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THE BELL CANYON TEST AND RESULTS*

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INTRODUCTION

The Borehole Plugging Program (BHP) at Sandia National Laboratories is sponsored by the Office of Nuclear Waste Isolation (ONWI) under contract to the U. S. Department of Energy (DOE). Its purposes are to identify issues associated with sealing boreholes and shafts, to establish a data base from which to assess the importance of these issues, and to develop sealing criteria, materials, and demonstrative test for the Waste Isolation Pilot Plant (WIPP).^{1,2}

The Bell Canyon Test (BCT)³ (Figure 1), described in this report is one part of that program. Its purpose was 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.

GROUT DEVELOPMENT

The most advanced candidate material currently available for plugging boreholes is high-quality cement. This material is the focus for the long-range development and testing program at the U.S. Army Corps of Engineers, Waterways Experiment Station (WES), Vicksburg, MI.²

Desirable properties of plugging grouts are: low permeability, low porosity, high bond strength, expansivity, homogeneity, easy pumpability, and stability. Lower water-to-cement (w/c) ratios, are correlated with lower permeability and porosity and higher density and strength. Reduction of the w/c ratio

Fig. 1. As-built BCT configuration during monitoring operation (not to scale)

has been achieved by controlling the coarseness of the cement grind, inclusion of super-plasticizers and turbulence-inducing compounds, use of retarders, and slurry temperature control.

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. WES formulated 24 candidate mixtures and tested these 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.

After the borehole was cored, the plug location was selected in the basal Castile anhydrite. Anhydrite core was tested for compatibility with BCT-1F by WES, PSU, Oak Ridge National Laboratory (ORNL), and Dowell.

Permeability of various grout/anhydrite samples ranged from 10^{-3} to 10^{-6} darcies. BCT-1F grout samples consistently had permeabilities less than 10^{-6} darcies. Grout-filled anhydrite cores leaked at the interface and some samples, particularly those cured at ambient temperatures of about 22°C (72°F), had white powder at the interface. The push-out bond strength was in excess of 2.5 MPa (360 lb/in²).

An alternate fresh-water 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, and push-out bond strengths were equal or greater than those of the salt-water grout. Fresh-water grout samples adhered more tightly to the rock, permeability at the interface was less (Table 2), and there was no observable leakage.⁴ The BCT-1FF mixture was selected for the BCT plug.

Results of studies to date have been published and investigations are continuing at Sandia, WES, and Pennsylvania State University (PSU).^{5,6,7,8}

Table 1
Salt and Fresh Water Grout Mixtures

Ingredients (Wt%)	BCT-1F	BCT-1FF
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
<u>Properties</u>		
Water-to-cement ratio	0.26:1.0	0.30:1.0
Fluid Density, g/cm ³ (lb/gal)	2.04 (17.0)	1.98 (17.0)

Table 2
Water Permeability of BCT-1FF Grout Lab Samples

Age (Days)	Permeability, (Microdarcies)		
	Curing Condition		
	1	2	3
25	2.26	13.1	0.88
50	1.37	3.3	0.73
82	1.49	2.09	0.56
110	2.25	4.12	0.73
210	2.84	4.76	0.58

1. Curing temperature curve to 66°C (150°F) at 12 hr, reduced to 38°C (100°F) at 24 hr; constant for 10 days; pressure of 10 MPa (1500 lb/in²) for 10 days
2. Constant temperature of 38°C; pressure of 10 MPa for 8 days
3. Constant temperature of 38°C; ambient pressure for 10 days

INSTRUMENTATION

Plug performance was evaluated by monitoring the upward migration of tracer gas and brine through the plugged region.

A packer below the plug was deflated after the cement had cured (Figure 1) to permit the aquifer brine to reach the plug. Below the plug an instrument package released electronegative tracer gas (SF_6) at various times. The instrumentation package monitored fluid pressure and temperature below the plug, and the tracer gas allowed for measurements of permeability through the plugged region.

TEST RESULTS

The test results are summarized from the work of Peterson and Christensen¹⁰ and are divided into two portions: system integrity and wellbore characterization tests prior to plug installation, and a series of tests to evaluate isolation characteristics of the 1.8-m-long plug. The various testing configurations employed are illustrated in Figure 2.

Fig. 2 BCT during monitor operations

System Integrity and Wellbore Characterization Test

System integrity and plug-zone characterization tests were conducted prior to installation of the plug by using an inflated bridge plug positioned at the plug location. These tests indicated permeabilities of the zone to be on the order of 175-350 microdarcies. The precision of these measurements was limited by the use of routine oil-field techniques.

