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January 31, 1984

WM Record File 106

WM Project 16
Docket No.
PDR ✓
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(Return to WM, 623-SS) 15

Mr. Jay Rhoderick
Division of Waste Management
U.S. Nuclear Regulatory Commission
Mail Stop SS 697
Washington, DC 20555

Dear Jay:

Enclosed is the promised borehole sealing opus. You will note that it deals primarily with salt areas and is pretty much applied to our studies in Texas. Time did not allow for an extensive survey of all sites--I will leave that up to you. Meanwhile, I have to start working on some publishable material.

Thanks for your help. Give my regards to Martha Pendleton.

Sincerely,

Bill Simpkins

William W. Simpkins
Research Associate

WWS:lml

Enclosure

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332 FI RELATIONSHIPS AMONG HYDROGEOLOGIC UNITS (5.6.2) STATUS OF BOREHOLE SEALING RESEARCH AND ITS APPLICATION TO THE PALO DURO BASIN

Introduction

Sites will soon (January, 1985) be chosen from locations for further characterization as nuclear waste repositories. A principal concern is the status of research in the borehole sealing program. Boreholes drilled for mineral (oil and gas) exploration, water resource development, or DOE site characterization work provide possible pathways for inter-aquifer communication and communication with the repository horizon. Boreholes thus increase the chance for radionuclide releases to the biosphere. At potential sites where salt is the host rock, salt dissolution at the repository horizon is also a major concern. Land surface structures may also be affected. This report briefly reviews the history of and current research in the borehole sealing program. The implications of that work for a waste repository in Permian salt beds of the Palo Duro Basin are also addressed.

Historical Perspective

The perception that abandoned boreholes might be a problem in the siting of a waste repository began with the proposed repository site at Lyons, Kansas. The National Academy of Sciences (NAS) recommended a study of abandoned boreholes in the immediate vicinity (NAS, 1970). Twenty-nine oil and gas wells were found to be within one mile of the site boundaries, with ten of those wells within 660 feet of the actual site (Culler, 1971). A report by the Kansas Geological Survey likened the site to a "piece of Swiss cheese" because of the potential for fluid circulation along boreholes down to and away from the repository horizon (Hambleton, 1972). Some wells penetrated the Arbuckle

Group rocks whose potentiometric surface is above the repository horizon. At one borehole hydrologic investigations documented a downward hydraulic gradient from the shallow aquifer (Angino and Hambleton, 1971).

After abandonment of the Lyons option in 1972, site screening identified the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The site had a very low well density, with the closest well being two miles away. Sandia Laboratories initiated the materials development program for borehole plugs at the WIPP site in 1975. Funding of the overall program was given to the Office of Nuclear Waste Isolation (ONWI) in 1977.

For the WIPP site, a comprehensive review of the penetration (borehole and shaft) sealing program was completed in 1979 by D'Appolonia Consulting Engineers, Inc. (ONWI, 1979). Topics of investigation included: (1) evaluation of existing materials and techniques, (2) hydrothermal transport, (3) plugging with earth materials, (4) in-situ instrumentation, (5) cement grouting, and (6) salt-dissolution modeling. The purpose of their report was to recommend to ONWI the direction of "penetration seal" (both borehole and shaft) research in the future. To this date, the areas of concentration have continued to be in the areas of testing and development of grouts in the laboratory. Consequence analysis and analytical modeling have only recently received attention in connection with site-specific investigations at WIPP. Detailed investigations of boreholes at potential NWTS salt repository sites have not been done. The most detailed characterization of boreholes and in-situ testing of a borehole plug has been accomplished at the WIPP site.

A Draft Technical Position (July 1983) has been issued by the U.S. Nuclear Regulatory Commission (NRC) on Borehole and Shaft Sealing of High-Level Waste Repositories. Specific instructions in technical rule 10CFR60 require DOE to perform several borehole-related investigations. Under 10CFR60.10 (Site Characterization) DOE is required: (d)(2) "As a minimum, the location of

exploratory boreholes and shafts shall be selected so as to limit the total number of subsurface penetrations above and around the underground facility consistent with the information needed for site characterization" (NRC, 1982). Under 10CFR60.142, DOE is also required to perform in-situ tests of borehole and shaft seals during the early stages of construction (but not in Site Characterization). NRC will also require a location and description of all abandoned boreholes along with their drilling records. These must include identification of areas with "poor recovery, fractured areas, and drilling fluid loss" (NRC, 1983). Although plans for borehole seal tests are not specifically outlined in the Nuclear Waste Policy Act of 1982 (PL97-425), that Act requires as part of site characterization " . . . plans for any investigation activities that may affect the capability of such candidate site to isolate high-level radioactive waste and spent nuclear fuel, and plans to control any adverse, safety-related impacts from such site characterization activities," (Congressional Record, 1983). Although there seems to be a great concern that site-related activities will increase the number of accessible pathways to the biosphere, these problems have not yet been addressed as on-site investigations.

Previous Investigations

Investigations into problems with borehole drilling and sealing in areas of proposed nuclear waste repositories have centered on four main areas: (1) studies of salt dissolution around wellbores drilled through salt horizons, (2) laboratory development and testing of grouts designed to plug boreholes, (3) actual in-situ testing of grouts, and (4) consequence assessment modeling. The emphasis of the program to date has been on laboratory development and

testing of grouts. This section discusses and evaluates some of the major results of each research area.

Salt Dissolution Studies

Studies on salt dissolution around boreholes have been a major focus of the sealing program because of earlier decisions naming salt as the most desirable host medium for high-level nuclear waste. Theoretical models of the dissolution process were constructed first by T. N. Dixon (1973) at The University of Texas and continued by A. L. Podio and R. M. Knapp from 1974 to 1979. Using both theoretically and physically based models, Knapp and Podio (1979) concluded that (1) a one-dimensional model appears adequate for representing salt transport in a vertical wellbore, (2) a wellbore will provide a significant avenue for brine transport from an upper salt unit to a lower permeable unit, (3) convective flow in a borehole can be physically modeled, and (4) the brine transport process can be reasonably approximated using finite-difference methods. The actual processes of salt dissolution were not modeled due to experimental difficulties.

Walters (1975, 1978) and Fader (1975) studied salt dissolution around abandoned boreholes related to subsidence in Kansas. Walters concluded that such dissolution was an uncommon process in Kansas oil fields. However, Fader (1975) concluded both that deterioration of the casing and cement in boreholes was common and that salt dissolution around boreholes was a common process. He calculated the amount of salt removed to cause land subsidence and estimated the flow rates needed to accomplish the dissolution. Flow estimates range from 5-24 gallons per minute. O'Connor (pers. comm., 1983) has documented significant flow along boreholes connecting shallow aquifers in Kansas--in effect, draining the upper aquifers. Connections to the deep basin have not been evaluated.

A report by Baumgardner and others (1982) documents the formation of the Wink Sink in Winkler County, Texas. The sinkhole was studied under the auspices of the NWTS program because (1) it documented the formation of a sinkhole over a salt dissolution zone similar to that in the Palo Duro Basin and (2) the possibility existed that the abandoned Hendrick #10A well located slightly off center of the sinkhole may have contributed to salt dissolution and sinkhole formation.

