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Rationale for the H-19 and H-11 Tracer Tests at the WIPP Site

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Abstract

The Waste Isolation Pilot Plant (WIPP) is a repository for transuranic wastes constructed in bedded Permian-age halite in the Delaware Basin, a sedimentary basin in southeastern New Mexico, USA. A drilling scenario has been identified during performance assessment (PA) that could lead to the release of radionuclides to the Culebra Dolomite Member of the Rustler Formation, the most transmissive water-saturated unit above the repository horizon. Were this to occur, the radionuclides would need to be largely contained within the Culebra (or neighboring strata) within the WIPP-site boundary through the period lasting for 10,000 years after repository closure for WIPP to remain in compliance with applicable regulations on allowable releases. Thus, processes affecting transport of radionuclides within the Culebra are of importance to PA.

The Culebra is an approximately 7-m-thick, variably fractured dolomite with massive and vuggy layers. Hydraulic tests conducted at 41 well locations showed that the transmissivity of the Culebra varies over six orders of magnitude in the vicinity of the WIPP site. Convergent-flow tracer tests were conducted in the Culebra at three high-transmissivity locations between 1981 and 1988. The breakthrough curves were successfully simulated using a homogeneous double-porosity model with directional anisotropy in permeability. For preliminary performance assessments, models of radionuclide transport treated the Culebra as a double-porosity medium with uniformly spaced horizontal fractures over its entire thickness and spatially varying transmissivity. Simulations with Monte Carlo sampling from varying representations of the Culebra transmissivity (T) field and varying values of fracture spacing, matrix porosity, fracture porosity, matrix distribution coefficients (K_ds), fracture-surface K_ds, radionuclide solubilities, and 42 other parameters were used to define complementary cumulative distribution functions (CCDFs) displaying the probability that radionuclide releases will exceed calculated quantities, as required by regulation. Based on sensitivity studies carried out in 1992, fracture spacing, matrix K_ds, and radionuclide solubilities were found to be "very important" parameters, the T field and matrix porosity to be "important" parameters, and fracture porosity and fracture-surface K_ds to be "less important" parameters in terms of reductions in their uncertainties being able to affect the position of the mean CCDF near the regulatory limits.

The model and parameter ranges used by PA were scrutinized by different review groups, who concluded that there was inadequate experimental justification to rule out alternative models and parameters. Accordingly, a new series of tracer tests was planned to address the review groups' criticisms and provide a defensible model and parameters for PA modelling. A new seven-well location, the H-19 hydropad, was established for the testing. The test design focused on improving our understanding of matrix diffusion, the effects of layering in the Culebra on transport, and the causes of directional differences in transport. The tracer tests were linked to a field hydraulic-testing program and laboratory studies measuring radionuclide solubilities, sorption on the Culebra matrix, and matrix porosity, tortuosity, and permeability to address all of the "very important" and "important" transport-related parameters identified from the 1992 PA sensitivity analyses. The data and, in some instances, revised conceptual models resulting from these studies were used in the performance assessment that was a part of the formal certification application for the WIPP submitted by the U.S. Department of Energy to the U.S. Environmental Protection Agency in October 1996.

DISCLAIMER

Introduction

The Waste Isolation Pilot Plant (WIPP) is a repository proposed by the U.S. Department of Energy (DOE) for disposal of defense-related transuranic wastes. The WIPP has been constructed in bedded Permian-age halite in the Delaware Basin, a sedimentary basin in southeastern New Mexico, USA (Figure 1). Because the Delaware Basin is the target of active drilling for energy resources, performance assessment (PA) for the WIPP must consider the possibility of inadvertent human intrusion at a time in the future when the existence of the WIPP is assumed to have been forgotten. Based on the understanding and knowledge of WIPP-site hydrogeology developed during site characterization, a drilling scenario has been identified that could lead to the release of radionuclides to the Culebra Dolomite Member of the Rustler Formation, the most transmissive water-saturated unit above the repository horizon (Figure 2). In this scenario, one borehole penetrates the repository, located 655 m below ground surface in bedded halite of the Salado Formation, and continues into the underlying Castile Formation, where it encounters a brine reservoir. Brine reservoirs have been encountered in approximately 30 of the 350+ boreholes drilled through the evaporite section in the Delaware Basin in the vicinity of the WIPP site. The reservoirs are pressurized and flow brine at the ground surface at initial rates between 100 and 3000 m^3/day [1]. The presence of one of these brine reservoirs beneath the WIPP repository is considered unlikely, but cannot be ruled out.

In some of the intrusion scenarios considered in the PA, the borehole penetrating the brine reservoir is plugged above the repository, leaving the repository connected to the brine reservoir. A second borehole is then hypothesized to penetrate the repository at another location. At some time in the future, whatever materials were used to plug the second borehole are assumed to degrade, and a flow path is established from the brine reservoir through the repository and into the Culebra. Were this to occur, any dissolved radionuclides that were transported up the borehole into the Culebra would need to be largely contained within the Culebra (or neighboring strata) within the WIPP-site boundary through the period lasting for 10,000 years after repository closure for WIPP to remain in compliance with applicable regulations on allowable releases. Thus, processes affecting transport of radionuclides within the Culebra are of importance to the WIPP project.

