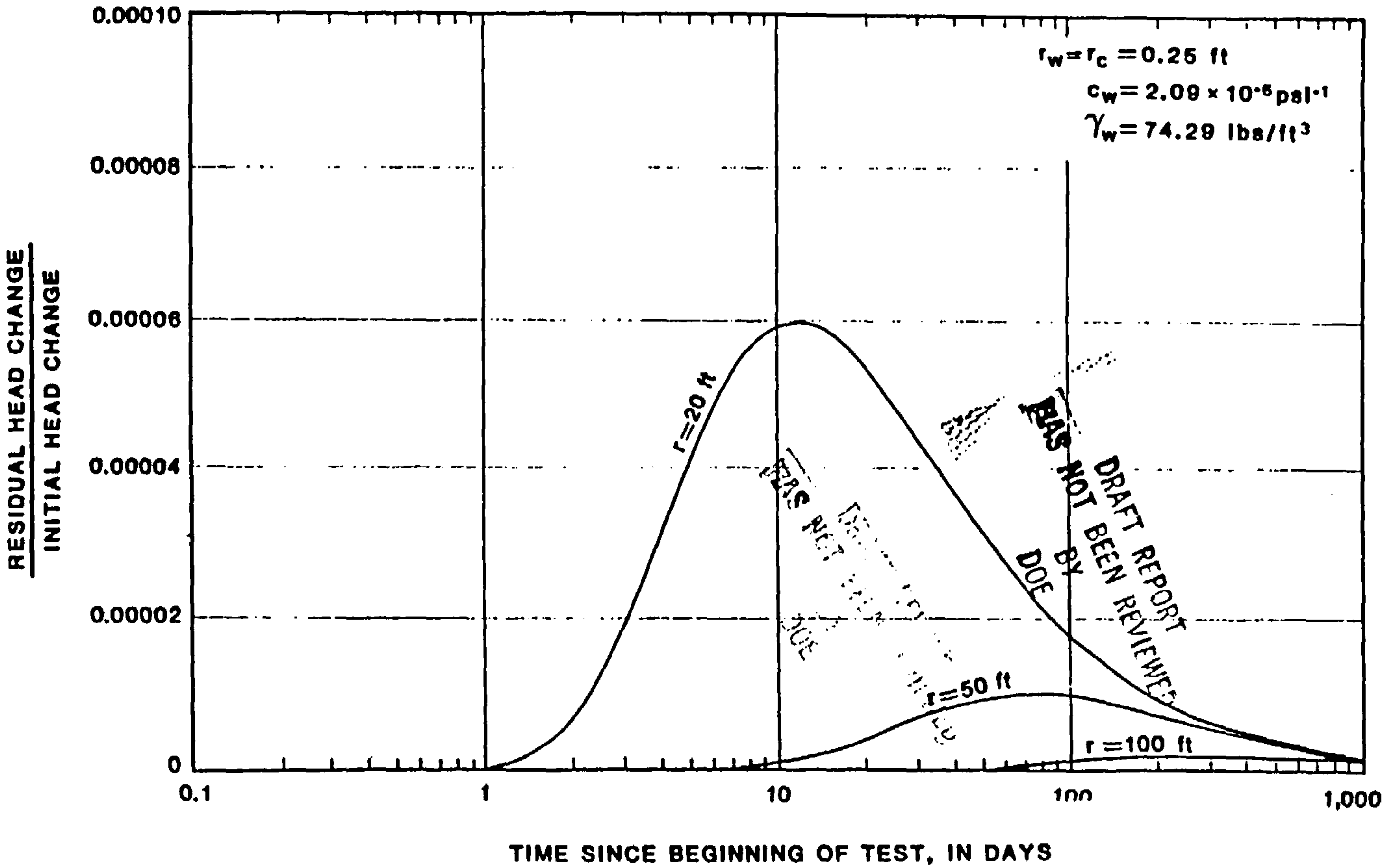
These results indicate that the response of observation wells during the conduct of slug tests is so delayed and so small that the value of data collected from these wells would be insignificant compared to those collected from the test well.



$T = 0.0099$ ft^2/d $S = 8.5 \times 10^{-5}$

Alibates
Expected Observation-Well Response to Standard Slug Test

Figure 3-10



$K = 9.2 \times 10^{-6}$ ft/d $\quad S_s = 9.4 \times 10^{-7}$

Dewey Lake
Expected Observation-Well
Response to Shut-in Slug Test

Figure 3-11

3.2.4 Pre-Test Hydraulic Head

The slug-test procedures discussed above require that the static, pre-test head of the formations to be tested be known. The drilling of the shallow hydro nest test wells will disturb the static head in the formations penetrated by these wells. Because of the very low hydraulic conductivity of some of these formations, recovery to static conditions may have not been reached prior to testing, especially if the wells are left open and a large volume of water must enter or leave the well in order to fill up or evacuate the well casing to the static water level. Furthermore, the water-level recovery in the open well may be so slow that water-level measurements made prior to testing may erroneously give the impression that the well has reached its static level.

To assess whether the water level in the well correctly reflects static conditions, the well should be shut in and the pressure observed in the shut-in well. Because recovery in shut in wells is faster, this procedure would be a better indicator of static conditions. If the test to be conducted is of the shut-in type, then the well could be left shut in until the test is conducted.

On the other hand, if the test requires an open well, the well casing or test tubing could be filled with water as close to the static level as possible, taking into consideration density and/or temperature differences between the formation water and the water used to fill the casing or tubing.

3.3 CONFINING BED RESPONSE

The testing procedures evaluated in the previous sections are aimed at determining the horizontal properties of the formations open to shallow hydro nest test wells. With the exception of the Ogallala and the principal water-bearing zone of the Dockum, the formations to be penetrated by shallow hydro nest test wells are confining beds, or aquitards, whose vertical properties may be more important than the horizontal ones for the hydrogeologic characterization of the site.

The sequence of formations between the principal water-bearing zone of the Dockum and the Alibates Formations and that between the Alibates and the Lower Seven Rivers Formations contain the less permeable formations to be penetrated by the shallow hydro nest test wells. In order to assess whether the vertical properties of these two sequences could be determined by in situ tests, an evaluation was made of the rate at which drawdowns within the principal zone of the Dockum, Alibates, or Lower Seven Rivers would propagate vertically through these two sequences.

An analytical solution describing the drawdown in a confining bed is given by Neuman and Witherspoon (1968). However, the following simpler equation (Ferris and others, 1962), was used for this evaluation:

$$s_c = s_o \operatorname{erfc}\left[(z/2)(S_s/K_v t)^{1/2}\right] \tag{3-7}$$

where s_c = drawdown in confining bed;

s_o = instantaneous constant drawdown in pumped formation;

z = vertical distance from top (or bottom) of pumped formation;

S_s = specific storage of confining bed;

K_v = vertical hydraulic conductivity of confining bed;

t = time since drawdown s_o occurs in the pumped formation; and

erfc(x) = is the complimentary error function.

Equation (3-7) assumes that the confining bed is infinitely thick. However, the equation is applicable to confining beds of finite thickness if within the time period considered in the calculations the drawdown does not propagate across the entire thickness of the confining bed. This condition was satisfied in the calculations made for this evaluation. Also, the equation assumes that the drawdown in the pumped formation occurs instantaneously, whereas during a pumping test the drawdown occurs gradually. The effect of this assumption is to overestimate the drawdowns in the formations adjacent to the pumped formation. Therefore, the calculations made in this evaluation are conservative in the sense that they exaggerate the drawdown in adjacent formations.

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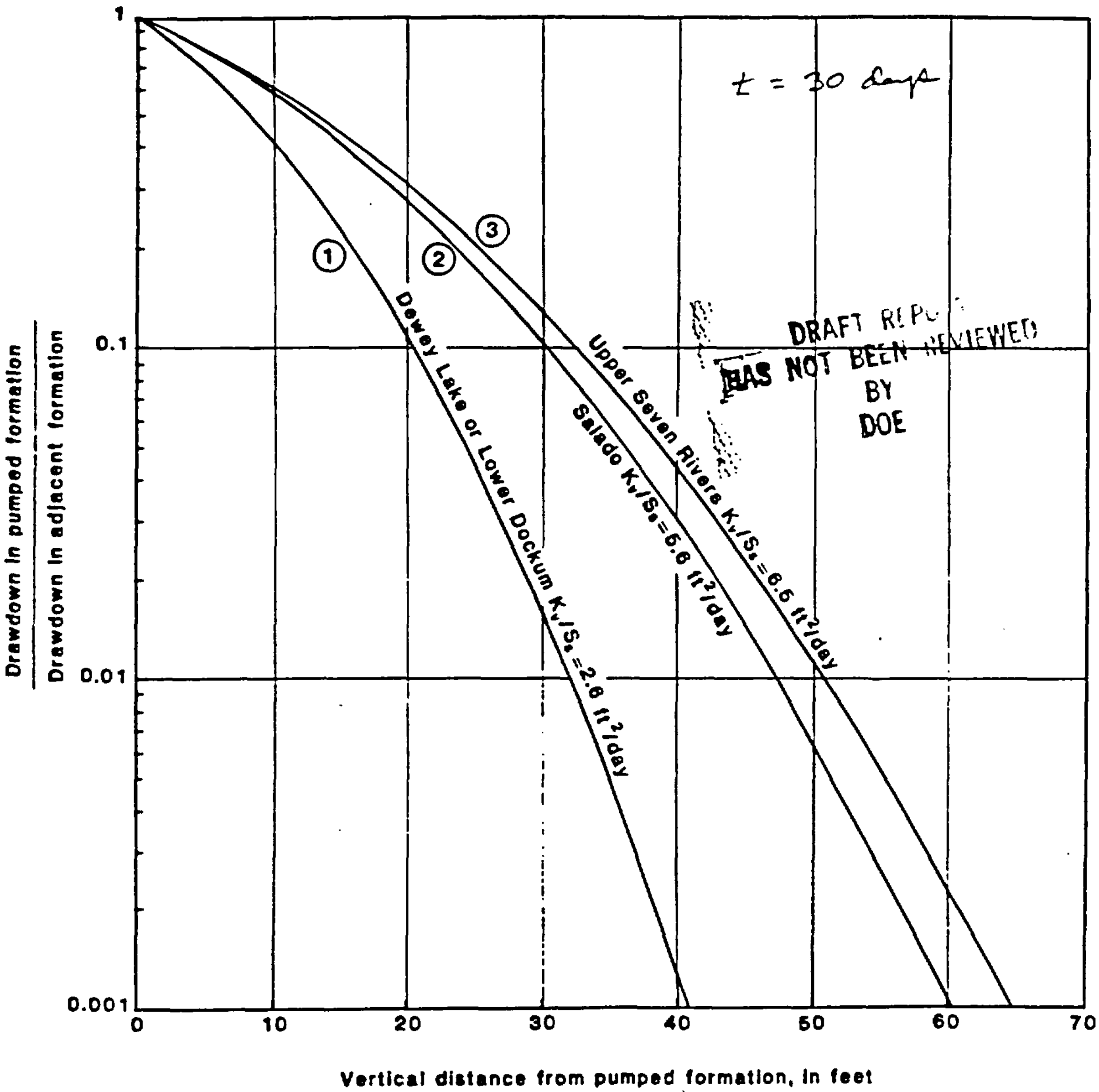
The design values of vertical hydraulic conductivity and specific storage (Table 2-1) were used in this evaluation, and the properties of the lower part of the Dockum were assumed to be the same as those of the Dewey Lake Formation. Also, a 30-day pumping period was assumed. Figure 3-12 shows the drawdown at different vertical distances from the pumped formation. Curve 1 of this figure depicts the drawdown in the lower part of the Dockum when the principal water-bearing zone of the Dockum is pumped, or the drawdown in the Dewey Lake when Alibates is pumped. Curve 2 depicts the drawdown in the Salado when Alibates is pumped and curve 3, the drawdown in the Upper Seven Rivers when the Lower Seven Rivers is pumped. Note that at distances beyond



Pumped Formation:

1. Alibates or Principal Zone of Dockum
2. Alibates
3. Lower Seven Rivers

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Vertical Distribution of Drawdown in Formations Adjacent to the Pumped Formation

Figure 3-12

40 to 65 feet from the pumped formations the drawdown in the adjacent formation would be less than 0.1 percent of that in the pumped formation.

These results indicate that, by conducting pumping tests of 30 days or more in the relatively more permeable formations, it may be possible to determine the vertical properties of a 30- to 40-foot thickness of the adjacent formation. However, the sequence that separates the principal water-bearing zone of the Dockum from the Alibates and that separating the Alibates from the Lower Seven Rivers are about 260 feet thick. Vertical ground-water flow through these sequences is governed by the hydraulic conductivity of the least permeable layer within the sequence. Thus, the vertical hydraulic conductivity of the upper or lower 30-40 feet of the sequence may not be representative of ground-water flow rates through the sequence.

Alternatively, if the horizontal properties are determined from hydrogeologic tests and the vertical and horizontal distribution of hydraulic head is known, it may be possible to determine representative vertical properties by numerical modeling of the hydrogeologic system at the site and its vicinity. In developing the hydrogeologic testing plan presented in the next section, consideration was given to this aspect of site characterization.

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4.0 DEVELOPMENT OF THE HYDROGEOLOGIC TESTING PLAN

The evaluation presented in Section 3.0 and those presented in an earlier SSP&A report (Papadopulos, 1986) indicate that the Ogallala Formation, the principal water-bearing zone of the Dockum Group and the Lower Seven Rivers Formations would be amenable to the characterization of their hydraulic properties by constant-rate pumping tests. The Alibates and the Queen/Grayburg Formations should be also amenable to characterization by constant-rate pumping tests; however, standard slug tests may be required to characterize these two formations if their transmissivities are lower than their estimated design values (DOE/SRPO, 1986). The evaluations also indicate that shut-in slug tests would be required to characterize the Dewey Lake, Salado, Yates and Upper Seven Rivers Formations, unless their transmissivities are higher than the estimated design values; under the latter conditions, standard slug tests would be feasible for characterizing these formations.

These tests should result in the determination of the horizontal hydraulic properties of these formations. However, to determine the vertical hydraulic properties of the least permeable formations within the sequence to be penetrated by shallow hydro nest test wells, tests of very long duration would be required. Alternatively, if the potentiometric surfaces of the more permeable formations in the sequence have features that reflect vertical leakage, it should be feasible to obtain representative values of the vertical properties of the intervening less permeable sequences by numerical modeling of the hydrogeology of the site and its vicinity. Therefore, detailed information on the configuration of potentiometric surfaces should be obtained. If attempts to determine vertical properties from this information are not successful, consideration could be given to the conduct of tests of 30- to 60-day duration.

