Field-Test Programs of Borehole Plugs in Southeastern New Mexico

C. L. Christensen* and E. W. Peterson†
*Sandia National Laboratories, Albuquerque, NM; †Systems, Science and Software, La Jolla, CA

This paper gives a general overview of the repository-sealing field test effort being conducted by Sandia National Laboratories in support of the Waste Isolation Pilot Plant in southeast New Mexico. Summary descriptions of supporting activities, such as performance assessment and plugging materials development, are included to create the connection between modeling and laboratory activities as they relate to field results. Results of tests on a portion of a 17-year-old plug (Plug 217) recovered from a mine horizon and the Bell Canyon Test, in which a cement plug was emplaced to isolate a naturally pressurized aquifer, are given. Conclusions from these field plugging tests are included.

Introduction

This paper provides an update on the Sandia Borehole Plugging Program (BHP) (Christensen and Hunter, 1979), as reported at the October 1979 National Waste Terminal Storage (NWTS) Information Meeting (Christensen, 1979b) sponsored by the Office of Nuclear Waste Isolation (ONWI) and included in the proceedings of the information meeting (Office of Nuclear Waste Isolation, 1979). As reported by Christensen, the Sandia BHP is specifically designed to support plugging activities for the proposed Waste Isolation Pilot Plant (WIPP) being considered by the Department of Energy (DOE) for storing defense non-heat-producing transuranic waste. This program will also provide generic information on bedded-salt formations to ONWI for inclusion in the NWTS commercial nuclear waste repository programs. The goal of the Sandia BHP is to provide the plugging technology that will be required at the decommissioning and final closure of the WIPP facility.

At the time of the 1979 meeting, the program and field-test emphasis was on using cementitious plugging materials and modifying existing industrial emplacement techniques as needed to suit repository plugging requirements. These efforts, coupled with supporting laboratory testing, consequence-assessment modeling of wellbores and plugs, and an ONWI-sponsored geochemical program to evaluate long-term interactions between the host rock and the plug were considered adequate to provide the technology required for repository plugging. It is encouraging that, at present, this emphasis is still considered adequate. Development and progress in the BHP from January 1979 through May 1981 disclosed no serious gaps in the program as originally planned, and there is high confidence that progress toward the goal will continue. Cementitious plugging materials are still considered appropriate for repository sealing. Two basic expansive grout formulations—a freshwater mix, designated BCT-1FF, and a brine-based mix, designated BCT-1F—having water-to-cement (w/c) ratios on the order of 0.3 and permeabilities in the range of 0.1 to 10 μdarcy (Gulick, 1980; Gulick et al., 1980) continue to be the prime candidates for plugging the overlying-underlying formations and the salt horizons, respectively, at the WIPP site. These mixes show evidence of good compatibility with the respective host rocks, and steps are now under way at the U. S. Army Corps of Engineers Waterways Experiment Station (WES) to assess the inclusion of $CaSO_4$ into the freshwater mixes to provide an enhanced compatibility. The ONWI-sponsored geochemical research programs at both WES (where the principal investigator is Katherine Mather) and the Pennsylvania State University (PSU) Materials Research Laboratory (where the principal investigator is Della Roy) include these mixes and modifications in the long-term geochemical assessment of material interactions. Steven Lambert, in the Sandia WIPP program, developed a theoretical technique for the continuous precipitation and deposition of particulate salt from brine within a wellbore to replace salt removed during drilling. Laboratory-scale demonstration of the process was completed in late 1981, and full-scale field-test demonstrations will follow. Successful demonstration of this salt deposition-replacement technique will provide confidence that the wellbore will eventually be healed by natural redistribution of stress, thus restoring the formation within the salt horizon to near its pre-drilled state. Progress in materials development suggests that the proper materials and techniques will be available when they are required at repository closure.

Field-testing experience with cementitious materials indicates that emplacement techniques routinely used within the oil-field cementing industry will be adequate for repository plugging operations. Any modifications that may be required are expected to involve only minor changes; no new technology will be required.

Consequence assessment calculations (Department of Energy, 1980) for the WIPP site indicate that even the most severe conditions of regional fluid flows through the repository via unplugged wellbores will not result in significant consequences to the public. Unplugged wellbores in and near a repository will be plugged, however, to develop even greater assurance in the isolation provided.

The proposed WIPP repository will be approximately 2150 ft deep in the Salado bedded-salt formation (Powers et al., 1978). Figure 1 shows a generalized stratigraphy of the site. The primary protection required of a wellbore plug is to minimize possible fluid migration through the repository. Consequently, the field effort is directed at understanding and quantifying the effect of a plug in reducing possible flows in the plugged region.

The first of the field efforts undertaken in 1979 assessed the effectiveness of an existing plug in media similar to those at the WIPP. A potash exploration hole drilled and plugged in 1961 was intercepted at the ore horizon in a working potash mine. Approximately 0.8 m^3 of rock, including the plug (Plug 217) was removed and sawed into nominal 20-cm-thick sections perpendicular to the plug axis. One sample section each was sent to the WES and PSU for analysis. The results of the petrographic analysis (Buck and Boa, 1979; Scheetz et al., 1979) indicated that the plug did set up and was relatively competent with regard to bond strength. The plug had a high water-to-cement (w/c) ratio (approximately 0.7), in contrast to the currently used high-strength expansive grouts with a w/c near 0.3. This difference could account for the permeabilities of the