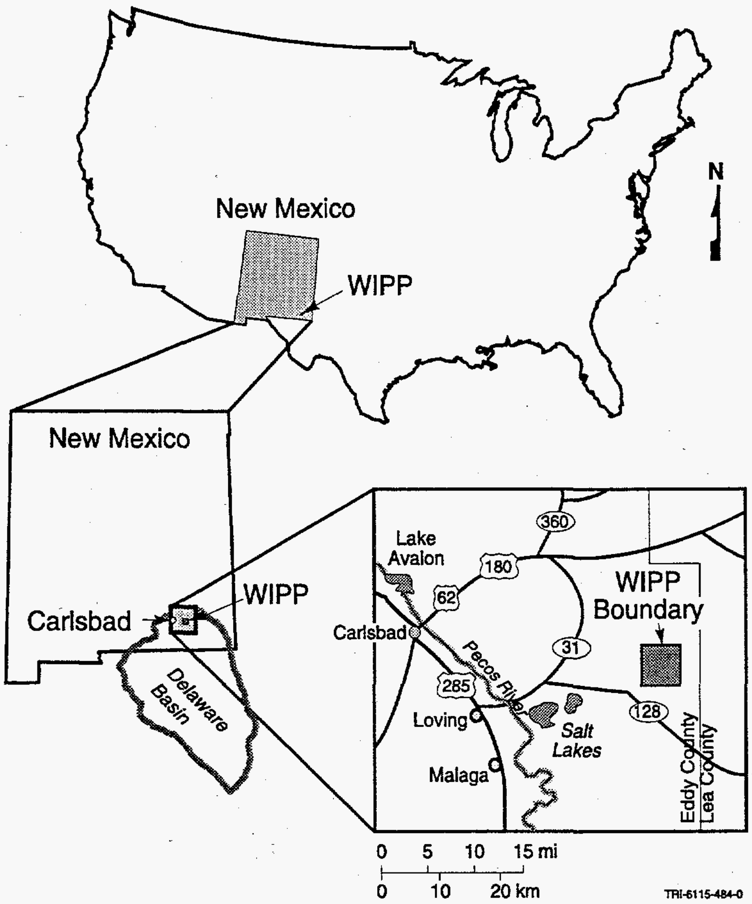

Figure 1. Location of the WIPP site

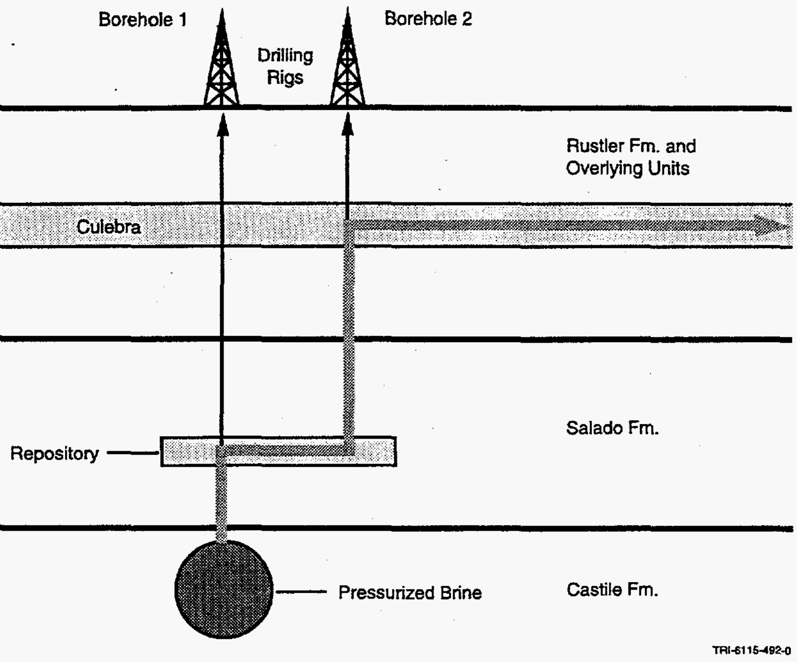

Figure 2. Drilling scenario for radionuclide release from the WIPP

Previous Testing of the Culebra

The Culebra is an approximately 7-m-thick, variably fractured dolomite with massive and vuggy layers. During site characterization from 1974 through 1988, 61 wells were completed to the Culebra at 41 locations around the WIPP site (Figure 3). Hydraulic testing was performed at each of these locations to determine the local transmissivity of the Culebra and to provide information on the regional distribution of transmissivity. At some of these locations (see Figure 3), open fractures were observed in Culebra core and hydraulic tests indicated relatively high transmissivity. Hydraulic tests at these locations could be readily interpreted using double-porosity models that assumed that most of the permeability of the medium was provided by fractures while most of the storage capacity was provided by the primary porosity of the rock matrix between the fractures. At other locations (see Figure 3), the fractures in the Culebra were found to be sealed with gypsum and the Culebra had relatively low transmissivity. Hydraulic tests at these locations were most simply interpreted using single-porosity models for flow through a porous medium.

The hydraulic tests showed that the transmissivity of the Culebra varies over at least six orders of magnitude in the vicinity of the WIPP site. To represent this heterogeneity in flow and transport simulations, multiple realizations of the transmissivity (T) field are generated. Initial information for the T fields comes from the transmissivities and steady-state hydraulic heads measured at the individual wells. The T fields are calibrated by comparing simulated responses to the transient pressure/water-level responses observed while performing large-scale pumping tests of several months' duration and while sinking the shafts at the WIPP site. An automated inverse code, GRASP-INV [2, 3] uses pilot points (synthetic measured-transmissivity locations) to improve the model fit to the observed data until acceptance criteria are met. Using GRASP-INV, as many different but equally likely representations of the T field can be generated as desired (Figure 4).

Convergent-flow tracer tests were conducted in the Culebra at three of the high-transmissivity (double-porosity) locations between 1981 and 1988. The tracer-breakthrough curves obtained from these tests showed two major characteristics, as exemplified by the data from the H-6 test (Figure 5): First, the rate of transport was directionally dependent, with rapid transport and relatively high peak concentrations occurring along one direction while slower transport and lower peak concentrations occurred along another direction. Second, the breakthrough curves showed long "tails", believed to reflect the influence of some type of physical-retardation mechanism, most likely matrix diffusion. The breakthrough curves were successfully simulated (Figure 6) using a homogeneous double-porosity model with uniform cubic matrix blocks and directional anisotropy in permeability [4]. The geometric conceptualization of the fracture-