Based on these results of the evaluation of the expected test responses, a hydrogeologic testing plan for the shallow hydro nest test wells was developed. The plan is aimed at providing the means of characterizing the hydraulic properties of formations by hydrogeologic tests, as well as, at providing a monitoring network for determining the configuration of the potentiometric surfaces of different formations at the vicinity of the site.

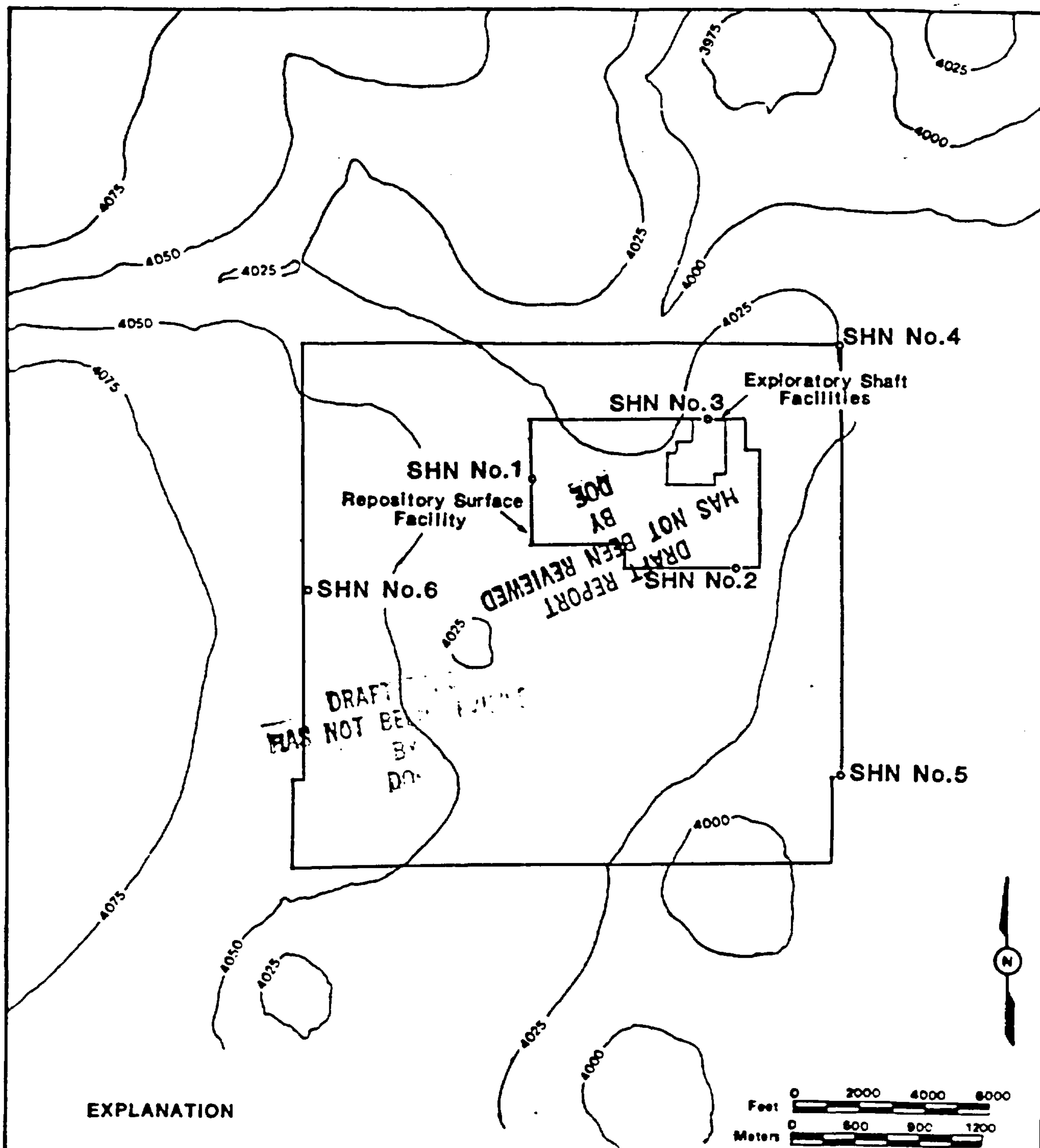
4.1 PROPOSED TESTING PLAN

The proposed hydrogeologic testing plan includes changes in the number and location of the shallow hydro nests and in the layout and design of the test wells. These proposed changes and an outline of the drilling and testing sequence at the nest locations are presented below.

4.1.1 Number and Location of Shallow Hydro Nests

Six shallow hydro nests are proposed, located as shown on Figure 4-1. Three of these nests are located along the boundary of the repository surface facility, and the remaining three along the site boundary. The locations shown on Figure 4-1 are approximate and are intended to indicate the general areas where the shallow hydro nests should be installed. Field conditions and land access would determine the actual locations in these general areas.

These proposed locations of the shallow hydro nests would provide a greater areal coverage on the hydraulic properties of the formations to be



EXPLANATION

—4075— Line of equal altitude of land surface, in feet above MSL

•SHN Shallow Hydro Nests

Adapted from : Environmental Assessment, Deaf Smith County Site, Texas, USDOE, May 1986, Figure 4-2

Proposed Changes in Location of Shallow Hydro Nests

Figure 4-1

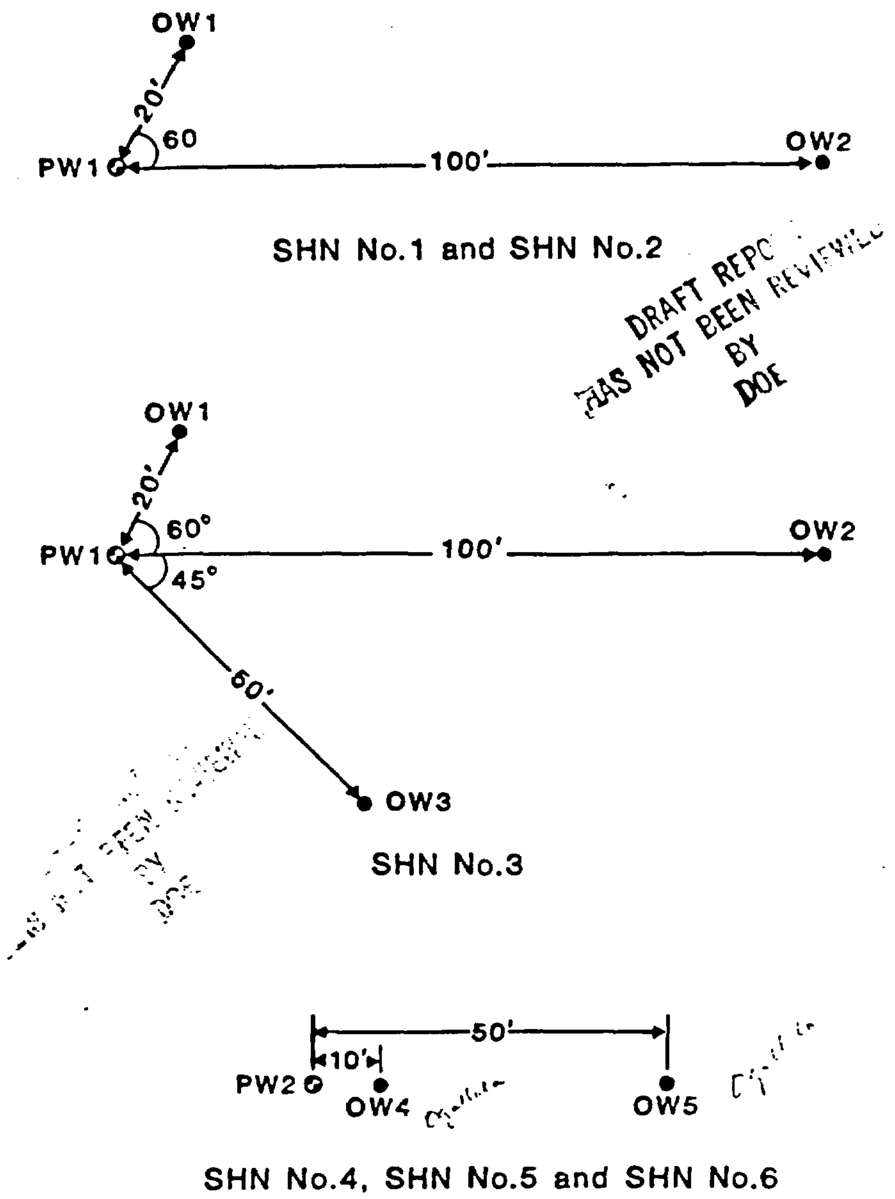
tested than the locations previously proposed by SWEC (1985a) or DOE (1986) (see Figures 1-2 and 1-3). The distribution of the nests would also provide for a better definition of the potentiometric surfaces.

4.1.2 Test Well Layout and Design

Three different test well layouts are proposed, as shown on Figure 4-2. Shallow hydro nests SHN No. 1 and SHN No. 2 consist of one pumping well and two observation wells. Nest SHN No. 3, located near the exploratory shaft facility, consists of one pumping well and three observation wells. Nests SHN No. 4, SHN No. 5 and SHN No. 6 also consist of one pumping well and two observation wells; however, the configuration of the wells is different than that at SHN No. 1 and SHN No. 2.

The pumping wells at all nest locations and the observation wells designated as OW1, OW2, OW3, and OW5 on Figure 4-2 extend to the top of the Upper San Andres Formation. The observation wells designated as OW4 extend to the top of the Dockum Group and are intended to serve as observation wells only during the testing of the Ogallala aquifer.

The Ogallala is an aquifer with the most available data on its hydraulic properties in the vicinity of the site. The aquifer will be tested in the exploratory shaft monitoring wells and it may also be tested in most of the 30 monitoring wells that are planned for installation in the vicinity of exploratory shaft facilities. Therefore, the proposed hydrogeologic testing plan does not include tests for the Ogallala at shallow hydro nests SHN No. 1, SHN No. 2 and SHN No. 3, which are located at, or relatively near,



LEGEND

PW Pumping Well

OW Observation Well

Shallow Hydro Nests
Test Well Layout

Figure 4-2

the exploratory shaft facility. It is proposed that the Ogallala be tested only at shallow hydro nests SHN No. 4, SHN No. 5 and SHN No. 6.

Figure 4-3 shows the shematic design for the pumping wells designated PW1 at SHN No. 1, SHN No. 2 and SHN No. 3. It is proposed that these wells be first completed as 12-in wells in the Ogallala with gravel pack and screen across the saturated part of the Ogallala. Drilling should then proceed through the completed well to the top of the Upper San Andres and 8-in casing should be cemented from total depth to the top of the Dockum. Testing would proceed from the bottom up by perforating and isolating the interval across the formation to be tested. After all the tests have been conducted, the well should be completed as a dual monitoring well for the Ogallala and the principal water-bearing zone of the Dockum (Santa Rosa).

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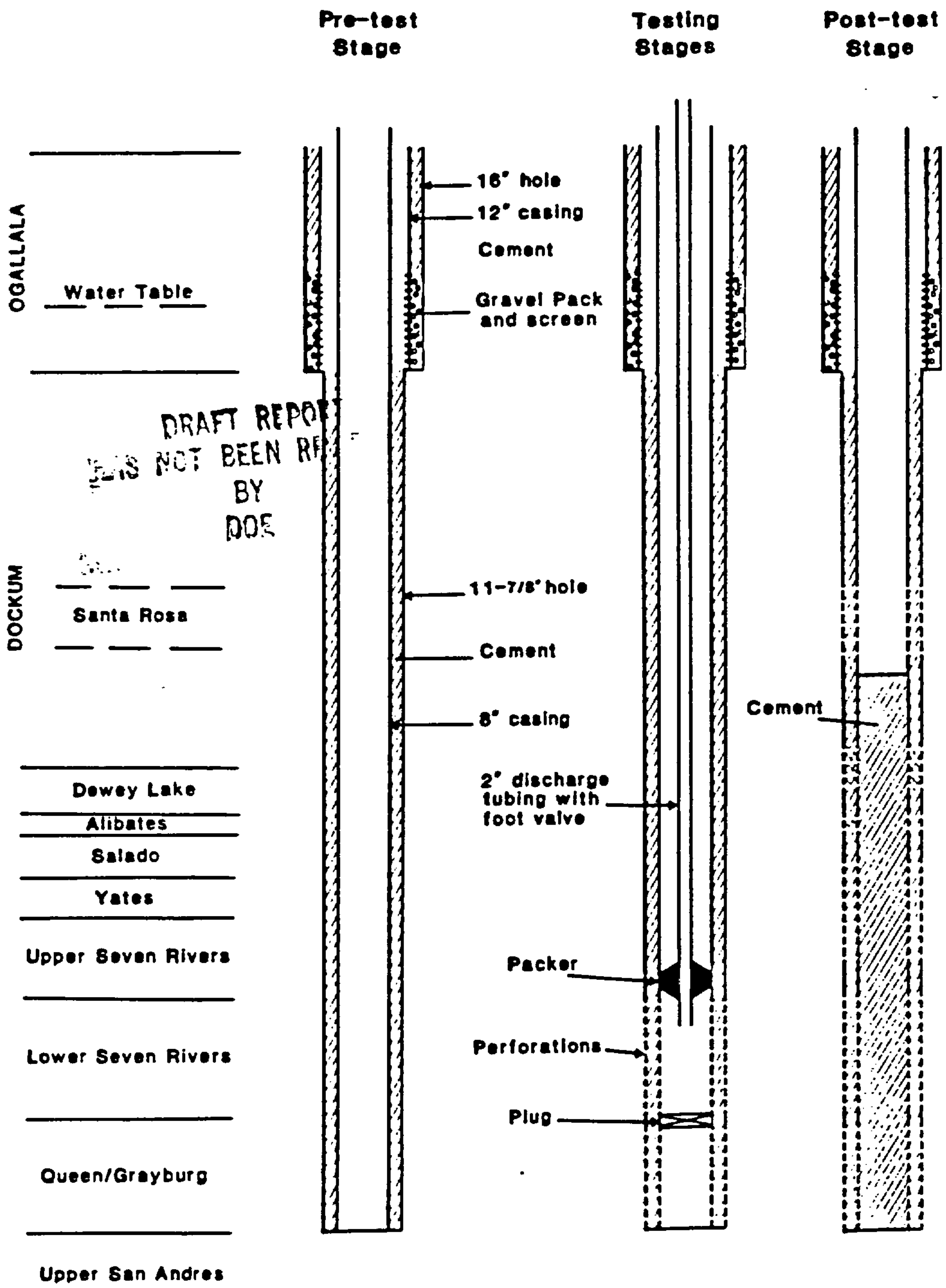
Figure 4-4 shows the proposed schematic design for the observation wells designated as OW1 and OW2 at SHN No. 1, SHN No. 2 and SHN No. 3 and the third observation well (OW3) at SHN No. 3 After drilling through the Ogallala and installing surface casing, these wells should be also drilled to the top of the Upper San Andres and 6-in casing should be cemented from total depth to the surface. As testing proceeds, the wells would be perforated across formations tested by constant-rate pumping tests. After all tests have been conducted, the wells should be completed as dual monitoring wells, each open to two different formations, as shown on Figure 4-5.

