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IN SITU WASTE GROUTING OF AN ORNL TRENCH USING A PARTICULATE-TYPE GROUT

T. Tamura
R. D. Spence
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T. Tamura, R. D. Spence,* O. K. Tallent,* and O. M. Sealand

Environmental Sciences Division

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* Chemical Technology Division

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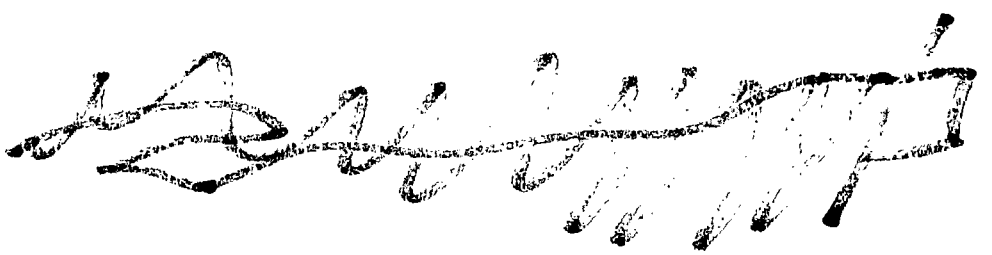

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IN SITU WASTE GROUTING OF AN ORNL TRENCH USING A PARTICULATE TYPE GROUT

T. Tamura, R. D. Spence, O. K. Tallent, and O. M. Sealand

ABSTRACT

A formerly used low-level radioactive solid waste trench measuring 17 X 2.8 m x 3.6 m deep was grouted with a cement-based particulate grout. Of 36 injection points, 5 positions took 78.3% of the 8081 gal (30,585 L) pumped into the trench. The calculated accessible void was 7385 gal (27,950 L); the excess take of the grout could be due to breakthroughs observed in six locations outside the trench. After grouting, samples of water taken from a permanent well located within the trench showed greatly reduced concentrations of calcium, magnesium, and ^{90}Sr as compared with pregrouted conditions. Penetrometer measurements revealed the denser nature of the grouted trench as compared with a bordering ungrouted trench. Recovered cores were generally intact only when penetrating the cover material; when grout was encountered, the core was characterized by small lumps (bigger voids) or brittle small pieces intermixed with soil.

EXECUTIVE SUMMARY

Inefficient waste packaging and possible rupture of organic containers results in trench subsidence, leads to enhanced water entry, and thus could ultimately result in radionuclide migration. Previous demonstrations have utilized chemical grouts that performed well in filling the voids but were relatively expensive and of unknown long-term durability. It was thus desirable to evaluate the use of cement-based grouts that are inexpensive and have demonstrated durability.

The more specific objectives of this demonstration were to select and characterize a trench, formulate a cement-based grout suitable for application in an existing radioactive waste-filled trench, inject the grout using suitable equipment to fill the accessible voids, and evaluate the condition of the trench after grouting.

The selected trench was located in Solid Waste Storage Area (SWSA) 6 and was previously suspected to be the source of ^{90}Sr in a nearby seep; it was filled with low-level radioactive waste in 1975. The particular trench selected (trench 150), measuring 56 ft x 9.2 ft x 11.8 ft deep (17 m x 2.8 m x 3.6 m) was water tested to determine the total void volume; after corrections were made for seepage losses, the accessible void volume was calculated to be 28.0 m^3 (7385 gal).

Field injection operations consisted of preblending the solids (cement, fly ash, bentonite), mixing the blend with water in a cement truck, transferring to a grout slurry tank equipped with a pump, and pumping the grout into 2-in.-diam lances that were driven into the

trench. Of the 36 injection sites, spaced 5 ft apart, 5 holes took 78% of the grout. The average pumping rate was 6.1 gpm at a pressure range of 5 to 10 psig. The total volume of grout injected was 30.6 m^3 (8081 gal). The excess above that calculated may be due to grout leaving the trench, because six breakthroughs occurred on the surface outside the trench.

The cost for grout and grout injection, which took 11 days, was approximately $55,000. About 85% was manpower costs. Based on manhours, 14 man-days/day were used for this field demonstration; if all workers could have worked interchangeably as commonly done in grouting operations, then 6 man-days/day could have accomplished the tasks.

The demonstration showed that a cement-based grout can be formulated to meet the specifications for pressure injection and successfully placed in a solid waste trench. Spacings could have been farther apart since five holes took 78% of the grout. Water injection tests revealed that conductivity was reduced on the average by 2 orders of magnitude. More importantly, the accessible void volume was reduced by three orders of magnitude and the ^{90}Sr concentration in one monitoring well by 2 orders of magnitude. The major need appears to be a more cost-effective way to apply the grout; mechanized units with multiple lances do exist in the private sector but their availability for use in radioactive trenches has not been explored.

1. INTRODUCTION

Inefficient packing of waste containers and possible rupture of organic containers (wood, cardboard, etc.) result in trench subsidence leading to enhanced water entry into filled trenches; in addition, void spaces existing in the trenches may serve as habitat for burrowing animals. The percolating water can leach radionuclides from the waste and induce migration of the nuclides eventually to other parts of the biosphere. By filling the void spaces in the trenches with an economical, durable grout, subsidence would be prevented, water and animal intrusion would be kept at a minimum, and radionuclide migration would be mitigated.

Grouting of low activity solid wastes has been considered earlier (Arora et al., 1980). In addition to information requirements of the trenches including geology, hydrology, overburden materials, and waste materials, characteristics of the grout relative to performance criteria in a given situation must be evaluated. Cost estimates for in situ stabilization are determined by experience and include the cost of labor, equipment, drilling, radiation safety measures, and grout materials.

Several field tests of grouting have been conducted. At Oak Ridge National Laboratory (ORNL) a cement-bentonite grout referred to as a particulate grout was used to fill the crevices of a newly filled test trench prior to the application of final cover. In this situation, the slurry was poured between waste bales using a standard cement mixer delivery truck; filling of the trench could thus be observed directly (Davis and Spalding, 1986). The objective of this test was to study trench grouting as a possible improvement to existing practices. Based

on comparison with a plastic liner and the control trenches, the cement-bentonite appeared to offer the highest level of water protection. In a similar type of field test, suspect waste was placed in pilot-scale trenches, appropriate injection and monitoring wells were installed, and then the trench was backfilled with soil. The grout used in these tests was sodium silicate and polyacrylamide, which belong to a family of grouts referred to as chemical (solution) grouts. These chemical grouts with their low viscosities readily filled the voids of the trenches and reduced the hydraulic conductivities by several orders of magnitude (Spalding et al., 1985).

Using a formulation of sodium silicate grout developed at ORNL, a demonstration-scale test was conducted in a portion of a radioactive waste trench in Maxey Flats, Kentucky (Commonwealth of Kentucky, 1985). The goal set for this demonstration was to reduce the hydraulic conductivity to less than 10^{-4} cm/s, which was achieved. In another demonstration at ORNL, two filled trenches averaging about 5.5 x 3.8 m and 3.5 m deep were grouted using a polyacrylamide grout. Initial field results indicated that void spaces within the trenches were totally filled and the intratrench hydraulic conductivity was reduced to below field-measurable values (Spalding et al., 1986).

Chemical grouts exhibiting low viscosities used in the two demonstrations resulted in complete distribution of grout within the trench with only a few injection wells and achieved very low hydraulic conductivities after grouting. Remaining to be evaluated are the long-term stability and performance of the grouts. It should be noted

that the major focus of grouting trenches is to prevent migration of radionuclides from presently contained systems and to stop any presently migrating radionuclides due to leaching by subsurface water. In contrast to chemical grouts possessing high pore penetrability, particulate grouts containing cement and/or clay particles exhibit low soil pore penetrability. If filling of the larger accessible voids results in acceptable performance of trenches relative to reduced leaching and escape of radionuclides, then particulate grouts may have a place in stabilizing formerly utilized trenches. In this context it was deemed desirable to evaluate a particulate-type grout in meeting this goal.

The objectives of this demonstration were to select and characterize a trench for the test, formulate a cement-based particulate grout suitable for application to this existing waste-filled trench, inject the grout using suitable equipment to fill the accessible voids, and evaluate the condition of the trench after grouting. In addition, information on equipment performance and costs of performing the grouting would be gained; the information would be useful in evaluating the potential of this mode of trench stabilization.

2. SELECTION AND CHARACTERIZATION OF DEMONSTRATION TRENCH

2.1. SELECTION OF 49 TRENCH AREA IN SWSA 6

It has been known that a seep located in Solid Waste Storage Area (SWSA) 6 discharges small quantities of ^{90}Sr. Figure 1 locates SWSA 6 with respect to other disposal facilities and the main complex of Oak Ridge National Laboratory. Figure 2 shows the solid waste trenches found in SWSA 6 as of 1979; the suspected trench area responsible for the contaminated seep is labeled 49 trench area and is bounded on two sides by a French drain. The creek flowing between the 49 trench and the 22 trench area was sampled, and the point of discharge of the ^{90}Sr was identified by Cerling and Spalding (1982).

The location of the seep within the creek length and the topographic features of the area suggested that the 49 trench area was the likely source of the ^{90}Sr. Analysis of ^{90}Sr in water samples taken from selected trenches revealed that trenches 150 and 152 contained significant quantities of this radionuclide (Arora et al., 1981; E. C. Davis, personal communications) and were relatively close to the seep area.

Following the discovery of ^{90}Sr and location of the suspect trenches, several wells were installed between the creek and the trenches. Samples of water were collected from both suspect trenches and the installed wells. The results of ^{90}Sr analysis from samples collected in September 1982 are presented in Table 1; the labels corresponding to the wells and trenches can be found in Fig. 3. Note the higher concentration of the radioelement in trenches 150 and 152.

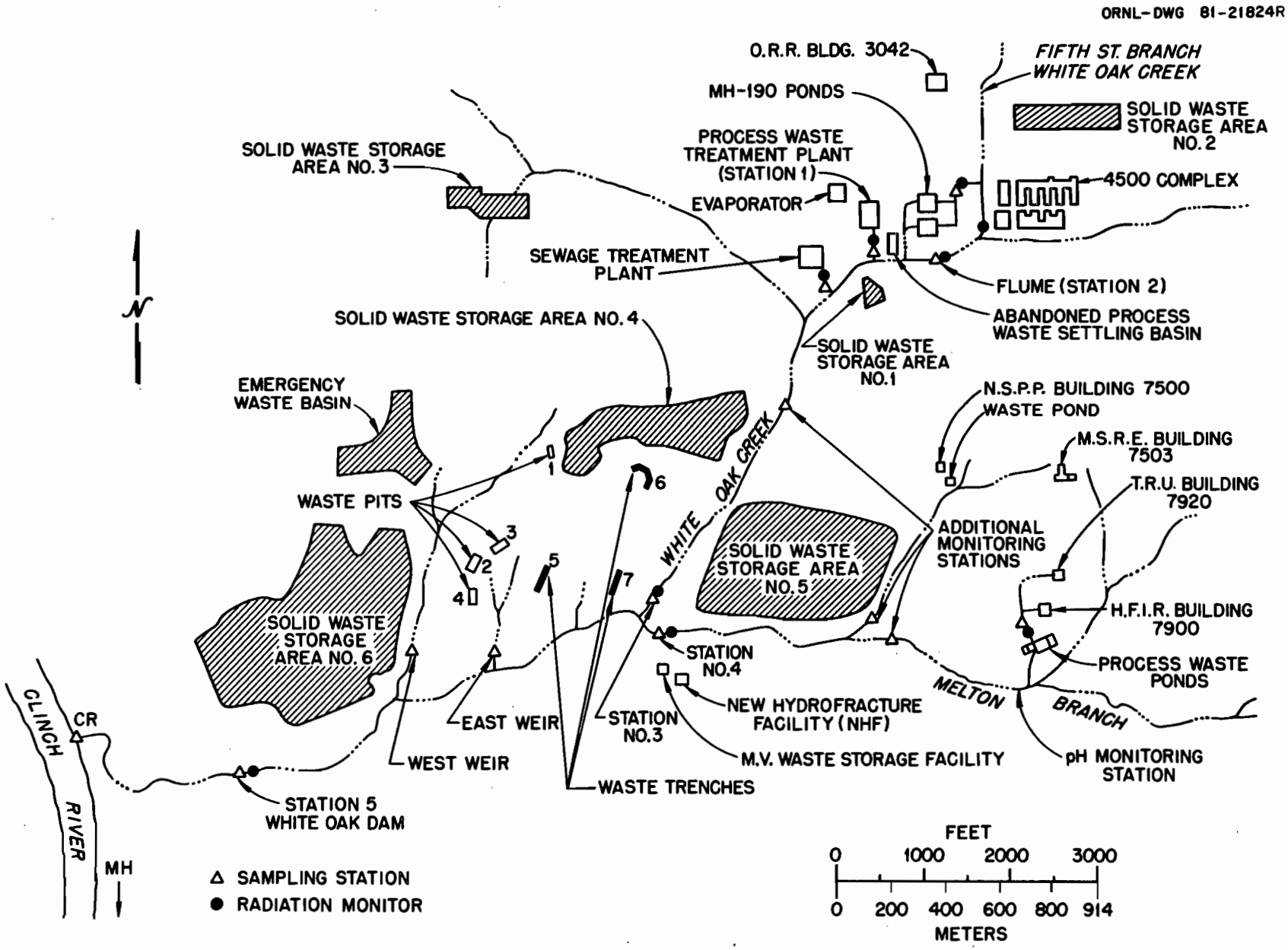

Fig. 1. Location plan for White Oak Creek sampling stations and rotation monitors including waste disposal areas.