Fluid Build-up Tests

Changes in fluid level were determined from measured pressure changes. Data from four of these are shown in Figure 3 and summarized in Table 3.

The October 9-10 data definitely indicate the lowest flow rates and are therefore most nearly representative of the plug/formation system performance. Leakage through or around the packer/tubing assembly will also result in increased fluid levels and probably explains the higher values.

Fig. 3. Fluid build-up test data obtained during plug performance evaluation studies

Table 3
Summary of Fluid Build-up Test Results

Test Initiation Date	Test Duration (Hours)	Measured Test Region Inflow Rate* (liters/day)	Permeability-Area Product, kA (10^{-10} cm ⁴)
10/09/79	18	0.32	0.9 (27 μ darcies)**
10/10/79	18	0.67	1.8 (57 μ darcies)
10/19/79	144	4.6	12.0 (385 μ darcies)***
12/12/79	16	7.1	20.0 (607 μ darcies)***
12/21/79	504	3.3	8.9 (275 μ darcies)***

* Inflow rate obtained, given a 12.4 MPa pressure differential across the 1.8-m-long plug.

** parentheses indicate the permeability for a flow path with "cross-section" area equal to the wellbore.

*** These values presumed to result from leakage into the test region through the tubing packer assembly.

Shut-in Tests

Figure 4 shows data from three shut-in tests. These data can be represented well by a simple one-dimensional model using those values of kA shown. The shut-in tests were all consistent, indicating that the plug/formation system responds like a flow path of approximately 50 microdarcies assuming a cross-section area equal to that of the wellbore.

During the December 19 shut-in test (Figure 4), the time lapse between shut-in and the initial pressure increase is believed to be caused by an air bubble trapped in the tubing below the umbrella packer. A slight flow from the annulus region can account for the higher pressure. (Both effects were modeled with a one-dimensional formulation and qualitatively explained.) Subsequently, the packer-valve-tubing assembly was modified to eliminate the possibility of air entrapment.

It is important to note that there is no evidence of flow from the high pressure annulus above the packer into the test region during the November 2 and January 18 shut-in tests. This strongly suggests that, at least in the area where the umbrella packer is positioned, wellbore damage is slight. Assuming a damage area cross-section equal to that of the wellbore, these shut-in tests indicate a permeability of less than 5 microdarcies.

Fig. 4. Shut-in test data obtained during plug performance evaluation studies

Tracer Flow Tests

Tracer arrival times measured during the December 9 test series indicated approximately a 36-hr interval between gas release and detection at the top of the plug. If the flow through a very small ($2 \times 10^{-5} \text{ cm}$) annulus around the circumference of the plug is modeled as classical porous flow, the tracer data indicate a permeability to porosity ratio (k/ϕ) of 3.3×10^{-3} darcies for this annulus. Since there is evidence that permeability of the plug material is less than this, the inference is that flow is through permeable microstructure at the interface between the plug and the borehole.⁴

CONCLUSIONS

The program to develop grouts provides materials that are effective for sealing boreholes. Brine and fresh-water grouts, with acceptable physical properties in the fluid and hardened states, have been developed.

The field data, taken together with laboratory data, suggest that the predominant flow into the test region occurs through the cement plug/borehole interface region, with lesser contributions occurring through the wellbore damage zone, the plug core, and the surrounding undisturbed anhydrite bed.

The 1.8-m-long by 20-cm-diameter grout plug, installed in anhydrite at a depth of 1370 m in the AEC-7 borehole, limits flow from the high pressure (12.4 MPa) Bell Canyon aquifer to 0.6 liters/day. Tracer flow studies suggest that most of the flow is through a region whose microstructure is porous, rather than through a finite number of fractures. If the flow path cross-section area is assumed equal to that of the wellbore, the corresponding permeability would be 50 microdarcies and the porosity would be 0.018. Data indicate that the flow through the formation surrounding the umbrella packer positioned approximately 4 m above the plug is at least one order of magnitude less than that through the plug/formation system. If the cross-section area of the wellbore damage region around the umbrella packer is assumed equal to that of the wellbore, it would have a permeability less than 5 microdarcies.

If more precision in measuring plug performance is required, current oil-field testing tools will not be adequate. New techniques and equipment will be required to measure plug-formation systems with effective permeabilities around 1 microdarcy.

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