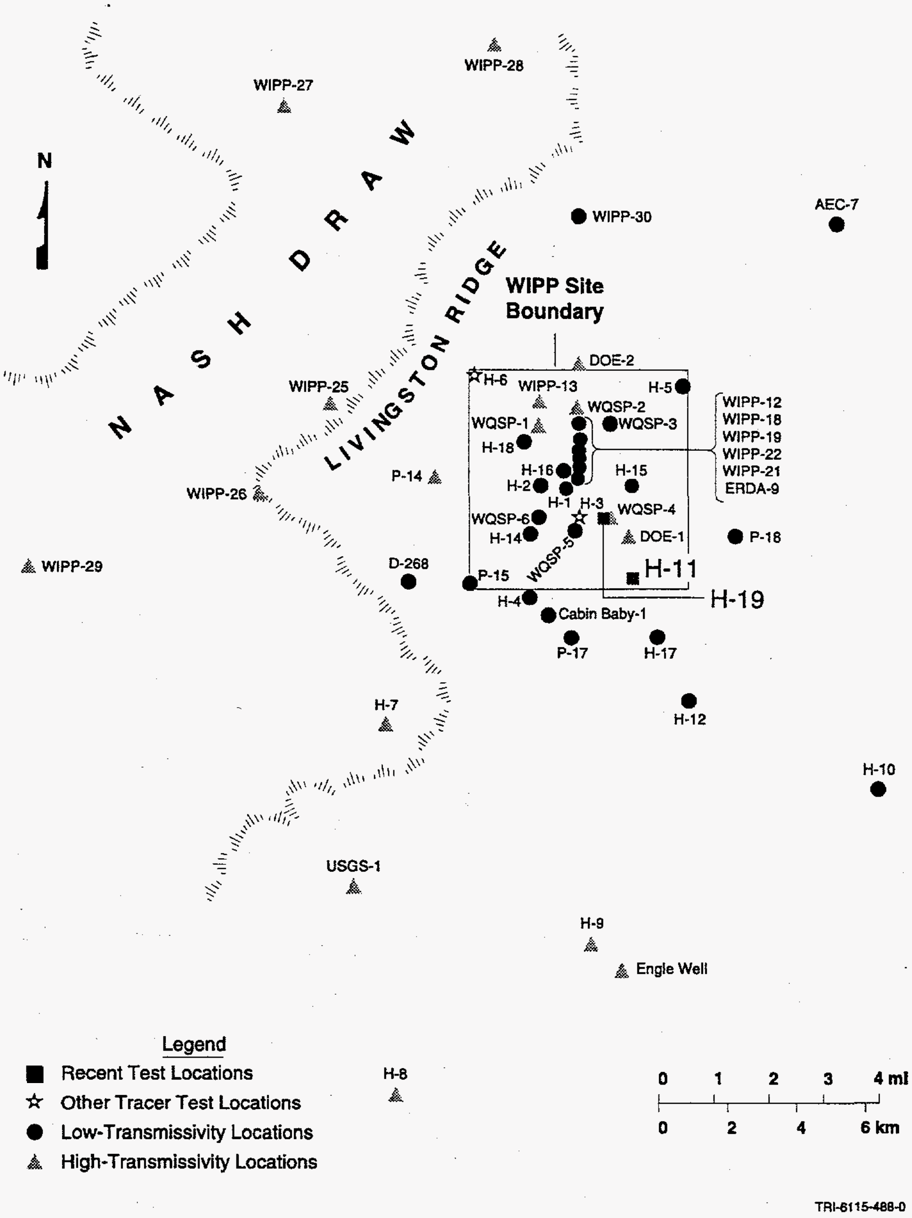

Figure 3. Locations of Culebra dolomite wells around the WIPP site

matrix system used in the model was found to be unimportant, as long as the ratio of fracture surface area to matrix volume was held constant and diffusion did not reach the center of the matrix blocks during the simulation. Thus, cubic matrix blocks (three orthogonal fracture sets) could be replaced with slabs (a single set of horizontal fractures) by decreasing the fracture spacing by a factor of three.

Preliminary Performance Assessment

For preliminary performance assessments, models of radionuclide transport treated the Culebra as a double-porosity medium with uniformly spaced horizontal fractures over its entire thickness and spatially varying transmissivity. The 1992 preliminary PA performed 70 simulations of the entire repository/geosphere system with Monte Carlo sampling of varying representations of the Culebra transmissivity field and varying values of fracture spacing (matrix block length), matrix porosity, fracture porosity, matrix distribution coefficients (K_ds), fracture-surface K_ds, radionuclide solubilities, and 42 other parameters. For each simulation, a complementary cumulative distribution function (CCDF) was calculated displaying the probability that radionuclide releases will exceed calculated quantities, as required by regulation (Figure 7). Based on sensitivity studies [5], the various sampled parameters were ranked as "critically important", "very important", "important", and "less important" in terms of their potential to affect releases of radionuclides from the site. For parameters in the first three categories, reductions in uncertainties have the potential to shift the position of the mean CCDF near the regulatory limit. The sensitivity analyses showed fracture spacing, matrix K_ds, and radionuclide solubilities to be "very important" parameters, the transmissivity field and matrix porosity to be "important" parameters, and fracture porosity and fracture-surface K_ds to be "less important" parameters.