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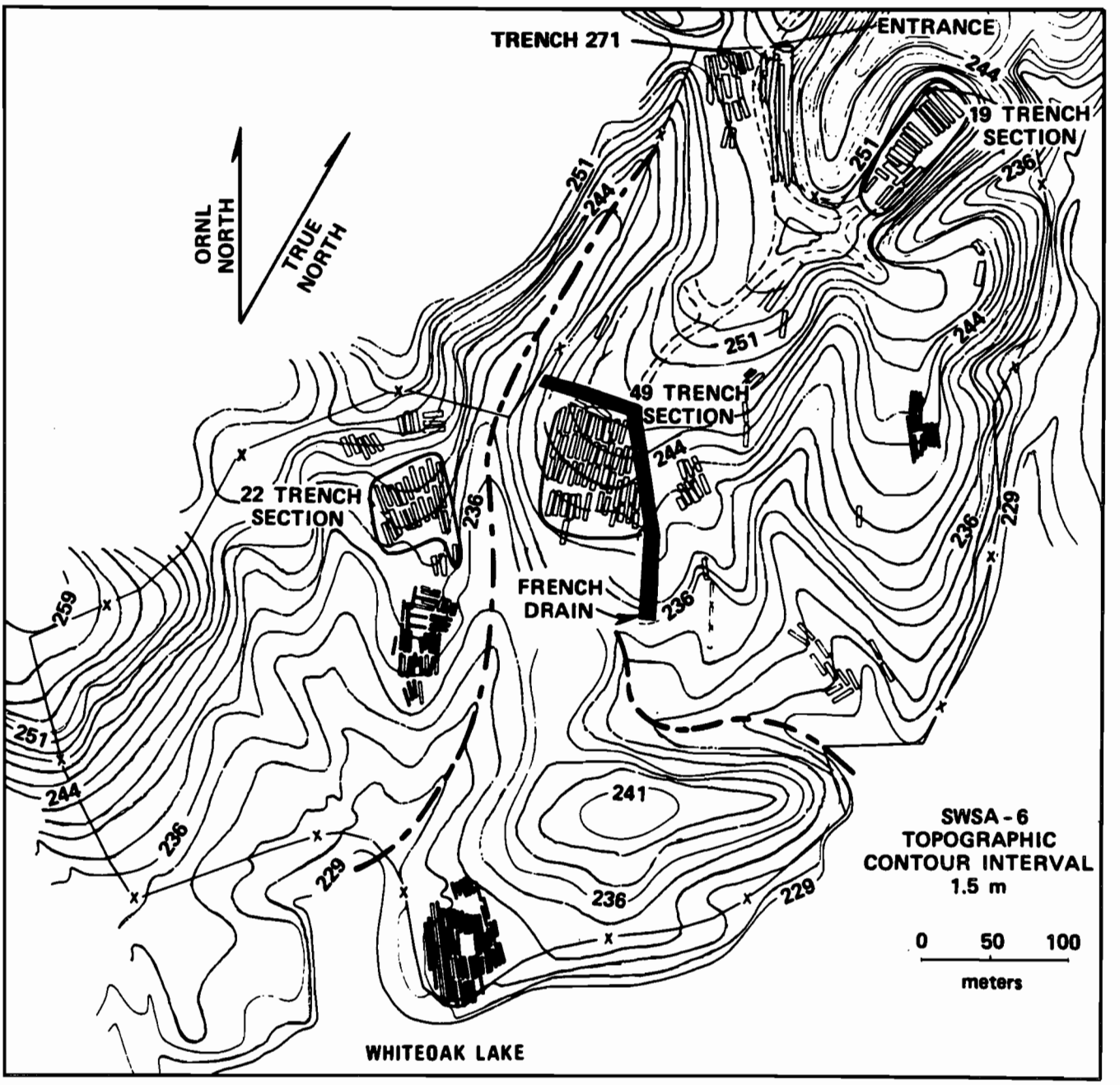

Fig. 2. Trench locations within SWSA 6.

Well 402, located very close to these two trenches, was near background. Well 389 west of the trenches contains significant concentrations of ^{90}Sr; and of the 400 series wells close to the seep, a small, but detectable, amount of this radionuclide is present. Surprisingly, the seep showed a higher concentration than the 400 series wells.

Examination of the existing data then led to the tentative conclusion that trenches 150 and 152 would be candidate trenches for grouting. In addition, discussions with other interested parties led to the suggestion that effects of grouting on ^{90}Sr behavior would be difficult to evaluate since existing adsorption on the soils along the migration pathway could continue to release ^{90}Sr even after grouting, which would make interpretations difficult. Hence, it was decided that a better tracer candidate to follow for evaluation of the effects of grouting would be tritium. Sampling was initiated in November 1984, initially starting with trenches 150 and 152 and the wells leading to the seep. These results are tabulated in Table 2.

Several problems arose during the sampling; the trenches were dry when sampling was initiated and the wells needed cleaning in order to obtain the water samples. However, the data in Table 2 raise several interesting questions regarding the source of the activity at the seep. The concentration of the tritium is high at the seep and the 400 series wells, especially when compared with the concentrations in the five trenches that were sampled. The higher tritium concentrations in wells 404 and 405 compared with the seep located nearby may be due to

Table 1. ^{90}Sr data from 49 trench area in SWSA 6, September 1982

(Data courtesy of Ed Davis)

Well/Trench No.	1 (Bq/L)	2 (Bq/L)	Average (Bq/L)
T 145	1.0	1.17	1.08
T 147	98.2	135.5	116.8
T 150	45,434.0	61,483.00	53,459.00
T 152	18,134.0	23,895.00	21,015.00
T 163	0.67	8.17	4.42
W 389	381.5	470.3	425.9
W 390	BG[a]	BG	
W 403	2.5	2.0	2.2
W 404	10.8	14.2	12.5
W 405	6.0	19.7	12.8
Seep	22.8	24.2	23.6

[a]BG = background.

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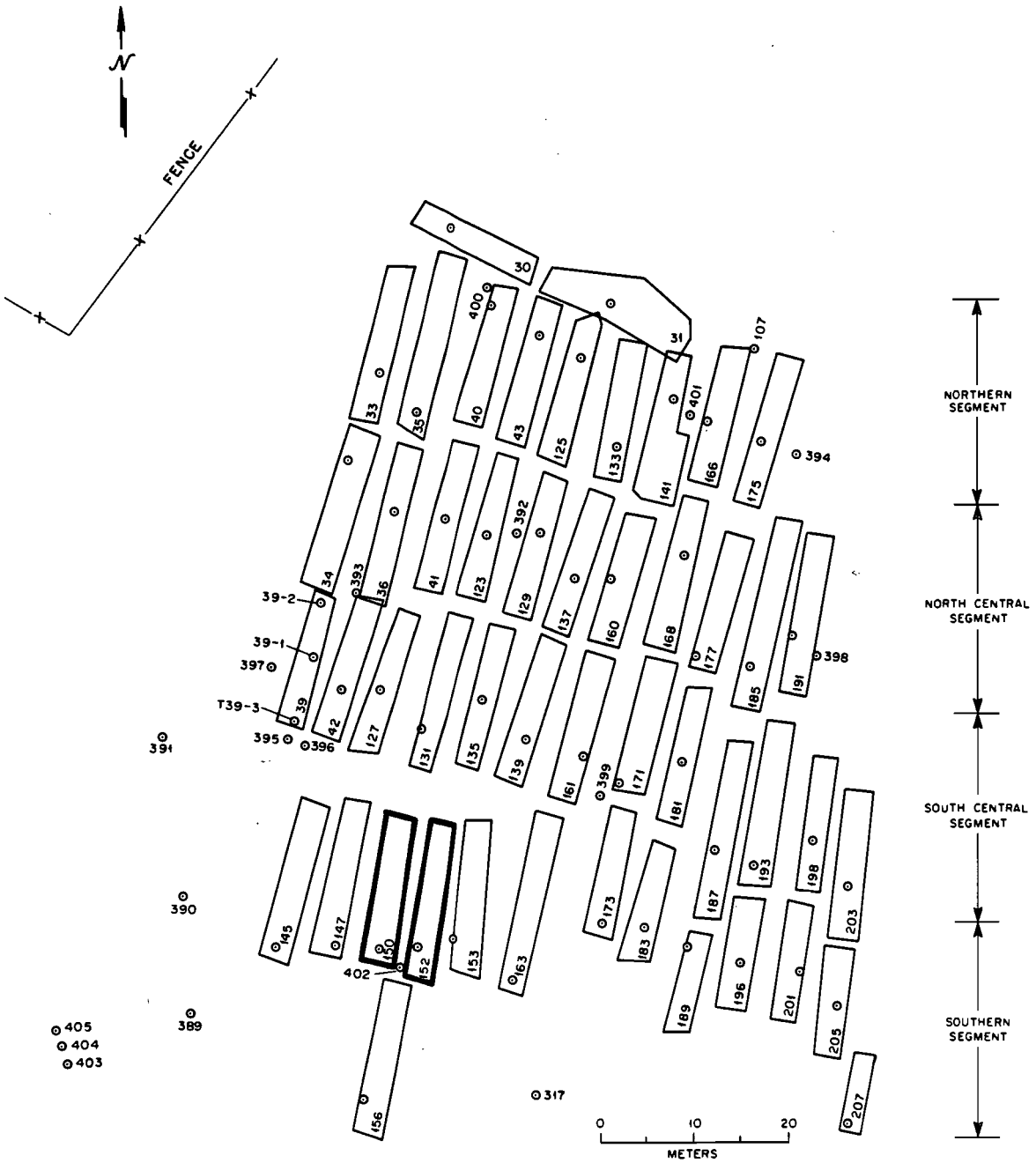

Fig. 3. Trench alignment and identification numbers with associated wells and seep in 49 trench section of SWSA 6.

Table 2. Radiochemical, pH, and electrical conductivity (EC) of water samples in trenches and wells in the 49 trench area

Trench wells	Sampling date	pH	EC (µs/cm)	^{90}Sr (Bq/L)	^{3}H (Bq/L)	^{137}Cs (Bq/L)
T-145	2-06-85	6.8	250	320	1.2×10^3	ND
	2-25-85	ND[a]	ND	32,350	ND	ND
T-147	2-06-85	6.85	250	727	3.2×10^4	2.96
	2-25-85	ND	ND	245	ND	ND
T-150	11-07-84	ND	ND	ND	ND	ND
	11-19-84	7.40	440	ND	ND	ND
	11-21-84	6.89	5.98	4,074	340	5.29
	12-05-84	ND	ND	ND	ND	ND
	12-07-84	6.94	605	14,648	320	37
	2-06-85	6.97	600	18,700	440	48.15
	2-25-85	6.60	430	21,300	ND	ND
	3-04-85	6.60	420	ND	ND	ND
T-152	11-07-84	ND	ND	ND	ND	ND
	11-19-84	7.49	420	ND	ND	ND
	11-21-84	6.65	620	24,944	950	16
	12-05-84	ND	ND	ND	ND	ND
	12-07-85	6.62	612	25,018	7,800	10.74
	2-06-85	6.50	450	32,550	960	4.4
	2-25-85	6.50	500	235	ND	ND
	3-04-85	6.70	480	ND	ND	ND
T-163	2-6-85	6.75	248	22	1,700	ND
	2-25-85	ND	ND	107.5	ND	ND
W-389	11-07-84	ND	ND	ND	ND	ND
	11-19-84	ND	ND	ND	ND	ND
	11-21-84	8.59	600	584	8,200	ND
	12-05-84	ND	ND	ND	ND	ND
	12-07-84	8.5	450	470	31,400	1.48
	2-06-85	8.2	620	18,950	ND	ND
	2-25-85	7.4	290	190	ND	ND
	3-04-85	6.5	250	ND	ND	ND
W-390	2-06-85	6.55	62	195	120	ND
	3-04-85	ND	ND	ND	ND	ND
W-403	11-07-84	ND	ND	37	3,900	ND
	11-21-84	7.28	269	ND	ND	ND
	12-07-84	7.23	275	59.26	7,800	0.74
	2-06-85	7.26	266	ND	27,000	ND
	2-25-85	7.20	220	1.0	ND	ND
	3-04-85	7.50	200	ND	ND	ND

Table 2 (continued)

Trench wells	Sampling date	pH	EC (µs/cm)	^{90}Sr (8q/L)	^{3}H (8q/L)	^{137}Cs (8q/L)
W-404	11-07-84	ND	ND	4.81	1,300,000	0.74
	11-21-84	7.43	588	ND	ND	ND
	12-07-84	7.65	595	55.5	1,600,000	0.74
	2-06-85	7.59	584	21.3	260,000	ND
	2-25-85	7.60	650	7.5	ND	ND
	3-04-85	6.0	650	ND	ND	ND
W-405	11-07-84	ND	ND	ND	780,000	1.85
	11-21-84	7.26	785	ND	ND	ND
	12-07-84	7.33	790	11.1	1,400,000	0.37
	2-06-85	7.28	7.40	5.25	2,500,000	ND
	2-25-85	7.10	570	2.5	ND	ND
	3-04-85	6.8	480	ND	ND	ND
Seep	11-07-84	ND	ND	15.6	200,000	1.1
	12-07-84	7.93	318	100	220,000	ND
	2-06-85	7.31	344	352.5	130,000	ND
	2-25-85	6.45	270	ND	ND	ND
	3-04-85	6.96	312	ND	ND	ND

[a]ND = Not determined; well dry or sample too small.

dilution by the creek water. However, if this were the situation, then the ^{90}Sr concentration at the seep, which is higher than at the wells, is counter to the dilution explanation. To define the actual source trench(es) is beyond the scope of this task. Hence, the decision was to concentrate future efforts on trenches 150 and 152.