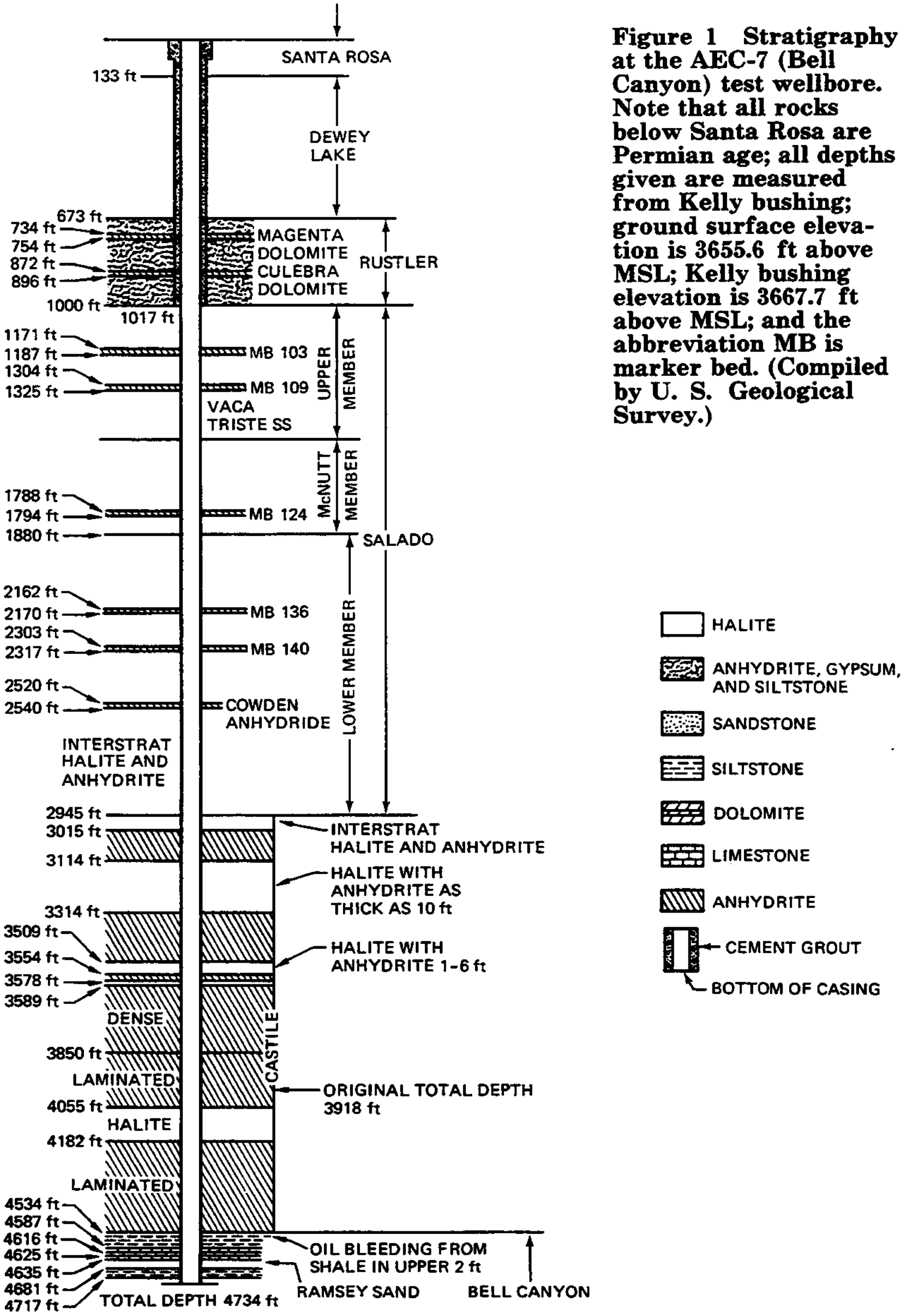

Figure 1 Stratigraphy at the AEC-7 (Bell Canyon) test wellbore. Note that all rocks below Santa Rosa are Permian age; all depths given are measured from Kelly bushing; ground surface elevation is 3655.6 ft above MSL; Kelly bushing elevation is 3667.7 ft above MSL; and the abbreviation MB is marker bed. (Compiled by U. S. Geological Survey.)

plug-formation complex, which were on the order 5 to 50 mdarcy—much higher than the values of 10 μdarcy possible with more recently designed plug mixes (Gulick, 1980). Consequently, it was determined that, even though the relatively long in-place time of the plug should lead to valuable insights on plug performance, the unknowns associated with the original mix preclude confidence in the 1961 technology.

The second field effort in 1979 was the initiation of the Bell Canyon Test (BCT) in late March in the AEC-7 wellbore, located near the proposed WIPP Site in southeast New Mexico. The results of this test are reported by Christensen and Peterson (1981). Excerpts from that report follow.

Background

The Bell Canyon Test was the culmination of prior efforts to develop materials tailored to the WIPP lithology. Previous work in the BHP program centered around cementitious grouts as candidate plug materials because the technology was available and developed, costs were reasonable, and these materials exhibited long-term stability and competency.

Before the BCT, grout development for borehole plugging had progressed to the point that candidate mixes were available (Gulick et al., 1980). Emplacement techniques had been demonstrated in an earlier field test which another drill hole, ERDA-10, was plugged (Gulick, 1979). It was appropriate then to test a grout mix in situ to determine the level of performance that could be obtained and compare the results with system performance. The Bell Canyon Test objectives were to evaluate in situ the state of the art in borehole plugs and to identify and resolve problems encountered in evaluating a "typical" plug installation in anhydrite.

The concept was to place a plug in contact with a naturally pressurized fluid source in the field and determine the resulting restriction of fluid flow. While simple in concept, the testing was complex in execution and evaluation: trade-offs had to be made between emplacing the shortest possible plug that would allow reasonable fluid flows over a short testing time and using the minimum length that could be physically emplaced as a representative installation. Clearly these are competing effects. The shorter the plug, the higher and faster is the flow under a given pressure differential; hence the time is shorter, and the expense of the test is lower. Conversely, the longer the plug, the more representative it is of a typical plug installation, and the time and expense required to assess its performance increase correspondingly. These details were resolved and presented in the test plan for peer review before the test began (Christensen, 1979a). After the peer reviews, the resulting comments and suggestions were considered, and an operational plan was developed for conducting the test. The Bell Canyon Test evaluated a 2-m-long grout plug 1370 m deep in a 20-cm-diameter borehole and exposed to a 12.4-MPa pressure differential.

Wellbore Preparation

An abandoned exploratory hole [AEC-7, which was drilled by Oak Ridge National Laboratory (ORNL) in April 1974 (Statler, 1980)], located approximately 11 km northeast of the center of the proposed WIPP site, was selected for the BCT. The wellbore configuration at the completion of the ORNL effort consisted of a surface conductor to 15 m, $8\frac{5}{8}$-in.-diameter cemented casing into the Salado Formation to 310 m, and a $7\frac{13}{16}$-in.-diameter open hole to total depth of 1194 m.