Figure 4-6 shows the proposed schematic design of the pumping wells designated as PW2 at SHN No. 4, SHN No. 5 and SHN No. 6. These wells are to be first completed as Ogallala wells for the testing of this aquifer. After the Ogallala test, the wells should be drilled to total depth and 8-in casing



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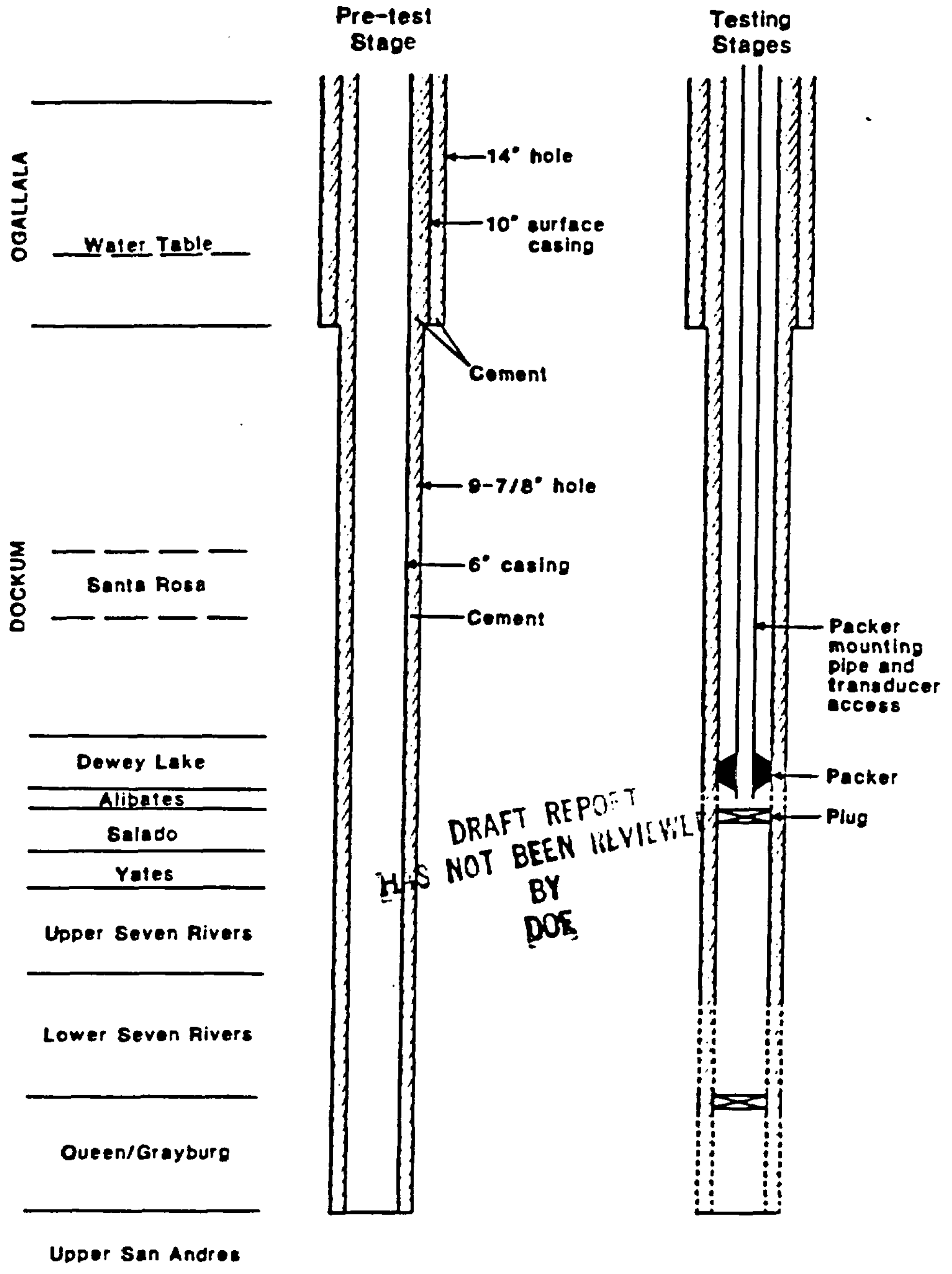
Shallow Hydro Nests
Schematic Design of
Pumping Well PW1

Figure 4-3



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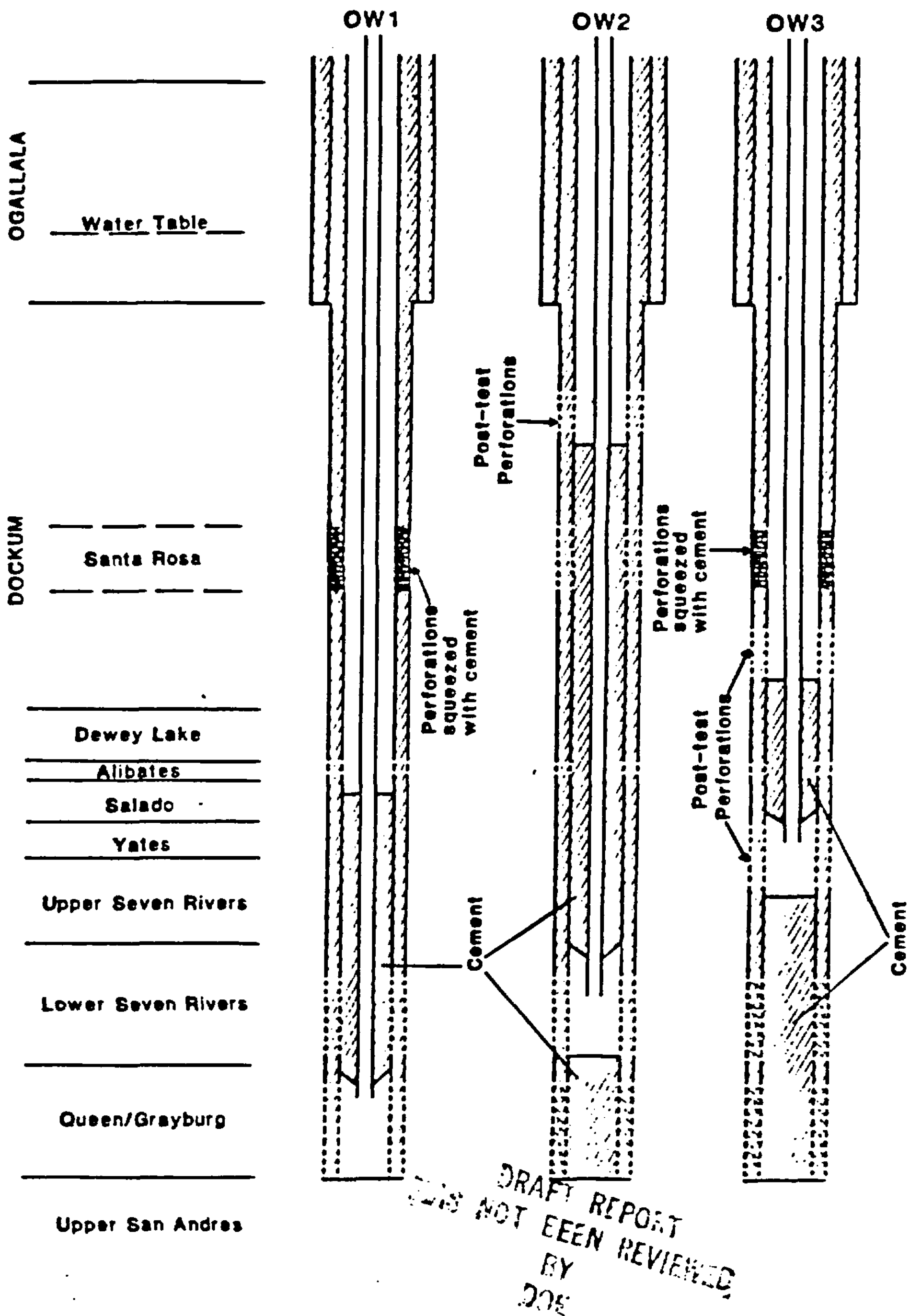
Shallow Hydro Nests
Schematic Design of Observation Wells OW1, OW2 and OW3

Figure 4-4



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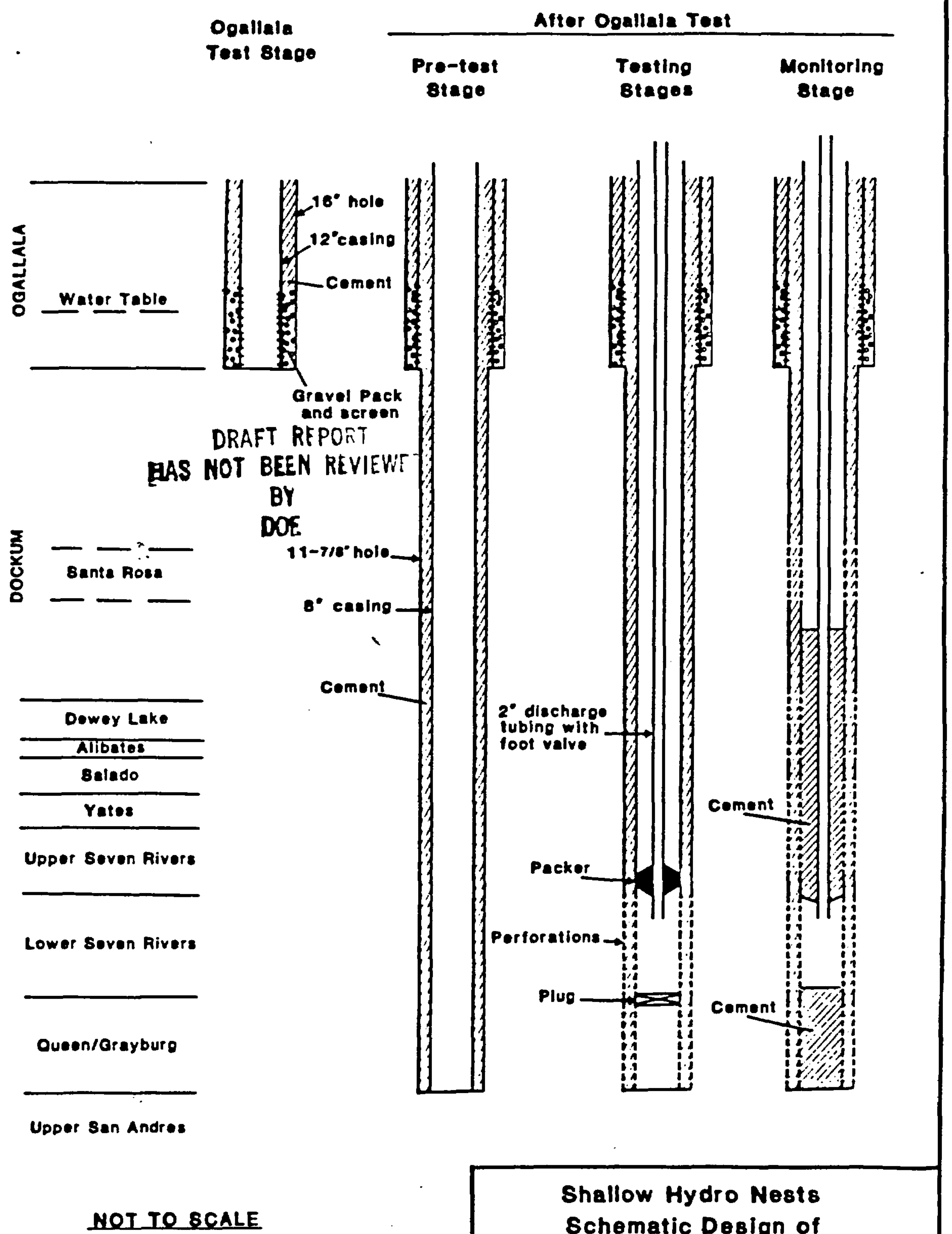
Shallow Hydro Nests Proposed Monitoring Stage for Observation Wells OW1, OW2 and OW3

Figure 4-5



Shallow Hydro Nests
Schematic Design of
Pumping Well PW2

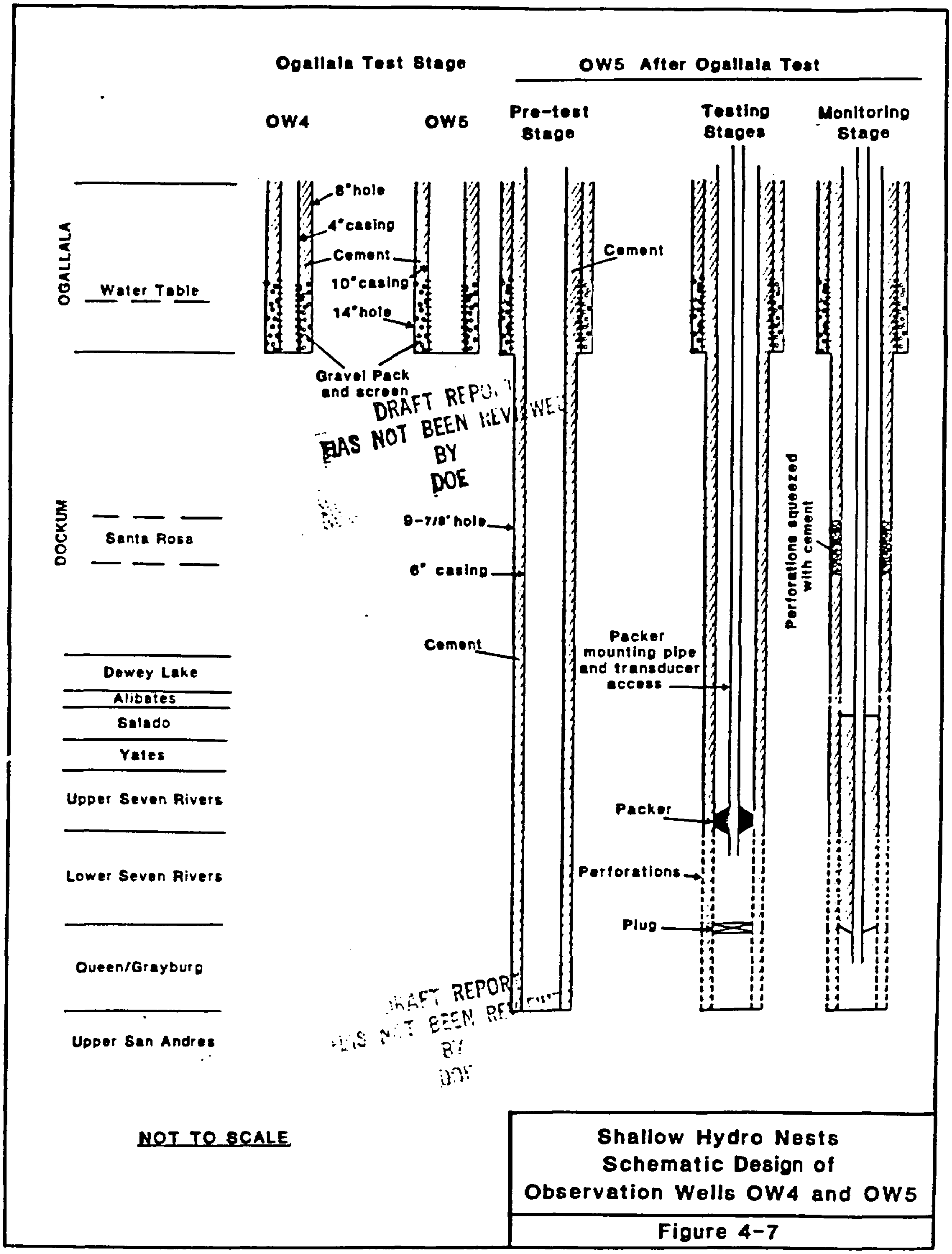
Figure 4-6

cemented to the surface. After the remaining tests have been conducted by perforating across the formations to be tested, the wells should be completed to monitor the Lower Seven Rivers Formation and the principal water-bearing zone of the Dockum, as shown on Figure 4-6.