Attention thus was directed mainly to trenches 150 and 152 henceforth; characteristics of these trenches will be provided and the reasons for the ultimate selection of trench 150 as the candidate trench for grouting will be given. Although the preliminary measurements of tritium in the trenches and wells did not show a direct relationship of the suspected source and migration pathway of this radionuclide, selected measurements of this radioelement were made to observe concentration patterns over time in later samplings.

2.2. TRENCH CHARACTERIZATION

Trench 150 has average surface dimensions of 56 ft (17 m) long and 9.2 ft (2.8 m) wide; the depth of the trench as measured by the permanent well is 11.8 ft (3.6 m). These dimensions translate to 6079 ft^3 (172 m^3) of volume. Trench 152 measures 60.5 ft X 10 ft X 13.2 ft (18.4 m X 3.05 m X 4.0 m)--total volume of 7962 ft^3 (225 m^3). Since trenches are filled to 2 ft beneath the surface and soil is used to cover the waste, the actual waste holding volume is reduced to 5049 ft^3 (143 m^3) and 6752 ft^3 (191 m^3) for trenches 150 and 152, respectively. These latter values further translate to 37,750 gal (1.43×10^5 L) and 50,480 gal (1.91×10^5 L) of volume.

Water level measurements in the two trenches and in surrounding wells were started on November 7, 1984. The readings are tabulated in Table 3. In addition to the two trenches, measurements were started on March 18, 1985, in well 402, located between the two trenches (Fig. 3). Well 402 is about 1.5-2 m deeper than the wells placed in the trenches, and can be viewed as indicating the groundwater level in this vicinity. Conversely, wells in the trenches are shallower and hence water level readings indicate a perched water level. Analysis of the data revealed an interesting trend; trench 150 loses water faster than trench 152. Trench 150 showed twice as many observations when the trench was dry; however, this in itself cannot be used to conclude that the water left the trench faster. A more meaningful calculation is the difference observed in the amount of water present in the trenches on any given day. The well in trench 152 is placed 0.07 m deeper than the well in trench 150, and this may account for the difference between the water level at any given day. Actual differences in water levels show that the trench 152 level is greater than the 0.07-m maximum allowable height difference. Since the water level in trench 150 decreases faster than that in trench 152, it signifies that any radionuclide dissolved in the water would be leaving the trench faster also. In choosing between the two trenches for grouting, the faster movement of water (and associated radionuclides) out of the trench suggests that trench 150 should be grouted.

In Table 4 are listed further analyses made of the water in the two trenches; included are results for well 402. No trends are noted for

Table 3. Water level readings in trenches 150 and 152 with the associated well 402 (see Fig. 3 for locations)

	Trench 150	Trench 152	Well 402
Surface elevation (m)	241.77	242.10	241.85
Depth of well (m)	3.61	4.01	5.61
Bottom of well (m)	238.16	238.09	236.24
Date			
11-07-84	238.16[a]	238.09[a]	ND[b]
11-19-84	238.38	238.80	ND
12-05-84	238.34	238.74	ND
12-17-84	238.34	238.66	ND
2-06-85	238.87	239.30	ND
2-25-85	238.88	239.42	ND
3-04-85	238.61	239.22	ND
3-18-85	238.83	238.91	238.98
4-01-85	238.31	238.44	238.24
4-09-85	238.26	238.42	238.16
4-17-85	238.18	238.35	238.12
4-22-85	238.16[a]	238.10	237.90
4-29-85	238.16[a]	238.11	237.52
5-07-85	238.16[a]	238.12	237.47
5-13-85	238.16[a]	238.10	237.35
5-20-85	238.17	238.11	237.24
6-24-85	238.16[a]	238.09[a]	237.07
6-10-85	238.16[a]	238.09[a]	237.24
6-17-85	238.16[a]	238.09[a]	237.12
6-25-85	238.16[a]	238.09[a]	237.11
7-03-85	238.16[a]	238.09[a]	237.83
7-09-85	238.16[a]	238.09[a]	237.26
7-16-85	238.16[a]	238.09[a]	237.92
7-23-85	238.16[a]	238.09[a]	237.52
7-30-85	238.16[a]	238.09[a]	237.53
8-06-85	238.16[a]	238.09[a]	237.57
8-13-85	238.16[a]	238.09[a]	237.83
8-19-85	238.41	238.89	237.94
8-27-85	238.48	238.93	239.82
8-29-85	238.52	238.84	239.02
9-03-85	c	238.90	238.29
9-06-85	239.01	240.38	ND
9-16-85	238.77	239.96	238.81
9-30-85	238.35	239.06	238.15
10-11-85	238.16[a]	238.09[a]	237.39
10-21-85	239.37[d]	239.69[d]	239.56[d]
10-29-85	239.14	239.26	239.18
11-05-85	239.08	239.17	239.12

Table 3 (continued)

	Trench 150	Trench 152	Well 402
Surface elevation (m)	241.77	242.10	241.85
Depth of well (m)	3.61	4.01	5.61
Bottom of well (m)	238.16	238.09	236.24
Date			
11-20-85	238.16[a]	238.82	238.89
12-02-85	238.42	238.99	239.01
1-06-86	238.16[a]	238.41	238.16
1-13-86	238.16[a]	238.63	238.09
1-20-86	238.16[a]	238.29	237.96
1-28-86	238.16[a]	238.24	237.94
2-03-86	238.16[a]	238.15	237.61
2-11-86	238.16[a]	238.16	237.62
2-18-86	238.79	239.47	240.87
2-24-86	238.79	239.37	239.05
3-03-86	238.16[a]	238.13	238.89

[a] = Bottom of trench.
[b] = ND = not detected.
[c] = Reading error; discarded.
[d] = Water added through trench 150.

Table 4. Radiochemical, pH, and electrical conductivity (EC) of water samples in trenches 150 and 152 and well 402 (compare with data in Table 2)

Trench/ Well No.	Sampling date	pH	EC (µs/cm)	^{90}Sr (Bq/L)	^{3}H (Bq/L)
T-150	4-17-85[a]				
	5-21-85[a]				
	7-03-85[a]				
	8-29-85	6.80	500	21,345	ND[b]
	11-05-85	6.90	510	21,125	5,200
	2-03-86[a]				
T-152	4-17-85	6.65	580	25,675	33,000
	5-21-85[a]				
	7-3-85[a]				
	8-29-85	6.70	420	35	ND[b]
	11-05-85	6.90	440	230	2,200
	2-03-86[a]				
W-402	4-17-85	7.10	250	7,080	130
	5-21-85	7.15	630	480	1,100
	7-03-85	6.60	350	715	830
	8-29-85	7.00	380	685	2,400
	11-05-85	7.10	375	665	2,200
	2-03-86	7.10	385	580	530

[a]Insufficient water in well.
[b]ND = not detected.

the concentrations of ^{90}Sr and ^{3}H in the samples. Though not included in Table 4, it should be noted that analysis of tritium at the seep and nearby wells consistently showed 10^5 to 10^6 Bq/L of this radionuclide. This strongly suggests that these two trenches are unlikely sources of tritium. The concentration of ^{90}Sr does appear to show a relatively constant value after the sampling of April 17 in well 402. As noted previously, this well is deeper than the nearby trench wells and is in the permanent water table. The concentration at the seep is approximately 0.1 the value found in well 402.

In addition to the pH and electrical conductivity values of Tables 2 and 4, additional water quality measurements are provided in Table 5. Due to the limited sampling and timing of the sampling during the drier periods, these data included samples other than trench 152 (trench 150 was dry). The main purpose of the water quality analysis is to establish whether the trench water possesses properties that may be deleterious to cement-based grouts. Both trenches show pH very close to neutral and the major cations are calcium and magnesium. These two elements are balanced by the bicarbonate for the alkalinity values reported in Table 5. In addition, the higher calcium and magnesium concentrations in the trenches account for the higher electrical conductivity readings shown in Tables 2 and 4. Normal electrical conductivity values in the Oak Ridge area range from 150 to 250 µs/cm with the higher values noted during low flow (dry) conditions.

It is important to emphasize that the injection of the grout was planned for the dry season when the trenches are normally without water. The make-up water to prepare the slurry will be uncontaminated process water, the same water that has been used to evaluate slurries in the laboratory for this field test. The injected grout then is expected to surround the containers and occupy void volumes resulting from relatively random arrangement of the waste packages.

Information on the characteristics of the waste was sought but the inventory procedures during the filling of these trenches in February 1975 did not require radioisotope identification. The radionuclides

Table 5. Water quality analysis of selected trenches, well, seep, and stream

Sample source	Sampling date	Alkalinity (ppm)	Chloride (ppm)	Sulfate (ppm)	Fe (ppm)	Ca (ppm)	Mg (ppm)	Na (ppm)	K (ppm)
T-147	4-17-85	230	7	10	<0.03	55	25	2.4	3.1
T-152	4-17-85	208	10	5	0.05	80	23	2.0	4.0
W-402	4-17-85	270	11	74	0.05	92	21	12.0	4.2
	10-14-85	153	5	9	0.58	55	7	8.3	ND
Seep	4-17-85	164	5	11	0.13	54	8	4.4	1.2
Sta 11[a]	4-17-85	156	5	11	0.05	51	7	4.1	1.2

[a]Station 11 is located 50 ft upstream of the seep.

were characterized only as low levels of alpha, beta, and gamma isotopes. The volume of the waste disposed in each trench was recorded; in trench 150, 5970 ft^3 (169 m^3) was buried and in trench 152, 6114 ft^3 (173 m^3) was buried. For comparative purposes these values represent 118% and 90% of the calculated volume for waste allowing for 2 ft of overburden soil on the top. Approximately 15-20% of the waste was classified as combustible.

The amount of slurry required to fill the voids was calculated from the volumes of waste and the dimensions of the trenches. Considering the water level data, which indicated that trench 150 drained its water faster than trench 152, it was decided to grout trench 150. Furthermore, the volume of slurry required would be less for trench 150. If one uses the calculated volume of waste based on the dimensions of the trenches and assumes a void volume of 30%, trench 150 requires 11,325 gal (4.3×10^4 L) of grout and trench 152 requires 15,150 gal (5.7×10^4 L). On the same assumption of void volume but using the reported waste volume disposed, the amount slurry required for trench 150 is 13,400 gal (5.1×10^4 L).

2.3. PRE-GROUTING PREPARATIONS

To prepare for the injection of the grout, several modifications were made to trenches 150 and 152. First, the surface soil to a depth of 1 ft (0.3 m) was removed from both trenches to confine any grout breaking to the surface during the injection within the trench perimeter. Although trench 152 was not intended to be grouted, it was desirable to maintain nearly identical conditions so that subsequent

evaluations of the trenches could be made without introducing the variable of dissimilar surfaces. In addition, five new wells were installed in both trenches to provide information on water take after the grouting operation. In Fig. 4 the locations and depths of the additional 2-in. (0.05-m) ID wells in trench 150 are depicted; the well marked 150 is the permanent 4-in. (0.10-m) id well for this trench. The layout for trench 152 for the additional wells is not shown since very little information was gained from them.

To obtain a more quantitative value for the accessible void volume calculations, a water test was performed prior to grouting. For this test, water was pumped into trench 150 through two of the five new wells. The gallons pumped as a function of time and the rise in the water level in well 150 (permanent well) were recorded. The pumping required two days to complete; however, the actual pumping time was 7.2 h. After the first day's pumping, readings of the water levels were taken for the two trenches adjoining trench 150 (trenches 152 and 147). On the following morning, it was noted that no changes had occurred in either adjoining trench; but the water level in trench 150 had dropped. From information on the volume of water pumped and the height of the water column, the volume that had seeped downward out of the trench or into the smaller soil pores was calculated. This volume of water loss per hour was used to determine the total volume leaving the trench or into soil pores as pumping was in progress: 508 gal.