Corrosion in casing in a nearby well suggests that the original 1928 casing and grout in the Hendrick #10A may have deteriorated to the point of allowing fresh water to flow either up or down past the salt (Baumgardner and others, 1982). The relative importance of this process versus regional salt dissolution is difficult to assess. In the Palo Duro Basin, where salt dissolution is an active process (Gustavson and others, 1981), dissolution of salt around abandoned boreholes may be significant but would also be difficult to separate from the regional process.

Development and Testing of Grouts

Design and testing of grout for borehole plugs has been performed by Buck and others (1981), Wakeley and others (1981), Sakhar and others (1982), and Roy and Grutzeck (1982). Materials development for the grouts has been the responsibility of Pennsylvania State University (Penn. State) and the U.S. Army Corps of Engineers Waterways Experiment Station (WES). Specific grouts for a bedded salt repository are discussed in Roy and others (1982). Scale model testing of grouts has recently been done by Terra Tek (J. Gould, pers. comm., 1983). One major criticism of the borehole sealing program is the large amount of time and money devoted to development of plugging materials by Penn. State and WES. Whereas materials development began shortly after the abandonment of

the Lyons site in 1972, the first and only in-situ borehole test of an experimental grout mixture did not begin until 1979 (Bell Canyon test at the WIPP site). Ground-water modeling studies associated with consequence assessment analysis were also not initiated until 1980. The major emphasis of the ONWI program continues to be on materials development and laboratory testing, even in light of the D'Appolonia recommendations (ONWI, 1979) and the site characterization activities required under the Nuclear Waste Policy Act of 1982.

In-Situ Testing

The Borehole Plugging Program (BHP) at Sandia Laboratories has conducted the only in-situ test of an experimental grout in a borehole. The Bell Canyon Test (BCT) evaluated experimental grout mixtures (Penn. State and WES) in an existing well deepened to the Bell Canyon aquifer at 4,534 ft (1,382 m). An 8-inch (20 cm) diameter, 6 ft (2 m) long plug was installed in the overlying Castille Formation (anhydrite) at 4,495 ft (1,310 m) (fig. 1). The grout used was a mixture of Class H cement and a proprietary additive provided by the Dowell Division of the Dow Chemical Company (Christensen and Peterson, 1981). Salt water (BCT-1F) and fresh water (BCT-1FF) versions of the grout were developed for the test. The fresh-water grout was selected because of lower permeabilities, tighter adherence of the grout to the anhydrite, and a lack of observable leakage of the grout-rock interface. Additional details on this grout are contained in Gulick (1980).

Pressure of the underlying Bell Canyon aquifer was determined to be 1811 psi (12.4 MPa) by a series of three drill-stem tests. Christensen and Peterson (1981) state that the Bell Canyon aquifer has a "production capability" of 10^4 gallons/day (38,000 liters/day). This term is assumed to infer a flowing rate at land surface, since no indication is given in the text that this is a pumping rate or a specific capacity term. Additional information about the

physical properties of the Bell Canyon aquifer must be derived from other sources. Hunter (1982) states that the Delaware Mountain Group (of which the Bell Canyon is part) has local hydraulic conductivities of 0.02 ft/day (7×10^{-8} m/sec). Hiss (1975) reported average hydraulic conductivities of 0.016 ft/day (0.0049 m/day) determined from 4,500 samples of rock core cut from the Delaware Mountain Group in New Mexico and Texas. Hogan and Sipes (1966) report permeability values of 12.9 to 24.5 millidarcys for much of the same part of the Delaware Basin.

Borehole plug performance was assessed using pressure buildup tests, shut-in tests and tracer transit-time tests (Christensen and Peterson, 1981). The grout plug was shown to limit upward-directed flow from the Bell Canyon aquifer to 0.2 gallons/day (0.6 liters/day). The importance of this term is misleading, however, if the flow rate of the Bell Canyon aquifer is significantly less than the "production capacity." Flow velocity in the plug from tracer studies was approximately 4 ft/day (1.2 m/day). Assuming the flow path cross-sectional area to equal that of the wellbore, the corresponding intrinsic permeability and porosity are 50 microdarcys and 1.5 percent, respectively. Although no direct permeabilty values from the Castille are available in situ, rock permeability values for the overlying Salado Formation (2,269 ft) were between 12 and 21 microdarcys (Peterson and others, 1981).

In summary, the test results showed the grout plug to be effective in decreasing the volume of water that could move up the wellbore from the Bell Canyon aquifer. However, the small difference in the permeability of the plug and the permeability of the surrounding formations suggests that an extensive borehole plugging program may not be necessary if fluids moving vertically through the existing strata pose a greater threat to the repository.

Consequence Assessment and Modeling

Intera (1981) has used the results of the Bell Canyon Test for a consequence assessment model of the WIPP site. They discuss four scenarios of inter-aquifer and intra-aquifer communication: (1) the U-tube scenario of one aquifer connected by two wells through a repository, (2) flow between two aquifers along a single borehole, and (3) both cases (1 and 2) where multiple boreholes exist. The concept of hydraulic conductance (HC) is defined for the borehole plug as the ability of a cylindrical plug of cross section (A) and length (L) to transmit fluid.

$$HC = \frac{kA}{L}$$

where A = cross-sectional area of the plug
L = length of the plug
k = intrinsic permeability

Hydraulic conductance is somewhat analogous to the transmissivity of a horizontal aquifer of hydraulic conductivity (K) and thickness (b). Units of HC are in millidarcy-feet (see Appendix A).

The use of this particular equation is somewhat vague throughout the Intera report. For example, there is no indication as to how flow rates were derived based on this equation. The type of model used to calculate flow rates and its assumptions were also not addressed. A clue to flow rate calculations is given by equation 3 in their Appendix A (Intera, 1981) although it appears that the equation is not balanced in terms of units. For the purposes of this discussion, however, we will calculate flow rates in the manner shown in Appendix A (this report).

In general, for the WIPP site, flow rates between aquifers increase until hydraulic conductances of the plug approach 1,000 md-feet, after which point the transmissivity of the Rustler aquifer is the main control on flow rate

(fig. 2). A typical plug with HC = 2.91 x 10^{-3} md-ft (k = 50 microdarcys from the in-situ tests) would limit flow between the Bell Canyon and Rustler aquifers to less than 10^{-3} ft^3/day (fig. 2). All calculations are based on freshwater heads for both the Rustler and Bell Canyon aquifers. The modeling by Intera (1981) demonstrates that (1) flow through a repository is controlled by plug conductance, borehole distribution, regional hydraulic gradient and aquifer permeability, (2) flow rates (total volume per time) are greater for multiple borehole scenarios, but flow rates (total volume per time) do not increase in a linear fashion with the number of boreholes, and (3) that borehole plugs are not essential to isolate waste under the hydrologic conditions given. Additional work has shown the simplistic equations used in the Intera report to be inadequate, and that a more complex numerical model encompassing salt dissolution, salt creep and aquifer transmissivities must be used to accurately describe the situation (L. Rickertson, pers. comm., 1983).