Reentry began on Mar. 19, 1979, and the wellbore was cleared to total depth in preparation for drilling to the Bell Canyon high-pressure aquifer. The wellbore was deepened by continuous coring through the lower anhydrite of the Castile Formation into the Delaware Mountain Group until the high-pressure aquifer was intercepted in the Ramsey sands between 1413 and 1426 m. The hole was extended to a total depth of 1435 m. Figure 1 shows the stratigraphy of the AEC-7 wellbore, and Fig. 2 shows the BCT configuration as emplaced. Before the plug was installed, the Bell Canyon aquifer pressure was established at 12.4 MPa at the intended plug location (1370 m) by a series of three drill-stem tests. Once the high-pressure aquifer was intercepted and the suitability of the wellbore as a test bed for the BCT was established, preparation continued for the emplacement of the plug. During and after the reentry and coring phases, routine geophysical logs and permeability testing of the Salado Formation were conducted to support the BHP and other WIPP-related tasks (Statler, 1980; Peterson, 1981)

Grout Development

The most advanced candidate material currently available for plugging boreholes is high-quality cement grout, which is the focus for the

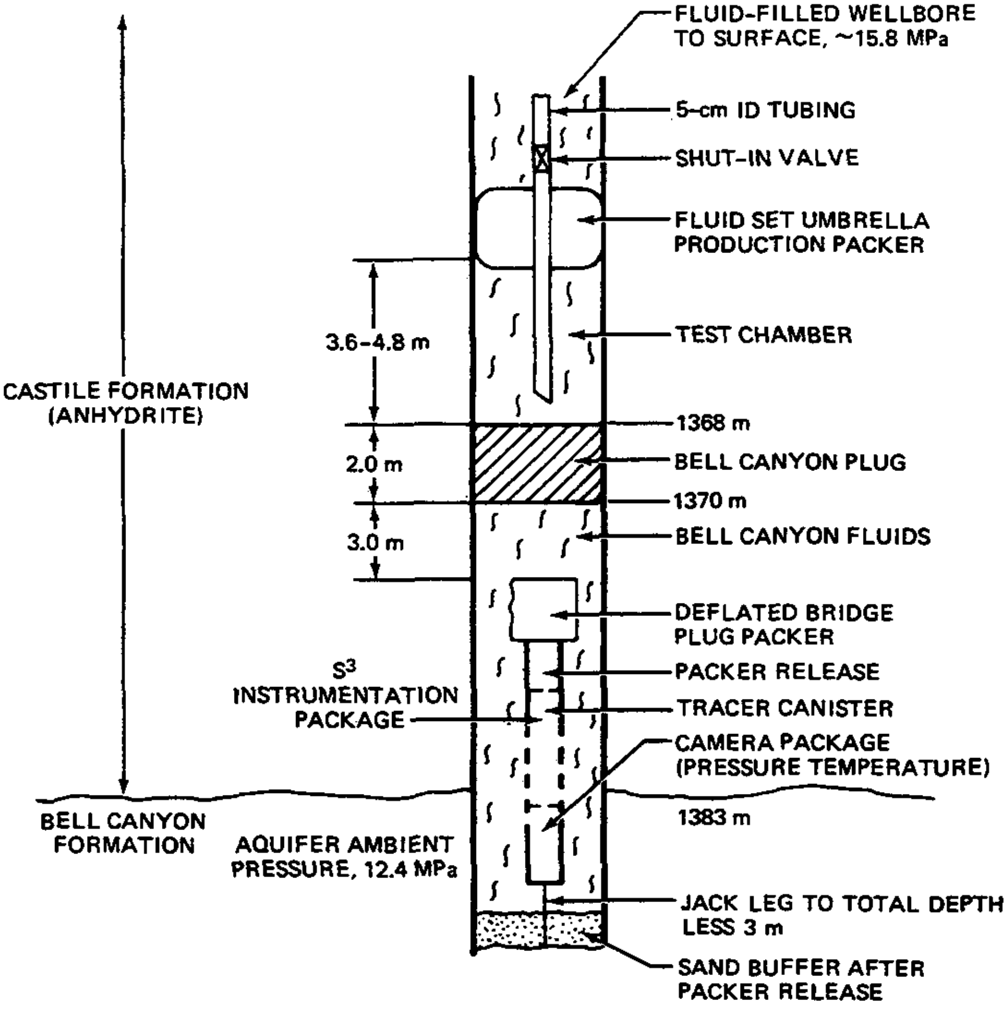

Figure 2 As-built BCT test bed (not to scale).

long-range development and testing program at WES (Gulick, 1978) and which provided the basis for selecting the BCT plug mix.

In general, desirable properties of plugging grouts are low permeability, low porosity, high mechanical bond strength with the host rock, expansivity, homogeneity, pumpability, and geochemical stability. Lower w/c ratios are correlated with lower permeability and porosity and higher density and strength. The w/c ratio has been reduced by controlling the coarseness of the cement; including super plasticizers and turbulence-inducing compounds, which enhance the fluidity of the mix; using retarders to control set times; and controlling slurry temperature (Gulick et al., 1980).

Previous laboratory experience at WES suggested a grout mixture of Class H cement and a proprietary additive provided by Dowell Division of the Dow Chemical Company. Twenty-four candidate mixtures were formulated and tested by WES for time of efflux, workability, density, and strength under accelerated curing. Dowell further developed this mixture (Table 1), designated BCT-1F, by including a powder dispersant (Gulick, 1980).

After the borehole was cored to intercept the Bell Canyon aquifer, the plug location was selected in the basal Castile anhydrite. The BCT-1F was tested for short-term compatibility with anhydrite core by WES, PSU, ORNL, and Dowell (Gulick, 1980; Grutzeck et al., 1980; Moore et al., 1981).

These investigators found permeabilities of the various grout-anhydrite samples ranging from 10^{-3} to 10^{-6} darcy. The BCT-1F grout samples consistently had permeabilities less than 10^{-6} darcy. Grout-filled anhydrite cores leaked at the interface, and some samples, particularly those cured at ambient temperatures of about 22°C, exhibited a white powdery deposit at the interface (Gulick, 1980). The push-out bond strength was in excess of 2.5 MPa (Gulick, 1978; Grutzeck et al., 1980; Moore et al., 1981).

An alternate freshwater grout, designated BCT-1FF, was also formulated for further testing (Table 1). The w/c ratio was increased to an acceptable viscosity and pumpability. The fresh-water grout had a higher strength and greater expansion than the salt grout (BCT-1F), and its push-out bond strengths were equal to or greater than those of the saltwater

Table 1 Ingredients and Properties of Grout

	BCT-1F	BCT-1FF
Ingredients, wt.%		
Class H cement	50.1	52.2
Expansive additive*	6.7	7.0
Fly ash	16.9	17.6
Salt (NaCl)	6.5	
Dispersant*	0.2	0.2
Defoamer*	0.02	0.02
Water	19.5	23.0
Properties		
Water-to-cement ratio	0.26:1.0	0.30:1.0
Fluid density, g/cm^3	2.04	1.98

**Proprietary additives of the supplier (Dowell).*

grout. Permeabilities of the BCT-1FF grout-rock sample ranged from 1 to 15 μdarcy. The grout adhered more tightly to the rock, and there was no observable leakage at the interface (Gulick, 1980). The BCT-1FF mixture was selected for the BCT plug.