In addition to the volume that seeped out of the trench or into soil pores within the trench, it was noted that as the water elevation approached the upper portion of the trench, the rate of rise to the

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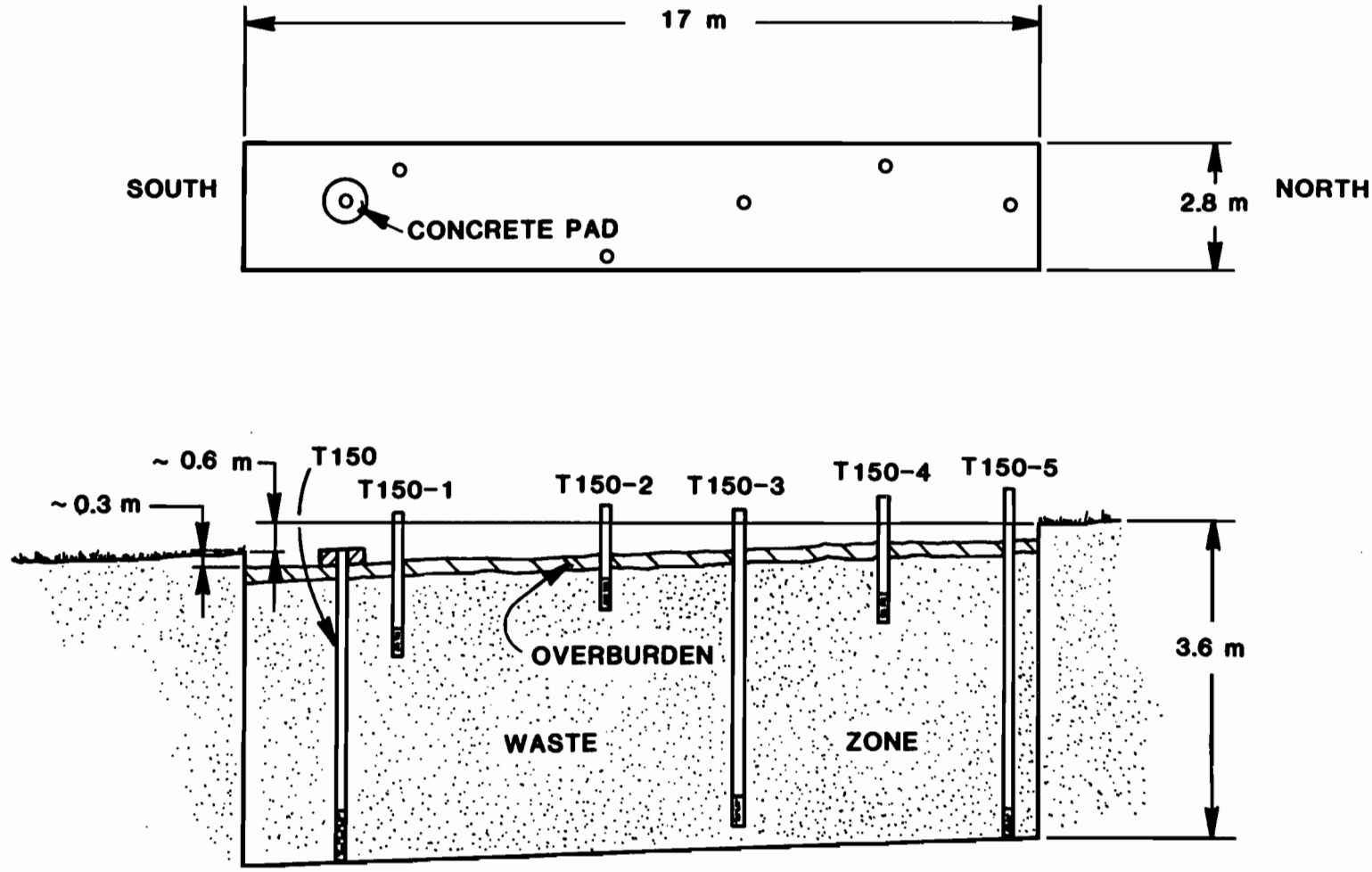

Fig. 4. Monitoring well locations in trench 150 including the permanent well labeled T-150.

surface was reduced. In addition, after filling trench 150, measurements of trenches 152 and 147 showed a rise in water. Hence the pumped water not only occupied voids in the intended trench but had seeped out to the adjoining trenches during the pumping. Plotting the rise in the water level over time revealed that a linear relationship existed up to approximately 80% of the waste-filled trench. Extrapolating the linearity to the top of the waste and estimating the volume based on the linear extension showed that approximately 2/3 of the total voids represented the larger voids and 1/3 represented the amount that found its way out of trench 150. Thus about 28.0 m^3 (7385 gal) represents the larger voids accessible to the particulate grout and 13.8 m^3 (3640 gal) represents the water that escaped from the trench during pumping.

It might be mentioned that in the particulate grout test using lime-fly ash, the injected volume was 7500 gal, representing an accessible void volume of 20%; the volume of 7385 gal for trench 150 represents 19.5% accessible voids. For comparison the demonstration at Maxey Flats injected 10,067 gal of sodium silicate grout that represented 23% void volume and the experience at ORNL using polyacrylamide showed 4100 gal injected representing 20% voids. These results suggest that for planning purposes, a void volume of 20% may be considered for the humid east's solid waste trenches.

The water injection test to obtain the void volume calculations also served to provide information to determine the effectiveness of the injection. Periodic measurement of the pump rate showed that >16.5

gal/min (62.5 L/min) could be injected without overfilling the well. Based on the diameter of the tubing, the rate of take was calculated to be greater than 30.8 m/min. This value then was used after the grouting in determining the post-injection take rate of the five additionally installed wells.

3. GROUT SELECTION

3.1. BLEND COMPOSITION AND PREPARATION

The grout development for this application was relatively straightforward since the liquid phase was ordinary tap water that had been shown previously to have no adverse components. Furthermore, the injection was planned when the trench was dry and no waste solution was anticipated. The main emphasis was to develop a grout that could flow from one end of the trench to the other if a suitable flow path existed, that would remain fluid long enough for a relatively large batch to be injected, that would set into a strong solid mass, and that would not spread the waste contamination beyond its present limits.

The criteria selected to meet these goals were the following:

1. Apparent viscosity of $\leq$50 mPa•s ($\leq$50 cP)
2. 10-min gel strength $\leq$48 Pa ($\leq$100 lb_f/100 ft^2)
3. Phase separation after 28 d of 0 vol %
4. Compressive strength after 28 d of $\geq$414 kPa ($\geq$60 psi)

A low apparent viscosity is needed to ensure that the grout will flow and effectively penetrate existing voids in the trench matrix. The gel strength requirement is the force needed to restart flow of a grout in a pipe after standing (nonflow). The phase separation requirement is to ensure that the grout will set without production of a liquid phase, which could leach contaminants. Although only a nominal compressive strength was required, the acceptable formulation resulted in much higher strengths.

Dry-solid blends containing type I Portland cement (regular type), ASTM fly ash (Classes C and F) (ASTM, 1981), and bentonite were mixed

with water at different ratios. Phase separation, compressive strength, gel strength, apparent viscosity, and other rheological tests were then conducted on the resulting grout mixes. It is recognized that some of the measured properties were not required for this shallow depth application but will provide valuable information for possible later applications of grouting.

Two dry-solid blends were prepared: (1) a type containing ASTM Class C fly ash and (2) a type containing cheaper ASTM Class F fly ash. The composition of three test blends containing ASTM Class C fly ash is shown in Table 6; and blends using Class F fly ash are shown in Table 7. The amount of solid per gallon (3.78 L) of water ranged from 10 lb (4.5 kg) to 15 lb (6.8 kg). Addition of fly ash increases the durability of cements, and Class C fly ash exhibits cementitious properties by itself in contrast to Class F, which does not. Bentonite was added to increase the water absorption properties of the grouts. The blends were tumbled in a V-blender for 2 h before being mixed with water. The CFR-1 is a proprietary agent dissolved in water to delay the setting time of the grout and to reduce the apparent viscosity of the grout slurry.

3.2. PROPERTIES OF SELECTED BLENDS

The results of tests with blends 1, 2, and 3 using ASTM Class C fly ash are shown in Tables 8, 9, and 10, respectively. The apparent viscosities for all of the mix ratios were less than 50 mPa•s, except the 15 lb/gal (1.8 kg/L) mixes for blends 1 and 2. The 10-min gel strengths for all blend 1, 2, and 3 mixes were less than 24 Pa, well

Table 6. Blends of solids containing ASTM Class C fly ash[a]

Material	Blend 1 (wt %)	Blend 2 (wt %)	Blend 3 (wt %)
Type I Portland cement	36	41	30
ASTM Class C fly ash[b]	58	54	70
Bentonite	6	6	0.0
CFR-1[c]	0.02	0.02	0.02

[a]Blends mixed with water at ratios of 12, 13, 14, and 15 lb/gal.

[b]Obtained from American Fly Ash Co.; source = power plant at Owensboro, Ky.

[c]CFR-1, a sugar-type set retarder, was added as wt % of the blends and was dissolved in the water mixed with the blends.

Table 7. Blends of solids containing ASTM Class F fly ash

Material	Blend 4 (wt %)	Blend 5 (wt %)	Blend 6 (wt %)
Type I Portland cement	42.0	49.5	58.0
ASTM Class F fly ash[a]	50.0	41.5	33.0
Bentonite	8.0	9.0	9.0
CFR-1[b]	0.02	0.02	0.02

[a]Fly ash obtained from TVA power plant at Kingston, Tenn.

[b]CFR-1, a sugar type set retarder, was added as wt % of the blends and was dissolved in the water mixed with the blends.

Table 8. Properties of grouts prepared from blend 1[a] (Values are averages of duplicate measurements; criteria values in SI units provided in text.)

Mix ratio (lb/gal)	12	13	14	15
Apparent viscosity (cP)	23.5	31	41.8	55.5
10-min gel strength ($lb_f/100\ ft^2$)	23	30.5	33.5	40
Density (lb/gal)	13.44	13.71	14.00	14.26
Fluid consistency index, K', ($lb \cdot s^{n'}/ft^2$)	0.0054	0.0085	0.0125	0.0189
Flow behavior index, n'	0.6021	0.5768	0.5629	0.5389
28-d phase separation (vol %)	0 (21d)	0 (6d)	0 (2d)	0 (1d)
28-d compressive strength	1109 ± 230	1506 ± 135	2145 ± 54	2685 ± 146
At reference conditions[b]				
Reynolds number	2100	2100	2100	2100
Frictional pressure loss per 100 ft of pipe (psi)	1.8	2.8	4.4	6.4
Critical flow rate (gal/min)	29.5	36.6	44.8	53.8
Pump head pressure (psi)	3.8	5.1	5.6	6.7

[a]Type I Portland cement, 36 wt %; ASTM Class C fly ash, 58 wt %; bentonite, 6 wt %.

[b]2-in.-ID pipe arbitrarily chosen.

Table 9. Properties of grouts prepared from blend 2[a] (Values are averages of duplicate measurements; criteria values in SI units provided in text.)

Mix ratio (lb/gal)	12	13	14	15
Apparent viscosity (cP)	25	31.5	43	55
10-min gel strength ($lb_f/100\ ft^2$)	22.5	26	40	44.5
Density (lb/gal)	13.36	13.91	14.08	14.33
Fluid consistency index, K', ($lb \cdot s^{n'}/ft^2$)	0.0065	0.0087	0.0128	0.0189
Flow behavior index, n'	0.5754	0.5714	0.5611	0.5346
28-d phase separation (vol %)	0	0	0	0
28-d compressive strength	1476 ± 288	1725 ± 263	2238 ± 96	2953 ± 165
At reference conditions[b]				
Reynolds number	2100	2100	2100	2100
Frictional pressure loss per 100 ft of pipe (psi)	2.0	2.8	4.4	6.4
Critical flow rate (gal/min)	30.7	36.1	45.1	53.9
Pump head pressure (psi)	3.8	4.3	6.7	7.4

[a]Type I Portland cement, 41 wt %; ASTM Class C fly ash, 54 wt %; bentonite, 5 wt %.

[b]2-in.-ID pipe arbitrarily chosen.

Table 10. Properties of grouts prepared from blend 3[a] (Values are averages of duplicate measurements; criteria values in SI units provided in text.)