Application to the Palo Duro Basin

Consequence assessment and ground-water modeling studies (similar to WIPP) have been completed by Intera Environmental Consultants for all of the salt basins under consideration for a waste repository. These studies are currently in review at ONWI and will not be available until sometime in FY84 (letter, S. Goldsmith to E. G. Wermund, August 25, 1983).

Hydraulic head data, transmissivities, and hydraulic conductivities are available on a regional basis for the Ogallala and Deep-Basin Brine aquifers of the Palo Duro Basin. These data are used here in the construction of three hypothetical ground-water release scenarios for the Palo Duro Basin. All the scenarios here are adapted from Intera (1981), and each scenario can be extrapolated to the case of multiple boreholes, although that is not attempted in

this analysis. The scenarios discussed here include the potential release to the Ogallala aquifer (Scenario 1) and two to the Deep-Basin Brine Aquifer (Scenarios 2 and 3). Possible combinations of all three may exist.

Calculations are semiquantitative at best, because they are calculated from hydraulic potentials from the aquifers. We assume the pressure differential across the borehole plug is analogous to the hydraulic potential difference between the connected aquifers.

No consideration is given here to flow in water wells in the Ogallala aquifer. These wells would provide pathways for fluid movement to the surface (through pumpage) and within the aquifer. Since they do not intersect the repository horizon, however, they are not as critical to the integrity of the repository. The scenarios discussed here will deal only with oil and gas exploratory wells and DOE wells that have penetrated the proposed repository horizons.

Results of the scenario analysis indicate that while Scenario 1 (U-tube in the Ogallala aquifer) is potentially the most destructive, the probability of its occurrence is low due mostly to the paucity of deep wells in the region. Scenario 2 and Scenario 3 (release to the Deep-Basin Brine Aquifer) are more probable, but are unlikely to release radionuclides to the biosphere in a 10,000 yr time period because of the long travel times involved. The probability of these two scenarios would be increased as DOE begins more intensive site investigations .

Scenario 1 (U-tube Scenario)

In this scenario (fig. 5), a hydrologic connection is made between two separate but plugged boreholes, both open to the Ogallala aquifer and intersecting the repository horizon (adapted from Intera, 1981). Although this scenario is important to discuss because it represents a pathway for radionuclide

release to the biosphere, the paucity of wells in the region makes this scenario the most unlikely.

Assuming fresh-water conditions, infinite drainage capacity of the aquifer, and a totally closed system, a flow rate (Q) can be calculated using the equation:

$$Q = (HC1 + HC2)(\rho g/\mu g)(H2-H1)$$

HC1 and HC2 are the conductances of each borehole (assume 2.91×10^{-3} md-ft from Christensen and Peterson, 1981) plug and the quantity (H2-H1) is the hydraulic head difference between the two wells (see Appendix A). Using an average hydraulic gradient of 12.5 ft/mile (2.4 cm/km) in Swisher and Deaf Smith Counties (Weeks and Gutentag, 1981) and assuming the wells to be 1 mile apart (1.6 km), then $Q = 1.34 \times 10^{-5}$ ft^3/day (3.73×10^{-6} m^3/day) for this scenario (see Appendix A for complete calculations).

The U-tube Scenario is complicated by the fact that as water moves through the repository horizon towards the "down-gradient" borehole, dissolution of the salt will occur. Thus, the fluid would likely become saline, and not rise as high in that borehole as the calculations assume. Discharge would most likely be into the Dockum Group rocks and would come in contact with the Ogallala aquifer or the land surface only by dispersion.

Scenario 2 (Single Borehole Communication)

Hydraulic head data for the Wolfcamp aquifer in the Palo Duro Basin (fig. 3) and hydraulic head data for the Ogallala aquifer (Weeks and Gutentag, 1981) indicate that ground water in a borehole would flow from a zone of higher potential in the Ogallala aquifer to a zone of lower potential in the Deep-Basin Brine Aquifer (Wolfcamp aquifer). Assuming a hydrologic connection is made with the repository horizon, radionuclides and brine from salt dissolution

would travel down the borehole to the Deep-Basin Brine Aquifer (Wolfcamp aquifer) and from there to the discharge area (fig. 3). This scenario, while having a greater hydraulic head to drive fluids past the repository horizon and into the Deep-Basin Brine Aquifer (Wolfcamp aquifer) is not a viable method for radionuclide release given the long travel times to the biosphere along the flow path. Travel times are greater than 500,000 years for discharge points beyond the Amarillo Uplift (Wirojanagud and others, in press). Discharge upward along faults or fractures in the Palo Duro Basin is possible but will probably not reduce travel times significantly.

Using a head difference map (fig. 4; from Wirojanagud and others, in press) and assuming infinite drainage capacity of the upper aquifer, infinite transmissivity of the lower aquifer, and potential across the borehole plug to be approximately equal to the difference in hydraulic potentials between the two aquifers, flow rates (Q) are:

Deaf Smith County

$$Q = 9.27 \times 10^{-3}\ ft^3/day\ (2.58 \times 10^{-4}\ m^3/day)$$

Swisher County

$$Q = 7.08 \times 10^{-3}\ ft^3/day\ (1.97 \times 10^{-4}\ m^3/day)$$

Complete calculations are given in Appendix A.

In order to put the flow rates from these scenarios in perspective, it is useful to compare them with leakage rates through the salt. Figure 6 is a contour map of the hydraulic gradient across the salt section at any point. Multiplying the approximate gradient in the two locations by the estimated permeability of the evaporite section (k = 0.00008 md) (from Wirojanagud and others, in press) gives values of:

$Q = 1.21 \times 10^{7}\ ft^3/day/ft^2$ ($3.68 \times 10^{8}\ m^3/day/m^2$ for Deaf Smith County

$Q = 9.12 \times 10^{-8}\ ft^3/day/ft^2$ ($2.76 \times 10^{8}\ m^3/day/m^2$) for Swisher County

The flow rates through 1 square meter of salt (vertically) are less than borehole flow rates by four to five orders of magnitude. Over the entire grid representing the Palo Duro Basin, total leakage through the evaporite aquitard is 35,345 ft^3/day (984 m^3/day) (Wirojanagud and others, in press). Given the particular leakages values and areas for Deaf Smith and Swisher Counties, well spacings of 1 well per 166,617 ft^2 (15,300 m^2) and 1 well per 127,413 ft^2 (11,700 m^2) would be necessary in Deaf Smith and Swisher Counties, respectively, in order for flow down plugged boreholes to equal vertical flow (leakage) through the evaporite aquitard. Since well spacing in both counties is much less dense, we would conclude that leakage through the aquitard regionally is a greater threat than are the current plugged and abandoned boreholes. However, one borehole located strategically within the repository site would constitute the most dangerous scenario, regardless of the leakage through salt at that point or on a regional basis. Again, this conclusion is based on the hydraulic conductivity (K) of the evaporite section (salt) as 8×10^{-5} md.

