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IDENTIFICATION OF SPATIAL VARIABILITY AND HETEROGENEITY OF THE CULEBRA DOLOMITE AT THE WASTE ISOLATION PILOT PLANT SITE*

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ABSTRACT

The Culebra dolomite is a heterogeneous, locally fractured medium whose transmissivity varies over seven orders of magnitude in the vicinity of the Waste Isolation Pilot Plant site in southeastern New Mexico, USA. The spatial distribution of hydraulic properties within the Culebra has been defined by performing 150 hydraulic tests at 41 well locations. Different scales of tests are performed to provide data for different purposes. Small-scale tests such as drillstem tests and slug tests, and short, intermediate-scale pumping tests provide point data useful in developing initial parameters for numerical modeling. Large-scale pumping tests provide information on the distribution of fractures between widely spaced wells, and also provide data for model calibration. Tracer tests provide data on transport mechanisms needed for transport modeling.

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INTRODUCTION

For the past twelve years, the hydrogeologic characterization of the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico has centered on the Culebra dolomite, the most transmissive, laterally continuous water-bearing unit above the repository horizon. The Culebra is a locally fractured, vuggy dolomite approximately 8 m thick. Within the area of the WIPP investigations, the transmissivity of the Culebra varies over seven orders of magnitude. The Culebra is considered to be the most significant potential pathway for radionuclide transport to the accessible environment in the event of a human-induced breach of the WIPP facility.

Extensive hydraulic testing has been performed in the Culebra at 41 well locations, involving a total of 61 wells (Figure 1) and approximately 150 individual tests. This testing has been performed at a variety of scales: single-well drillstem tests (DSTs) and slug tests; single-well pumping tests; short-term (1-5 days) pumping tests involving observation wells up to 30 m away; and long-term (30-60 days) pumping tests involving observation wells up to 6 km away. Each scale of test provides different and complementary types of information on the distribution of fracturing. In addition, both convergent-flow and two-well recirculating tracer tests have been performed to allow quantification of parameters governing solute transport. Since 1985, the field program has been coordinated with a numerical modeling effort to simulate regional groundwater flow in the Culebra. Through this coordination, field efforts have concentrated on providing data from critical areas identified by the modeling.

EVOLUTION OF CULEBRA TEST-WELL NETWORK

The current distribution of Culebra test wells was not laid out in a master plan at the beginning of the project, but has instead evolved as our understanding of the Culebra has grown. When the hydrogeological characterization of the WIPP site began in 1976, only three wells (H-1, H-2b, and H-3; see Figure 1) were planned to be completed to the Culebra dolomite. Information from these three wells was anticipated to be adequate to define the transmissivity and hydraulic gradient of the Culebra. In 1977, however, an unanticipated opportunity allowed four out of 22 additional holes drilled for potash-resource evaluation to be converted to Culebra observation wells, and well H-2c was recompleted to the Culebra. Testing in these eight holes revealed that the Culebra was much more heterogeneous than anticipated, as transmissivity was found to increase by six orders of magnitude over a distance of 10 km from the easternmost well (P-18) to the westernmost well (P-14) [1].

Following this discovery, the United States Geological Survey (USGS) embarked on a more comprehensive characterization program in the Culebra, which entailed drilling and testing wells at seven additional locations (H-4b through H-10b), and converting six boreholes drilled for other purposes to Culebra test wells (WIPP-25 through WIPP-30). This program lasted from approximately 1978 to 1980.

In 1980, Sandia National Laboratories took over responsibility for the hydrogeological characterization of the WIPP site. Sandia began adding wells at existing drilling locations to allow multiwell testing, converting holes drilled for other purposes to Culebra wells, and also adding wells at new locations. From 1981 to 1988, 21 existing wells and boreholes were recompleted as Culebra test wells, and 15 new wells were drilled to the Culebra.

USE OF PRESSURE DERIVATIVE IN HYDRAULIC-TEST INTERPRETATION

In 1985, interpretation of a pumping test performed at well DOE-1 (Figure 2) provided the first recognition that the Culebra behaves hydraulically as a double-porosity medium where it is fractured [2]. Double-porosity behavior is characterized by two distinguishable pressure responses during hydraulic testing [3]. The first response observed is that of a fracture system having relatively high permeability and relatively low storativity. The second response observed is a combination of the fracture response and the response of the porous rock matrix, which has a lower permeability but higher storativity than the fractures.

Application of the pressure-derivative analysis techniques of Bourdet et al. [4] proved to be the key to unequivocal recognition of double-porosity behavior (Figure 3). Using pressure-derivative techniques, reexamination of data collected previously at other Culebra wells and interpretation of more recent tests have shown consistent double-porosity responses wherever the transmissivity of the Culebra is greater than about 10^{-6} m^2/s. Tests showing double-porosity responses coincide with locations where numerous open fractures are noted in core samples from the Culebra. At locations where little or no fracturing is noted, or where the fractures present are filled with gypsum, the apparent hydraulic behavior during testing is that of a single-porosity medium, and transmissivities are consistently less than 10^{-6} m^2/s.

Pressure-derivative analysis techniques have also aided in the recognition of heterogeneity. Pressure-derivative plots from most pumping tests show limited periods of derivative stabilization corresponding to the uniform response of a homogeneous aquifer. In almost all cases, pressure-derivative plots show a brief stabilization period, followed by apparent hydraulic boundary effects. Recharge-type (constant-head) boundaries are indicated by a decline in the pressure derivative, while discharge-type (no-flow) boundaries are indicated by an increase in the pressure derivative to a stabilized level twice that of the previous level (Figure 3). In a heterogeneous fractured medium such as the Culebra, we interpret apparent discharge boundaries as representing areas of decreased transmissivity caused by a decrease in the amount or interconnection of fractures. Apparent recharge boundaries are interpreted as representing areas of increased fracturing, and hence increased transmissivity. In some cases, the pressure derivative rises without stabilizing. Chang and Yortsos [5] attribute this type of behavior to fractures having a fractal, rather than Euclidean, geometry. The potential effects of fractal geometry on transport are not yet understood.