Mix ratio (lb/gal)	12	13	14	15
Apparent viscosity (cP)	16	19.5	26	34
10-min gel strength ($lb_f/100\ ft^2$)	13.5	21.5	25	30
Density (lb/gal)	13.30	13.63	13.95	14.22
Fluid consistency index, K', ($lb \cdot s^{n'}/ft^2$)	0.0026	0.0039	0.0053	0.0074
Flow behavior index, n'	0.6572	0.6338	0.6233	0.6082
28-d phase separation (vol %)	2.9	0.92	0	0
28-d compressive strength	914 ± 19	1258 ± 163	ND[b]	ND
At reference conditions[c]				
Reynolds number	2100	2100	2100	2100
Frictional pressure loss per 100 ft of pipe (psi)	0.92	1.4	2.0	2.9
Critical flow rate (gal/min)	21.1	25.8	30.5	36.3
Pump head pressure (psi)	2.3	3.6	4.2	5.0

[a]Type I Portland cement, 30 wt %; ASTM Class C fly ash, 70 wt %; bentonite, 0.0 wt %.

[b]ND = not determined.

[c]2-in.-ID pipe arbitrarily chosen.

within the acceptable range. The phase separation for all of the blend 1 and 2 mixes and for the 14- and 15-lb/gal (1.7- and 1.8-kg/L) mixes for blend 3 was 0.0 vol % by the 28th day. The compressive strengths for all of the blend 1 and 2 grouts and for the 12- and 13-lb/gal (1.4- and 1.6-kg/L) mixes ranged from 914 to 2953 psi (6297 to 20,350 kPa), well above the 60 psi requirement. As mentioned earlier, other properties of the mixes are given in Tables 8, 9, and 10; the significance and derivation of the values are given in a report by Tallent et al. (1987).

Tests of the ASTM Class F fly-ash-bearing grouts were conducted only to the scouting stage. Results of tests with blends 4, 5, and 6 using mix ratios of 12.5, 11, and 10 lb/gal (1.5, 1.3, and 1.2 kg/L) are shown in Table 11. Additional results for blend 5 using 11.5-, 12.0-, 12.5-, and 13.0-lb/gal (1.4-, 1.44-, 1.5-, and 1.6-kg/L) mixes are shown in Table 12. It can be seen that phase separation was greater for the grouts prepared with ASTM Class F fly ash than with grouts prepared with ASTM Class C fly ash, even though the Class F blends contained more bentonite clay. The compressive strengths reported in Table 11 are acceptable; the apparent viscosities and the 10-min gel strengths for all of the tests (Tables 11 and 12), although acceptable, were greater than would be preferred. In addition, they were generally greater than those obtained using blends with Class C fly ash. Therefore, the tests using mixes made with ASTM Class F fly ash were discontinued, mainly because of the phase separation and apparent viscosity results.

Table 11. Properties of grout mixes prepared from blends 4, 5, and 6[a] (Criteria values in SI units provided in text.)

Blend number	4	5	6
Mix ratio (lb/gal)	12.5	11	10
Apparent viscosity (cP)	ND[b]	35.5	ND
10-min gel strength ($lb_f/100\ ft^2$)	ND	26.5	ND
Density (lb/gal)	ND	13.03	ND
Fluid consistency index, K', ($lb \cdot s^{n'}/ft^2$)	ND	0.0103	ND
Flow behavior index, n'	ND	0.5614	ND
28-d phase separation (vol %)	1.7	2.9	5.3
28-d compressive strength	1213 ± 67	1229 ± 38	1315 ± 33

[a]Dry solids blend contents are shown in Table 7.

[b]ND = not determined.

Table 12. Properties of grout mixes prepared from blend 5[a]
(Criteria values in SI units provided in text.)

Mix ratio (lb/gal)	11.0	11.5	12.0	12.5	13.0
Apparent viscosity (cP)	34	40.5	46.5	ND[b]	ND
10-min gel strength ($lb_f/100\ ft^2$)	24.5	27	33.5	ND	ND
Density (lb/gal)	12.98	13.11	13.24	ND	ND
Fluid consistency index, K', ($lb \cdot s^{n'}/ft^2$)	0.0047	0.0126	0.0174	ND	ND
Flow behavior index, n'	0.5650	0.5509	0.5271	ND	ND
28-d phase separation (vol %)	1.4	1.2	0	0	0

[a]Type I Portland cement, 49.5 wt %; ASTM Class F fly ash, 41.5 wt %; bentonite, 9.0 wt %.

[b]ND = not determined.

Acceptable grouts were prepared from blends 1 and 2 using ASTM Class C fly ash (Table 6) at 12, 13, and 14 lb/gal (1.4, 1.6, and 1.7 kg/L) of water. To allow a latitude in acceptable properties during blending, the final recommended blend consisted of 39 wt % Type I Portland cement, 55.5 wt % Eastern Class C fly ash, and 5.5 wt % bentonite. The dry blend was to be mixed at 12.5 lb (5.7 kg) per gallon (3.78 L) of water. CFR-1 was added to the water to make up 0.02 wt % of the dry blend.

4. GROUT PREPARATION AND INJECTION

With the selection of the trench and the development of an acceptable grout mix, the next objective of this project could be pursued, namely, to inject the grout using suitable equipment to fill the accessible voids of the trench. The equipment and procedures used, the injection of the grout, a review of the lance technique, and economic analysis of the operation are covered in this section.

4.1. EQUIPMENT AND PROCEDURES

4.1.1. Solids Blending

Solids blending is the dry mixing of the grout solids to produce a homogeneous blend. The equipment at the New Hydrofracture Facility (NHF) was used for blending in this operation (see Fig. 5). This facility was not designed for such a small operation or to deliver the blended solids external to the facility. However, minor modifications resulted in satisfactory operation.

The dry blend components used were those recommended by Tallent et al. (1987): Type I Portland cement, Eastern Class C fly ash, and bentonite. The relative proportion of these components blended for the field operation was approximately the centroid of the acceptable range of compositions identified by Tallent et al. and consisted of 39% cement, 55.5% fly ash, and 5.5% bentonite. The bulk cement and fly ash were purchased and stored in tank trailers at the NHF. The bentonite came from an existing stockpile of 100-lb (45.4-kg) bags of bentonite at the NHF. The blending and transport operations were done pneumatically.

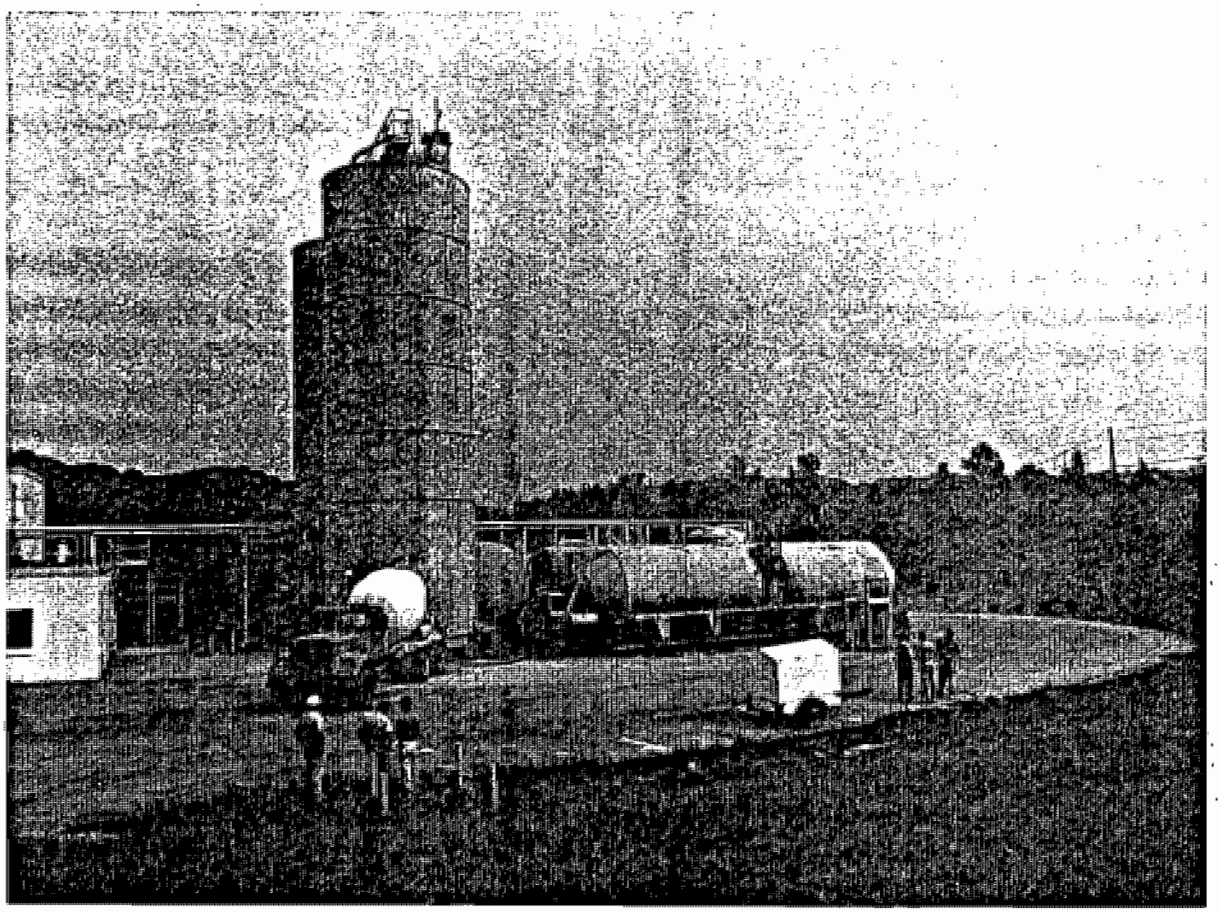

Fig. 5. Blending and storage equipment at the New Hydrofracture Facility. The concrete mixing truck is parked in front of vertical storage tanks.

The blending tanks at NHF consist of three pneumatic tanks, each capable of holding about 40,000 lb of dry solids. One of these tanks (weighing tank) is mounted on a set of accurate scales. The blending procedure started by adding each dry solid component to the weighing tank, noting the tank weight after each addition. Blending was done by blowing the entire tank contents from one tank to another three times. After blending, the blend was stored in the weighing tank for later use. About one tankful was blended at a time, enough dry blend to keep the grout injection going for three days at its optimum rate.

4.1.2. Grout Mixing

Grout mixing was done using a concrete mixing truck. A known quantity of blend was blown from the weighing tank to an empty blending tank (holding tank). Using a water meter, the proper amount of water was put into the truck drum and the set retarder/dispersing agent (delta gluconolactone, marketed by Halliburton as CFR-1 sugar) added. With the drum rotating at high speed, the holding tank contents were blown into the drum (see Fig. 5). The mix ratio and proper mixing of the grout were confirmed by measuring the grout density at the site just after mixing and several times during the injection. Another check on the weighing and mixing was to weigh the truck at each stage of the operation (i.e., empty, with water, and with grout).

Mixing in this manner was not recommended initially because a concrete mixer depends on the aggregate to shear the mix and break up lumps. This technique, however, worked for the demonstration because the grout used was fluid enough to be slurried by the agitated water

and few lumps were present in the purchased solids. A different technique (mixing in a 1500-gal tank) was attempted at the beginning of the field work but was abandoned because of its inability to produce a homogeneous grout and its lengthy mixing time.

For the initial and later abandoned technique, the preweighed quantity of blend was blown into the back of a dump truck covered with a tarpaulin and hauled to the injection site at SWSA 6. At the site, the proper amount of water was added to a 1500-gal tank (see the tank in the background of Fig. 6) and the CFR-1 sugar was added to the water. The blend was then scooped from the truck bed and dumped into the 1500-gal tank. The blend was mixed and kept suspended by recirculating the tank contents continuously through a diaphragm pump at about 80 gpm. In addition to the agitation provided by pumping the fluid, an impeller stirrer kept the upper two-thirds of the tank agitated. One tank full of grout was sufficient for one day's operation at average rates. The first batch made in this manner encountered no operational problems. However, the second batch became too thick to pump. A check of the weighing records quickly revealed that too much solid had been inadvertently added; not unexpectedly, there was no way to reslurry the grout with more water with this technique and the batch was dumped. In addition, this abandoned technique took longer than anticipated to mix a batch--close to half a workday.

The inherent instability of the abandoned technique was recognized prior to beginning field operations as well as the possibility of

Fig. 6. Assemblage of equipment used to grout trench 150. The 1500-gal mixing tank is located in background in front of the water truck. Boom is used to set lances and hold hammer.

mixing problems in the concrete mixer without the presence of aggregate. Both techniques were kept as options and tried in the field operation. The concrete mixer proved to be easier, quicker, and less troublesome for mixing and delivery, and because of its convenient opening it was less hazardous to operating personnel when visual inspection was required. Not surprisingly, neither technique exactly duplicated the mixing used in the laboratory, but the grouts produced were satisfactory. The recirculating pump technique has worked well for making large batches of lime-fly ash slurry, but unlike cement grouts, such a slurry may be left unagitated overnight and still be reslurried.