One conclusion resulting from the testing of grout-rock samples was that push-out bond-strength tests should not be related to plug permeability. This result has led to the inclusion of permeability testing as a routine part of plug material evaluation. Results of studies to date have been published, and investigations of grout properties are continuing at Sandia, WES, and PSU. Full details of the BCT grout development, selection, and emplacement are given by Gulick (1980).

Instrumentation

Instrumentation has been developed to evaluate the environment in which plugs are placed and to determine the performance of emplaced plugs (Cook, 1979; Cook et al., 1980). Developments to support specific tests include:

- A guarded straddle-packer system to evaluate the permeability of the formation
- A self-contained instrumentation package incorporating a timed-release tracer gas, temperature and pressure measurements, and a packer-release system
- A geophone system to monitor release functions
- Fluid buildup and shut-in pressure measurements with current oil-field systems
- Probes for measuring discrete fluid leaks, fluid electrical conductivity, pressure, and temperature
- A wire-line closed-circuit TV system capable of operating in drill holes to a depth of 1000 m

The instrumentation systems to monitor the migration of tracer gas and brine through the plugged region were used to evaluate the BCT plug performance. The original plan was to create a pressure differential across the plug by applying the Bell Canyon production zone pressure to the plug bottom, with the upper wellbore fluids evacuated. Upper wellbore fluid production precluded this approach, however, and an "umbrella" packer was used to create a test chamber above the plug (Fig. 2).

As shown in Fig. 2, a packer below the plug, deflated after the cement had cured, ensured that the plug was being loaded by the production zone. Also included below the plug was an instrumentation package containing multiple charges of time-released electronegative tracer gas (sulfur hexafluoride, SF_6). The instrumentation package monitored fluid pressure and temperature below the plug, and the tracer gas allowed for assessment of multiphase flow through the plugged region. Since there were no cable penetrations through the plug, all these functions were controlled by preset timers in the instrument canister (Cook et al., 1980).

Test Description

The test configurations used for evaluating the Bell Canyon plug performance are shown in Fig. 3. The plug was installed to isolate the upper regions of the borehole from the Bell Canyon aquifer, which has a 12.4-MPa shut-in pressure and a production capability of $3.8 \times 10^7\ cm^3/d$ (240 standard barrels per day, STB/d). The aquifer temperature and pressure were continuously monitored by the instrumentation package described. Measurements were made of both the volumetric flow and the velocity of fluid flowing from the aquifer through, or around, the plug into the upper wellbore. Because the upper portions of the borehole produce fluid, the umbrella packer was installed

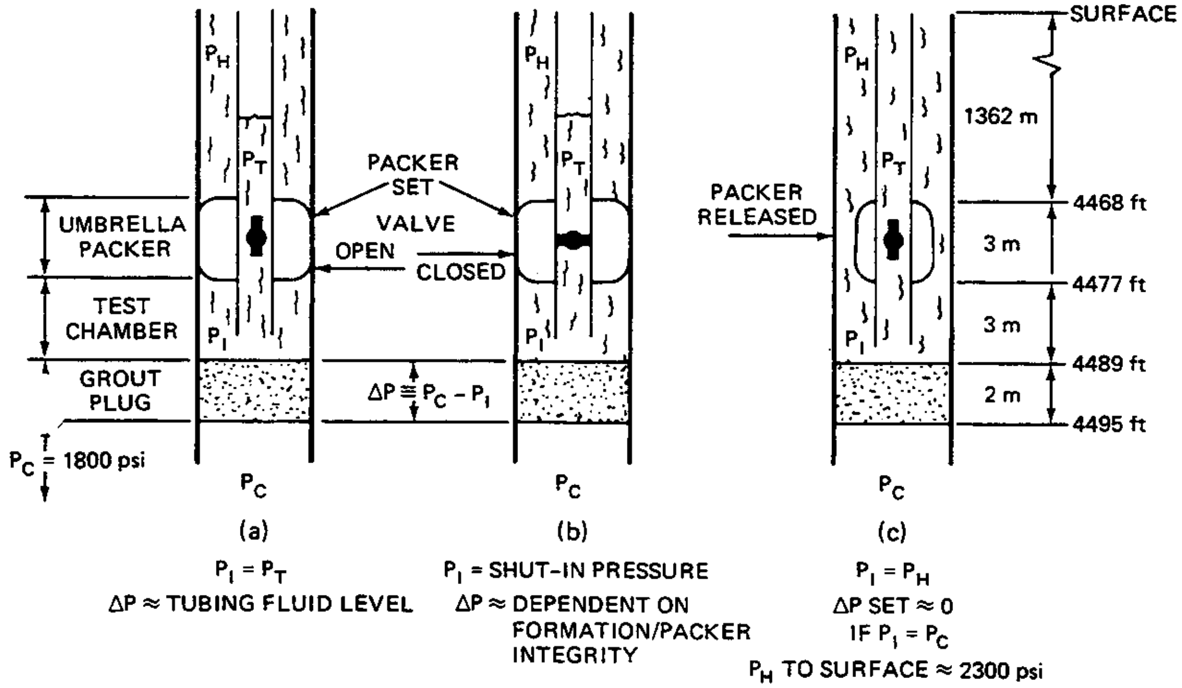

Figure 3 Schematic showing testing techniques. (a) Fluid buildup tracer flow. (b) Shut-in. (c) Neutral. P_H is hydrostatic pressure. Pressure is 0.519/ft depth.

(Fig. 3) to provide an isolated test chamber for measurement purposes. The pressure in the wellbore annulus above this packer was approximately 15.8 MPa.

Since plug performance is evaluated from measurements of fluid intrusion into the test chamber, it is important to identify possible flow paths into the region. As shown schematically in Fig. 4, four distinct fluid charge paths exist from the aquifer through, or around, the plug into the test region. These are the cement plug; the plug-borehole interface region, in which some porous microstructure may exist either as a result of bonding imperfections or chemical reactions; a possible damage region along the borehole wall resulting from drilling and coring operations; and the undisturbed formation surrounding the plug. It is, in fact, the flow occurring along all these paths, defined as the plug-formation system, which must be measured.

Additional possible paths along which fluid can enter or leave the test region also exist. These include flows from above the umbrella packer through the surrounding formation or wellbore damage region and flows occurring along some formation discontinuity leading to a distant source.