Scenario 3 (Brine Density Flow)

A third scenario not discussed in Intera (1981) is the invasion of the repository horizon by water travelling up the borehole from the Deep-Basin Brine Aquifer (Wolfcamp aquifer) (fig. 5). Two conditions must be met in this scenario: (1) the potentiometric surface of the lower aquifer (such as the Wolfcamp) must be higher or very near to the repository horizon depth and (2) the water in the lower aquifer be undersaturated with respect to halite so that dissolution can occur along the borehole or in the repository. Anderson and Kirkland (1979) have described the mechanism of brine density flow in the Delaware Basin, whereby undersaturated water from the Capitan (Bell Canyon) aquifer rises along fractures into the Castille Formation, dissolves salt, and

then descends along the same path back to the Capitan (Bell Canyon) aquifer. The differential density between the brine and fresh water causes the movement of saturated brine back downward along the fracture. Anderson and Kirkland (1979) produced a laboratory model similar to that of Knapp and Podio (1979) to demonstrate this mechanism. Abandoned boreholes in the Palo Duro Basin could provide a similar route for this dense brine to descend to the Deep-Basin Brine Aquifer (Wolfcamp aquifer).

The applicability of this scenario is partially dependent on the repository location. As an example, preferred repository horizons (ONWI, 1983) in Deaf Smith County are the Lower San Andres Cycle 4 salt at depths between 2,425-2,550 ft (approximate elevation 1,475-1,400 ft msl) and the Lower San Andres Cycle 5 salt at depths between 2,250-2,400 ft (approximate elevation 1,650-1,575 ft msl) (ONWI, 1983). Elevations of Wolfcamp aquifer hydraulic head in this area are approximately 2,100 ft (msl) (fig. 3) and are above the repository horizon. Preferred repository horizons in Swisher County are the Lower San Andres Cycle 4 salt at depths between 2,575-2,675 ft (approximate elevation 1,225-1,100 ft msl) and the Lower San Andres Cycle 5 salt at depths between 2,375-2,500 ft (approximate elevation 1,225-1,100 ft msl) (ONWI, 1983). Wolfcamp aquifer hydraulic heads in this area are approximately 2,300 ft (msl), again above the repository horizon. Since deep basin (Wolfcamp) brines are undersaturated with respect to halite (Bassett and Bentley, 1983), both salt dissolution and radionuclide migration could occur through the brine density flow system. The consequences and travel times for this scenario are similar to those of Scenario 2.

The directional component of flow within the Deep-Basin Brine Aquifer has implications for Scenarios 2 and 3. Using pressure-depth relationships across the basin, Orr and Kreitler (in press) have shown the Deep-Basin Brine Aquifer system to be underpressured and that potential within the aquifer for vertical

flow varies across the basin (fig. 7). The potential for downward flow within the Deep-Basin Brine Aquifer exists in the Swisher County location. This would possibly lengthen travel times of radionuclides to the biosphere. There are not sufficient data in Deaf Smith County to determine the components of vertical flow. However, test data from the #1 Mansfield well in nearby Oldham County indicate that hydraulic heads in the Pennsylvanian aquifer (granite wash/carbonate) are 300 to 400 feet higher than heads in the Wolfcamp aquifer at that location, indicating that the potential exists for upward-directed cross-formational flow. In either case, it is doubtful whether this relationship would significantly decrease travel times to the discharge area. More hydrologic data from Deaf Smith County are needed to resolve the components of vertical flow there.

Recommendations for the Palo Duro Basin

A salient feature of the Palo Duro Basin for radioactive waste isolation is the paucity of oil and gas exploration and production wells in the region. At least for the present, the possibilities of resource conflicts and drilling into the repository are minimized. County maps current to 1977 show only 13 known wells (3 DOE wells) in the Deaf Smith location and 8 known wells (3 DOE wells) in the Swisher location that may go to repository depth. Their distribution density is much less than the worst case projections of Intera (1981) that used 1 well per 40 acres as a typical well density. This density of wells could, of course, change in the future with continued interest of oil companies in exploratory drilling (Dutton and others, 1982) and stratigraphic/hydrologic investigations associated with repository site characterization activities. The WIPP site now has a fairly high well density as a result of exploration efforts there (Christensen and others, 1982).

Currently, wells in the Palo Duro Basin are plugged in accordance with the State of Texas regulations (Texas Railroad Commission 051.02.02.014 - Rule 14) that state:

> All oil, gas or geothermal resource bearing formations must be protected. Place a 100 foot cement plug immediately above the upper-most perforated zone or produced horizon. If screen or perforated liners cannot be removed, place plug across zone to 100 feet above top liner. If production casing is removed, place a cement plug from 50 feet below surface casing shoe to 50 feet above.
>
> If fresh-water horizons are exposed, place cement plug from 50 feet below base of lowest sand to 50 feet above top of sand.
>
> This plug must be checked for location by landing. Place 10 foot cement plug at surface. Use mud of 9.5 lbs/gal or better in other portions of well.

Although these specifications may be considered adequate for oil and gas well exploration, if either of the present two locations are chosen as the repository site, a systematic study of existing boreholes and their sealing will need to be done using a system similar to that of Christensen and others (1982). Their system defines plugging criteria for boreholes based on the distance of the borehole to the repository site, using State of New Mexico plugging criteria only for the more distant wells, and more stringent requirements for wells closer to the repository.

Much information could be obtained by site investigations of some actual boreholes in the Palo Duro Basin and other salt basins of interest. Reentry of cased and plugged boreholes would give some indication of how deterioration of both materials takes place over time. Detailed hydrologic investigations at a borehole could detect depressions of the Ogallala/Dockum water table or mounding (recharge) of the Wolfcamp potentiometric surface as a result of flow down a borehole. Present data are limited in defining any mounding on the Wolfcamp surface, and the effects of pumpage of the Ogallala aquifer for agriculture would effectively mask any depressions in the water table resulting from flow

down a borehole. There are no plans at present to engage in this type of activity before initiation of site characterization studies. As a result, borehole distribution and condition is presently not a screening factor for proposed sites within the preferred locations. Given the potential consequences of Scenarios 1-3, a cursory examination of the problem is warranted (perhaps earlier than site characterization). In-situ borehole tests should be initiated early enough in the site characterization process so that potential borehole hazards can be identified and investigated thoroughly.

Figure Captions

Figure 1. Schematic drawing of apparatus used in the Bell Canyon in-situ test of a borehole plug (from Christensen and Peterson, 1981).

Figure 2. Graph showing the relationship of borehole plug conductance (abscissa) to flow rate (ordinate) for the case of flow between the Bell Canyon and Rustler aquifers at the WIPP site. Flow rates become asymptotic as conductances approach the transmissivities of the aquifer(s) (from Intera, 1981).

Figure 3. Potentiometric head map (contours in 50 meter increments) for the Wolfcamp aquifer constructed from kriged estimates of head for regular blocks of 20,000 meters squared (from Smith, pers. comm., 1983).

Figure 4. Contours of head difference between the Ogallala aquifer and the Wolfcamp aquifer (from Wirojanagud and others, in press). Contours are in meters (C.I. = 50 m).

Figure 5. Cartoon depicting borehole Scenarios 1-3 in text. Combinations of the various scenarios can be made depending on the distribution of boreholes. Figure not to scale.

Figure 6. Map depicting gradient contours through the salt section at a point (from Wirojanagud and others, in press). Contours are in meters.