SCALES OF HYDRAULIC TESTING

Testing within the Culebra has been performed at a number of different scales. The choice of scale for a particular test depends on the intended use of the data. Small-scale tests, such as DSTs and slug tests, are typically performed to provide an initial estimate of the local transmissivity within a few meters to tens of meters around a well. If the small-scale test indicates that the transmissivity is less than 10^{-6} m^2/s, then the Culebra is probably relatively unfractured at that location. That low a transmissivity also indicates that the well is probably not productive enough to support a pumping test, so no additional testing is attempted at that location.

If the small-scale test indicates that the transmissivity is greater than 10^{-6} m^2/s, then the Culebra probably is fractured at that location. In this case, we perform a pumping test to learn more about the hydraulic properties at that location. Pumping tests of at least two to three days' duration are adequate to provide information on hydraulic properties over a scale of several hundred meters. Using pressure-derivative analysis techniques, as discussed above, we can confirm the presence of double-porosity behavior and determine the approximate scale over which fracturing is relatively uniform around the well. That is, we can determine the approximate distance at which changes in fracture density and/or interconnection cause apparent boundary effects.

At those locations where observation wells are present within 50 m of a pumping well, additional data can be collected during pumping tests that allow calculation of storativity and horizontal anisotropy. In many cases, however, the heterogeneous fractured nature of the Culebra precludes definition of a transmissivity tensor. Observation-well data can also be useful in defining the nature of, and approximate distance(s) to, apparent hydraulic boundaries.

Typical regional groundwater-flow models include grid blocks or elements tens to thousands of meters on a side. Thus, the scales of tests discussed above all provide information on hydraulic properties that can reasonably be considered to be "point" data in the context of such a model. That is, the data can be considered to be representative of properties on a scale smaller than a grid block. Interpolation techniques such as kriging can be used with these "point" data to derive a transmissivity distribution over the entire model domain.

Testing can also be performed on a scale larger than a grid block. Large-scale testing does not provide quantitative data to be used directly in model construction, but instead provides data against which the model can be calibrated. At the WIPP, three large-scale pumping tests have been performed with the express purpose of providing calibration data for numerical models. These tests were located so as to have overlapping zones of influence which together covered most of the WIPP site (Figure 4). In addition to providing the desired calibration data, however, the large-scale pumping tests have also provided direct evidence on the distribution of interconnected fractures. In some areas, the large-scale tests have shown our previous conceptualizations of the distribution of fracturing to be incorrect.

INTEGRATION OF TESTING WITH MODELING

The first of the large-scale pumping tests was performed in late 1985. For the test, well H-3b2 in the central part of the WIPP site was pumped at a rate of 924 m^3/day for a period of 62 days. Responses to the pumping were observed at most wells within 2.5 km [6]. The drawdowns resulting from this test were asymmetrically distributed (Figure 4). More drawdown and more rapid responses were observed southeast of the pumping well at DOE-1 and H-11 than to the northwest at H-1 and H-2. H-3, DOE-1, and H-11 lie in a region of the Culebra that is fractured and exhibits double-porosity hydraulic behavior, whereas H-1 and H-2 lie in a relatively unfractured area where apparent single-porosity hydraulic behavior is observed. The timing and magnitude of responses observed during the H-3b2 large-scale pumping test are interpreted to show that the fractures found at H-3, DOE-1, and H-11 are connected, and that H-1 and H-2 are not within that system of fractures. Thus, this test demonstrated that continuity of fracturing could be demonstrated on a scale of several kilometers.

In 1987, Haug et al. [7] produced a groundwater-flow model of the Culebra calibrated to estimated steady-state conditions. This model simulated an area of about 140 km^2 around the WIPP site and included data from only 16 well locations. While not specifically calibrated to transient conditions, an attempt was made to use the model to simulate the responses to the H-3b2 large-scale pumping test. Both the steady-state calibration exercise and the attempted transient simulation showed that the transmissivity field used in the model needed changes that were not supported by the existing sparse field data. In particular, the simulations indicated the presence of a zone of relatively high transmissivity extending to the south from DOE-1 and H-11, passing east of P-17 (see Figure 1). Little well data were available to support the existence of this hypothesized high-transmissivity zone.

This finding provided the impetus for a controlled-source audiofrequency magnetotelluric (CSAMT) geophysical survey of the region from about H-1 near the center of the WIPP site to H-12 in the south [8]. Six east-west lines were surveyed, and areas of low resistivity were interpreted as being representative of areas of high fracture transmissivity. Based on this survey, well H-17 (see Figure 1) was drilled in 1987 in what was expected to be a high-transmissivity region. DSTs and slug tests in H-17, however, revealed low transmissivity [2].

A second large-scale pumping test was performed in early 1987. For this test, well WIPP-13 in the northwestern part of the WIPP site was pumped at a rate of 5775 m^3/day for a period of 36 days. Responses to this test were observed up to 6.3 km from WIPP-13 [9]. Drawdowns resulting from this test were asymmetrically distributed, with the most drawdown observed north and west of the pumping well (Figure 4). With one exception, rapid and high-magnitude drawdowns were observed at wells already known to be in fractured regions (e.g., H-6a), while delayed, low-magnitude responses were observed at wells located in relatively unfractured regions of the Culebra (e.g., WIPP-21; Figure 5). The response at well WIPP-30, however, 5.6 km north of WIPP-13, was typical of the responses in fractured regions even though single-well testing at WIPP-30 shows it to be in a region of low transmissivity [2]. We interpreted this response as indicating that while WIPP-30 does not itself intersect fractures in the Culebra, it must be close to fractures connected to WIPP-13.