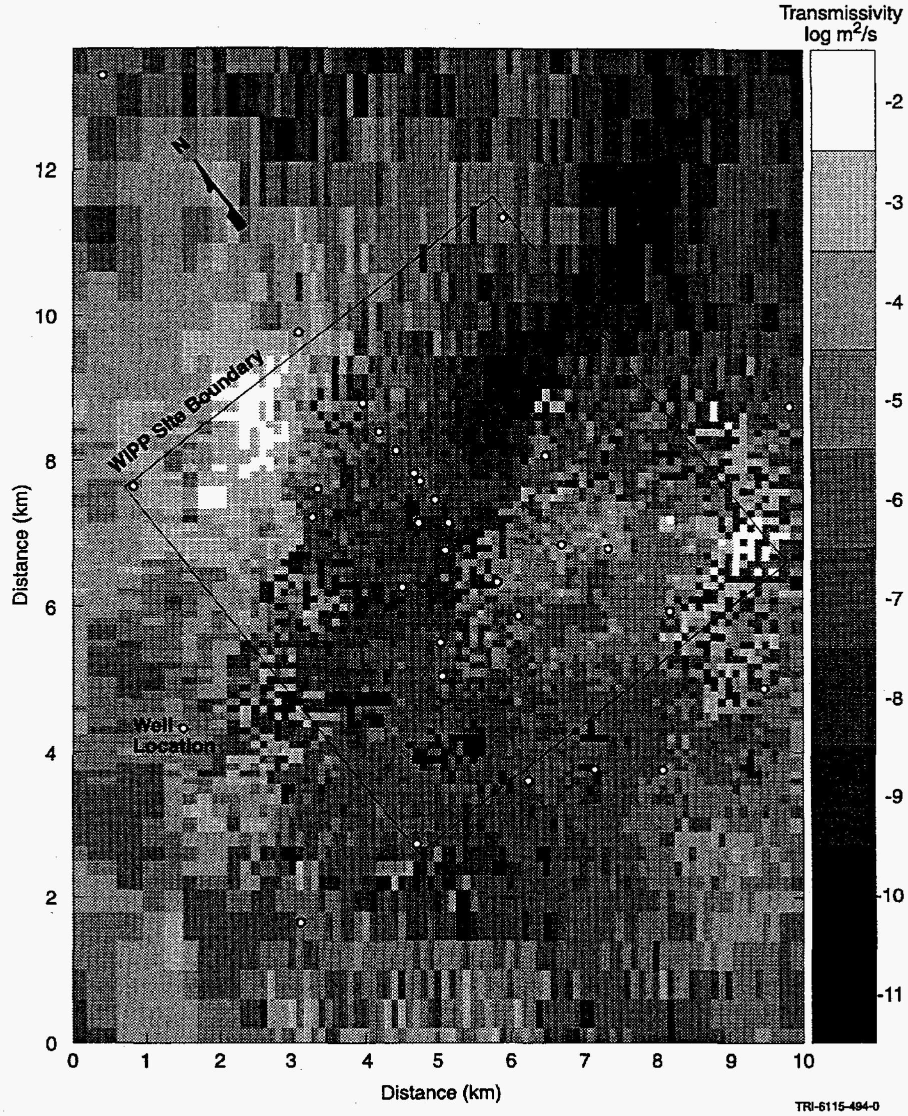

Figure 4. Transient-calibrated transmissivity field no. 77

Two questions arose from the PA sensitivity studies: (1) Is the interpretive model applied to the tracer-test data, and extended to PA, defensible? (2) If so, can the ranges of parameter values used by PA be justified and defensibly narrowed if necessary and, in particular, can we confidently quantify the amount of diffusion we expect to occur? To gain insight into these questions, the tracer-test interpretations and PA modelling were presented to numerous review and regulatory groups, including INTRAVAL, the U.S. National Academy of Sciences, the U.S. Environmental Protection Agency (EPA), and the New Mexico Environmental Evaluation Group. Comments received from these groups indicated that the data were not adequate to rule out alternative conceptual models for transport that might have different implications when applied to PA. Specific comments pertained to: (1) the interpretive model's reliance on matrix diffusion as the sole cause of the tailing of the breakthrough curves, neglecting the possible effects of complexities in the tracer source term, small-scale heterogeneity in permeability along the travel paths, and diffusion into stagnant (or slow-moving) water within low-aperture or poorly connected parts of fractures; (2) the validity of the assumption that the Culebra is vertically homogeneous; and (3) reliance on hydraulic anisotropy to explain directional differences in transport.

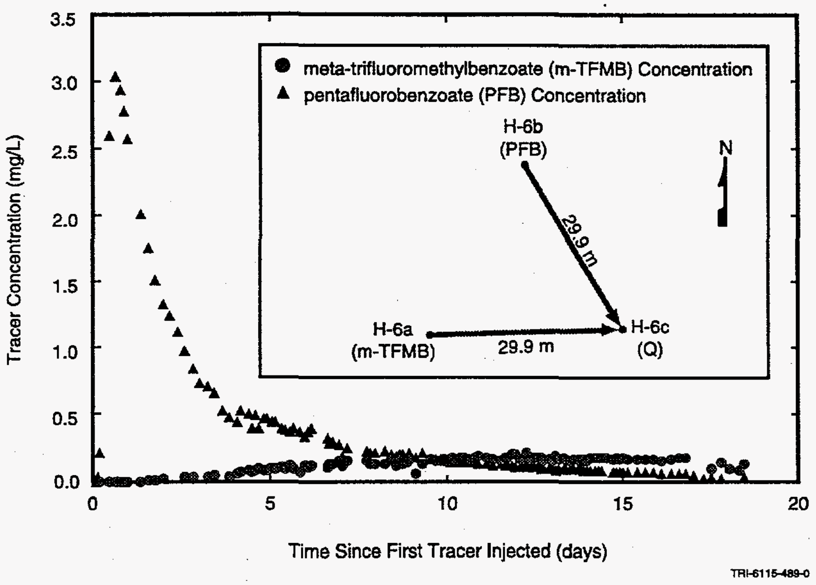

Figure 5. Breakthrough curves for the H-6 convergent-flow tracer test

New Tracer Tests

As a result of these comments, an expanded field tracer-testing program was developed [6], with strong ties to laboratory programs. The scope of the field program was developed through extensive interactions with the review groups and other interested scientists. The primary objectives of the tracer-testing program were to: (1) test for the occurrence of matrix diffusion in the Culebra; (2) quantify or bound the amount of matrix diffusion occurring, which involves a combination of fracture spacing, matrix porosity, and matrix tortuosity; (3) evaluate the effects of layering within the Culebra on flow and transport; and (4) investigate the causes of directional differences in transport within the Culebra. We anticipated that by meeting these objectives, we would be able to either verify that the model previously used was adequate or develop a new model, as well as develop defensible ranges for the parameters needed for modelling.