Figure 4-7 shows the proposed schematic design of the observation wells designated as OW4 and OW5 at SHN No. 4, SHN No. 5 and SHN No. 6. Both wells at each nest location are to be first completed as Ogallala wells for the testing of this aquifer. After the Ogallala test, well OW4 is to remain as an Ogallala monitoring well. Well OW5 is to be drilled to the top of the San Andres and, after the tests, to be completed as a dual monitor for the Alibates and the Queen/Grayburg Formations.

After all the tests are completed, this proposed well design will result in monitoring wells at each shallow hydro nest location for the five more permeable zones or formations, namely, the Ogallala, the principal water-bearing zone of the Dockum, Alibates, Lower Seven Rivers and Queen/Grayburg. In addition, at nests SHN No. 1, SHN No. 2 and SHN No. 3, some of the intervening less permeable zones will also be accessible to monitoring.

Previous plans for the shallow hydro nests (SWEC, 1985a; DOE, 1986) have proposed a total of sixteen wells at the nest locations. The plan presented above proposes nineteen wells. However, only sixteen of these wells extend to the top of the Upper San Andres Formation. The remaining three extend to the top of the Dockum.



Shallow Hydro Nests Schematic Design of Observation Wells OW4 and OW5

Figure 4-7

4.1.3 Drilling and Testing Sequence

In this section, the drilling and testing sequence briefly discussed above is presented in step-by-step detail.

4.1.3.1 Hydro Nests SHN No. 1, SHN No. 2 and SHN No. 3

1. Drill the pumping well as a 16-in hole to the top of the Dockum. Install 12-in casing with gravel pack and screen across the entire saturated thickness of the Ogallala and cement the annulus above the gravel pack to the surface. Develop the well.

2. Drill 11 7/8-in hole through the 12-in casing to the top of the Upper San Andres. Install 8-in casing and cement the annulus from total depth to the top of the Dockum.

3. Drill observation wells OW1 and OW2, and OW3 at SHN No. 3, as 14-in holes to the top of the Dockum. Install 10-in casing and cement the annulus to the surface.

4. Drill 9 7/8-in hole through the 10-in casing to the top of Upper San Andres. Install 6-in casing and cement the annulus to the surface.

5. Install a barometric pressure recorder at the nest location and begin collecting data on barometric pressure changes. Continue this barometric data collection program until all testing activities at the nest location have been completed.

6. Perforate the pumping well across the Queen/Grayburg Formation and develop well, if feasible. Install a packer mounted on tubing with a foot-valve and shut-in the perforated interval. Observe pressure changes within the interval for about two days, or until either the pressure has stabilized, or a correlation with barometric pressure or a seasonal trend has been established.

7. Conduct a shut-in slug test in the interval by suddenly injecting into or removing from the interval a known volume of water. (Injection or removal of a volume equal to about 0.02 percent of the volume within the shut-in interval would be expected to produce a pressure change of about 100 psi.)

8. Collect pressure data from the interval for one day or until the pressure recovers to the pre-test level or trend, if this occurs sooner. If recovery after one day is less than 50 percent, continue data collection until 50 percent recovery occurs.

9. Make a field analysis of the data to estimate the transmissivity of the formation and evaluate whether the formation can sustain a discharge rate suitable for a constant-rate pumping test, or whether a standard slug test would be appropriate. If a pumping test is feasible, go to step 13. If neither a pumping test nor a standard slug test is feasible, go to step 15.

10. Open foot-valve on packer tubing and allow water level inside tubing to reach the pre-test water level indicated by the pre-test shut-in

pressure. If necessary, fill or evacuate tubing to accelerate recovery to pre-test water-level.

11. Conduct a standard slug test by suddenly inserting a displacement device below the water level in the tubing or by suddenly pumping or injecting a known volume of water.

12. Collect water-level recovery data for two days or until full recovery, if this occurs sooner. If recovery after one day is less than 50 percent, continue data collection until 50 percent recovery occurs. Go to step 15.

13. Perforate the observation wells in the same horizon as the pumping well and develop wells. Shut in the wells and collect pressure data for about three days or until trends and correlations have been established.

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14. Install pump (submersible or walking-beam type, depending on discharge rate) in the pumping well and shut in well until pressure returns to pre-pump-installation trends. Conduct a two-day constant-rate pumping test followed by an equal recovery period, under shut-in conditions. Collect pressure data throughout the pumping and recovery periods in the pumped well and in all the observation wells. Maintain field plots of data to assess adequacy of testing period and adjust length of testing period, if necessary.

15. Install a plug above the perforated interval in the pumped well, perforate well across the overlying formation (Lower Seven Rivers) and develop the perforated interval, if feasible. Shut in the

perforated interval and observe pressure changes within the interval for about two days, or until trends and correlations have been established.

16. Repeat steps 7 through 14.

17. Repeat steps 15 and 16 for the Upper Seven Rivers, Yates, Salado, Alibates and Dewey Lake Formations.

18. Install a plug in the pumping and observation wells above the perforated interval of the Dewey Lake and perforate the wells across the principal water-bearing zone of the Dockum. Develop the wells and conduct a step-drawdown test in the pumping well using 3 steps of 1-hour duration. Evaluate the step-test data to estimate the discharge rate for a constant-rate pumping test.

19. Install a water-level recording device in one of the wells and collect water-level data for about a week, or until trends or correlations with barometric pressure and other factors affecting water levels have been established. Make occasional water-level measurements in the other wells to determine whether they are subject to the same trends and correlations as the well with the recorder.

20. Conduct a two-day pumping test followed by a two-day recovery period. Collect water-level data from the pumped well and from all the observation wells. Maintain field plots of data throughout the test and adjust length of testing period, if necessary.

21. After all test data have been analyzed, and it has been established that there is no need for repeat tests, remove plugs between perforated zones and complete each well as a dual monitoring well by filling sections of the well with cement and/or opening new perforations or squeezing cement into existing perforations, as shown on Figures 4-3 and 4-5.

22. Initiate a systematic water-level data collection program for the monitoring wells.

It is estimated that, at each nest location, the testing program outlined above will have a duration of about three months after the pumping well and the observation wells have been drilled to total depth.

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Note that observation wells OW2 (Figure 4-5), at shallow hydro nests SHN No. 1, SHN No. 2 and SHN No. 3, are to be perforated in the upper part of the Dockum, between the Ogallala and the principal water-bearing zone of the Dockum, to monitor this interval. Similarly, well OW3 at SHN No. 3 is to be perforated in the lower part of the Dockum, between the principal water-bearing zone of the Dockum and Dewey Lake. Therefore, these observation wells could be used to test these intervals either as part of the overall testing program at shallow hydro nests, or at a later date. These intervals are estimated to have a low permeability (Papadopulos, 1986) and thus, the applicable testing procedures would be the standard or the shut-in slug test.

4.1.3.2 Hydro Nests SHN No. 4, SHN No. 5 and SHN No. 6

1. Drill the pumping well as a 16-in hole to the top of the Dockum. Install 12-in casing with gravel pack and screen across the entire

saturated thickness of the Ogallala and cement the annulus above the gravel pack to the surface. Develop the well.

2. Drill observation well OW4 as a 8-in hole and observation well OW5 as a 14-in hole to the top of the Dockum. Install 4-in casing and screen in OW4 and 10-in casing and screen in OW5, with the screens extending from the water table to the top of the Dockum. Complete the wells with gravel pack behind the screen and cement the annulus from above the gravel pack to the surface. Develop the wells.

3. Install a barometric pressure recorder at the nest location and begin collecting data on barometric pressure changes. Continue this barometric data collection program until all drilling and testing activites at the nest location have been completed.

4. Install pump in pumping well and conduct a step-drawdown test in this well using three steps of 2-hour druration. Evaluate the step-test data to estimate the discharge rate for the constant-rate pumping test of the Ogallala. Install a water-level recording device in one of the wells and begin to collect pre-test water-level data.

5. Continue to collect pre-test data for about two weeks or until water-level trends and correlations with climatic and other factors that might affect water levels have been established.

6. Conduct a six-day pumping test followed by a six-day recovery period. Collect water-level data from the pumped well and the two observation wells. Also collect data on factors that have been

determined to affect water levels in step 5.

7. During the test, maintain field plots of the data. Evaluate these plots at least daily to assess the adequacy of the pumping period; extend or reduce the pumping and recovery periods, if necessary.

8. Analyze the test data and establish whether the test is satisfactory. If not satisfactory, determine reasons and repeat the test, if necessary, after taking corrective actions.

9. Deepen the pumping well by drilling an 11 7/8-in hole through the 12-in casing to the top of the Upper San Andres Formation. Install 8-in casing and cement the annulus from total depth to land surface.

10. Deepen observation well OW5 by drilling 9 7/8 hole through the 10-in casing to the top of the Upper San Andres Formation. Install 6-in casing and cement annulus from total depth to land surface.

11. Proceed with the testing of the deeper formations following the procedures described in steps 6 through 20 of Section 4.1.3.1. Note that, at these hydro nest locations, the tests will involve the pumping well and only one observation well.

12. After all test data have been analyzed, and it has been established that there is no need for repeat tests, remove plugs between perforated zones and complete each well as a dual monitoring well as shown on Figures 4-6 and 4-7.

13. Initiate a systematic water-level data collection program for the monitoring wells.

It is estimated that, at each nest location, the testing program outlined above will have a duration of about four months, excluding the initial installation and subsequent deepening of the wells.

4.2 ADDITIONAL TESTS

The proposed hydrogeologic testing program would provide data on the hydraulic properties of the tested formations in the horizontal direction. The subsequent monitoring of water levels in the test wells converted to dual-completion monitoring wells would provide data on the configuration of the potentiometric surfaces of the formations.

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As stated earlier, if the potentiometric surfaces display features that reflect vertical leakage and the hydraulic properties in the horizontal direction are known, the hydraulic properties in the vertical direction could be determined, or at least an upper bound could be placed on these properties, by numerical modeling of the hydrogeology of the site and its vicinity.

However, in the event that the results of such numerical modeling are not satisfactory, or in the event that in-situ determination of vertical hydraulic properties becomes necessary, a long-term pumping test may have to be conducted at the site. The information to be obtained from the proposed hydrogeologic testing plan would facilitate the planning of such a long-term pumping test at a later time.

Therefore, to eliminate the need of drilling new test wells for such a long-term pumping test, if deemed necessary, it would be advisable that the wells are not converted to permanent dual-monitoring wells at one of the shallow hydro nest locations, preferably at SHN No. 3. At this location, the dual monitoring function of the wells could be temporarily accomplished by installing packers at appropriate depths within the well, at least until the issue on the need for a long-term pumping test is resolved.

5.0 DATA ANALYSIS PROCEDURES

The data collected from the conduct of hydrogeologic tests in the shallow hydro nest wells must be analyzed to determine the hydraulic parameters of the tested formations. Methods of analyzing hydrogeologic test data are based either on a comparison of the shape of the observed response to that of a theoretical response (type-curve methods), or on features common to both the observed and theoretical response, such as slope, intercept, etc. (straight-line methods).

Three different types of testing procedures have been proposed in the testing plan: 1) constant-rate pumping tests, 2) standard slug tests, and 3) shut-in slug tests. The methods of analyzing test data obtained from these three types of tests are discussed below and illustrated with examples of analyses of the expected responses during the tests.

5.1 CONSTANT-RATE PUMPING TESTS

As discussed earlier, the formations or zones that would be amenable to testing by constant-rate pumping tests are the Ogallala, the principal water-bearing zone of the Dockum, the Lower Seven Rivers and probably the Alibates and Queen/Grayburg.

The Ogallala is an unconfined aquifer and is expected to respond to pumping in a manner typical of unconfined aquifers (Boulton, 1954, 1963, 1970; Boulton and Pontin, 1971; Neuman, 1972, 1973, 1974). Methods of analyzing data from unconfined aquifers are discussed by Boulton (1963, 1970), Prickett (1965) and Neuman (1975). The application of Neuman's (1975) type-curve and straight-line methods to the analysis of the expected response of the Ogallala during tests in the exploratory shaft monitoring wells, was demonstrated in an earlier SSP&A report (Papadopulos, 1986). An example of the type-curve analysis of the expected test data from shallow hydro nest observation wells OW4 and OW5 (SNH No. 4, SHN No. 5, or SNH No. 6) is presented below.