4.1.3. Lance Placement

The lances were sections of 2-in. Schedule 80 steel pipe. Disposable points were placed in the end of the lance prior to driving it into the trench to enhance penetration of the backfill and prevent soil blocking of the grout exit. A 120-lb portable air hammer was used to drive the lances into the trench (see Fig. 7). The lances were driven either to the bottom of the trench or until an obstruction was encountered. Once in place, the lance was pulled up 6 in., the point was knocked out of the end (the points remained in the ground at the bottom of the holes), and the lance was pulled up another 6 in., ready for grout injection. Upon grout refusal at a given depth, the lance was pulled up 1 ft and grouting continued. Injection into a given hole was terminated if grout appeared on the surface of the trench or if the pressure required to inject was excessive (~20 psi).

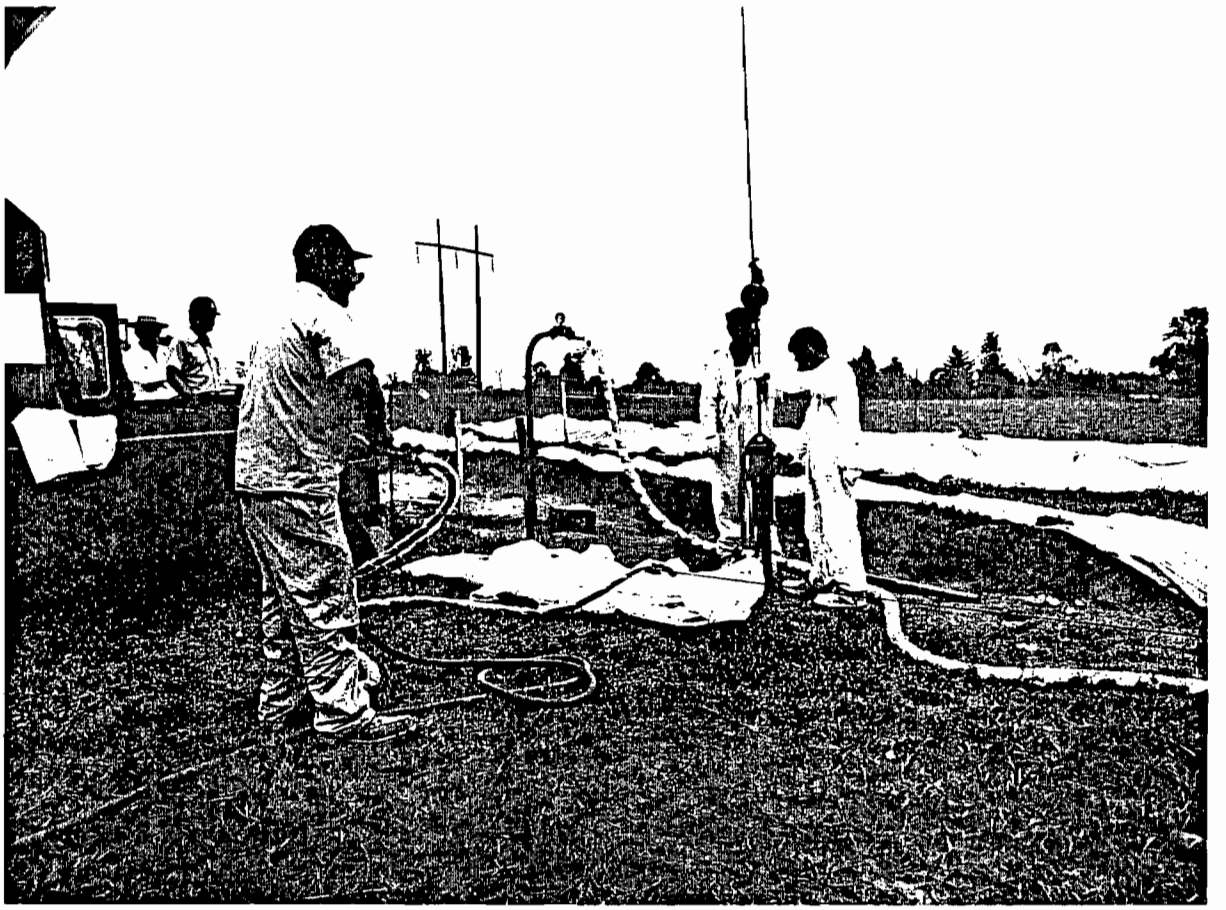

Fig. 7. Driving lances into trench. Operator at left controls air pressure to control the portable hammer. Note also the high-pressure grout delivery tube connected to a lance previously installed.

Long lances could not be handled with this manual placement procedure. Thus, the placement was handled in segments of 7 ft or less by using pipe couplings to keep adding length to the lance until the desired depth was achieved. For trench 150, two 7-ft sections were more than sufficient to reach the bottom. In practice, the lances usually could not be driven as much as 7 ft. The trench bottom was approached in only 4 placements out of the 36 used. In some cases, obstructions prevented penetration to the trench bottom, but in general, the 2-in. pipes offered more resistance to driving into the backfill than expected. The 120-lb hammer just was not adequate to force the 2-in. pipes through the backfill at most locations. However, this limitation did not affect the final outcome. As expected, injection into one placement gave access to a large area of the trench, including several other placements. In other words, the trench's accessible voids were so interconnected that the large number of placements ensured complete grouting of the trench. Nevertheless, smaller diameter pipes are recommended for any future injections using this placement technique to permit deeper penetrations. Lances made from 3/4-in. Schedule 40 pipe or standard AW drill rod should work for the SWSA 6 trench depths at the grout take rates observed for trench 150.

4.1.4. Grout Injection Mode

The grout injection was done using a progressive cavity pump with a maximum rate of about 15 gpm. The pump was fed by two 70-gal slurry mixing tanks. While one was being pumped, the other was being filled

Fig. 8. Transfer of grout to slurry tanks. Pumps to deliver grout to lances are located behind wall.

with grout from the concrete truck (see Fig. 8). The grout was pumped through 50 to 100 ft of 2-in. high-pressure hose, past a pressure gauge, through the lance, and into the trench (see Fig. 6).

A pressure of 5 to 10 psig was used for the injection as long as possible. Once the voids accessible at a given location began to fill, the pressure would begin to creep up and the pump rate would be decreased. Pump rates lower than about 5 gpm resulted in operational problems for the motor and slurry agitators (the motor ran the pump and agitators). Thus, rates at 4 $\pm$ 1 gpm were not decreased further. A slow rise in pressure indicated steady filling of the voids, and a sharp rise indicated a bottleneck to flow or no further room for grout take. Injection was continued as long as possible while the pressure rose slowly. Depending on the depth and grout take behavior, injection would be stopped at 15 to 20 psig. Sharp rises were treated more carefully. Stopping sometimes relieved the pressure, indicating that a grout flow path existed but resistance to grout movement was high. In such cases, higher pressures sometimes caused a breakthrough in the bottleneck, allowing continued operation. If high pressure was not relieved by stopping the pump, then the lance depth or location was changed. Injection was also stopped as soon as any grout broke through to the surface.

The lance depth was changed by pulling the lance up 1 ft. At the new depth, grout injection was continued until refusal. Then the entire process was repeated. This procedure changed once the lance was within 2 ft of the surface, where effective grouting could not occur.

At this point, the lance was withdrawn from the ground and the grout injection operation moved to a new location. The lance was pulled up by either a hydraulic jack or a small crane. The jack was small, portable, and easy to operate but took longer to use and was subject to contamination. The crane was used exclusively after the first two days because it was quicker, operated more smoothly, and eliminated the possibility of contaminating the jack. The crane was also needed to safely handle the air hammer for lance placement and easily handled both jobs.

The procedure was different once breakthrough to the surface occurred. Such breakthroughs can be categorized as oozing around the injection lance, oozing around another previously installed lance, oozing up a previous injection hole, or oozing out of a new pathway on the surface. Sometimes packing the exit at the surface and waiting a few minutes allowed injection to continue. This worked especially well for oozing around the lances and occasionally worked for the new pathways. Once a pathway developed at the surface at one depth, injection at a shallower depth in the hole would not work because grout would follow this same pathway to the surface. Therefore, the lance was removed and the hole was abandoned once such a breakthrough occurred. Most of the injection holes did result in one of the four breakthroughs described above rather than the orderly withdrawal to the surface described previously.

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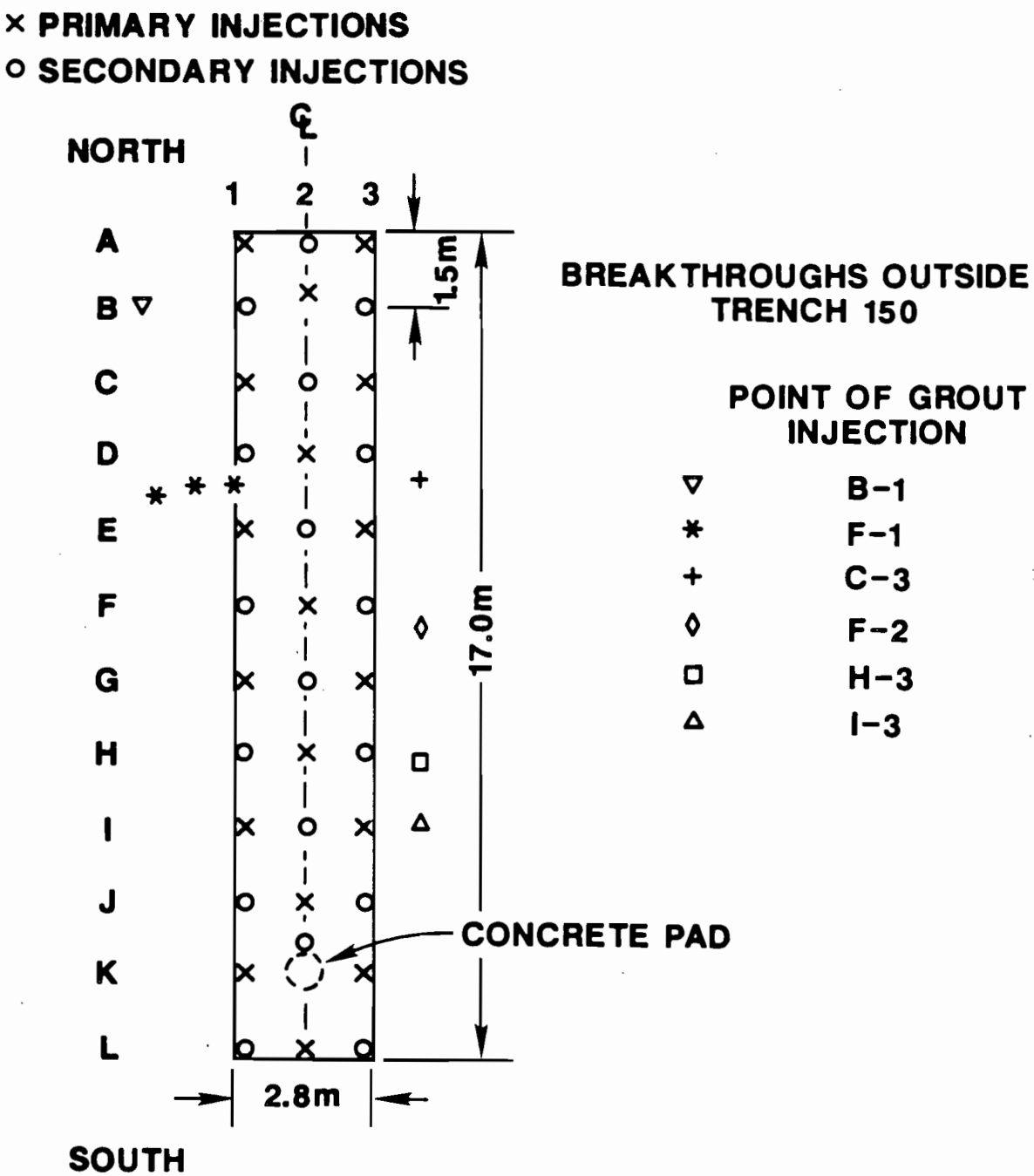

Fig. 9. Grid locations used in grouting and breakthrough positions outside of trench 150.