In 1988, LaVenue et al. [11] produced an expanded Culebra flow model calibrated to estimated steady-state conditions. This model simulated an area of 600 km^2, and included data from 37 well locations. The model was used to simulate the major transient stresses that had affected the Culebra over the previous seven years, including the H-3b2 and WIPP-13 large-scale pumping tests and the hydraulic effects of shaft construction. Despite the finding of low transmissivity at H-17, this model also indicated that a high-transmissivity zone had to be present south of H-11. Sensitivity analyses performed using the model showed that transmissivities between WIPP-13 and the WIPP-series of wells extending north from the center of the site (see Figure 1) would have to be increased relative to their steady-state-calibrated values to improve the agreement between simulated and observed responses to the WIPP-13 pumping test.

The third large-scale pumping test was planned for the southern WIPP site area where more information could be gained on the high-transmissivity zone. Well H-11b1 was pumped for 63 days in 1988 at a rate of 1165 m^3/day. Responses to this test were observed at other wells up to 4.7 km away [12]. Drawdown contours from this test formed an elliptical shape, with more drawdown being observed north and south of H-11 than to the east or west (Figure 4). As expected, DOE-1 and H-3 responded strongly to this test, confirming our interpretation from the H-3 large-scale pumping test of interconnected fractures. However, wells H-15 and H-17 also responded strongly to the pumping test. In the case of H-17, this was not entirely surprising because ongoing modeling efforts had continued to show the presence of a high-transmissivity zone south of H-11 despite the low transmissivity observed at H-17. Similar to our interpretation of the WIPP-30 response to WIPP-13 pumping, we believe that the H-17 response to H-11b1 pumping shows that a fractured zone extends from H-11 <u>near</u> to H-17 and continuing to the south.

Similarly, the H-15 response to H-11b1 pumping can be explained by assuming that the fracture zone connecting H-11 and DOE-1 extends farther to the north close to H-15. This finding was unexpected, however, as the low transmissivity measured from DSTs and slug tests at H-15 had led us to believe that H-15 was well isolated from any fracture zone. Had the H-15 well existed during the H-3b2 large-scale pumping test, we likely would have learned at that time that the DOE-1 fracture zone extended farther to the north. This observation shows the importance of having wells distributed throughout the area of interest, even though they may be widely spaced, and of being able to test across the distances between wells.

In 1990, LaVenue et al. [13] produced a model calibrated to the transient responses created by all three large-scale pumping tests, as well as by other significant hydraulic stresses dating back to 1981. This model simulated a region of about 650 km^2, and included data from 41 well locations. This model confirmed the need for a high-transmissivity zone south of H-11. Furthermore, simulation of the response at well H-15 to the H-11b1 pumping test required that the high-transmissivity zone be extended farther to the north past DOE-1 than had been necessary during previous modeling efforts when no data from H-15 were available. Because transport modeling has shown this high-transmissivity feature to exert a controlling influence on groundwater travel times to the accessible environment, precise delineation of this feature remains of concern to the WIPP project.

In summary, small- and intermediate-scale hydraulic tests have proved useful in providing point values of hydraulic properties, defining the presence or absence of hydraulically significant fracturing, and in defining how the density and/or interconnection of fracturing changes over distances of several hundred meters. Large-scale hydraulic tests have provided important information on the distribution of fractures on a scale of several kilometers, and have provided valuable data against which to calibrate regional groundwater-flow models.

TRACER TESTING

A program of tracer testing was initiated in the Culebra in 1980, when a recirculating tracer test was performed between wells H-2b and H-2c. This test at a location where the Culebra is relatively unfractured showed the effective transport porosity of the Culebra to be between 11 and 19% [14]. In comparison, laboratory measurements performed on core samples show the matrix porosity of the Culebra to range from 3 to 30% [15]. Another recirculating tracer test was performed at the H-6 hydropad (location with multiple wells) in 1983. Convergent-flow tracer tests were performed at the H-3 (1984), H-4 (1982-1984), H-6 (1981 and 1982), and H-11 (1988) hydropads.

Just as hydraulic tests have shown a transmissivity of 10^{-6} m^2/s to represent the approximate dividing line between single-porosity and double-porosity hydraulic behavior, so too do the convergent-flow tracer tests show pronounced differences in transport behavior between locations where the Culebra transmissivity is less than (H-4) and greater than (H-3, H-6, and H-11) this threshold value. At H-4, tracer breakthrough at the pumping well along both 30-m flow paths took several hundred days [16]. At H-3, H-6, and H-11, breakthroughs along some 20- to 30-m flow paths occurred in less than one day.

The convergent-flow tracer tests at the H-3, H-6, and H-11 hydropads have all shown one flow path between wells to allow more rapid transport than the other flow path(s) (Figure 6). No consistency in the orientation of the fastest flow paths is noted among the different hydropads, however. The breakthrough curves along the fast flow paths appear to show rapid transport through fractures, with diffusion into the rock matrix delaying the transport of a portion of the tracer mass. Interpreting the fastest flow paths as representing direct fracture transport between wells leads to estimates of fracture porosity of about 0.15% [16]. The slower flow paths appear to represent more circuitous flow (i.e., at least partially transverse to the preferred fracture orientation), with accordingly greater matrix diffusion. Assuming a homogeneous distribution of fractures, interpreted matrix-block sizes (distances between fractures) range from about 1 to 2 m. Preliminary interpretation of the H-11 tracer test, however, casts doubt on the validity of this assumption. At H-11, the two flow paths with orientations differing by only 15° showed the widest range in transport behaviors, as shown by differences in initial breakthrough times and peak concentrations (Figure 7).

In summary, tracer tests confirm the heterogeneous double-porosity conceptualization of the Culebra derived from the hydraulic-test interpretations. Tracer tests are inherently limited, however, in terms of the scales at which they can be performed. Whereas the pressure transients induced by hydraulic tests can be easily propagated and measured over distances of several kilometers, transport and subsequent detection of tracers cannot readily be accomplished over distances of about 100 m. Thus, prediction of solute transport over large distances must rely on the understanding of transport mechanisms derived from small-scale tests, with those mechanisms applied to a well-characterized hydraulic model.