Figure 5-1 shows a logarithmic plot of the drawdown adjusted for dewatering effects (Jacob, 1944; Neuman, 1975), against the ratio t/r^2, where t is time since pumping started and r is the radial distance to the observation wells. Data from both observation wells have been combined in this plot. The data are matched to Neuman's type-B curves, which are logarithmic plots of the dimensionless drawdown s_D against the dimensionless time t_y for different values of the parameter β. The dimensionless parameters s_D, t_y and β are defined as follows:

$$s_D = 4\pi Ts^*/Q \; ; \tag{5-1}$$

$$t_y = Tt/r^2S_y \; ; \tag{5-2}$$

$$\beta = r^2K_z/b^2K_h \; ; \tag{5-3}$$

where

T = transmissivity;

s^* = $s-(s^2/2b)$ = adjusted drawdown;

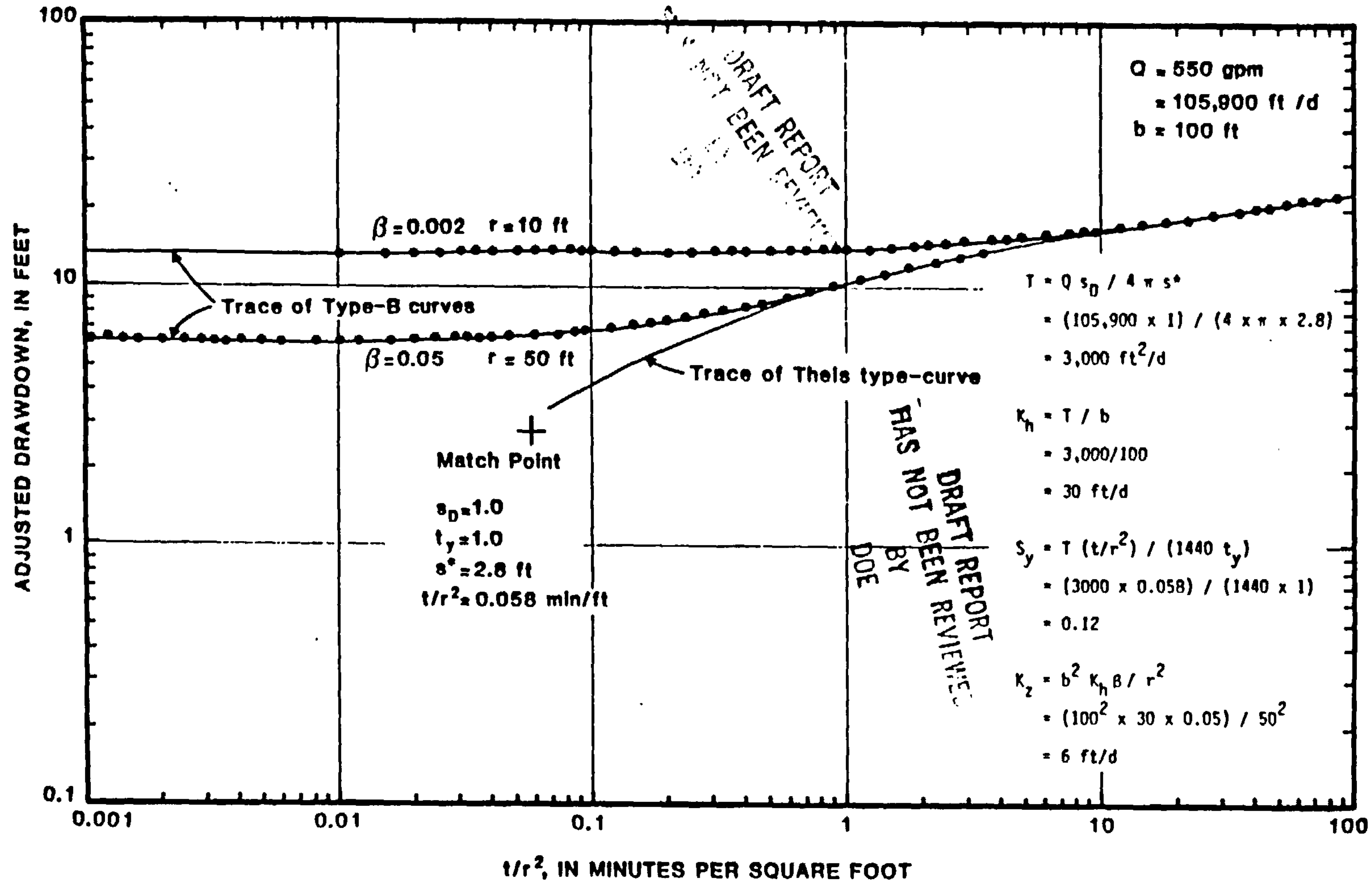
s = drawdown;

t = time since pumping started;

r = radial distance to observation well;

S_y = specific yield;

K_z = vertical hydraulic conductivity;



Ogallala Test
Type-Curve Analysis of Data from Observation Wells

Figure 5-1

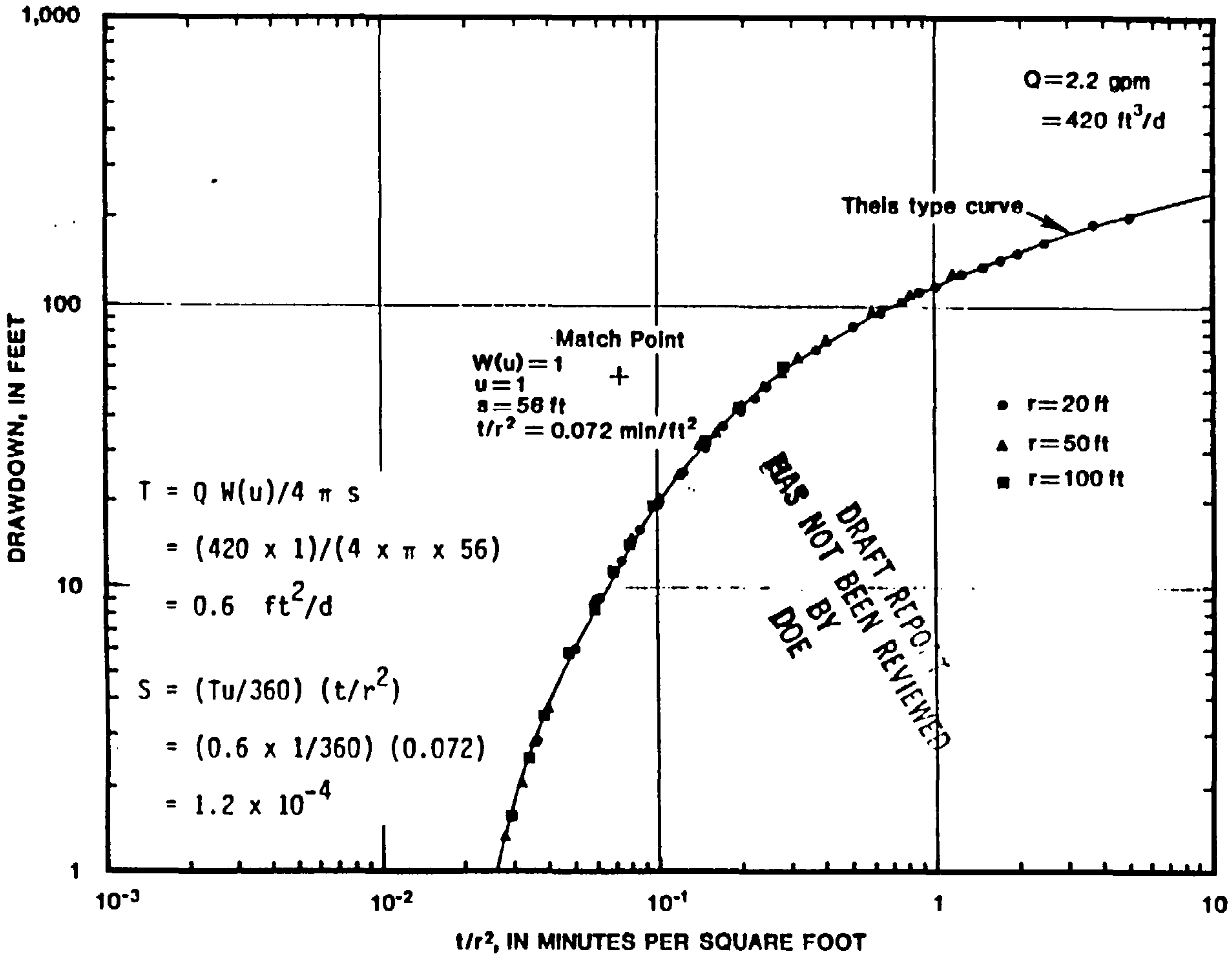
K_h = horizontal hydraulic conductivity; and

b = initial saturated thickness,

all expressed in consistent measurement units. Note that the data from each observation well fall on a type curve having a different value of the parameter β and that the ratio of the β values is the same as the ratio of the squares of the radial distances to the observation wells. This is consistent with the definition of the parameter β (equation 5-3) and it is a point to which attention should be paid in matching the data to the type curves. A match point common to both plots is selected as shown on Figure 5-1. The transmissivity and the specific yield are determined from the coordinates of the match point and the above definition of s_D and t_y. The vertical hydraulic conductivity is determined from either value of β and the corresponding radial distance. The calculations involved in this type-curve method of analysis and the results are shown on Figure 5-1.

The other formations or zones to be tested by constant-rate pumping tests are confined and are expected to respond to tests in accordance with Theis's (1935) model for infinite, isotropic, confined aquifers. The type-curve method (Theis, 1935) and, under certain conditions, the straight-line method (Cooper and Jacob, 1946) can be used to analyze data by this model. Examples of both methods are presented below.

Figure 5-2 illustrates the application of the type-curve method of analysis to the expected response of observation wells during the testing of the Lower Seven Rivers Formation at shallow hydro nest SHN No. 3. The type curve is a logarithmic plot of the dimensionless function W(u) - equivalent to dimensionless drawdown and often referred to as the "well function" - against



Lower Seven Rivers Test
Type–Curve Analysis
of Data from Observation Wells

Figure 5–2

the inverse of the dimensionless parameter u. The function W(u) and the parameter u are defined as follows:

$$W(u) = 4\pi Ts/Q \tag{5-4}$$

$$u = r^2 S/4Tt \tag{5-5}$$

where

S = storage coefficient;

and all other symbols are as previously defined. The data plot is also a logarithmic plot of the drawdown against the ratio t/r^2. Note that data from the three observation wells OW1, OW2 and OW3 have been combined and that data from each well fall on a different but overlapping segment of the type curve. As shown on the figure, a match point is selected and the transmissivity and storage coefficient are calculated from the coordinates of the match point and equations (5-4) and (5-5).

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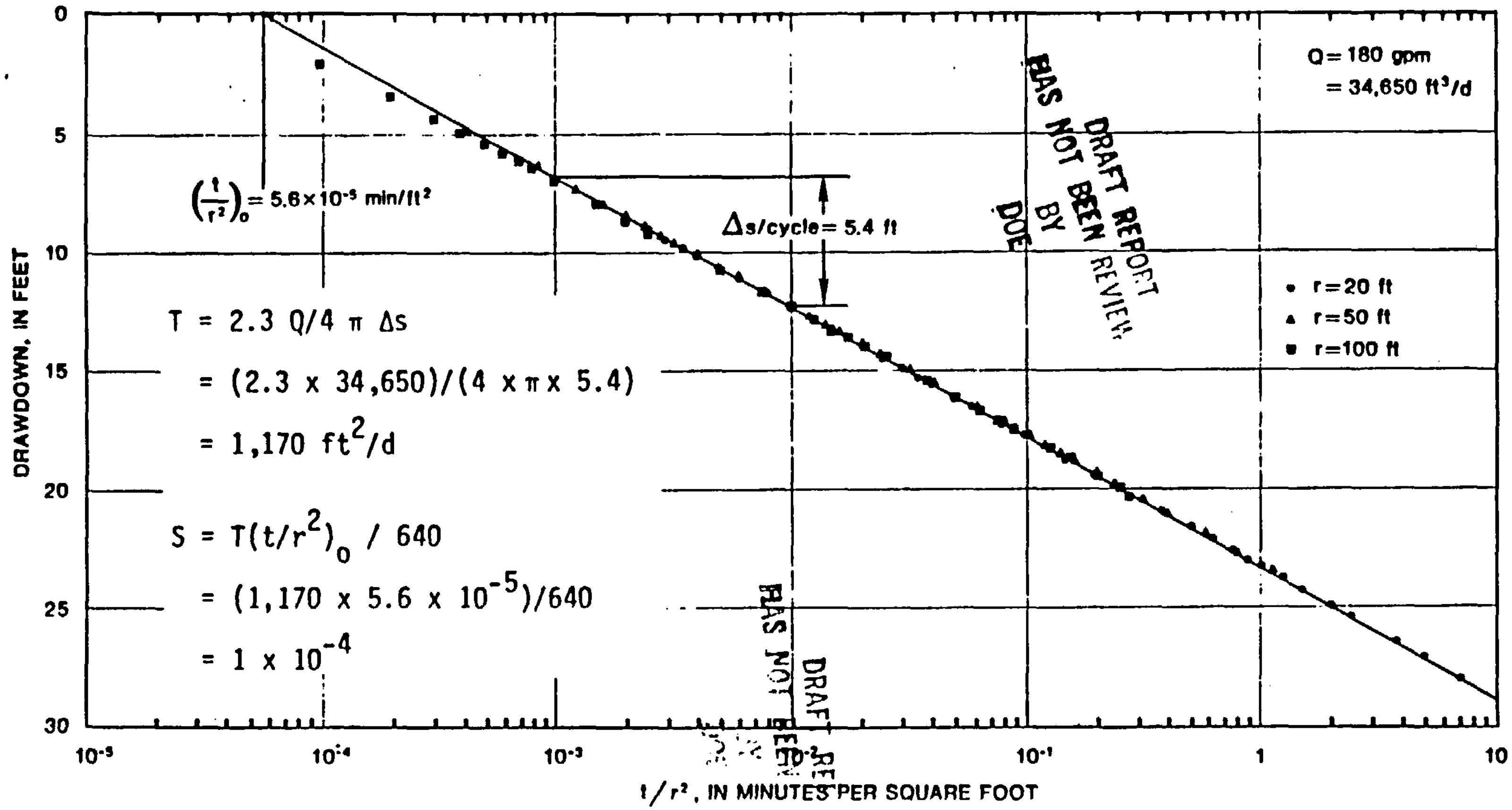
The straight-line method of analysis is applicable only to data that fall in the range of $u < 0.01$ (Cooper and Jacob, 1946) or $t > r^2S/0.04T$. Most of the formations to be tested at shallow hydro nests are expected to have a low transmissivity. For these low-transmissivity formations, the above criterion would not be expected to be met within the proposed two-day pumping period, except at the pumped well. Therefore, analyses of observation well data obtained during the testing of these formations would be limited to the type-curve method. However, observation well data from the tests of the water-bearing zone of the Dockum and of the Ogallala, which are estimated to have high transmissivities, would be expected to meet this criterion and be amenable to analysis by straight-line methods.