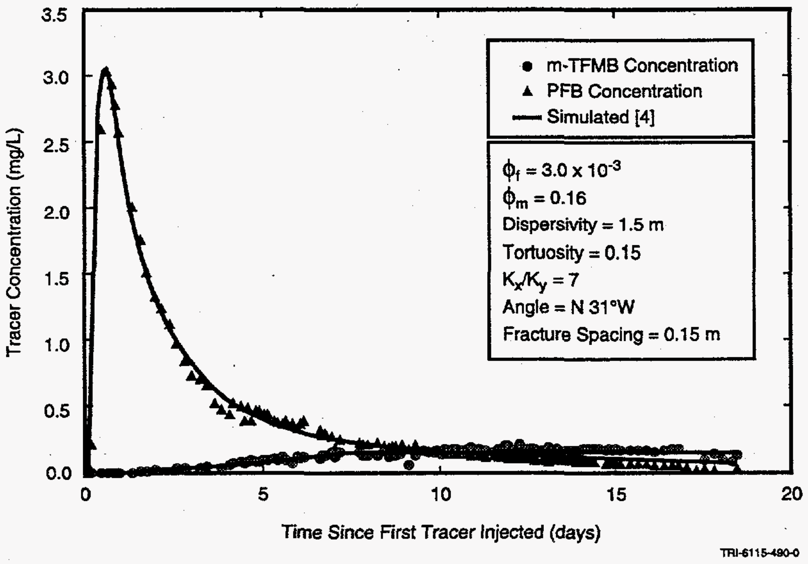

Figure 6. Anisotropic double-porosity simulation of H-6 breakthrough curves

Four elements in the design of the new tests were focused on the demonstration and quantification of

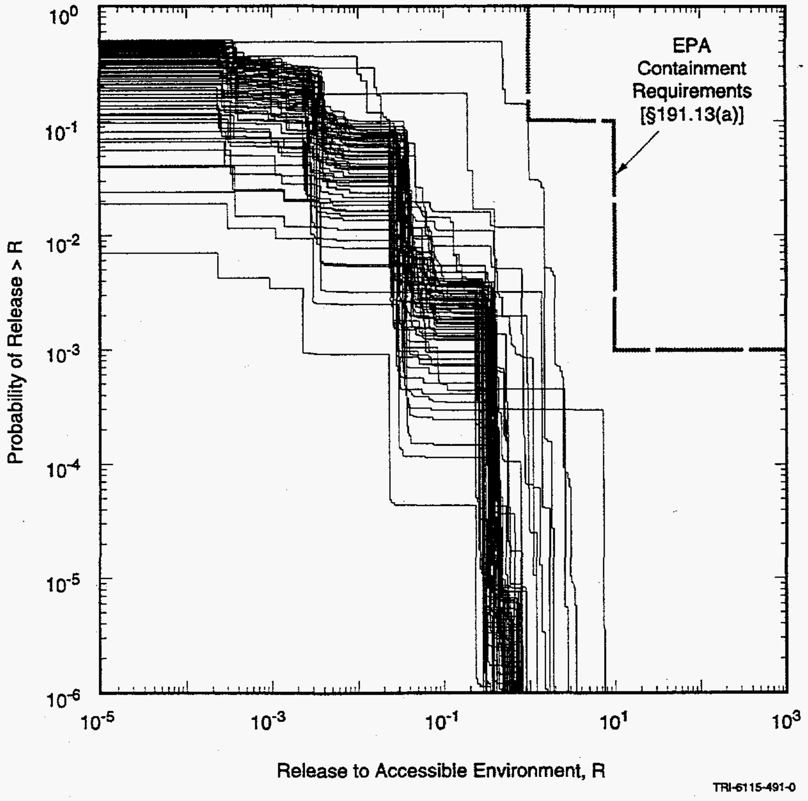

Figure 7. Example of CCDFs for normalized radionuclide release to the accessible environment from the WIPP [5]

matrix diffusion. First, a single-well injection-withdrawal (SWIW) tracer test was planned which was expected to distinguish clearly between the effects of matrix diffusion and heterogeneity in permeability. Pretest simulations comparing the effects of matrix diffusion and heterogeneity showed that the recovery curves were significantly different for single-porosity as compared to double-porosity conditions. Double-porosity simulations produce a recovery curve with tracer concentration decreasing asymptotically as $1/t^{3/2}$, which appears as a constant slope of -3/2 on a log-log plot of normalized tracer concentration (C/C_0) vs. time since injection (t) (Figure 8). All single-porosity models, regardless of the degree of heterogeneity, showed more rapid tracer-mass recovery than the models that included matrix diffusion (Figure 9). Second, two different conservative tracers having different free-water diffusion coefficients were to be injected together in a convergent-flow tracer test to show the effects of different amounts of diffusion (Figure 10). Third, tracer injections were to be repeated in convergent-flow tests performed at different pumping rates to show the effects of velocity on diffusion (Figure 10). Fourth, a tool was designed that would allow (1) release of tracer downhole without overpressurizing the wellbore and (2) measurement of the downhole tracer concentration in an injection well as a function of time. By comparing the breakthrough curve obtained using this type of "passive" injection and a known source term to those obtained using pressurized "slug" injections with uncertain source terms, we hoped to

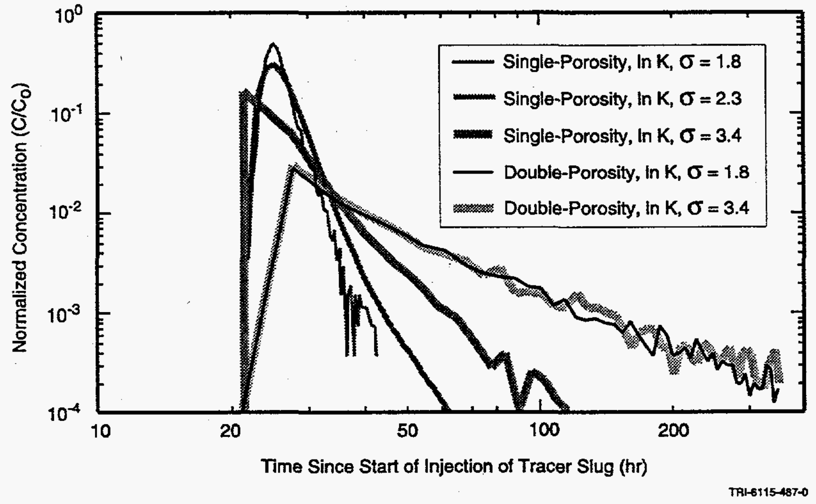

Figure 8. Example tracer-recovery curves for single-well test: heterogeneous, single- and double-porosity models