SUMMARY

In a heterogeneous fractured medium such as the Culebra dolomite, hydraulic testing should be performed on a variety of scales to provide different types of information needed for the overall characterization of the medium. Small-scale tests provide the point data on hydraulic properties that provide the essential database for numerical modeling. Intermediate-scale tests provide additional point data, and also provide information on how the distribution of fractures changes over distances of a few hundred meters. Large-scale tests provide information on the distribution of fractures between widely spaced wells, showing where new wells should be drilled to characterize important features. In addition, large-scale tests provide data for model calibration on a scale approaching that at which the model will be expected to make reliable predictions.

Tracer tests can provide information on parameters such as fracture porosity and matrix-block size that affect solute transport, but are limited in terms of the spatial scale at which they can be performed. For this reason, tracer tests should be performed at many sites to evaluate transport mechanisms where hydraulic properties may be different.

In summary, a complete understanding of a heterogeneous system can be best obtained by integrating the complementary types of information obtained from hydraulic and tracer testing performed on different scales. A particular emphasis should be placed on performing hydraulic testing on as large a scale as possible.

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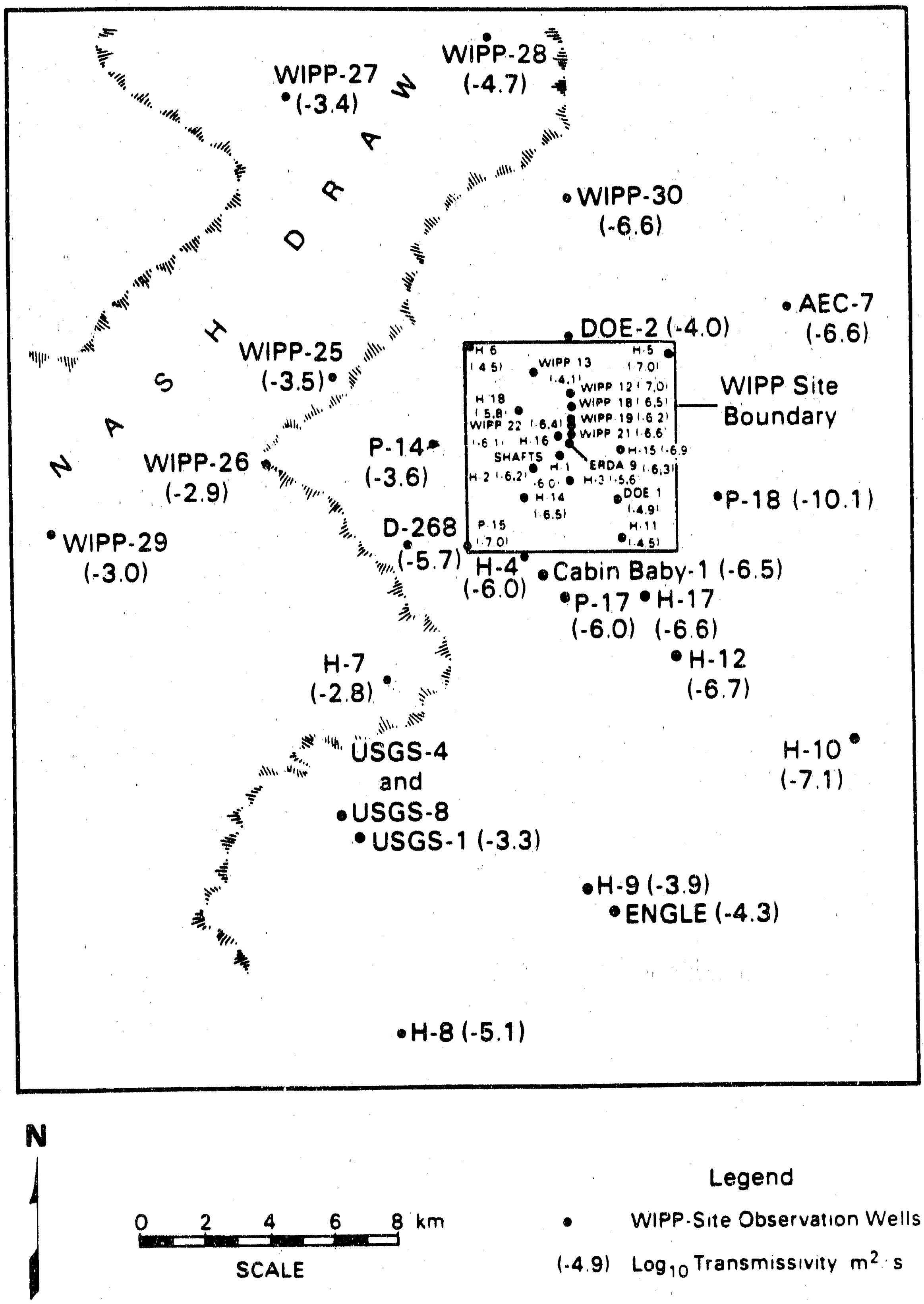
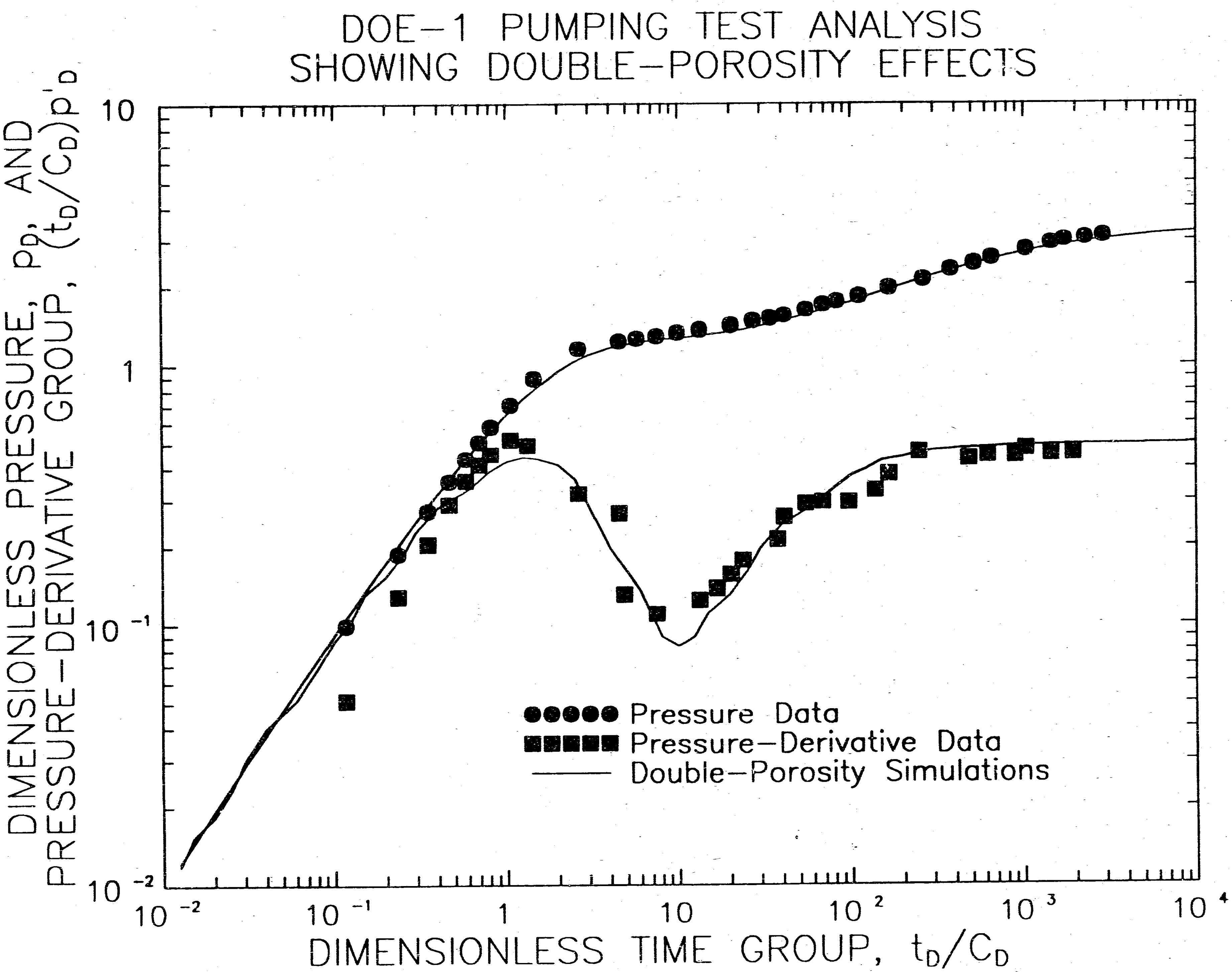