Figure 5-3 shows the straight-line analysis of the expected response of observation wells during the testing of the principal water-bearing zone of the Dockum. The figure is a semilogarithmic plot of the drawdown against the ratio t/r^2. Again, data from three observation wells have been combined on this plot. A straight line is drawn through the data points and, as shown on Figure 5-3, the transmissivity is determined from the slope of the line - the change in drawdown Δs per log-cycle of t/r^2 - and the storage coefficient from the intercept of the line $(t/r^2)_o$ - the value of t/r^2 at the point the line intercepts the zero drawdown axis - (Cooper and Jacob, 1946).

In the above examples the methods of analysis were applied to data from observation wells. The methods are equally applicable to data from the pumped well, if there are no well losses or skin effects. Well losses refer to head losses that occur due to turbulent flow as water enters and moves up the well. At the discharge rates dictated by the transmissivity of the formations, turbulent flow would not be expected to occur and well losses would be negligible. Skin effects refer to an increase or reduction in the drawdown of the pumped well due to a reduction or increase in the transmissivity of the formation in the immediate vicinity of the well caused by the drilling process, or by well development. Their presence affects the shape of logarithmic plots of the pumped-well drawdown against time. Therefore, when skin effects are present, type-curve methods of analysis would lead to erroneous results. In semilogarithmic plots of the drawdown against time, skin effects would cause a shift in the position of the data points. The slope of a line drawn through the data would not be significantly affected, but the intercept of the line with the zero drawdown axis would be different



Dockum Test
Straight-Line Analysis of
Data from Observation Wells

Figure 5-3

than that which would occur without skin effects. Thus, while good estimates of transmissivity can be obtained by the straight-line method, estimates of the storage coefficient would be erroneous.

The transmissivity can be also determined from pumped-well data obtained during the recovery period. The method of analysis consists of plotting the residual drawdown s', that is the drawdown during the recovery period, against the logarithm of the ratio t/t', where t is time since pumping started and t' is time since pumping stopped. Late recovery data, that is the data for values of t/t' near one, would fall on a straight line and the transmissivity can be determined from the slope of this line. It should be noted, however, that two conditions must be met before this method is applicable. First, it should have been established from the pumping cycle that the aquifer response conforms with the Theis response curve and, second, the time t' should satisfy the criterion presented earlier in discussing the applicability of the straight-line method of analysis.

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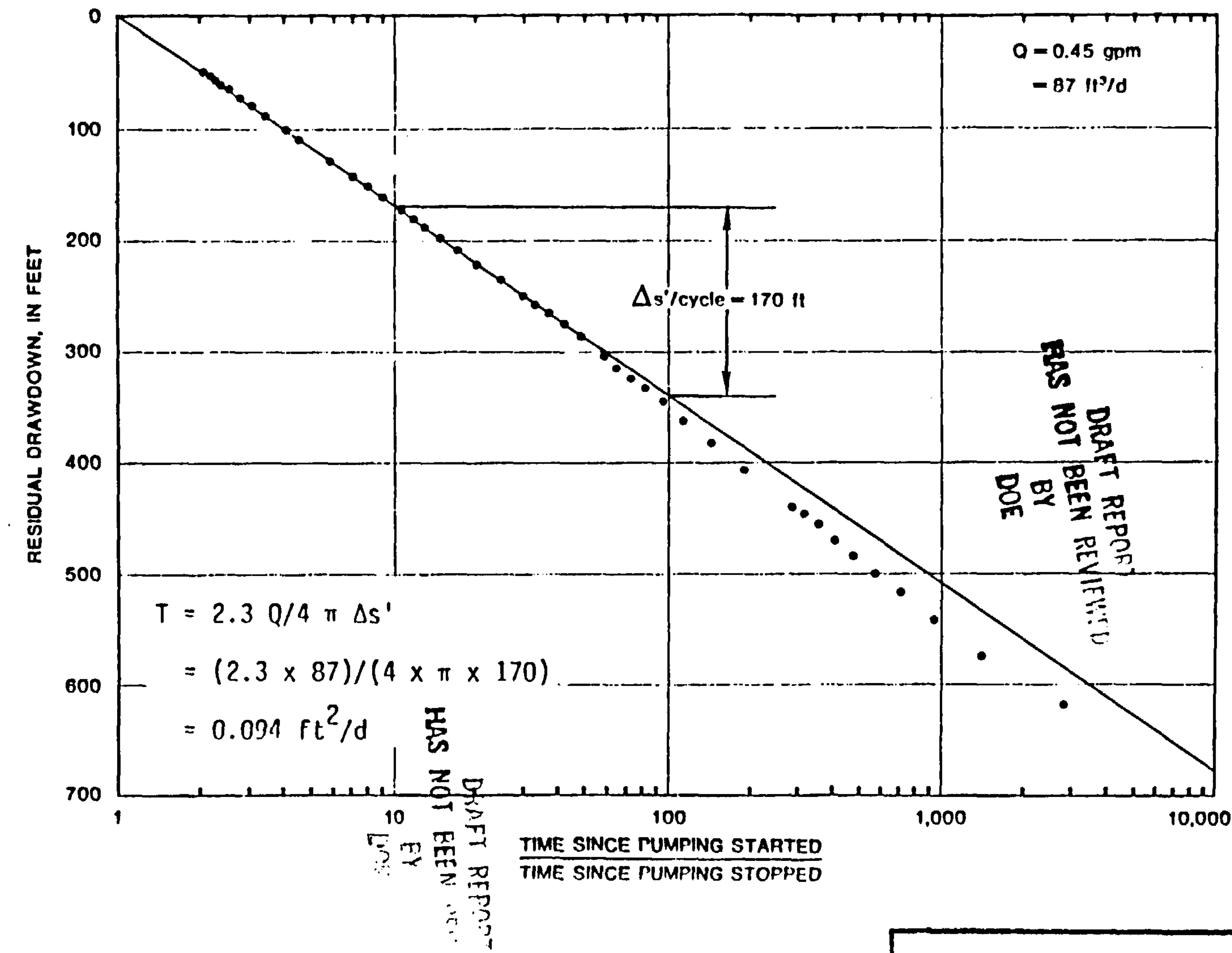
Figure 5-4 shows the analysis of the expected response in the pumped well during the recovery period following the constant-rate testing of the Queen/Grayburg Formation. Although the time criterion for the applicability of the straight-line method is satisfied within one minute after the end of the pumping period, note that early recovery data, that is data for large values of t/t', do not fall on the straight line drawn through the late recovery data. This is due to compressive borehole storage effects.

Recovery data can also be used to extend the pumping cycle data from the pumped well or from an observation well, beyond the end of the pumping period. This could be particularly useful if, after the end of the test, it is



Queen/Grayburg Test
Analysis of Recovery Data
from Pumped Well

Figure 5-4

discovered that the pumping period was not sufficiently long to permit a complete analysis. The method of extending the pumping cycle data through use of recovery data is discussed in detail in an earlier SSP&A report (Papadopulos, 1986).

5.2 STANDARD SLUG TESTS

The analysis of data from standard slug tests is discussed by Cooper and Jacob (1967) and Papadopulos and others (1973). The method of analysis is a type-curve method involving a family of type curves. The ratio of the residual water-level change to the initial water-level change caused by the introduction or the removal of the slug is plotted against the logarithm of time since the beginning of the test. The type curves are similar plots of the dimensionless slug test function $F(\alpha,\beta)$ against the logarithm of the dimensionless time parameter β for different values of the parameter α. The function $F(\alpha,\beta)$ is defined by an infinite integral for which tabular values are available (Cooper and others, 1967; Papadopulos and others, 1973; Bredehoeft and Papadopulos, 1980). The parameters α and β are defined as follows:

$$\alpha = r_w^2 S/r_c^2 \tag{5-6}$$

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$$\beta = Tt/r_c^2 \tag{5-7}$$

where

r_w = effective radius of the test well;

r_c = radius of casing or tubing in the interval of water-level change;

and all other symbols are as previously defined.

The data plot is superimposed on the type curves and, with the arithmetic axes coincident, it is translated horizontally to a position where the data best fit one of the type curves. A match point is selected and the transmissivity is determined from the coordinates of the match point and the definition of β given by equation (5-7). The storage coefficient is estimated from the value of α for the type curve to which the data were matched and the definition (5-6) of α. Figure 5-5 illustrates the application of the method to the analysis of expected data from the testing of the Alibates Formation by the standard slug test (low transmissivity, high storage coefficient case).

5.3 SHUT-IN SLUG TEST

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The analysis of data from shut-in slug tests is identical to that for data from standard slug tests. It involves the same dimensionless function and, therefore, the same family of type curves. However, the dimensionless parameters α and β have different definitions. To differentiate from the standard slug test, the dimensionless function can be denoted as $F(\alpha_S, \beta_S)$ with the parameters α_S and β_S defined as follows:

$$\alpha_s = \pi r_w^2 S/\gamma_w c_w V_w ; \qquad (5\text{-}8)$$

$$\beta_s = \pi Tt/\gamma_w c_w V_w ; \qquad (5\text{-}9)$$

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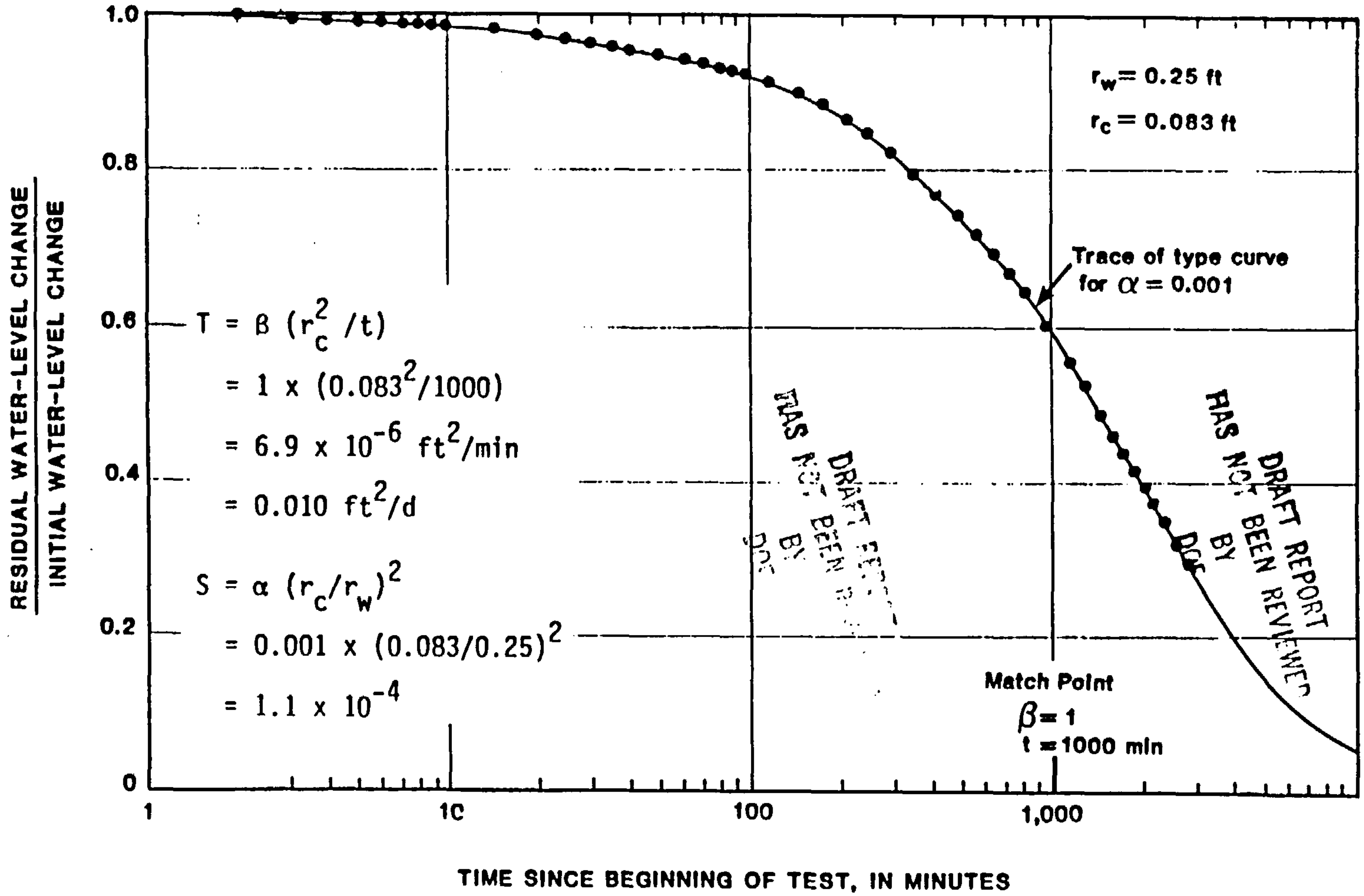
where

γ_w = unit weight of water within the shut-in interval;

c_w = aggregate compressibility of the shut-in interval;

V_w = volume of water within the shut-in interval;

and all other symbols are as peviously defined. The aggregate compressibility



Alibates Test
Analysis of Data from
Standard Slug Test

Figure 5-5

c_w of the shut-in interval should be determined in the field (Neuzil, 1982). If an initial pressure change Δp_o is caused by the sudden introduction into or removal from the interval of a volume ΔV_o, then c_w can be determined from the following equation (Neuzil, 1982):

$$c_w = (\Delta V_o / V_w) / \Delta p_o \tag{5-10}$$

If the length of the shut-in interval is equal to the thickness of the tested formation, then

$$V_w = \pi r_c^2 b \tag{5-11}$$

Substitution of (5-11) into (5-8) and (5-9) changes the definitions of α_S and β_S to

$$\alpha_s = r_w^2 S_s / \gamma_w c_w r_c^2 \tag{5-12}$$

$$\beta_s = Kt / \gamma_w c_w r_c^2 \tag{5-13}$$

where

S_s = specific storage;

K = hydraulic conductivity;

and all other parameters are as previously defined.

Plots of the ratio of the residual head change to the initial head change (or the ratio of the residual pressure change to the initial pressure change) against time are matched to the type curves. The transmissivity and storage coefficient are determined from match-point coordinates, the value of α_S for the matched type curve and the definitions of α_S and β_S given by equations (5-8) and (5-9) or (5-12)and (5-13).