Finally, depending on the configuration, test measurements are influenced by leakage from the umbrella packer (including leakage from the packer valves) and attached tubing assembly through joints in the 2-in. tubing string leading to the surface. Flow occurring along these paths must be differentiated from that occurring through the plug-formation system.

In addition to tests to characterize the wellbore in the vicinity of the plug, three specific techniques to evaluate the plug-formation system performance are shown schematically in Fig. 3. These include the fluid

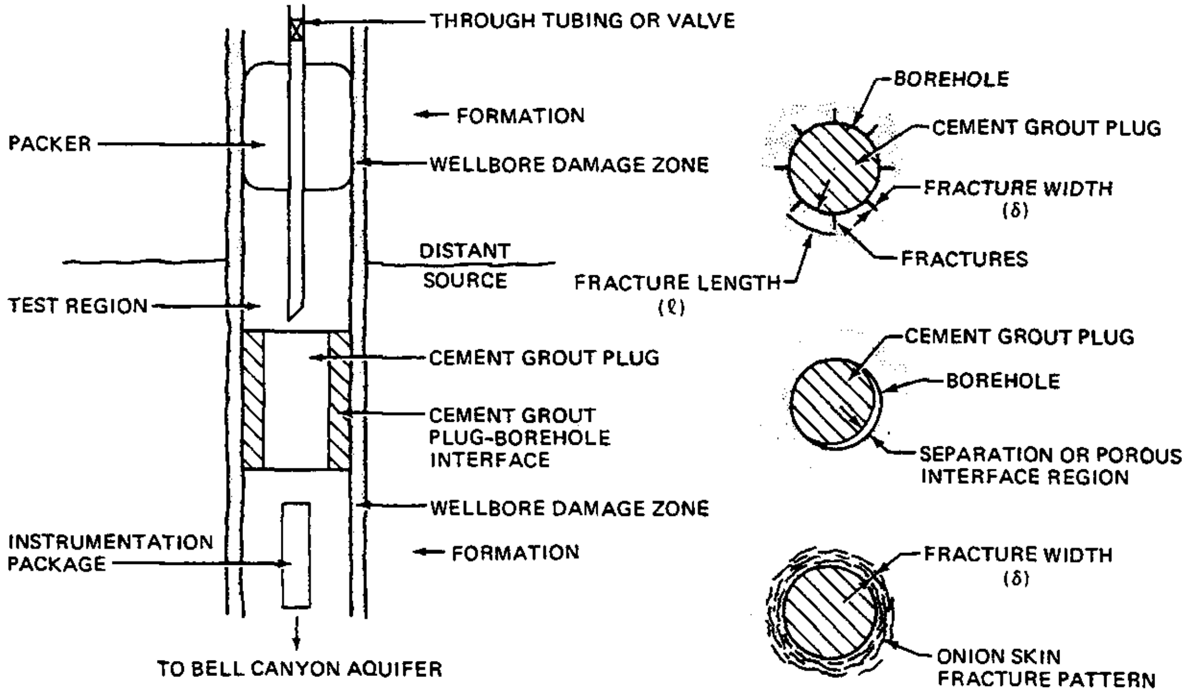

Figure 4 Schematic showing possible fluid charge paths in the test region.

buildup, shut-in, and tracer-flow tests discussed in detail in the following paragraphs. Since standard oil-field technology was used for data acquisition, the measurement sensitivity of these techniques and its associated impact on plug performance assessment is also discussed by Christensen and Peterson (1981).

Data Analysis

The data analysis is intended to characterize (i.e., to determine the permeability, porosity, cross-sectional area, fracture extent, etc.) the flow paths originating below the plug and penetrating into the test region (shown in Fig. 4). Available data include the experimentally measured test-region pressures, water accumulation rates, tracer arrival times, and pressures in the annulus and Bell Canyon aquifer. Additional inferences can be made by using data from laboratory tests of grout and grout anhydrite permeability. Therefore there is a classic problem under a specified set of boundary conditions in which a number of constants, representing the formation characteristics and flow-path geometries, need to be evaluated. A rigorous derivation of the equations defining the flow through this plug-formation system is given by Christensen and Peterson (1981).

Test Results

System Integrity–Wellbore Characterization Test Results. Before the BCT grout plug was installed, system-integrity and plug zone characterization tests were performed. The system configuration generally appeared as shown in Fig. 2, with the exception that the inflated bridge plug was positioned at the cement grout plug location and Freon tracer gases were used to preclude "poisoning" the wellbore with the SF_6 used after plug emplacement. Fluid buildup test rates are shown in Fig. 5 for two potential plug locations.

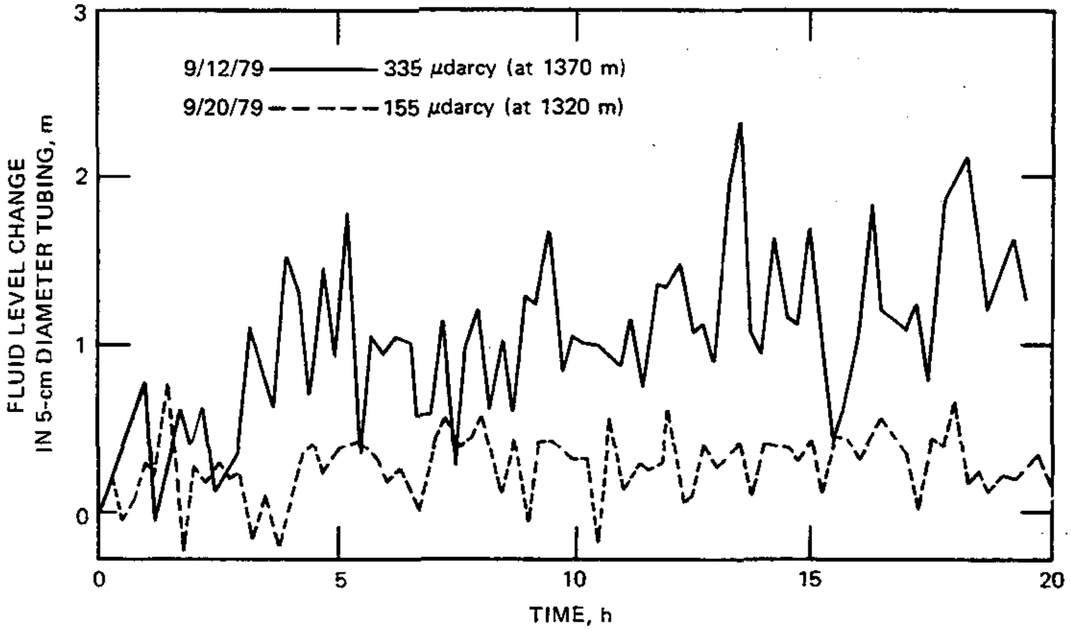

Figure 5 **Fluid buildup test data obtained during plug zone characterization studies. Changes in fluid level were determined from pressure changes measured with the Lynes CWL system.**

Plug Performance Test Results. Performance characteristics of the emplaced BCT grout plug were monitored over a 4-month period, beginning Oct. 9, 1979. Results of the fluid buildup, shut-in, and tracer-flow tests are summarized in Tables 2, 3, and 4, respectively. Individual test results are discussed in the following paragraphs, and the overall system performance is described fully.