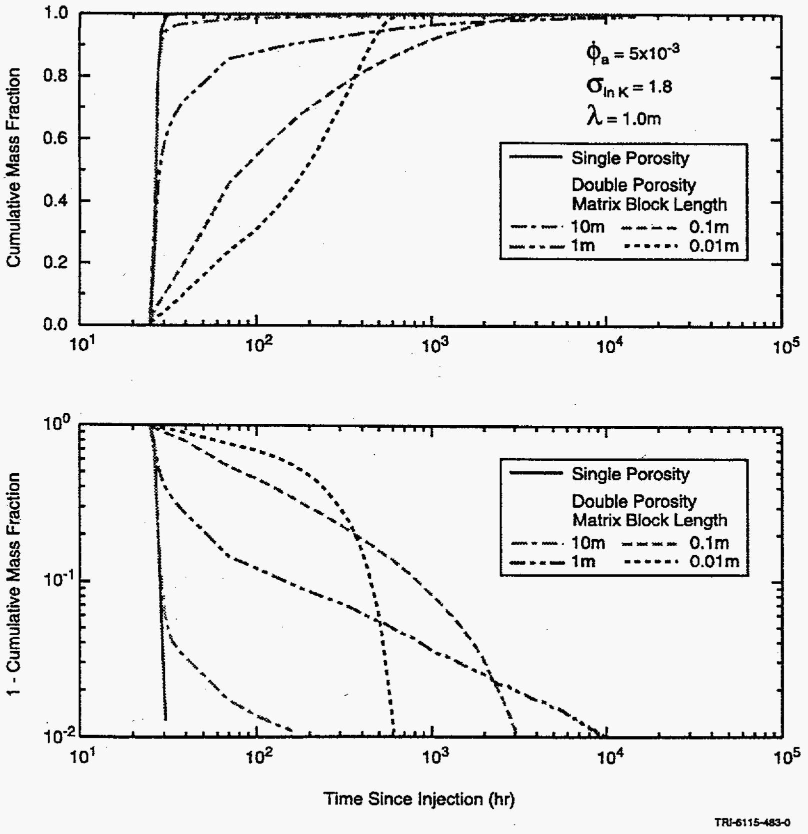

Figure 9. Example mass recovery curves for single-well test using heterogeneous, single- and double-porosity models

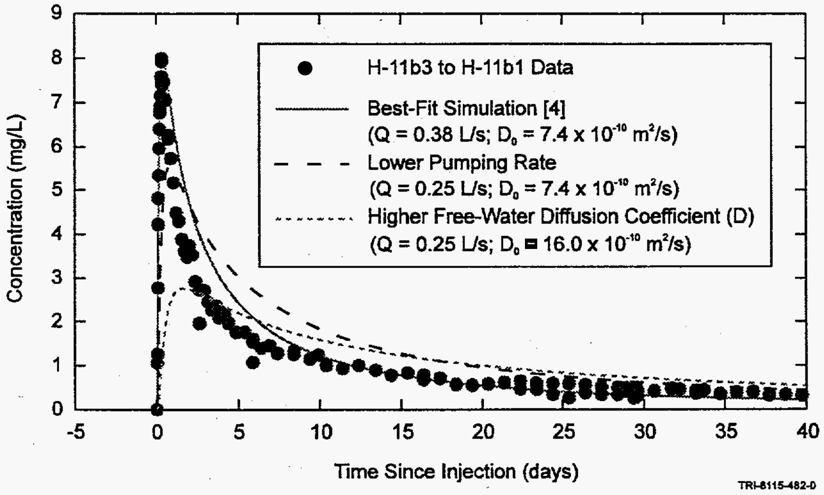

Figure 10. Simulations showing effects of decreased pumping rate and increased diffusion coefficient

determine if we were inappropriately attributing the effects of source-term complexities to matrix diffusion. Unfortunately, problems with this tool prevented its use during the tracer tests.

To evaluate the significance of layering in the Culebra, tracer injections were planned into the upper and lower portions of the Culebra to provide breakthrough curves to compare to those obtained from injections over the full thickness. To evaluate whether directional differences in transport were caused by anisotropy alone or combined with heterogeneity, tracer injections were planned in six wells at different distances and orientations from a central pumping well. If all six tracer-breakthrough curves could not be matched using a single anisotropic model, heterogeneity would be assumed to be a significant factor in transport.

A new seven-well location, the H-19 hydropad, was established for the tracer testing (Figure 11). The H-19 hydropad was located along what is believed to be the likely groundwater pathway in the Culebra from above the repository to the WIPP site boundary. Tracer testing was planned in stages, with a preliminary test to be performed after four wells had been completed to aid in selecting locations for the remaining three wells. The