Figure 1

Culebra Wells and Measured Transmissivities Near the WIPP Site



DOE-1 PUMPING TEST ANALYSIS
SHOWING DOUBLE-POROSITY EFFECTS
DIMENSIONLESS PRESSURE, p_D, AND
PRESSURE-DERIVATIVE GROUP, $(t_D/C_D)p'_D$
10
1
10^{-1}
10^{-2}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
DIMENSIONLESS TIME GROUP, t_D/C_D
Pressure Data
Pressure-Derivative Data
Double-Porosity Simulations

Figure 2

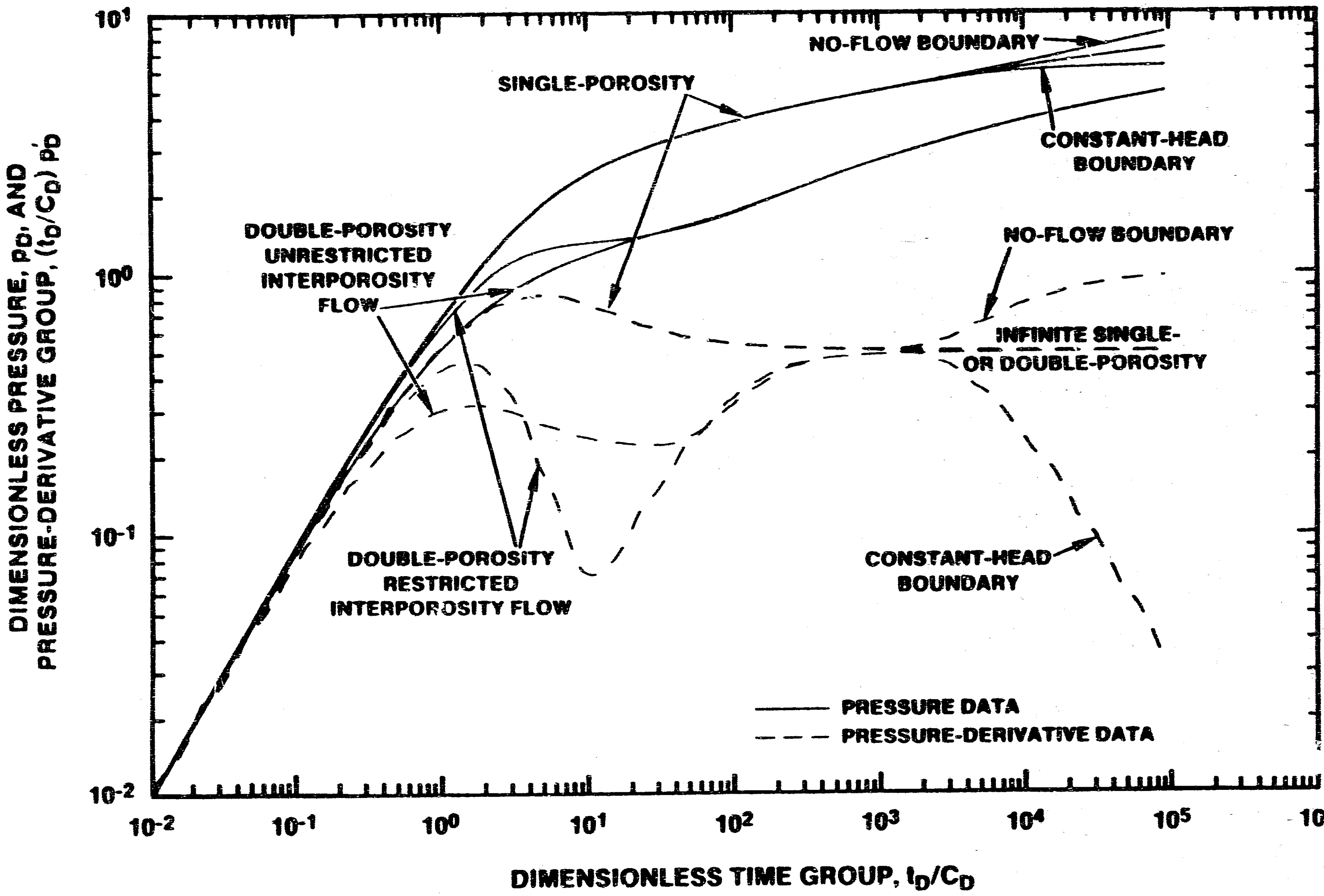


Figure 3

Pressure and Pressure-Derivative Type Curves Showing the Effects of Different Hydraulic Conditions