Fluid Buildup Tests. Five fluid buildup tests were conducted. Data obtained during four of these tests are shown in Fig. 6. The Oct. 19 test was continued for a total of 144 hr, with the fluid rise continuing at roughly the rate shown in the figure. The fluid level was measured with a wire-line tool at 1330 and 1296 m on Dec. 21 and Jan. 11, respectively. These measurements represent the data for the last test shown in Table 2.

The changes in fluid level in the 5-cm diameter tubing (Fig. 6) were determined from measured pressure changes. The relatively rapid fluctuations do not represent actual changes in fluid level but reflect noise in the pressure-monitoring system.

The permeability-area (kA) products shown in Table 3 were determined from measured inflow rates (Q) in the test region. Inflow rates were evaluated using straight-line approximations of the data shown in Fig. 6. Since fluctuations in the Oct. 9 and 10 data are large in comparison with the average increase in fluid level occurring during the 18-hr test periods, the method of least squares was used to obtain best straight-line fits for these data. Because of the intensity of the fluctuations, we can only state that the data indicate that kA values are less than 2.5×10^{-10} cm^4 (80 μdarcy under the wellbore cross-sectional area assumption).

The Oct. 9 and 10 data definitely indicate the lowest test-chamber inflow rates. Any leakage through, or around, the packer–tubing assembly would result in increased rates. Therefore, of the fluid buildup test results, these are probably most representative of the plug–formation system performance.

Table 2 Summary of Fluid Buildup Test Results

Test initiation date	Test duration, h	Measured test region inflow rate,* cm^3/d	Flow path permeability area† (kA), 10^{-10} cm^4
10/09/79	18	320	0.9 (27 μdarcy)
10/10/79	18	670	1.8 (57 μdarcy)
10/19/79	144	4600	12.0 (385 μdarcy)‡
12/12/79	16	7100	(607 μdarcy)‡
12/21/79	504	3300	(275 μdarcy)‡

**Inflow rate obtained for a 12.4-MPa pressure differential across the 2.0-m-long cement grout plug.*

†Numbers in parentheses indicate the permeability for a flow path whose cross-sectional area is taken equal to that of the wellbore.

‡High values are thought to result from leakage into the test region through the tubing packer assembly since they are not supported by shut-in test or tracer-transit data.

Table 3 Summary of Shut-In Test Results

Test initiation date	Test duration, h	Measured test region inflow rate,* cm^3/d	Flow path permeability area† (kA), 10^{-10} cm^4
11/05/79	67	610	1.6 (51 μdarcy)
12/19/79	62	830	2.3 (70 μdarcy)
01/18/80	100	550	1.5 (46 μdarcy)

**Inflow rate obtained for a 12.4-MPa pressure differential across the 2.0-m-long cement grout plug.*

†Numbers in parentheses indicate the permeability for a flow path whose cross-sectional area is taken equal to that of the wellbore.

Table 4 Summary of Tracer Flow Test Results

Tracer release	Time until first arrival,* h	Permeability-to-porosity ratio (k/ϕ), 10^{-11} cm^2	Maximum flow channel width (δ), 10^{-5} cm	Maximum channel flow velocity, m/d
10/09/79	68	2.2	1.5	.6
10/30/79	36	3.3	2.0	1.2
12/12/79	36	3/3	2/0	1.2
01/18/80	No sampling			

**Time until first arrival for a continuous 12.4-MPa pressure differential acting across the 2.0-m-long cement grout plug.*

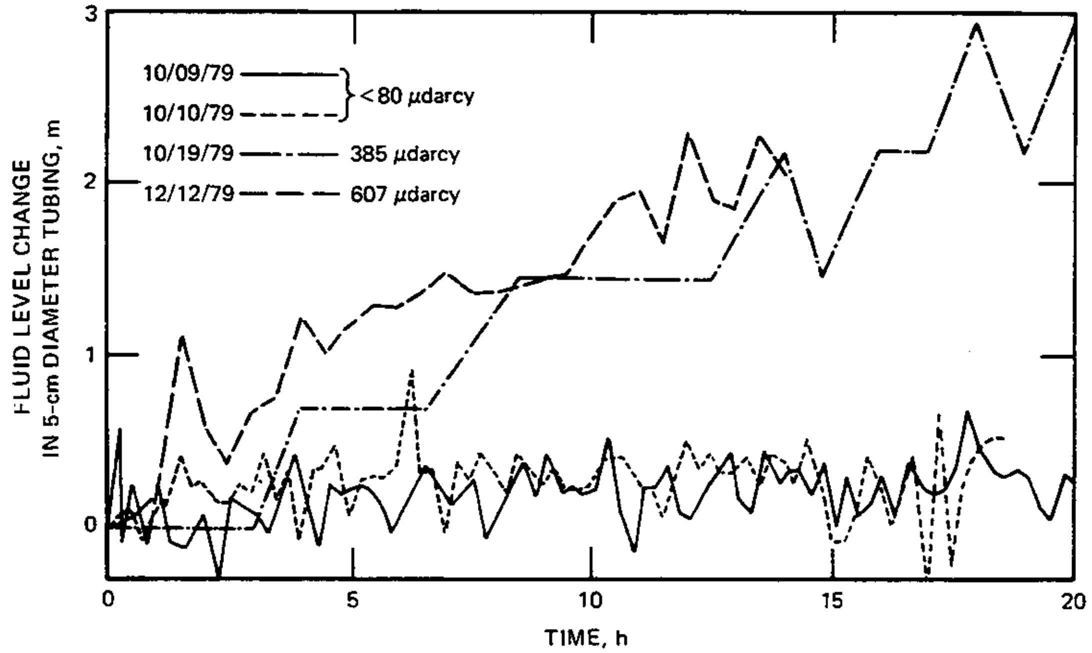

Figure 6 Fluid buildup test data obtained during plug performance evaluation studies. Fluid level changes were derived from pressure changes.