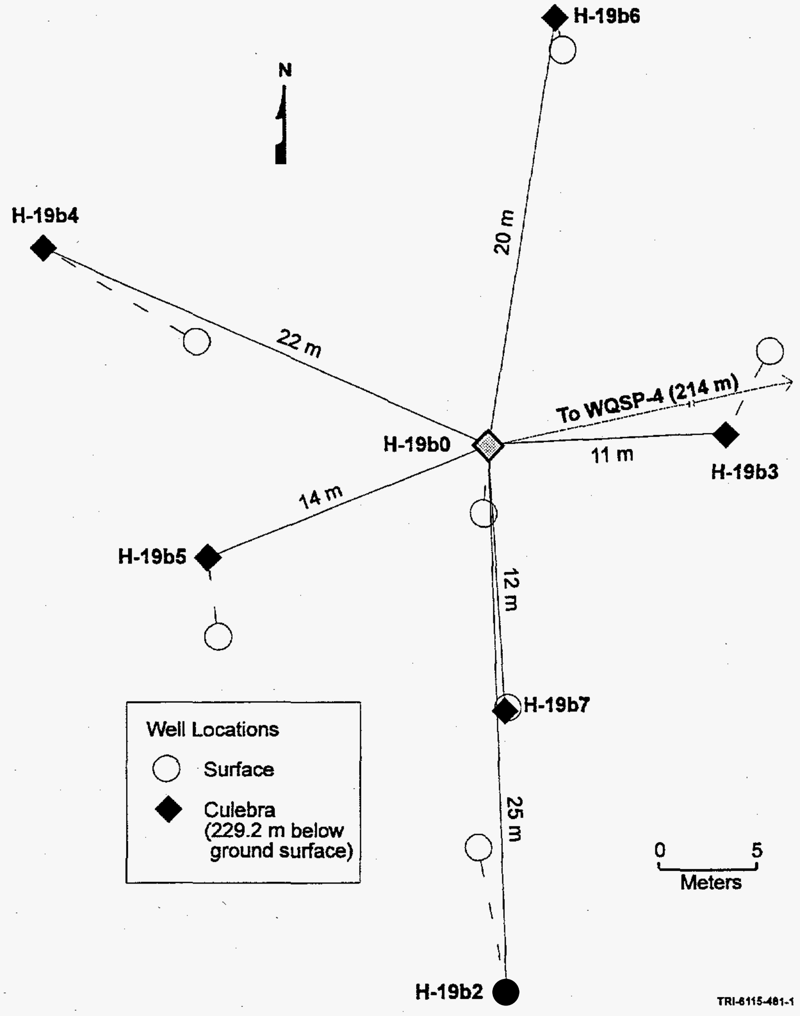

Figure 11. Well locations at the H-19 hydropad

information obtained from the preliminary test would also aid in the design of a more comprehensive series of tests to be performed involving the full seven-well array. Based on the information obtained from the preliminary test, additional testing was also planned for one of the locations previously tested, the H-11 hydropad, to resolve uncertainties associated with the previous test at that location. Information on the results of the tracer testing at the H-19 and H-11 hydropads is presented in a companion paper [7].

Associated Testing

In conjunction with the tracer-testing program, a hydraulic-testing program was established to: (1) characterize the between-well hydraulics of the Culebra at the H-19 hydropad; (2) measure vertical variations in permeability at the H-19 hydropad; and (3) allow for better definition of the Culebra transmissivity field. The information obtained in meeting the first two objectives listed above was used in refining the design of the tracer tests at the H-19 hydropad. The between-well hydraulics at the H-19 hydropad were evaluated by performing cross-hole sinusoidal pumping tests. For these tests, packers were set in each of the wells on the hydropad to divide the Culebra into upper and lower segments. Four tests were then performed by successively pumping the upper and lower Culebra in wells H-19b0 and H-19b4 while monitoring pressure responses in the other isolated zones in the various wells. The pumping began with a constant-rate phase to establish a dominant pressure trend at the hydropad, and then shifted to a sinusoidal rate sequence. The sinusoidal pumping rates produced sinusoidal pressure responses in the observation zones that could be readily distinguished from on-going responses to other hydraulic stresses (Figure 12). The test responses showed the upper and lower Culebra to be poorly connected over at least a portion of the H-19 hydropad. Also, anisotropy alone probably could not explain the directional differences observed in the responses.

Vertical variations in permeability were evaluated using three different techniques. First, water production was monitored during drilling in those wells in which the Culebra was cored using compressed air as the circulation medium, while pressures in nearby wells were monitored to see if the responses differed as different parts of the Culebra were penetrated. Little water production and negligible pressure responses were observed when the upper approximately 3 m of Culebra was drilled. Water production and

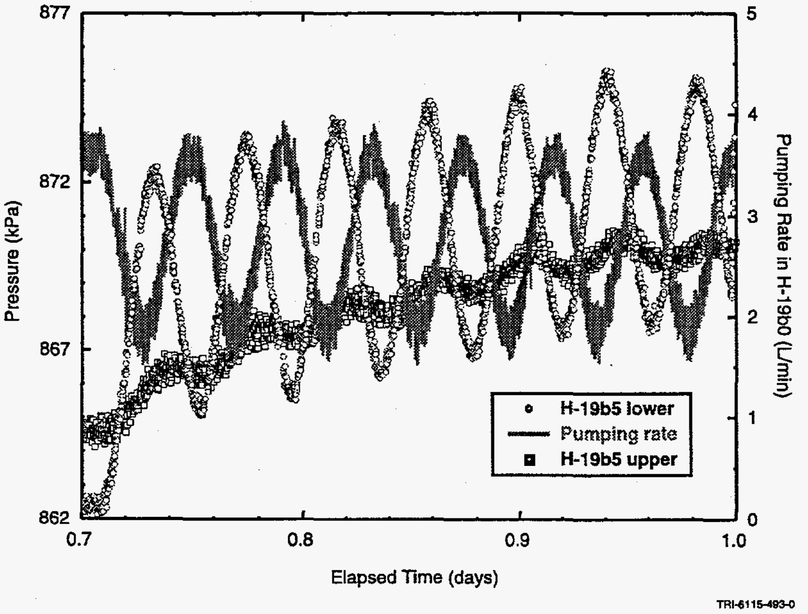

Figure 12. Pressure responses in monitoring well H-19b5 and rate sequence in lower zone of active well H-19b0

pressure responses increased significantly as the lower portion of the Culebra was drilled (Figure 13). Second, upper and lower Culebra permeabilities were assessed from the sinusoidal pumping tests discussed above. Third, hydrophysical logging [8] was conducted in three of the H-19 boreholes. This logging confirmed the absence of significant flow in the upper few meters of Culebra and showed unevenly distributed flow throughout the lower section of the Culebra (Figure 14).