Figure 7. Regions in the Palo Duro Basin having potential vertical components of ground-water flow in the Deep-Basin Brine Aquifer. Interpretation is based on comparisons of observed pressure-depth relationships and modelled pressure-depth data for parallel flow in similar hydrogeologic settings (from Orr and Kreitler, in press).

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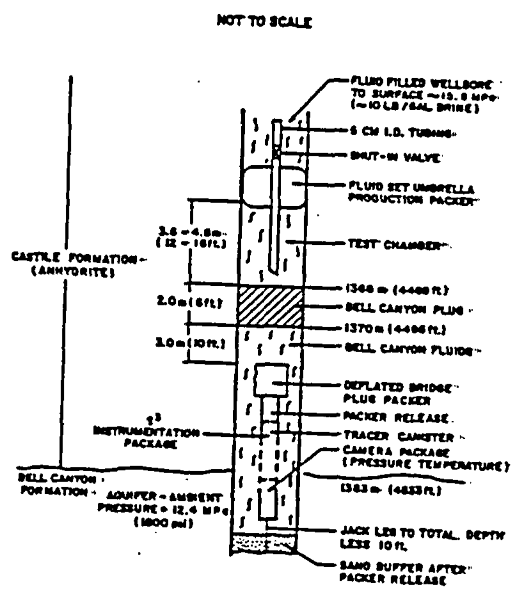
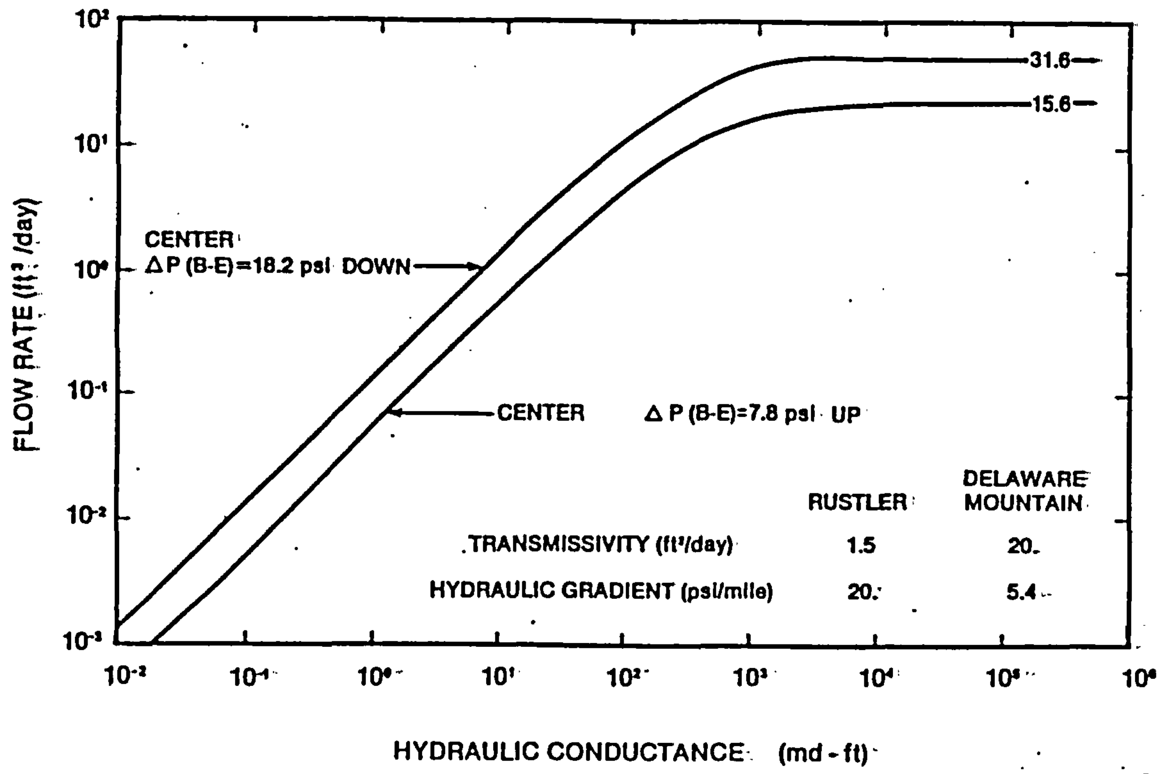

NOT TO SCALE
FLUID FILLED WELLBORE
TO SURFACE
SHUT-IN VALVE
FLUID SET UMBRELLA
PRODUCTION PACKER
TEST CHAMBER
CASTILE FORMATION
(ANHYDRITE)
2.0 m (6 ft)
BELL CANYON PLUG
3.0 m (10 ft.)
BELL CANYON FLUIDS
DEFLATED BRIDGE
PLUG PACKER
PACKER RELEASE
INSTRUMENTATION
PACKAGE
TRACER CANISTER
CAMERA PACKAGE
(PRESSURE TEMPERATURE)
BELL CANYON
FORMATION
AQUIFER - AMBIENT
PRESSURE = 12.4 MPa
(1800 psi)
JACK LEG TO TOTAL DEPTH
LESS 10 ft.
SAND BUFFER AFTER
PACKER RELEASE

Figure 1



FLOW RATE (ft³/day)
HYDRAULIC CONDUCTANCE (md - ft)
CENTER
ΔP (B-E)=18.2 psi DOWN
CENTER ΔP (B-E)=7.8 psi UP
31.6
15.6
RUSTLER
DELAWARE MOUNTAIN
TRANSMISSIVITY (ft²/day) 1.5 20.
HYDRAULIC GRADIENT (psi/mile) 20. 5.4