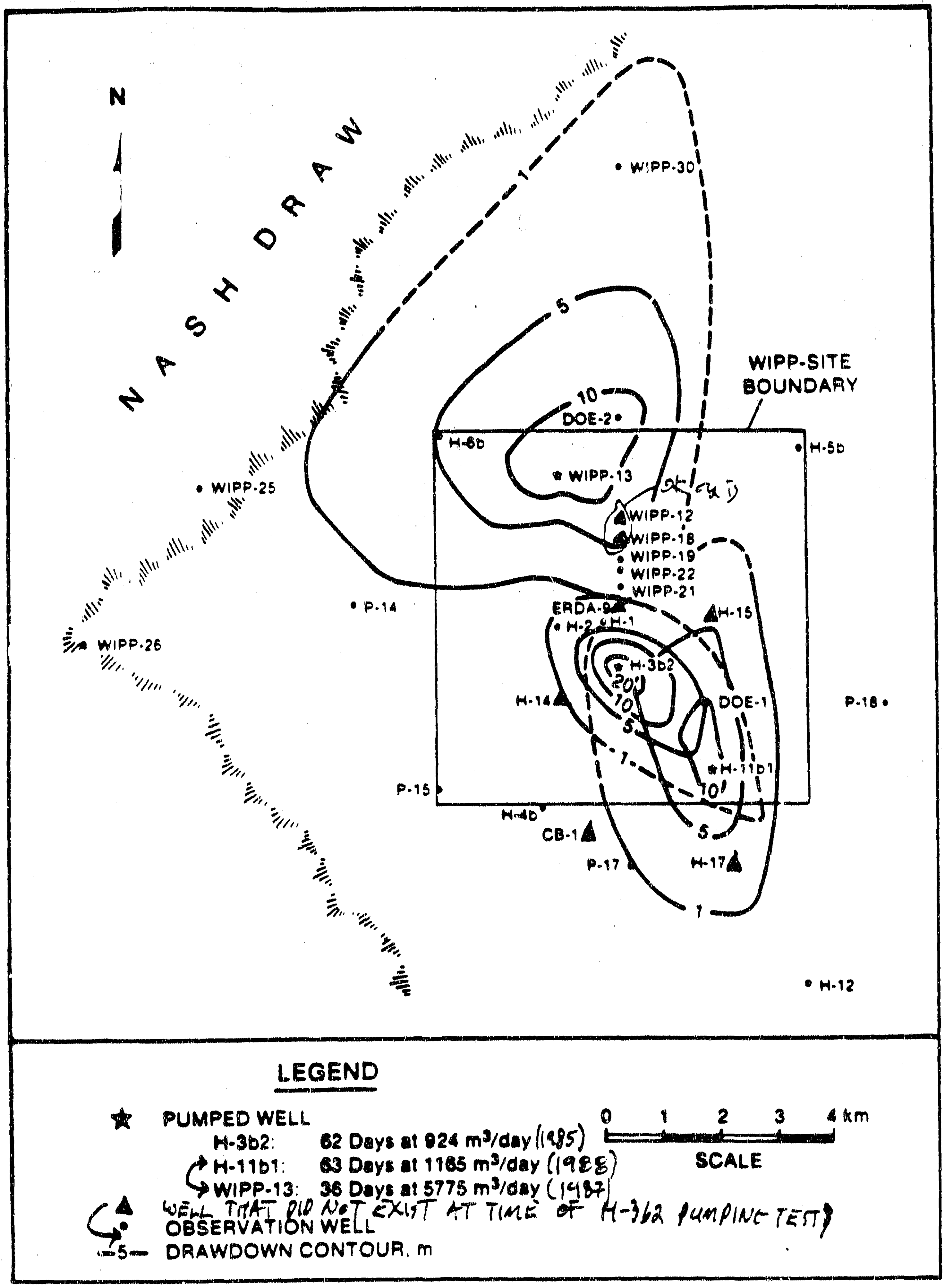


Figure 4

Drawdowns Observed at the End of Long-Term Pumping Tests

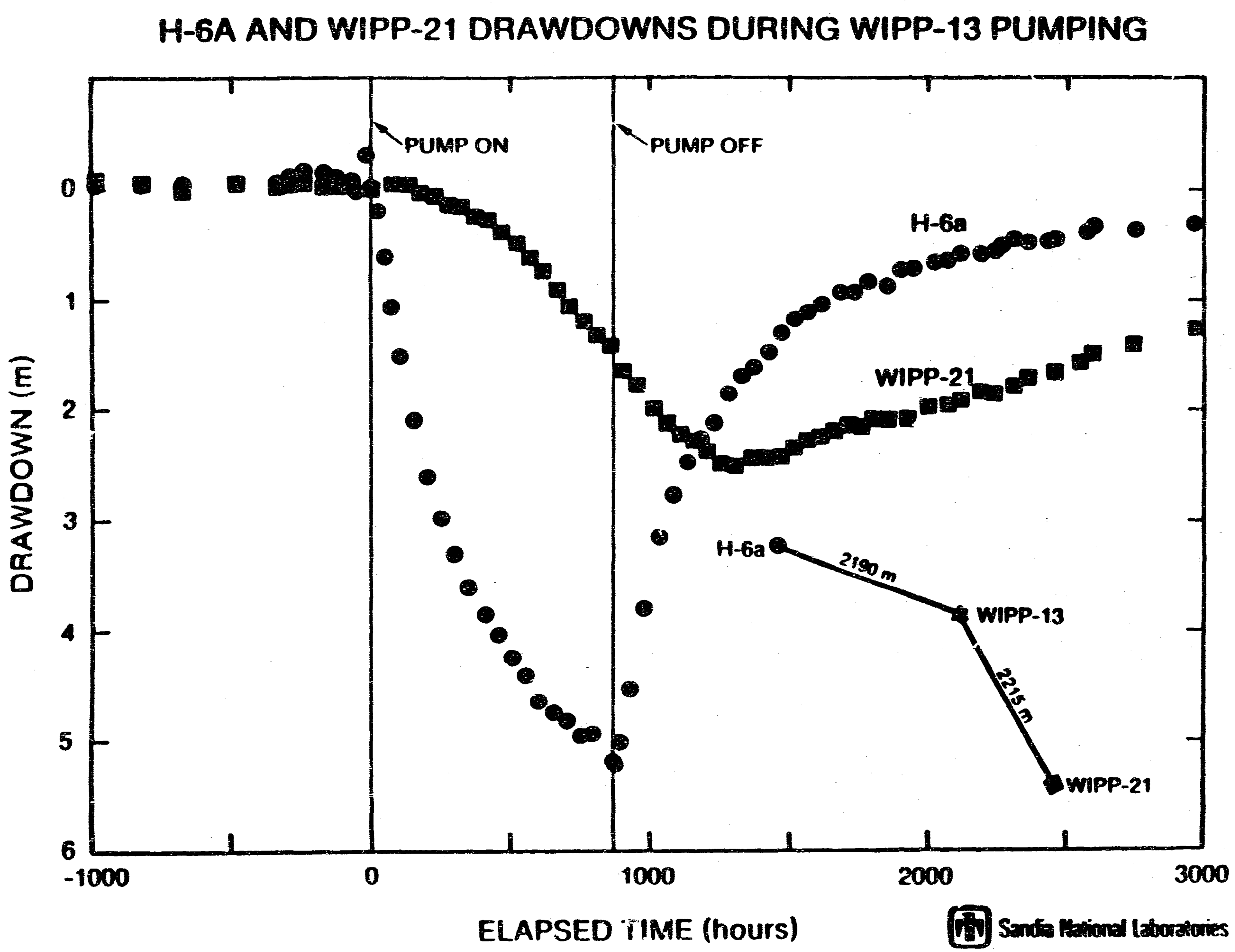

H-6A AND WIPP-21 DRAWDOWNS DURING WIPP-13 PUMPING
PUMP ON
PUMP OFF
H-6a
WIPP-21
H-6a
2190 m
WIPP-13
2215 m
WIPP-21
DRAWDOWN (m)
0
1
2
3
4
5
6
-1000
0
1000
2000
3000
ELAPSED TIME (hours)
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Figure 5