Because a convergent-flow tracer test also constitutes *de facto* a long-term pumping test, pressures/water levels were monitored during the tracer test in all observation wells that had responded to previous tests on the H-19 hydropad. The transient responses observed in these wells were used to improve the calibration of the Culebra T fields.

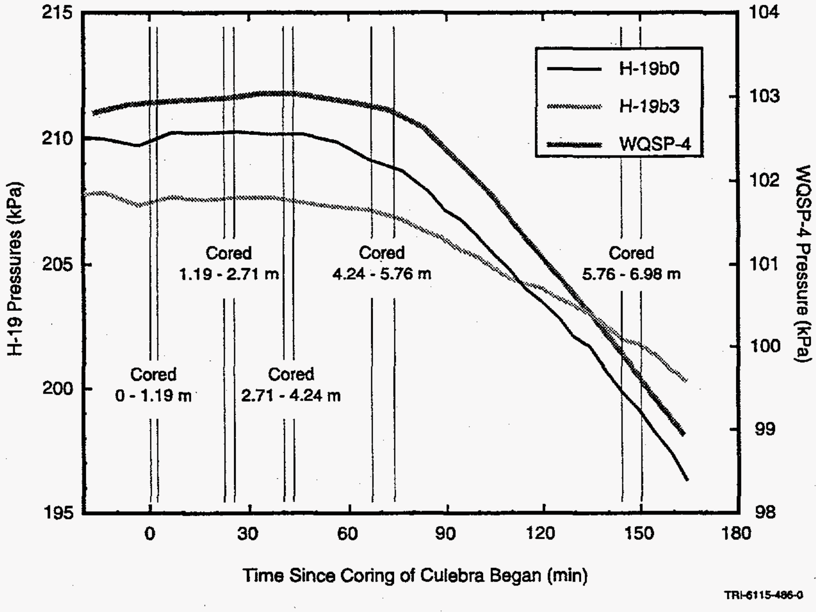

Figure 13. Pressure changes in observation wells during coring of H-19b2

The field program was also integrated with laboratory programs measuring radionuclide solubilities, sorption on the Culebra matrix, and matrix porosity, tortuosity, and permeability. The combination of these field and laboratory programs addressed all of the "very important" and "important" transport-related parameters identified from the 1992 PA sensitivity analyses. The data and, in some instances, revised conceptual models resulting from these studies were used in the performance assessment that was a part of the Compliance Certification Application submitted by the DOE to the EPA in October 1996.

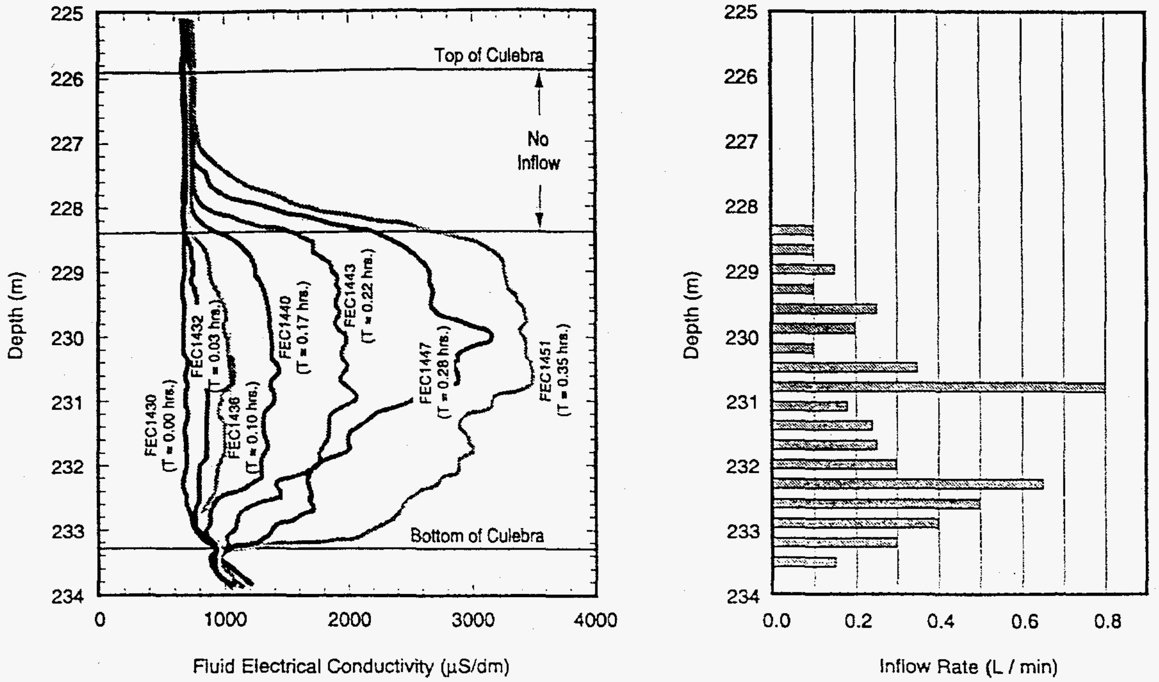

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Figure 14. Hydrophysical logging results and inflow simulation for H-19b0

Summary

In summary, information gathered during site characterization was used to develop a conceptual model of the hydrogeology of the WIPP site. Regulatory requirements led to the consideration of a pathway from a Castile brine reservoir through the repository to the Culebra. Preliminary PA modelling of this pathway showed that WIPP's compliance with regulatory release limits could be affected by the model and parameter ranges used to describe transport in the Culebra. The model and parameter ranges used by PA were scrutinized by different review groups, who concluded that there was inadequate experimental justification to rule out alternative models and parameters. Accordingly, a new series of tracer tests was planned to address the review groups' criticisms and provide a defensible model and parameters for PA modelling. The test design focused on improving our understanding of matrix diffusion, the effects of layering in the Culebra on transport, and the causes of directional differences in transport. The tracer tests were linked to other field and laboratory studies providing additional data needed by PA. The data and, in some instances, revised conceptual models resulting from these studies were used in the performance assessment that was a part of the formal certification application for the WIPP submitted by the DOE to the EPA in October 1996.

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