Figure 2

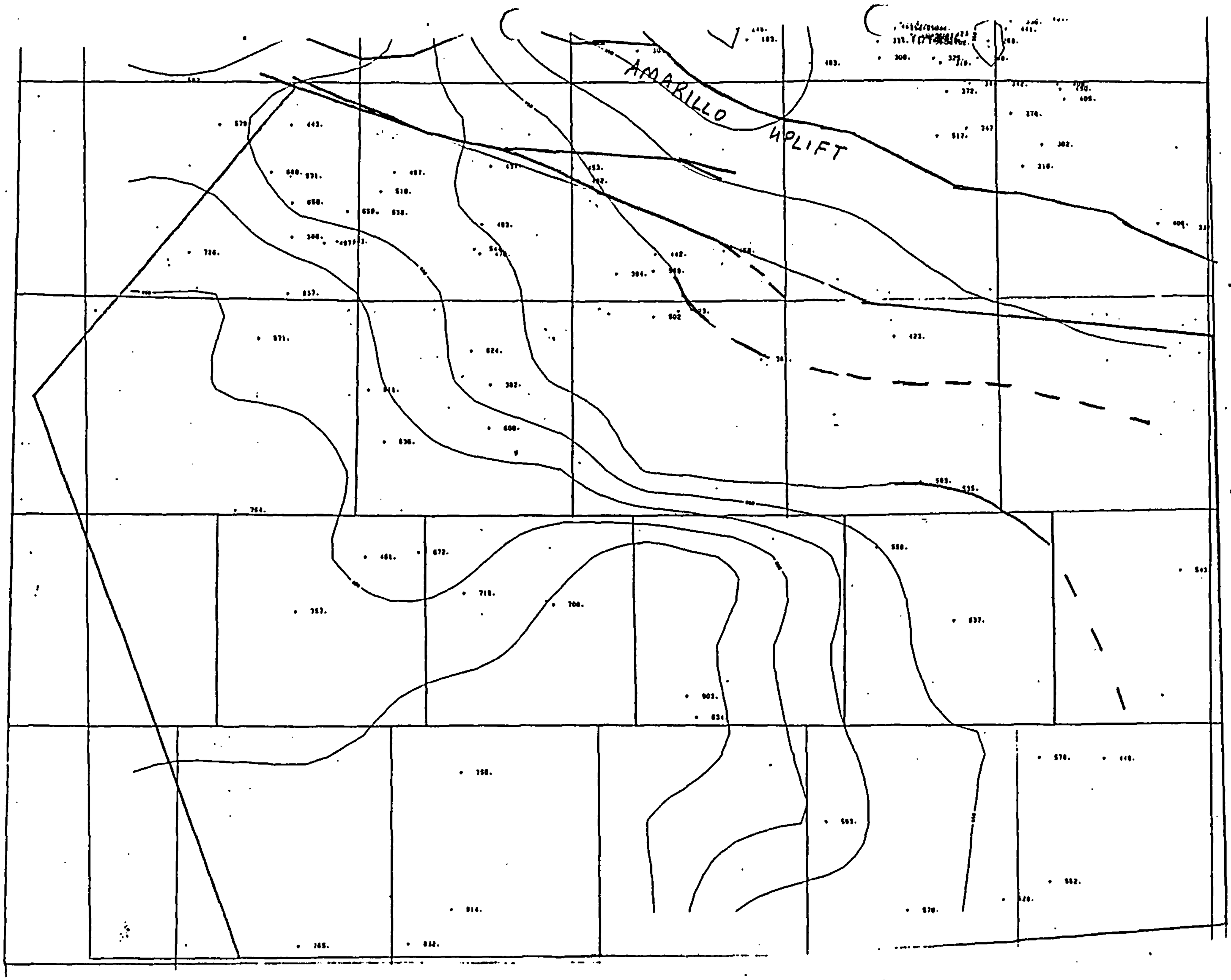
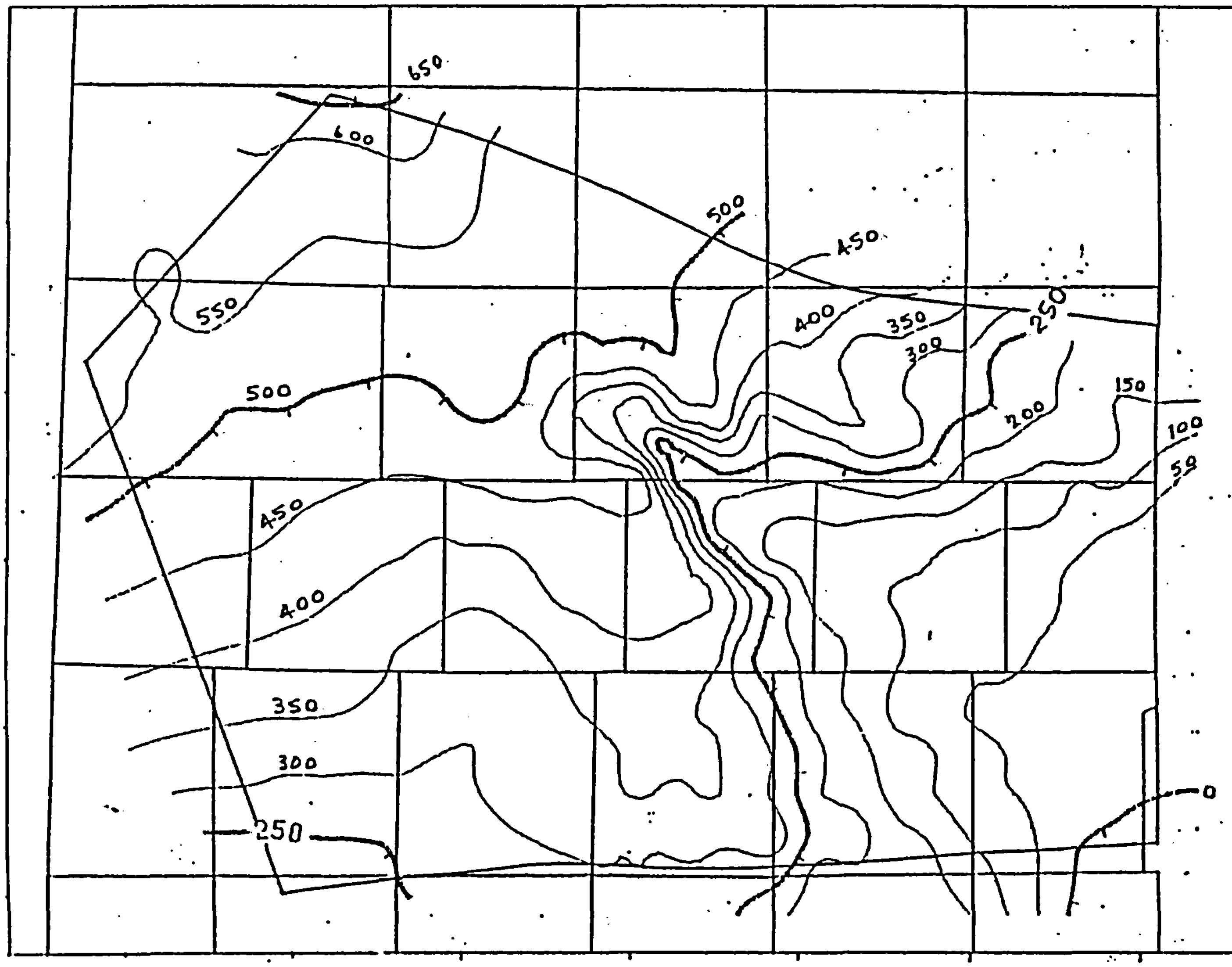