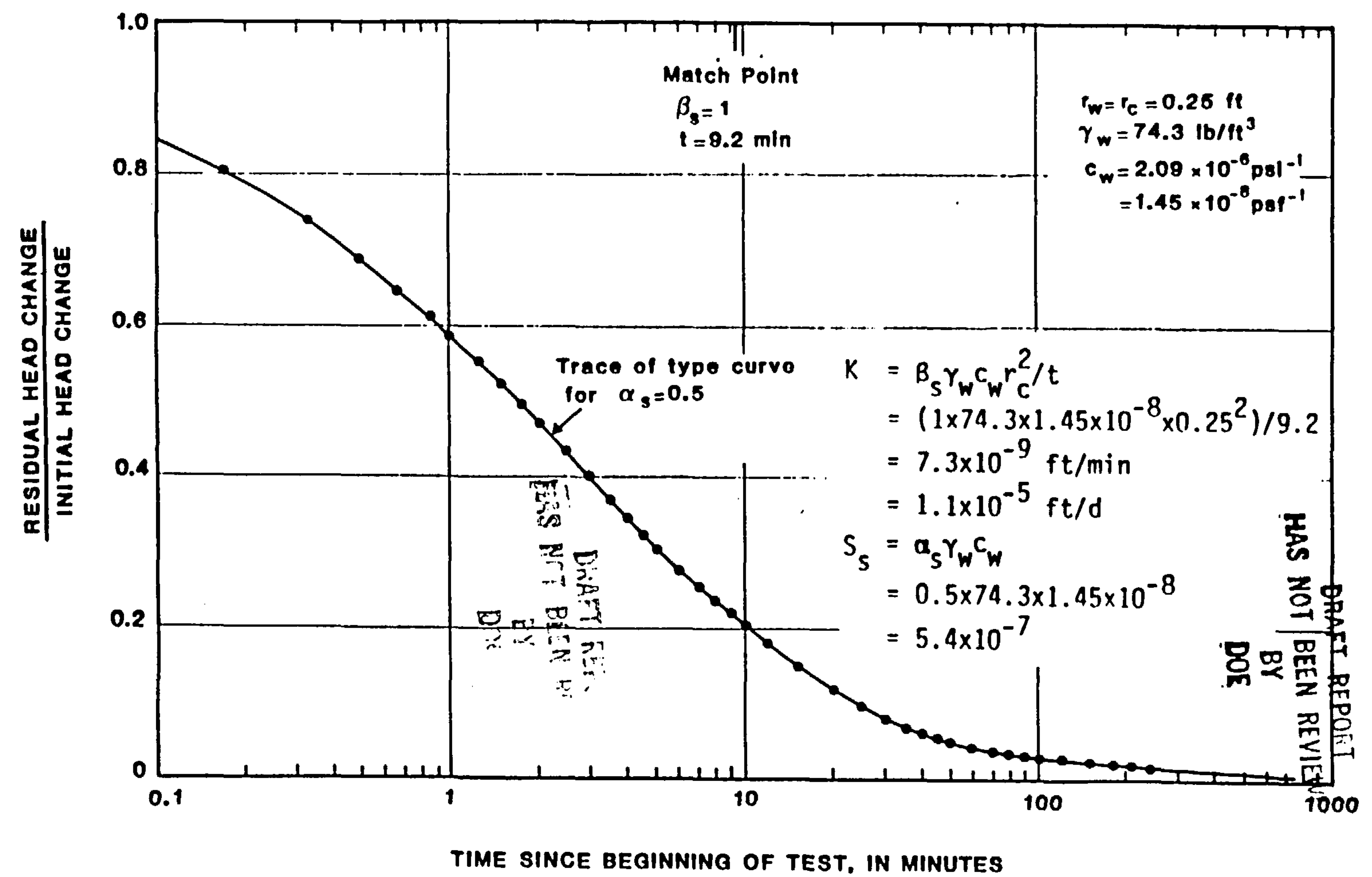
Figure 5-6 shows the analysis of the expected response during a shut-in test of the Yates Formation. The expected response was generated by assuming that the aggregate compressibility was equal to the compressibility of the water in the shut-in interval and, therefore, this value is used in the analysis. Also, the length of the shut-in interval was assumed to be equal to the formation thickness and the effective well radius equal to the casing radius. Therefore, equations (5-12) and (5-13) are used in the analysis.

5.4 OTHER POTENTIAL RESPONSES

The above discussion of data analysis procedures assumes that, with the exception of the Ogallala, the formations or zones to be pump-tested will respond in accordance with Theis' (1935) model. However, other potential responses are possible. These may include the effects of leakage from adjacent formations, the presence of nearby hydrologic boundaries, or the presence of secondary permeability due to fractures and/or joints.

Calculations based on the estimated vertical hydraulic conductivities of the formations (see Table 2-1) indicate that leakage would not have a significant effect on the test response during the two-day testing period proposed for most of the tests. However, if leakage becomes a factor during the tests, the test data could be analyzed using the methods discussed by Hantush (1956, 1960).

The presence of hydrologic boundaries such as nearby faults or abrupt changes in transmissivity would also cause the test responses to deviate from the Theis (1935) model. Under such conditions, the analysis of test data may require the use of the method of images (Ferris and others, 1962).



Yates Test
Analysis of Data from
Shut-in Slug Test

Figure 5-6

Several methods of analyzing test data from fractured formations have been developed. Some of these methods consider ground-water flow in vertical fractures (Scott, 1963; Russel and Truitt, 1964; Huskey and Crawford, 1967). Some consider flow in a single fracture of given extent and orientation (Gringarten and Witherspoon, 1972; Gringarten and Ramey, 1974; Gringarten and others, 1974, 1975). Some (Streltsova, 1976; Boulton and Streltsova, 1977) are based on the double-porosity concept of Barenblatt and others (1960), which considers the fractured formation to consist of matrix blocks having primary porosity separated by many randomly distributed fractures. And some consider fractured formations in which a consistent orientation of fractures has resulted in anisotropic conditions (Papadopulos, 1965; Hantush, 1966).

Two examples are presented below to illustrate the potential response of observation wells if the formations to be tested are fractured and the methods of analysis that could be applicable under these conditions. The Alibates Formation is used for both examples. In the first example, the formation is assumed to respond as a double-porosity medium and, in the second, as an anisotropic medium.

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5.4.1 <u>Double-Porosity Response</u>

Streltsova-Adams (1978) presents an excellent review of analytical models applicable to fractured formations responding as double-porosity media. One of these models idealizes the double-porosity medium as consisting of a series of horizontal fractures separated by matrix blocks of uniform thickness. The potential response and method of analysis presented in this example are based on this model.

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To generate the potential response of the Alibates Formation based on this model, the matrix blocks were assumed to be six feet thick and to have the design values of the transmissivity and storage coefficient (see Table 2-1). The fractures were assumed to have a transmissivity one hundred times larger than that of the matrix blocks and a storage coefficient equal to one-tenth of that of the matrix blocks. Based on the available drawdown (see Table 3-1) and the above hydraulic parameters, the discharge rate that can be sustained for a two-day pumping test was calculated to be 14.6 gpm (2,810 ft^3/d). Figure 5-7 shows a logarithmic plot of the drawdown that would be expected to occur in the three observation wells OW1, OW2 and OW3, against the ratio t/r^2.

The method of analysis involves a family of type curves consisting of logarithmic plots of the dimensionless drawdown function $W(t_D,r/B,n)$ against the dimensionless time parameter t_D for different values of the dimensionless parameters r/B and n. The function $W(t_D,r/B,n)$ and the parameters t_D, B and n are defined as follows:

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$$W(t_D,r/B,n) = 4\pi T_f\, s/Q \tag{5-14}$$

$$t_D = 4T_f t/r^2 S_f \tag{5-15}$$

$$B = [T_f/(K_m/H)]^{1/2} \tag{5-16}$$

$$n = (S_m/S_f) + 1 \tag{5-17}$$

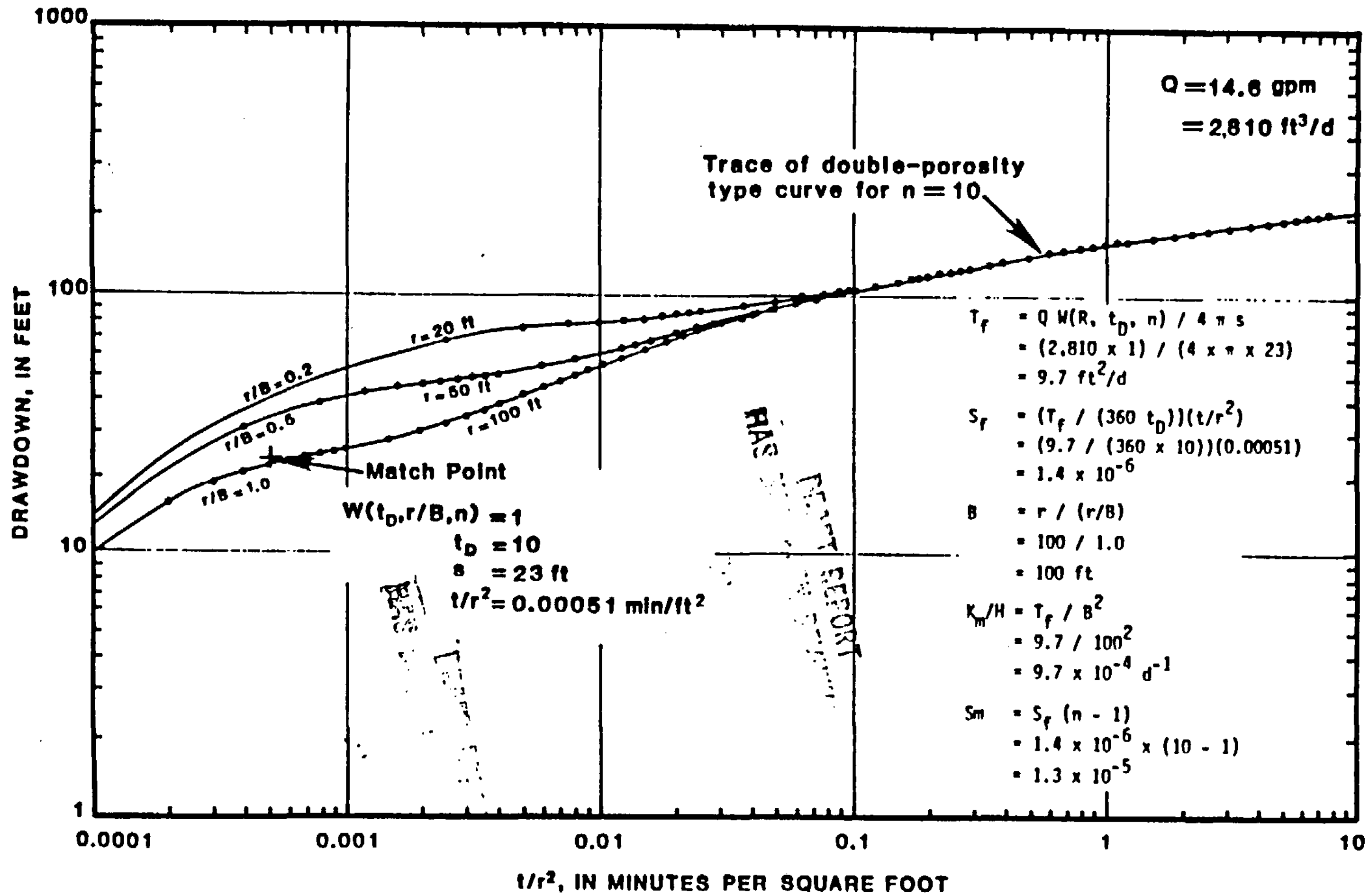
where

T_f = transmissivity of fractures;

S_f = storage coefficient of fractures;

K_m = hydraulic conductivity of matrix blocks;

S_m = storage coefficient of matrix blocks;



Alibates Test
Analysis of Double-Porosity Response in Observation Wells

Figure 5-7

H = one-half of the block thickness or of the spacing beween the fractures;

and all other symbols are as previously defined.

As shown on Figure 5-7, the data are matched to the type curves and the hydraulic parameters of the fractures and of the matrix blocks are determined from the match-point coordinates, the values of r/B and n corresponding to the matched type curves and the above definitions of the dimensionless function and parameters. Note that, since the spacing between fractures normally would not be known, the analysis yields the ratio K_m/H rather than the hydraulic conductivity of the matrix blocks. This ratio is equivalent to the "leakance" in a leaky aquifer system and points out the similarity between the idealized double-porosity system and leaky systems. In fact, for large values of the parameter t_D, that is for large values of time, the type curves for all values of r/B collapse to a Theis curve controlled by the transmissivity of the fractures and a storage coefficient equal to the sum of the fracture and matrix block storage coefficients. This is similar to the behavior of leaky aquifers when the confining beds supplying the leakage are bounded by impermeable formations (Hantush, 1960).

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5.4.2 Anisotropic Response

As stated earlier, if the fractures in a formation have a consistent orientation such that the transmissivity has a maximum value in the direction of the fractures and a minimum value in the direction perpendicular to the fractures, the formation would behave as an anisotropic aquifer. In an anisotropic aquifer the transmissivity is a tensor. The maximum and minimum values of the transmissivity are referred to as the principal components of transmissivity and the directions along which they occur as the principal axes (Scheidegger, 1954).