Table 13. Summary of the grout injection of trench 150

No.	Location	Depth (ft)	Vol (gal)	Time (min)	Rate (gpm)	Reasons for stopping
1	B-2	9.5	360	38	9.5	Breakthru 1.7 ft S of B-1
		7.5	25	2	12.5	Changing depth no help
2	C-3	2.5	1740	300	5.8	Breakthru between 150 & 152
3	C-1	6.75	207	30	6.9	Breakthru at B-2
4	D-2	5.2	0	0		High pressure
		4.0	0	0		Breakthru at C-1
5	E-3	6.0	60	5	12.0	Breakthru at C-1
6	E-1	5.5	38	5	7.6	Breakthru at D-2
7	F-2	8.5	171	64	2.7	High pressure, low rate
		7.5	591	80	7.4	Grout thickening
		6.5	1685	260	6.5	High pressure, low rate
		5.0	180	40	4.5	High pressure, low rate
		3.0	480	75	6.4	Breakthru between 150 & 152
8	G-3	5.9	0	0		Breakthru at F-2
9	G-1	10.0	85	10	8.5	Breakthru 3 ft S of D-2
10	H-2	4.0	0	0		Breakthru at G-3
11	I-2	6.1	625	65	9.6	Breakthru between 150 & 152
12	I-1	3.25	150	17	8.8	Breakthru within 1 ft I-1
13	J-2	4.4	80	11	7.3	Breakthru at I-3
14	K-3	3.8	70	10	7.0	Breakthru at K-3 wall
15	L-2	4.8	150	15	10.0	Breakthru at K-1 & pad
16	K-1	7.2	30	3	10.0	Breakthru within 1 ft K-1
17	A-1	6.0	185	45	4.1	Breakthru 1 ft N of F-1
18	A-3	6.0	7	1	7.0	Breakthru at A-1
19	F-1	8.5	480	60	8.0	Breakthru W 150 & S D-1
20	F-3	8.2	80	10	8.0	Breakthru S of D-1
21	G-2	3.75	0	0		Breakthru at G-1 wall
22	H-1	5.25	20	3	6.7	Breakthru 4 ft N of H-1
23	H-3	4.6	110	15	7.3	Breakthru between 150 & 152
24	E-2	5.3	10	2	5.0	Breakthru at F-3
25	D-3	1.0	0	0	0	Too shallow
26	D-1	2.5	10	2	5.0	Breakthru at D-3
27	A-2	4.7	20	12	1.7	Breakthru 2 ft N C-2 & C-3
28	B-1	4.1	25	7	3.6	Breakthru W of 150
29	B-3	4.1	55	15	3.7	Breakthru at C-2
30	C-2	5.75	125	29	4.3	Breakthru at B-3
31	I-2	3.0	30	6	5.0	Breakthru 1 ft S of H-1
32	J-1	6.6	40	8	5.0	Breakthru 1 ft N of L-1
33	J-3	3.4	10	2	5.0	Breakthru J-3, 1 ft S K-3
34	K-2	2.8	5	1	5.0	Same as J-3
35	L-3	2.3	135	45	3.0	Breakthru 3 ft W of L-3
36	L-1	2.0	7	2	3.5	Too shallow
		Total	8081	1325	6.1 avg.	

4.2. INJECTION

4.2.1. Grout Quantity and Location

Figure 9 illustrates the grout location points used. Table 13 lists the quantity of grout injected at each location and the depth at which injection occurred. The depths referred to in Table 13 were the distances below the excavated surface; thus the trench bottom was at a depth of 10.8 ft (3.3 m) because a nominal 1 ft of cover soil had been removed. The total trench volume for this depth was 5564 ft^3 (41,619 gal or 157,000 L). A total of 8081 gal of grout was injected into the trench, representing 19.4% of the trench volume (excavated). The accessible void volume was initially estimated at 20% and the amount of grout injected thus is 97% of this estimate. Water tests suggest 7385 gal of accessible voids; thus 8081 represents 109% based on the water test results.

The injection was completed in two steps. The 18 primary injections were done in a diamond pattern with a 10-ft center-to-center basis. The 18 secondary injections were done midway between the primary points, meaning injections were done about every 5 ft counting both the primary and secondary injections. Over 85% of the total was injected in the primary injections. Most of the grout was injected into only a few holes. From the primary injection, F-2, C-3, I-3, and B-2 accounted for 38.4%, 21.5%, 7.7%, and 4.8% of the total respectively, cumulatively 72.4%. From the secondary injection, only F-1 took a large amount at 4.9% of the total. These five holes took 78.3% of the grout injected.

Based on the location of the grout takes, the trench can be roughly divided into three regions, north, central, and south. As expected, a great deal of hydraulic interconnection exists within the trench and partially defines these three regions. Once a region was saturated with grout, further addition resulted in upwelling of grout from another hole or a previous breakthrough. The northern region was saturated by the injections into B-2, C-3, and C-1. The central region was saturated by the injection into F-2 and the southern region by the injection into I-3. For the secondary injection only the first injection took a large amount and it was in the middle portion of the trench at F-1. The remaining 30 injections still accounted for 20% of the grout injected and cannot be disregarded.

Based on the results of this demonstration, the initial injections could have been made on 20- to 25-ft centers. Also, stopping at the end of the workday when a given hole is still taking the grout at a good rate may seal off some accessible voids when the grout sets overnight (only the injections into C-2 and F-2 were not completed in one workday). To prevent this in the future, operation should be stopped only after grout refusal of a given hole. Once a region was saturated, further injection while the injected grout was still fluid was usually pointless because the region was so hydraulically connected that forcing in grout at one point just forced grout out at another point. To be more effective in the future, after reaching saturation in a given region, the grout should be allowed to set before any more grout is injected into the region. This would plug the previous hydraulic connections and allow grout into new areas.

4.2.2. Time and Rate

The time and rate can be defined in several ways. For example, according to Table 13, it took 22 h to inject 8081 gal of grout into trench 150 at an overall rate of 6.1 gpm. However, this time and rate can be misleading because the job took a total of 11 d. The values reported in Table 13 represent only the times when injection was occurring and ignore support operations such as blending, mixing, and lance placement. In general, grout take rates started high and had to be reduced as the voids filled and pressure increased, but the rates reported in Table 13 are an overall average for a given injection. Spot checks of the pump rate agreed with these overall rates, so the times and rates reported in Table 13 are indicative of the grout take for a given injection.

The field operation was completed in 11 days, meaning that an average of 735 gal/d was injected into trench 150. This period includes set-up days and training. The first two days were used to set up the operation and equipment and no grout was injected. The next two days were spent familiarizing the personnel with the operation and equipment and trying the recirculation mixing technique, and only 385 gal was injected. Thus, the daily rates can be summarized at 0 gal/day for the first two days, about 200 gal/d for the next two days, and about 1100 gal/d for the remaining seven days.

The field operation was designed around an 8-h workday and a 1500-gal batch of grout. It was expected that 1500 gal of grout could be mixed and injected into the ground within a normal 8-h workday with

time for cleanup and setting up for the next day. Thus, the workday was defined around the grout batch with the hours remaining flexible (i.e., the workday ended when the batch was injected and the equipment was cleaned). At the beginning 1500-gal batches were used and, as expected, the entire batch could be injected in close to the desired time. As the trench became saturated and the grout take rate slowed, the batch size was cut in half (to 750 gal). The workday hours remained about the same because the mixing operation took just as long as the larger batch, the injections took longer, and much more time was taken in moving from hole to hole and driving lances.

In the transition period when 1500-gal batches were still being used but the time for injection was significantly longer, the grout thickened unexpectedly early towards the end of a batch. Laboratory tests had demonstrated that the grout would set overnight and not thicken during agitation for 8 h or more. Thickening occurred in the field after only 7.5 h, probably because direct sunlight and higher temperatures speeded up the cement reactions. All of the equipment was cleared of the rapidly thickening grout except for two sections of lance pipe. Operation close to this time period after grout mixing was avoided for the remainder of the operation.

4.3. ANALYSIS OF THE LANCE TECHNIQUE

4.3.1. Small-Scale Manual Effort

The grouting technique used in this demonstration was simple and straightforward and easily learned by an inexperienced crew. Only inexpensive and readily available equipment was needed. Driving the

pipe was hindered by the choice of the large pipe size (2 in.), but using a smaller pipe size (3/4 in.) would have solved this problem.

This technique was labor intensive. A minimum of two men could have performed all of the operations, but at the sacrifice of time. Only the mixing and injection had to be done sequentially; blending and lance placement were done at the same time as other operations. Ten workers were used for this field demonstration, more when blending or truck driving was required, which was more workers than necessary. The work was performed by craft workers and no craft exists for "grout worker" at ORNL, so two or more different crafts were required in situations that one worker handled for commercial grouting firms. Also, some duplication was necessary to continue operation during breaktimes and mealtimes. Two workers can handle all of the tasks if the grout batch can be used over a period of several days, as in the case of lime-fly ash. Cement grouts must be injected in a matter of hours and more workers are necessary to handle different tasks simultaneously. If all the workers can work interchangeably, then the minimum number is four or five. This supplies enough workers to blend, mix, place lances, and inject and still have coverage for staggered breaks and meals.

Maneuvering around buried objects would be more time consuming and complex with this technique than for a mobile lance machine. Several steps involving two or more workers would be required: (1) driving the lance down to the obstruction, (2) removing the hammer and attaching the puller, (3) pulling up the lance, and (4) repositioning the lance

and driving at the new location. The actual driving only takes a couple of minutes, but relocating can take 15 minutes or more, especially if the hydraulic jack is used to pull up the lance.

One way to speed up the grouting operation would be to use a manifold system and inject into more than one lance at a time. Initially, the grout take rates were close to the pump maximum and dividing the flow would not have helped much.

4.3.2. Comparison with Mobile Lance Machine

The mobile lance machine is not a standard grouting machine routinely available from the typical grouting vendor. Its operation is based on a concept of a lance or lances mounted on a machine able to quickly and easily position itself at any point desired, insert the lance to the desired depth, stop or reposition the lance if an obstruction is encountered, and inject grout as soon as the lance is in place. Such machines have not been routinely used with cement-based grouts. They were originally developed for lime-fly ash injections into railroad beds. Companies such as Woodbine, Inc., Fort Worth, Texas, have machines with up to four independent lances that go as deep as 40 ft. The lances are not as rugged as the thick-walled pipe used in this demonstration, but proved to be rugged enough both in undisturbed Conasauga shale and in the loose trench backfill for a previous demonstration conducted by Woodbine in 1983 in a nonradioactive trench at SWSA 6 (see truck unit in background of Fig. 10). With such a machine, the grouting of trench 150 could have started with four evenly spaced, simultaneous injections along the north-south

Fig. 10. Mobile grouting equipment. Triple-lance truck-mounted unit in background with double-lance modified fork lift unit in foreground. Cylindrical 10,000-gal mixing tank located at left.

axis. Based on the results reported in Table 13, 75 to 80% of the trench may have been grouted from this initial set of injections. Next, as many injections as desired, wherever desired, could have been done to ensure topping off the trench.

The equipment that was used to grout the asbestos trench is shown in Fig. 10; the unit that successfully grouted the trench is the modified truck shown with its lances lying parallel over the roof of the truck that is kept in this mode for transport purposes. When positioned over a trench, the lances are set vertically and are driven into the ground hydraulically. The truck unit successfully injected 7500 gal of lime-fly ash grout in one day. The grout was prepared in the cylindrical container located in the left background of the figure and is capable of mixing 10,000 gal per batch.

The unit in the foreground of Fig. 10 is a modified fork lift adapted to inject grout. In the demonstration this unit was used to test whether it was capable of penetrating the undisturbed material in which trenches are made. The unit was incapable of penetrating the material, which is similar to that found near trench 150, but likely can penetrate disturbed trench material. Considering the number of poundings required to penetrate the local undisturbed material (see Sect. 5), it is not too surprising that this lighter unit failed. The larger truck unit did successfully penetrate the undisturbed formation.

The concept appears feasible and offers the advantages of quicker, less labor-intensive operation over the technique used in the demonstration. Difficulties do exist in acquiring the services of such a

machine. The lime-fly ash vendors possess the most advanced machines but have little experience with cement grouts. The cement grout vendors have little experience with such machines. The few vendors that claim experience with both may not wish to work in areas contaminated with radioactivity. The advantages of this technique over the labor-intensive technique would be much more apparent for larger jobs, e.g., grouting all the trenches in SWSA 6. For small jobs, such as grouting trench 150, the time advantage may be small or non-existent. Small jobs may cost more considering the large mobilization cost to move the machine to the site.

4.4. ECONOMIC ANALYSIS

Table 14 reports the cost of the dry blend components. No bentonite was purchased for this demonstration since sufficient 100-lb

Table 14. Cost of dry blend components

Component	Source	Quantity	Cost	
			Unit	Total
Type 1 Portland cement	Dixie Cement	23.5 t	$61.32/t	$1441
Eastern Class C fly ash	Amer. Fly ash	50. t	$40/t	$2000
Bentonite	Black Hills		$38/t	

bags were available for use at NHF. The cost for bentonite given in Table 2 was that quoted in the economic analysis of in situ grouting done for EG&G Idaho. For only a few tons of bentonite, the shipping charges are higher than the cost of bentonite. From Table 14, the purchase price of bentonite was about 2¢/lb (4.4¢/kg). The delivered

cost was assumed to be 5¢/lb (11¢/kg). From Table 14, the delivered costs of cement and fly ash were 3¢/lb (6.6¢/kg) and 2¢/lb (4.4¢/kg), respectively. The target mix ratio of 12.5 dry blend/gal water had a resultant density of about 13.5 lb/gal of grout (1.62 kg/L). Therefore, each gallon of grout was calculated to contain 3.2 lb of cement, 4.5 lb of fly ash, and 0.4 lb of bentonite. Ignoring water costs, each gallon of grout costs 10¢ for cement, 9¢ for fly ash, and 2¢ for bentonite, for a total of 21¢/gal of grout (5.5¢/L). Thus, the total cost of the grout injected into trench 150 was $1697. About 3000 gal was dumped or wasted because of learning errors, representing $630.