Figure 3



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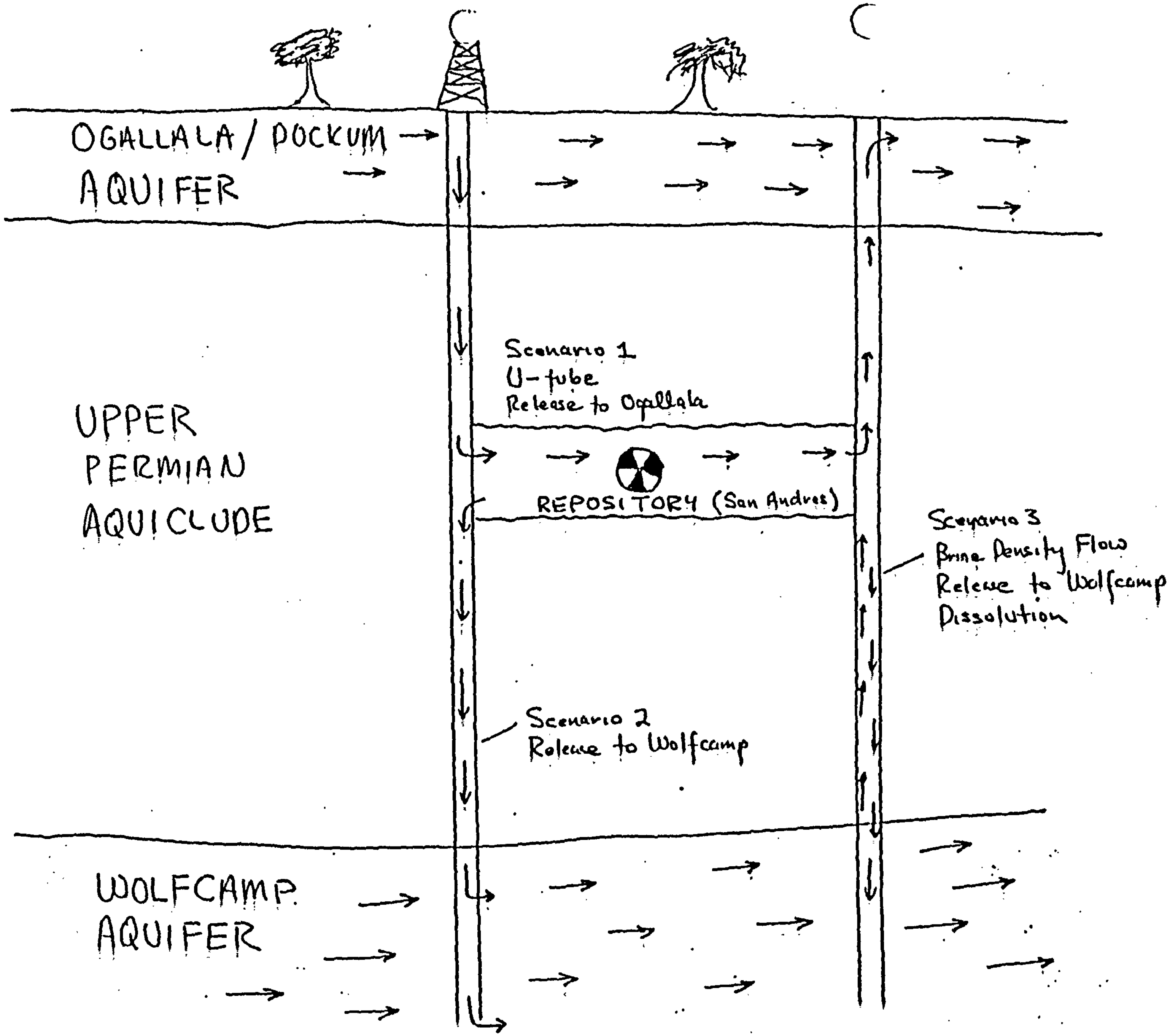
OGALLALA / DOCKUM
AQUIFER
UPPER
PERMIAN
AQUICLUDE
Scenario 1
U-tube
Release to Ogallala
REPOSITORY (San Andres)
Scenario 3
Brine Density Flow
Release to Wolfcamp
Dissolution
Scenario 2
Release to Wolfcamp
WOLFCAMP
AQUIFER