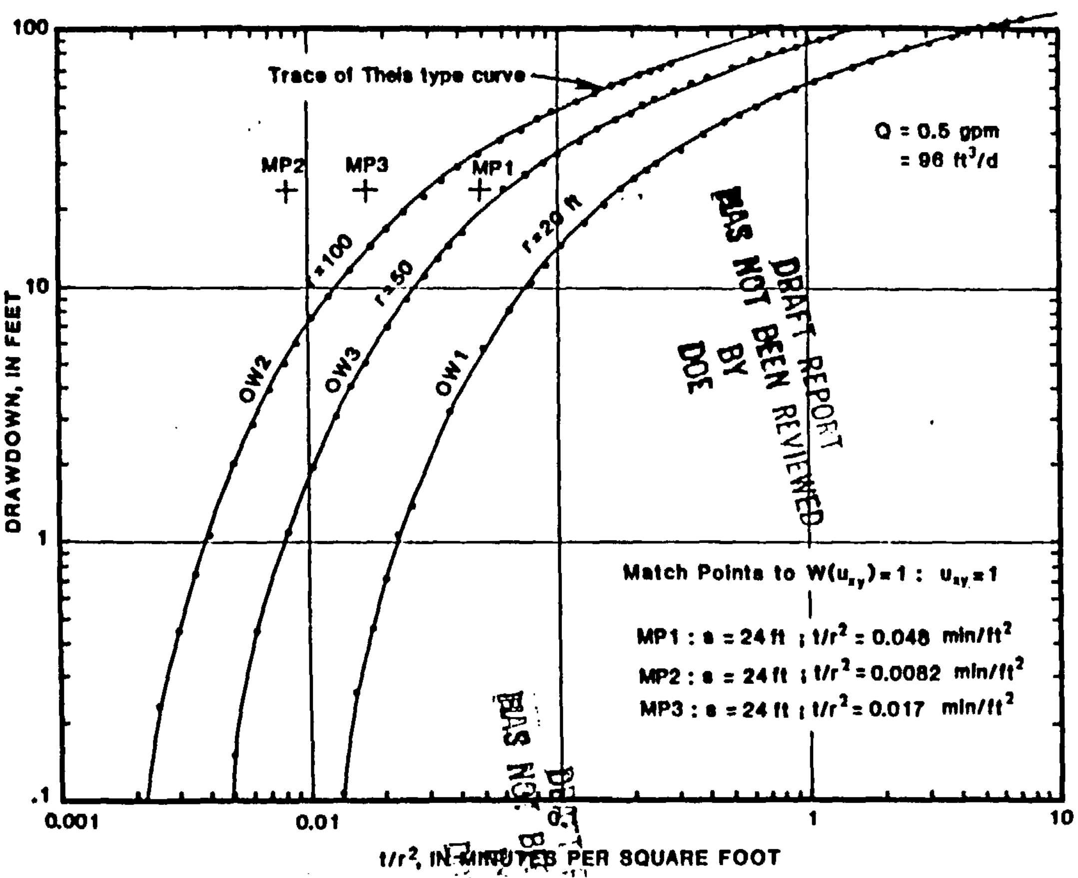
To generate the potential response of the Alibates Formation under such conditions, well OW2 (see Figure 4-2) was assumed to be to the east of the pumped well and the orientation of the fractures assumed to be E15°S. Along this direction the transmissivity was assumed to be equal to ten times the design value of transmissivity of the Alibates (see Table 2-1). Perpendicular to this direction the transmissivity was assumed to be equal to the design value. The sustainable discharge rate for a two-day pumping test was calculated to be 0.5 gpm (96 ft^3/d).

Figure 5-8 shows a logarithmic plot of the expected drawdown in the three observation wells OW1, OW2 and OW3 against the ratio t/r^2. Note that, under anisotropic conditions, the data from each observation well plot as separate curves, each identical to the Theis (1935) type curve.

The methods of analysis for anisotropic aquifers presented by Papadopulos (1965) and Hantush (1966) are essentially identical, except that Papadopulos bases the analysis on cartesian coordinates and Hantush on polar coordinates. A type curve approach that combines features of both methods will be used in this example.

The type curve is a logarithmic plot of the of the dimensionless drawdown function $W(u_{xy})$ against the dimensionless parameter u_{xy}. The function $W(u_{xy})$ and the parameter u_{xy} are defined as

$$W(u_{xy}) = 4\pi T_e \, s/Q \qquad (5\text{-}18)$$



Analysis :

OW1 : $x = 10$ ft $y = 17.3$ ft
OW2 : $x = 100$ ft $y = 0$
OW3 : $x = 35.4$ ft $y = 35.4$ ft

$$T_e = Q\,W(u_{xy}) / 4\pi s = (96 \times 1) / (4 \times \pi \times 24) = 0.32\ ft^2/d$$

$$T_e^2 = 0.10\ ft^4/d^2$$

$$S(T_{xx}y^2 + T_{yy}x^2 + 2T_{xy}xy) = u_{xy}(r^2(t/r^2)T_e^2) / 360$$

OW1 : $S(17.3^2T_{xx} + 10^2T_{yy} - 2(10)(17.3)T_{xy}) = (1)(20)^2(0.048)(0.10) / 360 = 5.33 \times 10^{-3}$

OW2 : $S(100^2T_{yy}) = (1)(100)^2(0.0082)(0.10) / 360 = 2.28 \times 10^{-2}$

OW3 : $S(35.4^2T_{xx} + 35.4^2T_{yy} - 2(35.4)(35.4)T_{xy}) = (1)(50)^2(0.017)(0.10) / 360 = 1.18 \times 10^{-2}$

Solving the three equations simultaneously:

$ST_{xx} = 1.34 \times 10^{-5}\ ft^2/d$
$ST_{yy} = 2.28 \times 10^{-6}\ ft^2/d$
$ST_{xy} = -3.12 \times 10^{-6}\ ft^2/d$

$$S^2 = ((ST_{xx})(ST_{yy}) - (ST_{xy})^2) / T_e^2 = ((1.34 \times 10^{-5})(2.28 \times 10^{-6}) - (-3.12 \times 10^{-6})^2) / 0.10 = 2.08 \times 10^{-10}$$

$S = 1.44 \times 10^{-5}$
$T_{xx} = 0.93\ ft^2/d$
$T_{yy} = 0.16\ ft^2/d$
$T_{xy} = -0.22\ ft^2/d$

$$T_{\xi\xi} = 0.5\,((T_{xx} + T_{yy}) + ((T_{xx} - T_{yy})^2 + 4\,T_{xy}^2)^{0.5}) = 0.5\,((0.93 + 0.16) + ((0.93 - 0.16)^2 + 4(-0.22)^2)^{0.5}) = 0.99\ ft^2/d$$

$$T_{\eta\eta} = 0.5\,((T_{xx} + T_{yy}) - ((T_{xx} - T_{yy})^2 + 4\,T_{xy}^2)^{0.5}) = 0.5\,((0.93 + 0.16) - ((0.93 - 0.16)^2 + 4(-0.22)^2)^{0.5}) = 0.11\ ft^2/d$$

$$\theta = \tan^{-1}((T_{\xi\xi} - T_{xx}) / T_{xy}) = \tan^{-1}((0.99 - 0.93) / (-0.22)) = \tan^{-1}(-0.27) = -15^{0}$$

Alibates Test
Analysis of Anisotropic Response in Observation Wells

Figure 5-8

$$u_{xy} = [S(T_{xx}y^2+T_{yy}x^2-2T_{xy}xy)] \; / \; [4\; T_e^2\; r^2(t/r^2)] \tag{5-19}$$

where T_e is the effective transmissivity defined as

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$$T_e = (T_{xx}T_{yy} - T_{xy}^2)^{\frac{1}{2}} = (T_{\xi\xi}T_{\eta\eta})^{\frac{1}{2}} \tag{5-20}$$

and in which

x,y = Cartesian coordinates of the observation well based on an arbitrary coordinate system with origin at the pumped well;

T_{xx},T_{yy},T_{xy} = Components of the transmissivity tensor in the x-y coordinate system;

$\xi\ ,\eta$ = Coordinate system along the principal axes of anisotropy;

$T_{\xi\xi},T_{\eta\eta}$ = Principal components of transmissivity;

and all other symbols are as previously defined. Note that the function $W(u_{xy})$ is identical to Theis' (1935) W(u) function. That is for equal values of u_{xy} and u, $W(u_{xy})$ and W(u) have equal values.

Since the principal axes of anisotropy may not be known a priori, the parameter u_{xy} is defined in terms of an arbitrarily chosen x-y coordinate system. After the components T_{xx}, T_{yy} and T_{xy} of the transmissivity in the x-y coordinate system have been determined through the analysis of test data, the maximum and minimum values of transmissivity and the principal axes of anisotropy are determined from the following relationships (Papadopulos, 1965):

$$T_{\xi\xi} = 0.5\ \{(T_{xx}+ T_{yy}) + [(T_{xx}- T_{yy})^2 + 4T_{xy}{}^2\ ]^{\frac{1}{2}}\} \tag{5-21}$$

$$T_{\eta\eta} = 0.5\ \{(T_{xx}+ T_{yy}) - [(T_{xx}- T_{yy})^2 + 4T_{xy}{}^2\ ]^{\frac{1}{2}}\} \tag{5-22}$$

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$$\theta = \tan^{-1} [(T_{\xi\xi} - T_{xx})/T_{xy}] \quad (5\text{-}23)$$

where θ is the angle between the arbitrary x-axis and the principal ξ-axis.

When the direction of the principal axes of anisotropy are not known, a complete analysis requires data from at least three observation wells. Data from two wells is sufficient if the directions of the principal axes are known. As shown on Figure 5-8, the data from each observation well are matched to the type curve and a match point is selected. The effective transmissivity is determined from the drawdown and $W(u_{xy})$ values at the match points using equation (5-18). The effective transmissivity determined from each match point should be the same. Therefore, in matching the data, attention must be paid to keeping the match points along the same horizontal line.

An arbitrary coordinate system is chosen and the x-y coordinates of each observation well are defined. In this example the x-axis was chosen to coincide with the line joining the pumped well to observation well OW2 (see Figure 4-2). Equation (5-19) is written for each well using the x-y coordinates of the well and the u_{xy} and t/r^2 values at the match point corresponding to data from that well. The process results in three equations. These three equations and the definition of the effective transmissivity (equation 5-20) provide the four equations necessary for determining the components T_{xx}, T_{yy} and T_{xy} of the transmissivity tensor and the storage coefficient. The principal components of the transmissivity and the directions of the principal axes are then determined from equations (5-21), (5-22) and (5-23). The calculations involved in this analysis are presented on Figure 5-8.

5.5 NUMERICAL METHODS

All of the analysis procedures discussed above rely on available analytical models for analyzing test data. Analytical models have inherent assumptions regarding the hydrogeologic setting and the nature of the hydraulic parameters controlling the test response. If field conditions differ significantly from these assumptions, the data may not be amenable to analysis by available analytical models and numerical aquifer simulation models may have to be considered. Numerical aquifer models provide the flexibility of simulating complex aquifer boundaries, nonhomogeneities in the hydraulic parameters of the aquifer and many other hydrogeologic conditions which cannot be considered by analytical models. Thus, they provide a powerful tool for the analysis of test data that are not amenable to analysis by analytical models.

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6.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The Deaf Smith County, Texas site is one of the three sites approved for characterization as a potential repository for high-level radioactive wastes. To characterize the hydraulic properties of shallow formations overlying the proposed repository horizon - the Lower San Andres Unit 4 salt -, shallow hydro nests will be installed at the site and hydrogeologic tests will be conducted. At each nest, test wells will extend to the top of the Upper San Andres Formation and will penetrate the Ogallala Formation, the Dockum Group and the Dewey Lake, Alibates, Salado, Yates, Upper Seven Rivers, Lower Seven Rivers and Queen/Grayburg Formations.

To develop a hydrogeologic testing plan for the shallow hydro nests, the response of each formation to potential testing procedures was evaluated. The evaluations were based on design values of the hydraulic parameters (DOE/SRP,1986) and an assumed range for these parameters. The results of these evaluations led to the following conclusions:

- The horizontal hydraulic properties of the Ogallala Formation, the principal water-bearing zone of the Dockum, the lower Seven Rivers Formation and possibly of the Alibates and Queen/Grayburg Formations can be characterized by constant-rate pumping tests.

- Constant-rate pumping tests for the Lower Seven Rivers, the Alibates and Queen/Grayburg must be conducted under shut-in conditions to minimize borehole storage effects.

- Standard slug tests may be required to characterize the Alibates and the Queen/Grayburg if their transmissivities are lower than the estimated design values.

- Shut-in slug tests will be required to characterize the Dewey Lake, Salado, Yates and Upper Seven Rivers Formations. Standard slug tests in these formations may be feasible if their transmissivities are higher than the estimated design values.

- Characterization of the vertical hydraulic properties of the less permeable formations would require tests of a very long duration in intervening relatively more permeable formations. Alternatively, if the horizontal hydraulic properties have been determined and the configuration of potentiometric surfaces is defined by an appropriate monitoring network, representative values of the vertical hydraulic properties could be determined by numerical modeling of the hydrogeology of the site and its vicinity.

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Based on these conclusions a hydrogeologic testing plan for the shallow hydro nests was developed. The plan recommends the following with respect to the number and location of the shallow hydro nests and the number and depth of wells at each nest location.

- Install six shallow hydro nests consisting of three inner nests located along the boundary of the repository surface facility and of three outer nests located along or near the site boundary.

- Construct a total of nineteen test wells at the nest locations, consisting of one pumping well and two observation wells at each nest location and of a third observation well at one of the inner nests near the exploratory shaft facility.

- Drill one observation well at each of the three outer nests to the bottom of the Ogallala Formation. Drill all other pumping and observation wells to the top of the Upper San Andres Formation.

The plan recommends that the Ogallala aquifer be tested only at the three outer nests and that all other water-bearing zones and formations be tested at all six nest locations. The following drilling and testing sequence is recommended:

- At the three outer nests, complete the pumping and observation wells in the Ogallala aquifer. Conduct a step-drawdown test to determine discharge rate and then a six-day pumping test followed by a six-day recovery period. Deepen the pumping well and one of the observation wells to the top of the Upper San Andres, install and cement casing. Leave the second observation well as an Ogallala monitor.

- At the three inner nests, complete the pumping well in the Ogallala. Then drill through the well to the top of the Upper San Andres, install casing and cement to the top of the Dockum leaving the annular space above the Dockum as an Ogallala monitor. Drill the observation wells to the top of the Upper San Andres, install and cement casing.

- Proceed with the testing from the bottom up by perforating and isolating each test interval. Except for the principal water-bearing zone of the Dockum, conduct a shut-in slug test at each test interval and obtain data for one day or until at least 50 percent recovery occurs.

- Evaluate shut-in slug test and, based on results, either move to the next test interval, or conduct a standard slug test, or conduct a constant-rate pumping test. Data collection from standard slug tests should be for two days or until at least 50 percent recovery occurs. Constant-rate pumping tests should consist of a two-day pumping period followed by an equal recovery period.

- At the principal water-bearing zone of the Dockum, conduct a step-drawdown test to determine discharge rate and then a two-day pumping test followed by an equal recovery period.

- After all testing has been completed, convert each well to a dual monitoring well and initiate a water-level data collection program.

The recommended testing plan is designed to provide data on the hydraulic properties of the formations and, at its completion, to provide a monitoring network for defining the configuration of potentiometric surfaces. It is estimated that the testing program at each nest location will have a duration of three to four months, excluding well installation.

The data from the Ogallala tests would most likely be amenable to analysis by Neuman's (1975) type-curve or straight-line methods for unconfined aquifers with delayed gravity response from the water table. Data from other constant-rate pumping tests would most likely be amenable to analysis by Theis' (1935) type-curve method and possibly also by Cooper and Jacob's (1946) straight-line method. Data from standard slug tests could ba analyzed by the type-curve method of Cooper and others (1967) and those from shut-in slug tests by the similar type-curve method of Bredehoeft and Papadopulos (1980). Other analysis methods applicable to leaky aquifers or to fractured aquifers, or numerical models may be required if the tested formations respond to testing in a manner different than that expected.

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