Shut-In Tests. Data obtained during the three shut-in tests, shown in Fig. 7, can be well represented by the simple one-dimensional model and the values of kA shown in Table 3. Results of the shut-in tests were consistent and indicated that the plug-formation system responds as if there were an approximately 50-μdarcy flow path of cross-sectional area equal to that of the wellbore.

During the Dec. 19 test, a significant time lapse occurred between shut-in and the onset of the rapid pressure buildup phase. Also, at late times the pressure continued to increase above the Bell Canyon value. The delayed initial response is thought to be the result of an air bubble trapped in the tubing that extends into the test region below the umbrella packer. A small flow from the annulus region can account for the higher late-time pressure. Both of these effects were modeled (as illustrated in Fig. 7) with the simple one-dimensional formulation. The air bubble was modeled as a 1.1 l void, on the basis of the field-determined geometry of the test assembly. The product $(kA)_a = 3.3 \times 10^{-11}$ cm^4 refers to an assumed annular formation disturbed zone surrounding the umbrella packer. Using a cross-section area of this zone equal to the wellbore cross section (325 cm^2), we obtain a value of 10 μdarcy for the disturbed zone, in comparison with 70 μdarcy for the plug zone. Subsequently, the packer-valve-tubing assembly was modified to eliminate the possibility of air entrapment, and the Jan. 18 test was performed for data verification.

It is important to note that there is no evidence of flow from the high-pressure annulus into the test region during the Nov. 5 and Jan. 18 pressure buildup tests. This strongly suggests that, at least in the area where the umbrella packer is positioned, wellbore damage is slight. Assuming a damage area equal to the wellbore area, these shut-in tests are consistent with an equivalent permeability on the order of 10 μdarcy. Note also that the flow observed from the

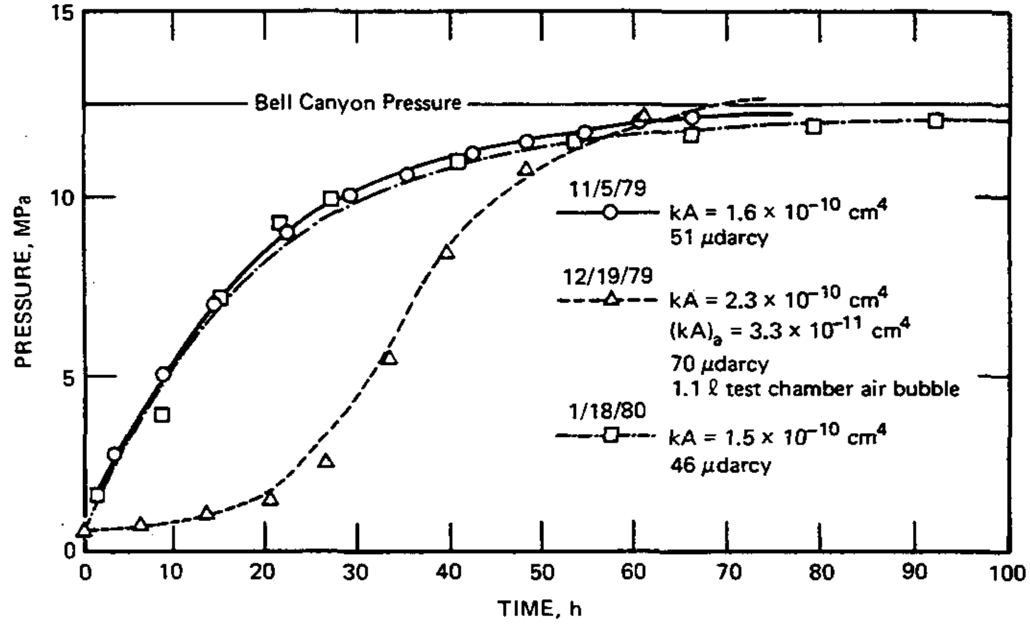

Figure 7 Shut-in test data obtained during plug performance evaluation studies. The symbols (○, △, □) indicate measured data, and curves show calculated response.

annulus region during the Dec. 19 test could have just as readily occurred through the packer-valve-tubing assembly. Leakage through this assembly is believed to be responsible for the higher flow rates measured during the fluid buildup tests.

Tracer-Flow Tests. A history of the tracer sampling tests is presented in Table 5. The approximately 36-hr time interval between gas release and detection at the top surface of the plug was well established after the Dec. 12 series of tests. Further sampling was, therefore, discontinued.

Tracer release and arrival time measurements are consistent with having flow occur from below the plug into the test region through a channel (i.e., fracture) that is 2.0 m long and 2×10^{-5} cm wide at a velocity of 1.2 m/d. Analysis indicates that larger channel widths would allow significantly higher velocities and correspondingly earlier tracer arrivals. If all flow were to occur through such fractures (e.g., if the wellbore exhibited an onion-skin-type failure, as illustrated in Fig. 4) and if the individual fracture lengths (l) (measured in the horizontal plane having a depth of the 2.0-m plug vertically) were equal to the wellbore circumference, then approximately 4000 such fractures would be required to produce the measured volumetric flow rate. This suggests that flow through the plug-formation system does not occur through a small number of fractures but rather through a region where the behavior of the microstructure approximates, to a reasonable extent, that of a porous medium.

When interpreted in terms of flow through a classical porous medium, the tracer data indicate a permeability-to-porosity ratio of $k/\phi = 3.3 \times 10^{-11}$ cm^2 (33 μdarcy, assuming $\phi = 0.01$). If the actual cross-sectional area (A) of the flow path through the plug-formation system (see Fig. 4) is known, the associated permeabilities and porosities cannot be determined. There is evidence that plug permeabilities are small and that flow occurs primarily through a

Table 5 History of Tracer Sampling Tests

Tracer release date	Sampling date	Tracer detected	Remarks*
	10/08/79	No	Background check
10/09/79	10/12/79	Yes	Arrival had occurred in 68 h
	10/18/79	Yes	
	10/27/79	Yes	Wellbore fluid replaced
	10/29/79	Trace	Background check
10/30/79	10/31/79	Trace	
	11/01/79	Yes	Arrival had occurred in 36 h
	12/06/79	Trace	Background check
12/09/79	12/11/79	No	
	12/12/79	No	
	12/13/79	Yes	Arrival had occurred in 36 h
01/18/80			No further tracer samples were taken

**Arrival times represent the tracer transit time, given a continuous 12.4-MPa pressure differential across the 2.0-m cement grout plug. The actual wellbore pressure history is used to determine this value.*

permeable microstructure at the plug borehole interface (Gulick, 1980; Grutzeck et al., 1980). Required permeabilities and porosities of such an interface zone (see Fig. 4) are shown in Fig. 8 as a function of flow-zone cross-sectional area.