Figure 5

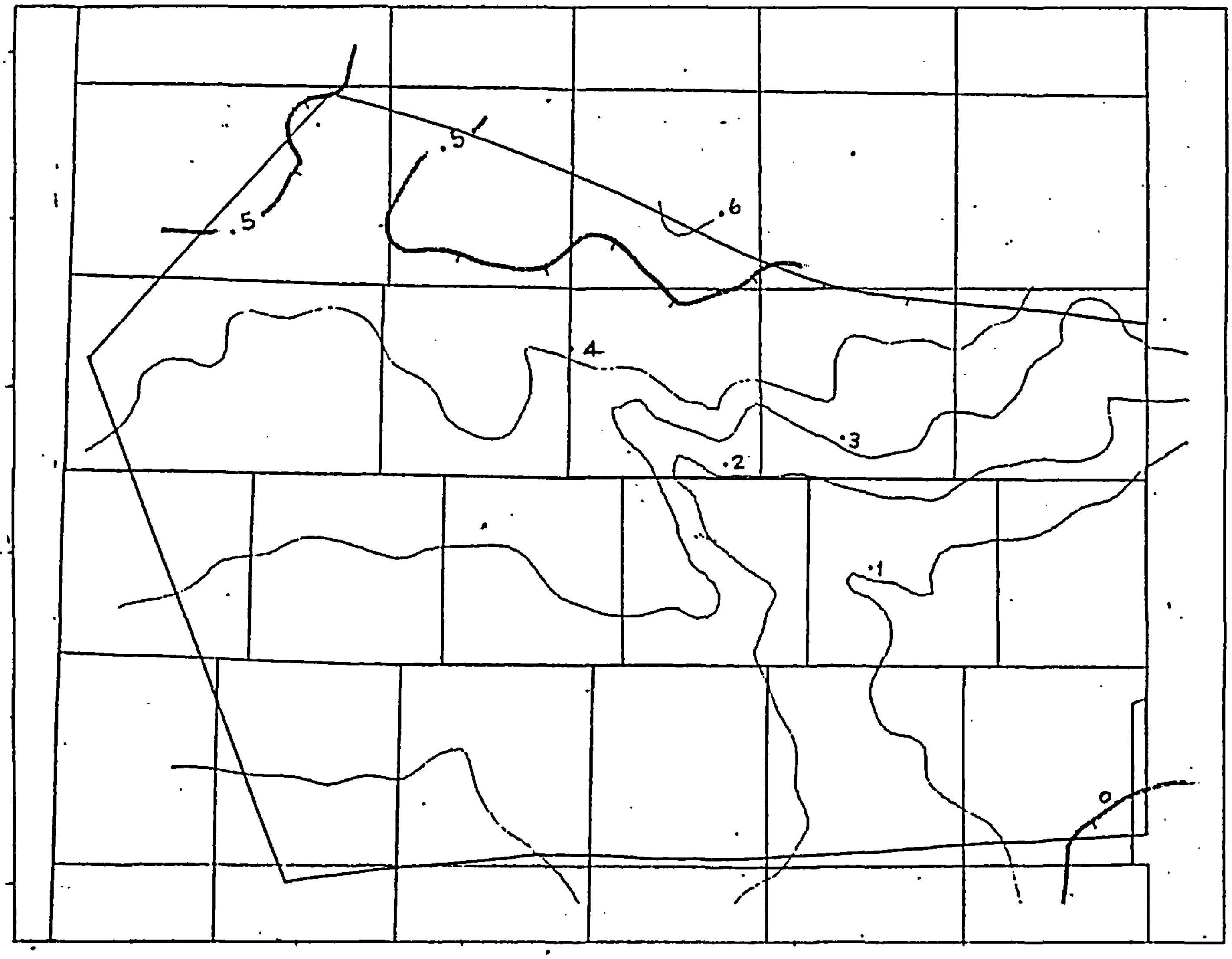

Figure 6

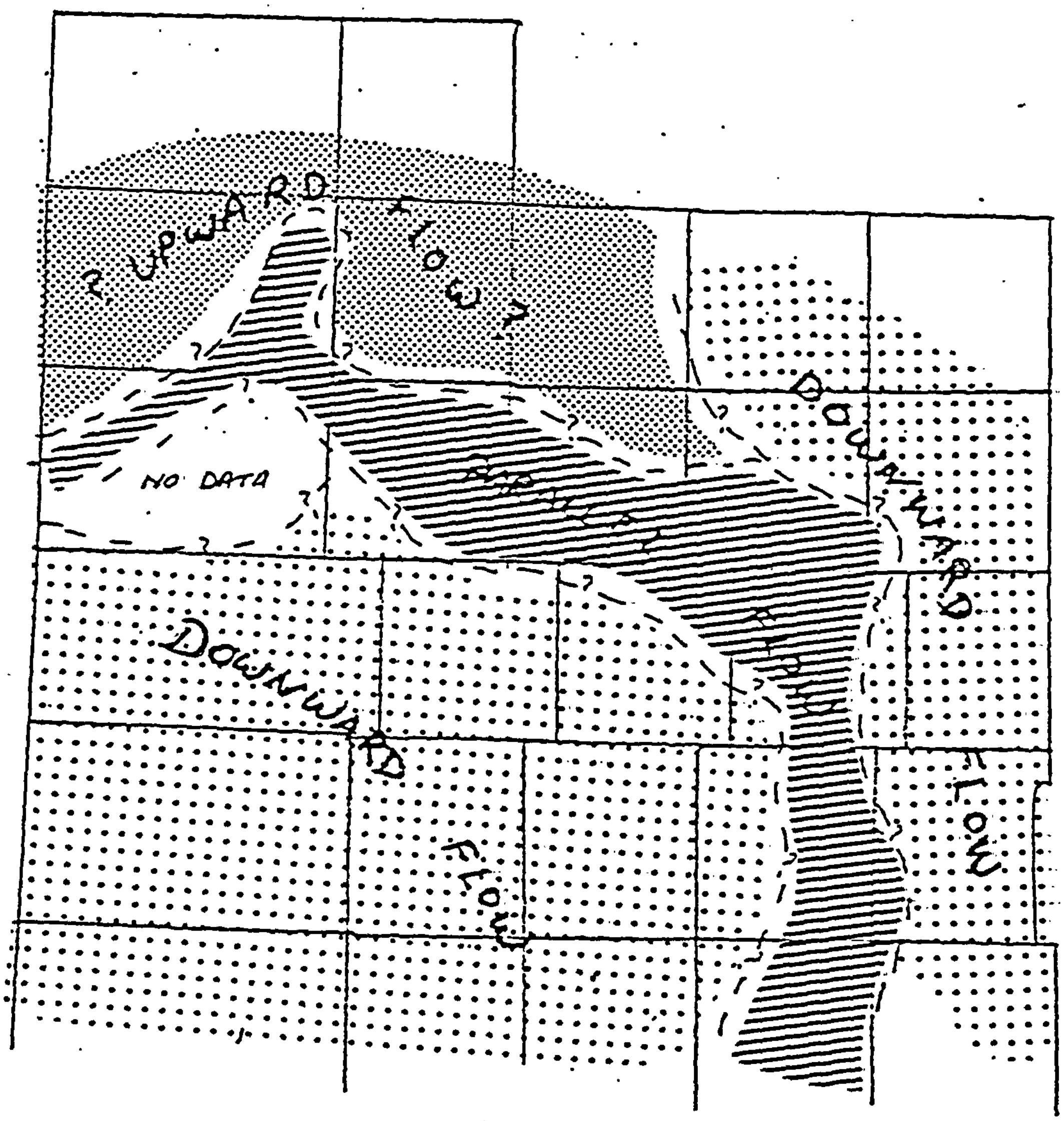

Figure 7

Appendix A - Calculation of Flow Rates

Darcy's Law is used to calculate flow rates:

$$Q = KAI = KA\frac{\Delta H}{L}$$

where Q = flow rate (L^3/r)
K = hydraulic conductivity (L/T)
A = cross-sectional area of flow (L^2)
$\frac{\Delta H}{L}$ = hydraulic gradient (dimensionless)

The term Hydraulic Conductance (HC) of Intera (1981) is:

$$HC = k\frac{A}{L}$$

where k = intrinsic permeability (millidarcys)
HC = Hydraulic conductance (millidarcy-ft)

To convert k (intrinsic permeability) to K (hydraulic conductivity) requires use of the physical properties of the fluid, such that:

$$K = k\frac{\rho g}{\mu g_c} \quad \text{or} \quad K = k\frac{g}{\nu}$$

where ρ = freshwater density of the fluid (kg/m^3)
μ = freshwater viscosity of the fluid ($N \cdot sec/m^2$)
g = gravitational acceleration (m/sec^2)
g_c = gravitational constant ($kg \cdot m/N \cdot sec^2$)
ν = kinematic viscosity (m^2/s)

In this analysis, a conversion factor of $5.5714176 \times 10^{-4} \frac{m}{day \cdot md}$ is used to convert HC (hydraulic conductance) to K(A/L). Substituting these equations we find that:

$$Q = (g/\nu)HC \cdot \Delta H$$

In the following scenarios, the hydraulic conductance is assumed to be that calculated for a plug in the Bell Canyon Test described by Christenson and Peterson (1981), where HC = 2.91×10^{-3} md-ft. Values of ΔH (in feet or meters) are differences in hydraulic potential between aquifers. Hydraulic heads were used in calculations because pressure differentials were not available.

Scenario 1 (U-tube in Ogallala)

$$Q = HC(g/\nu) \cdot \Delta H$$
$$Q = (5.82 \times 10^{-3} \text{ md-ft})(1.83856 \times 10^{-3} \frac{ft}{md \cdot day})(12.5 \text{ ft})$$
$$Q = 1.34 \times 10^{-4} \text{ ft}^3/\text{day}$$
$$Q = 3.73 \times 10^{-6} \text{ m}^3/\text{day}$$

Scenario 2

Deaf Smith County

$$Q = HC(g/\nu)\Delta H$$
$$Q = (2.91 \times 10^{-3} \text{ md-ft})(1 \text{ m}/3.3 \text{ ft})(5.5714 \times 10^{-4} \frac{\text{m}}{\text{d}\cdot\text{md}})(525 \text{ m})$$
$$Q = 2.58 \times 10^{-4} \text{ m}^3/\text{day}$$
$$Q = 9.27 \times 10^{-3} \text{ ft}^3/\text{day}$$

Swisher County

$$Q = HC(g/\nu)\Delta H$$
$$Q = (2.91 \times 10^{-3} \text{ md-ft})(1 \text{ m}/3.3 \text{ ft})(5.5714 \times 10^{-4} \frac{\text{m}}{\text{d}\cdot\text{md}})(400 \text{ m})$$
$$Q = 1.97 \times 10^{-4} \text{ m}^3/\text{day}$$
$$Q = 7.08 \times 10^{-3} \text{ ft}^3/\text{day}$$