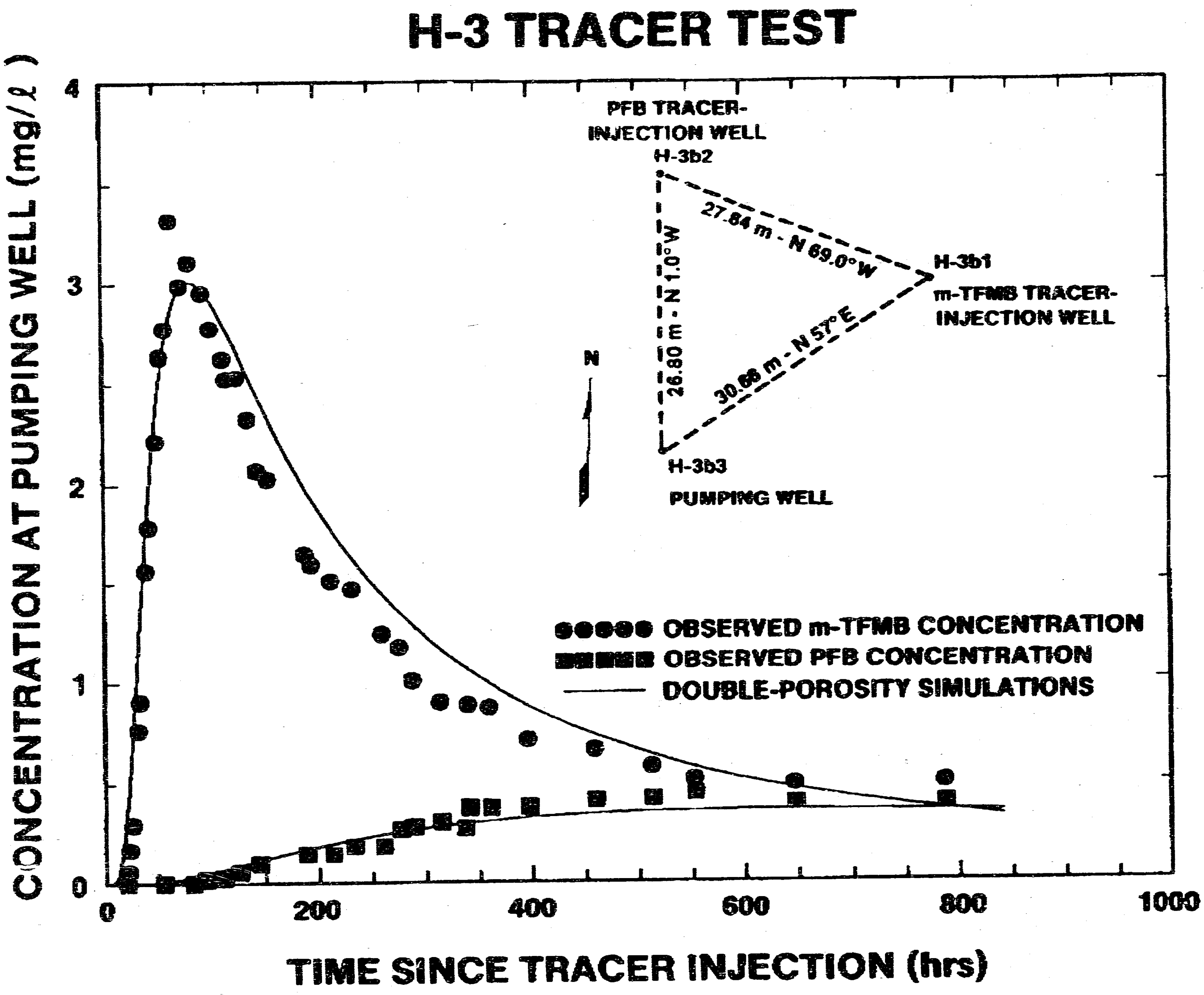

Figure 6
Observed Data and Double-Porosity Simulations of H-3 Convergent-Flow Tracer Test

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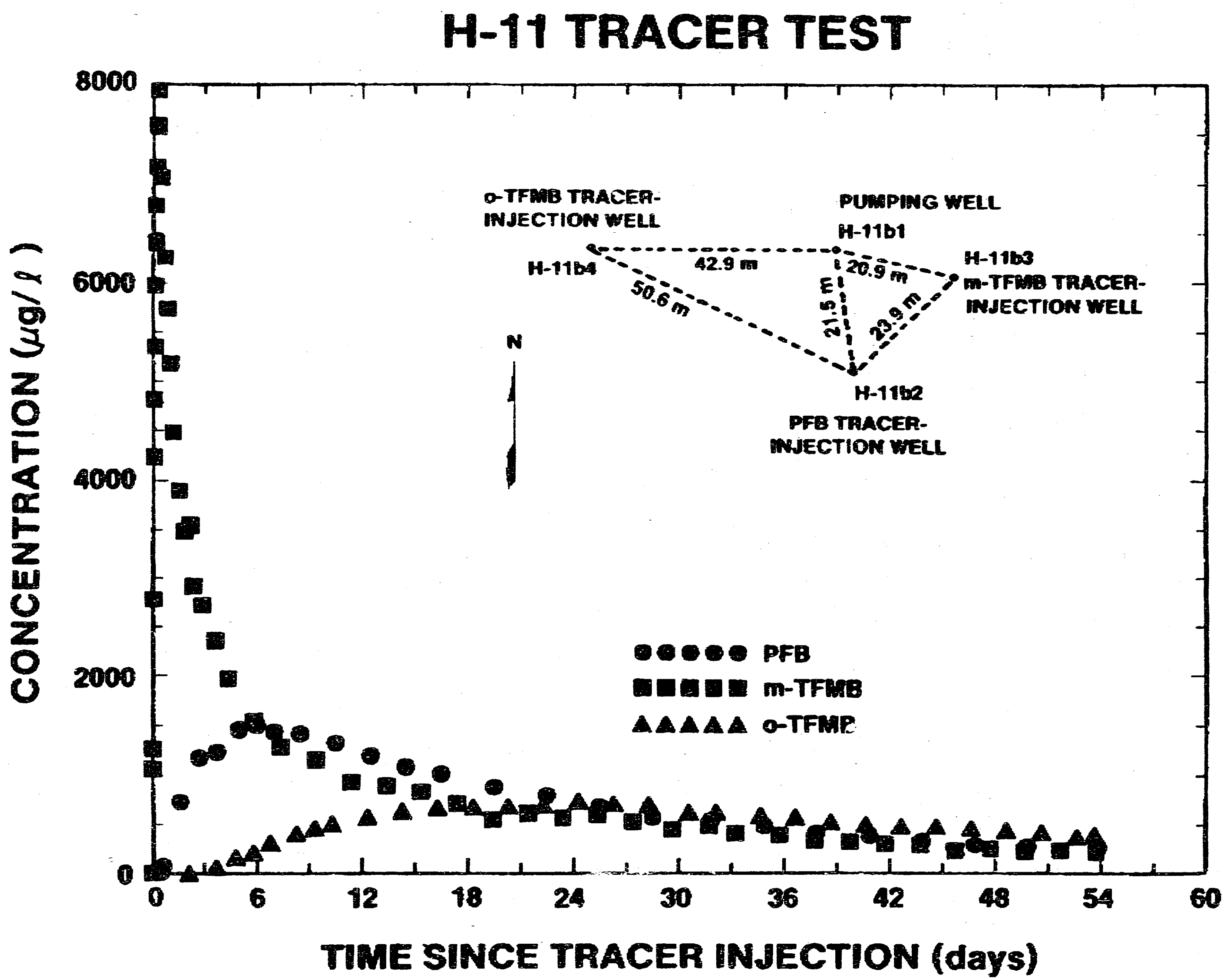

Figure 7

Observed Data from H-11 Convergent-Flow Tracer Test

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