Conclusions

The field test programs undertaken thus far provide confidence that satisfactory isolation of radioactive waste is technically feasible. Results from Plug 217 testing and the Bell Canyon t[illegible] show that fluid flow restrictions can be achieved by cementitious plugs. The degree of restriction can be included in transport models to predict radionuclide egress rates through wellbores from the geologic storage horizons. These, in turn, can be used to provide estimates of the amount of radionuclide reentry to the biosphere and the resulting consequences with regard to public health and safety.

Both freshwater and brine-based grouts, suitable for field emplacement, are available now to provide sealing functions if the proper care is exercised in matching physical properties of the local rock. The reduction in fluid flow provided by even limited-length plugs is far in excess of that required by bounding safety assessments for the WIPP.

Field-testing techniques to evaluate in situ plugs have been developed. Although these techniques were generally adequate to evaluate the Bell Canyon plug, some improvements must be made in the system if resolution for lower (less than 50 to 100 μdarcy) permeabilities are needed.

References

Buck, A. D., and J. P. Boa, 1979, *Examination of Grout and Rock from Duval Mine, New Mexico,* Miscellaneous Paper SL-79-16, U. S. Army Corps of Engineers, Waterways Experiment Sta-

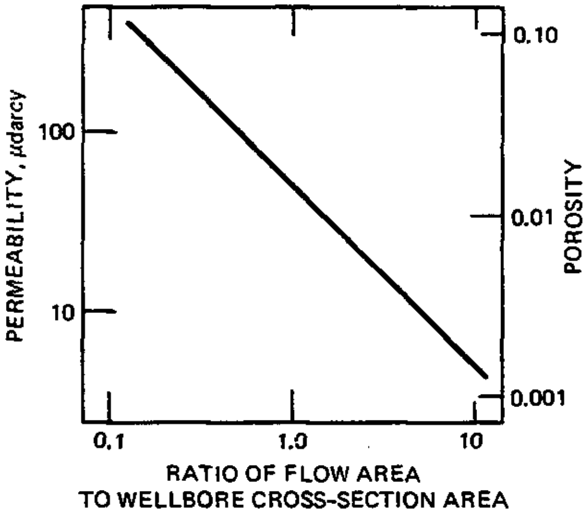

Figure 8 Relationship between flow zone permeability, porosity, and cross-sectional area, based on one-dimensional analysis of measured data.

tion, Structures Laboratory, Vicksburg, MI.

Christensen, C. L., 1979a, Test Plan, *Bell Canyon Test, WIPP Experimental Program, Borehole Plugging,* DOE Report SAND-79-0739, Sandia National Laboratories, NTIS.

——, 1979b, *Field Test Programs of Borehole Plugs in Southeastern New Mexico,* DOE Report SAND-79-1634C, Sandia National Laboratories.

——, and T. O. Hunter, 1979, *Waste Isolation Pilot Plant (WIPP), Borehole Plugging Program Description, January 1979,* DOE Report SAND-79-0640, Sandia National Laboratories, NTIS.

——, and E. W. Peterson, 1981, *The Bell Canyon Test Summary Report,* DOE Report SAND-80-1375, Sandia National Laboratories, NTIS.

Cook, C. W., 1979, *Instrumentation Development for the Waste Isolation Pilot Plant (WIPP) Borehole Plugging Program (BHP),* DOE Report SAND-79-1902, Sandia National Laboratories, NTIS.

——, C. B. Kinabrew, P. Lagus, and R. Broce, 1980, *Bell Canyon Test (BCT) Instrumentation Development,* DOE Report SAND-80-0408C, Sandia National Laboratories, NTIS.

Department of Energy, 1980, *Final Environmental Impact Statement, Waste Isolation Pilot Plant,* Vols. 1 and 2, DOE Report DOE/EIS-0026, Assistant Secretary for Defense Programs, Washington, DC.

Grutzeck, M. W., B. E. Scheetz, E. L. White, and D. M. Roy, 1980, Modified Cement-Based Borehole Plugging Materials: Properties and Potential Longevity, in *Proceedings of the OECD/DOE Workshop on Borehole and Shaft Plugging,* Columbus, OH, May 7–9, 1980, Organization for Economic Cooperation and Development, Paris.

Gulick, C. W., Jr., 1978, *Borehole Plugging—Materials Development Program,* DOE Report SAND-78-0715, Sandia National Laboratories, NTIS.

——, 1979, *Borehole Plugging Program, Plugging of ERDA No. 10 Drill Hole,* DOE Report SAND-79-0789, Sandia National Laboratories, NTIS.

——, 1980, *Bell Canyon Test (BCT) Cement Grout Development Report,* DOE Report SAND-80-1928, Sandia National Laboratories, NTIS.

——, John A. Boa, Jr., Donald M. Walley, and Alan D. Buck, 1980, *Borehole Plugging Materials Development Program,* Report No. 2, DOE Report SAND-79-1514, Sandia National Laboratories, NTIS.

Moore, J. G., M. T. Morgan, E. W. McDaniel, H. B. Greene, and G. A. West, 1980, *Cement Technology for Plugging Boreholes in Radioactive Waste Repository Sites: Progress Report for the Period October 1, 1978, to September 30, 1979*, DOE Report ORNL-5610, Oak Ridge National Laboratory, NTIS.

Office of Nuclear Waste Isolation, *Proceedings of the National Waste Terminal Storage Program Information Meeting*, DOE Report ONWI-62, Columbus, Ohio, October 30–November 1, 1979, NTIS.

Peterson, E. W., 1981, *In Situ Permeability Testing of Rock Salt, Systems, Science and Software*, DOE Report SAND-81-7073, Sandia National Natoratories, NTIS.

Powers, D. W., S. J. Lambert, S-E. Shaffer, L. R. Hill, and W. D. Weart (Eds.), 1978, *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico*, Vols. I and II, Report SAND-78-1596, Sandia National Laboratories.

Scheetz, B. E., M. W. Grutzeck, L. D. Wakeley, and D. M. Roy, 1979, *Characterization of Samples of a Cement-Borehole Plug in Bedded Evaporites from Southeastern New Mexico*, DOE Report ONWI-70, Materials Research Laboratory, Pennsylvania State University, NTIS.

Statler, R. D., 1980, *Bell Canyon Test—Field Preparation and Operations*, Report SAND-80-0458C, Sandia National Laboratories.