Table 15 reports the costs of renting the grouting equipment from a local grouting firm. The total equipment costs were $3449. Discounting the learning and experimental period gives $1773 for the equipment costs during the period of active injection (cost for the technical advisor was also excluded). Table 16 reports the estimated manpower required to grout trench 150. A total of about 1217 manhours was used at an estimated cost of about $50,000. The cost of manpower and equipment was about $4800/d. Out of the 11 days of operation, 4 days were spent in setting up, instructing the workers, and experimenting with the mixing procedure, leaving 7 days for doing the bulk of the grouting. Using the estimated daily cost, these 7 days cost $33,600. Based only on the 7-d period, about 1150 gal/d was injected into trench 150 at a cost of $230/d for the grout, a total daily cost of $5030.

The manhours reported in Table 16 do include some overtime and some duplication of personnel. Based on the manhours used and an 8-h

workday, the job averaged 14 people including the foreman, the engineer, and the blending operators (hydrofracture). As noted previously, a commercial operation may have gotten by with a working crew of five (including the foreman) with an engineer part-time. ORNL would still need to provide some support, e.g., a health physicist (HP). Based on six people (including the HP), the need would have been 48 manhours/day, at a cost of $1920/d--totals of 336 manhours and $13,440 for grouting trench 150. The cost of manpower and equipment becomes about $2300/d. Adding the cost of the grout injected daily on the average gives a total cost of about $2530/d. Assume a commercial operation would charge about $3000/d, or about $2.60/gal grout injected, including overhead and profit. The commercial operation would require one day to set up, and the smaller crew would likely take longer to complete the job. Assume the job would take 11 days to do as in the demonstration, but without the necessary learning time. This assumption gives an expected cost of about $33,000 for a vendor to grout trench 150 using the same technique as in the demonstration. To use a mobile lance machine, a mobilization cost of several thousand dollars would be charged with little advantage in time or money for a small job such as grouting trench 150. Thus, the total cost could be $40,000 or more for a single trench. The benefits of using the machine would become more apparent as the size of the proposed job increased. In the 7500-gal lime-fly ash grout demonstration in 1983, the cost, including mobilization, estimated by Woodbine Company was approximately $16,000 with actual injection

Table 15. Cost of renting grouting equipment from Rembco Engineering Corp.

Equipment	Unit cost	Total cost for 11 days
Pump and tanks	$ 65/d	$ 715
Casing puller	20/d	220
Casing driver	20/d	220
1500-gal tank & pump	50/d	550
Mixer	50/d	550
Casing sections (98 ft)	14/d	154
Driver bullets (40)	6/ea	240
Technical advisor (5 d)	150/d	800
	Total	$3449

Table 16. Estimates of manpower used for grouting trench 150

Worker	Manhours	Cost @ $40/manhour
Laborers	473	$18,920
Truck drivers	191	7,640
Pipe fitters	135	5,400
Power equipment operators	132	5,280
Engineer	88	3,520
Health physicists	60	2,400
Hydrofracture operators	50	2,000
Total	1217	$48,680

requiring one day. In that demonstration, however, the company charged $5,000 since the operation was done between job assignments.

5. POST-INJECTION EVALUATION

5.1. ACCESSIBLE VOID VOLUME VERSUS INJECTED GROUT VOLUME

Based on water injection tests, the volume of accessible voids in trench 150 was 7385 gal (27,950 L). A total of 8081 gal (30,585 L) of grout was injected, representing 109% of the accessible voids. The discrepancy of 696 gal may not be excessive considering the assumptions made in arriving at the accessible void volume from the total water volume of 11,532 gal (43,650 L) and the observation that grout emerged outside the trench perimeter at six locations (Fig. 9). Based on the trench volume, the grout volume represents 18% accessible voids.

Comparison of the accessible voids filled with grout reveals that for the two particulate grout injections, the void volume was 20% for the lime-fly ash demonstration and 21.4% for this cement-fly ash-clay test. For the two chemical grouts, the volume percentage based on the total trench volumes as reported was 23% for the sodium silicate injected in Kentucky and 20% for the polyacrylamide grout injected at ORNL. One might expect a higher take for chemical grouts since their low viscosities would favor penetration into the smaller pores. A possible explanation for the similarity in void volume percentages may be that the pores of the soils are saturated with water and thus unavailable to chemical grouts. On the other hand, the slightly higher take of the chemical grouts likely represents filling of cracks and fractures inaccessible to particulate grouts (in contrast to soil pores), and may represent significant water pathways out of the trench.

5.2. RADIONUCLIDE AND WATER CHEMISTRY ANALYSIS

Following the completion of injection, samples of water were taken from the permanent wells (T-150 and T-152) of trenches 150 and 152. The results of the analysis are listed in Table 17. Pre-injection results taken in 1985 are also included to facilitate comparison. The pH and electrical conductivity (EC) of the two trenches were very similar before grouting. Unfortunately no information on Ca, Mg, and Na were available prior to grouting due to late selection of these particular trenches for the demonstration and the dry periods experienced in 1984-86. However, if one considers the Ca, Mg, and Na values for trench 147, which is adjacent to trench 150, and for well 402, which is located between trenches 150 and 152 (see Table 5), it is reasonable to assume that the water quality for trench 150 would be similar to these values.

On the supposition that water quality of trench 150 was similar to that of trench 152, it is easy to see that the quality changed drastically after grouting (Table 17). The pH and sodium concentration rose and the Ca and Mg concentrations decreased. An interesting result is the ^{90}Sr for the sampling of 1-16-87. The concentration was 8000 Bq/L in the grouted trench and 21 Bq/L in trench 152. Subsequent samplings showed that the ^{90}Sr concentrations are reversed from that observed on 1-16-87, when trench 150 was higher. The fact that the pH was high and Ca and Mg concentrations were low on 1-16-87 would suggest that ^{90}Sr concentrations are low (Spalding 1980). This anomalous observation of ^{90}Sr on 1-16-87 cannot be explained at this time.

Table 17. Selected properties of water samples collected from trenches 150 and 152

Trench No.	Sampling date	pH	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	EC[a] (µs/cm)	^{90}Sr (Bq/L)	^{3}H (Bq/L)
T-150	4-17-85[b]							
	8-29-85	6.80				500	21,345	
	11-05-85	6.90				510	21,125	5,200
	1-16-87	10.13	2.8	0.33	95	530	8,000	12,000
	3-03-87	9.88	6.9	0.93	42	280	56	58
	4-16-87	9.76	4.9	0.50	50	285	75	81
	4-30-87	10.01	7.4	0.56	76	340	77	53
	5-01-87	11.26	5.2	0.41	130	590	100	120
T-152	4-17-85	6.65	80	23	2.0	580	25,675	33,000
	8-29-85	6.70				420	35	
	11-05-85	6.90				230	230	2,200
	1-16-87	6.58	79	12	2.7	400	21	11,000
	3-03-87	6.62	52	7.4	2.1	275	3,200	440
	4-16-87	6.56	60	8.7	1.6	330	4,000	270
	4-30-87	6.55	68	9.7	2.4	400	6,600	200
	5-01-87	6.77	73	10.0	1.2	380	6,100	210

[a]EC = Electrical conductivity.

[b]Insufficient water in well.

The high pH is due ultimately to the presence of sodium ions. The introduction of sodium is likely through the exchange of sodium initially on the bentonite clay (present in the blend) by calcium from the cement as calcium hydroxide is formed in the reaction. No samples were taken from the five additional wells because the water level in them were very low; even well T-150-5 (see Fig. 4), which was inserted to the bottom of the trench on the north end, showed no presence of water (or very small amounts) at all measuring periods.

The last two samples were taken on two successive days (4-30-87 and 5-01-87); these samples are discussed in the next section.

5.3. HYDROLOGIC BEHAVIOR OF PRE- AND POST-GROUTED TRENCH

As just noted, the last two samples shown in Table 17 were taken within 24 hours of each other. The reason for this was to compare the water quality before and after pumping out the wells. Trench 150 had been pumped for only 15 minutes when the water level dropped to the bottom and no further water could be pumped. The volume of trench water removed was 8 L (2.1 gal) when pumping was stopped. In contrast, T-152 was pumped for 25 minutes, collecting 15.3 L (4.0 gal) when pumping was stopped. The water level had dropped only 1.8 cm (0.7 in.) from an original height of 38 cm (15 in.); this may be compared with T-150, which had a height of 116 cm (45.8 in.). After 24 hours, T-150 had recovered to 70% of the previous day's level; T-152 remained at the previous day's level.

Obviously the pool of water in T-150 must be relatively small. Since the well diameter is 10 cm (4 in.), the volume of water held

within the well was calculated. On the basis of 116 cm in height of water, the volume contained in the well tube calculates to 9.1 L (2.4 gal). During the water injection test prior to grouting, data were recorded on the gallonage pumped and the water level in the well. Using this relationship, the volume of water was 10,100 L (2668 gal). For T-152 with a 7.6-cm (3-in.) diameter well, the drop of 1.8 cm calculates to a cylindrical pool 51 cm (20 in.) in radius.

Although no samples were taken from the additional wells, pump tests were performed to measure the volume of water that could be recovered from the five additional wells (see Fig. 4 for locations and relative depths). T-150-5 inserted to the bottom yielded 0.24 L; the highest yield of 0.86 L was obtained from T-150-4, which is inserted down 1.5 m. Both T-150-3 and T-150-2 yielded no water, whereas T-150-1 yielded 0.25 L. With the exception of T-150-4, the amount of water may be considered negligible.

Earlier during the water injection test to obtain void volumes, the measurement of the pump rate showed that >16.5 gal/min per well could be injected without overfilling the well. Thus, based on the diameter of the tubing, the rate of take was calculated to be >30.8 m/min (101.2 ft/min). After grouting, measurements of water take were made again. For three of the wells (T-150-5, -3, and -2), the average was 0.4 m/min with values ranging from 0.3 to 0.6. The T-150-1 took water at the much slower rate of 0.005 m/min. In contrast, T-150-4 took water at 1.7 m/min. From the wide range in values, it is difficult to assign a reduction in the take of the trench after grouting, especially since the confining volumes represented by the wells are difficult to define.

Since T-150-4 had the highest take rate after grouting, it was decided to evaluate whether the pathway of water migration might be connected to the other wells. For this purpose, water was pumped into T-150-4 as rapidly as it could take the water without overflowing; with passage of time, the different wells in the trench were measured to see if water had reached the location and level. After passage of approximately 850 gal only T-150-3 showed any changes in water elevation--the maximum rise was 3 ft during a day of pumping followed by return to dry conditions on overnight standing. After the tank had drained its water of 867 gal, final readings were taken of the wells in trench 152 as well as the grouted trench. The only added well that showed any water was a well in trench 152, which was directly across (east) from T-150-4. As mentioned earlier, the additional wells located in trench 152 were not measured periodically since they consistently showed dry conditions except for the well closest to the permanent well (T-152) located at the south end of trench. However, in this test, considerable water must have migrated to the area of the well T-152-4 since the water level was at approximately 3.5 ft (1.0 m) from the surface and the well had been placed approximately 9.1 ft (2.8 m) deep. Obviously there exists an almost direct pathway for water passage between these two wells.

5.4. PENETROMETER AND CORING RESULTS

A potential way of locating the distribution of grout is to measure the resistance offered by the set grout possessing compressive strengths of over 1000 psi (6894 kPa) as determined in the laboratory.

It was also felt that by performing the tests in both the grouted and adjoining ungrouted trench, a better understanding of the grouted system would be obtained. Hence five locations per trench were selected for the penetrometer tests, shown in Fig. 11 for ungrouted trench 152 and Fig. 12 for grouted trench 150. The actual north-south positions were dictated to a large degree by the wells previously placed in the trenches, and efforts were made to make the measurements along the center line of the trench. Beside each trench, penetrometer readings were taken of the undisturbed section between trenches.

Figures 13 and 14 show the total number of poundings required to penetrate the trenches. The poundings refer to the number of times that a weight of 140 lb (63.6 kg) dropped from a distance of 30 in. (76 cm) was required to penetrate 1 ft (0.3 m). Results in Fig. 13 for trench 152 show that down to approximately 3 m, about 40 poundings were required; more poundings per unit depth were required to penetrate deeper in the ungrouted trench. Between 70 and 100 lifts were needed to reach the vicinity of the trench bottom (4 m). In contrast, in the undisturbed material (P-12), 100 poundings penetrated less than 2 m. In the grouted trench, 40 poundings penetrated about 1.5 m. Considering both trenches it appears that the first meter of penetration required approximately 20 poundings. As is noted later in discussing core recovery, the upper portion reflects the soil cover material placed above the waste. Although rather variable, over 120 poundings are required to reach the trench bottom in the grouted trench. Again the

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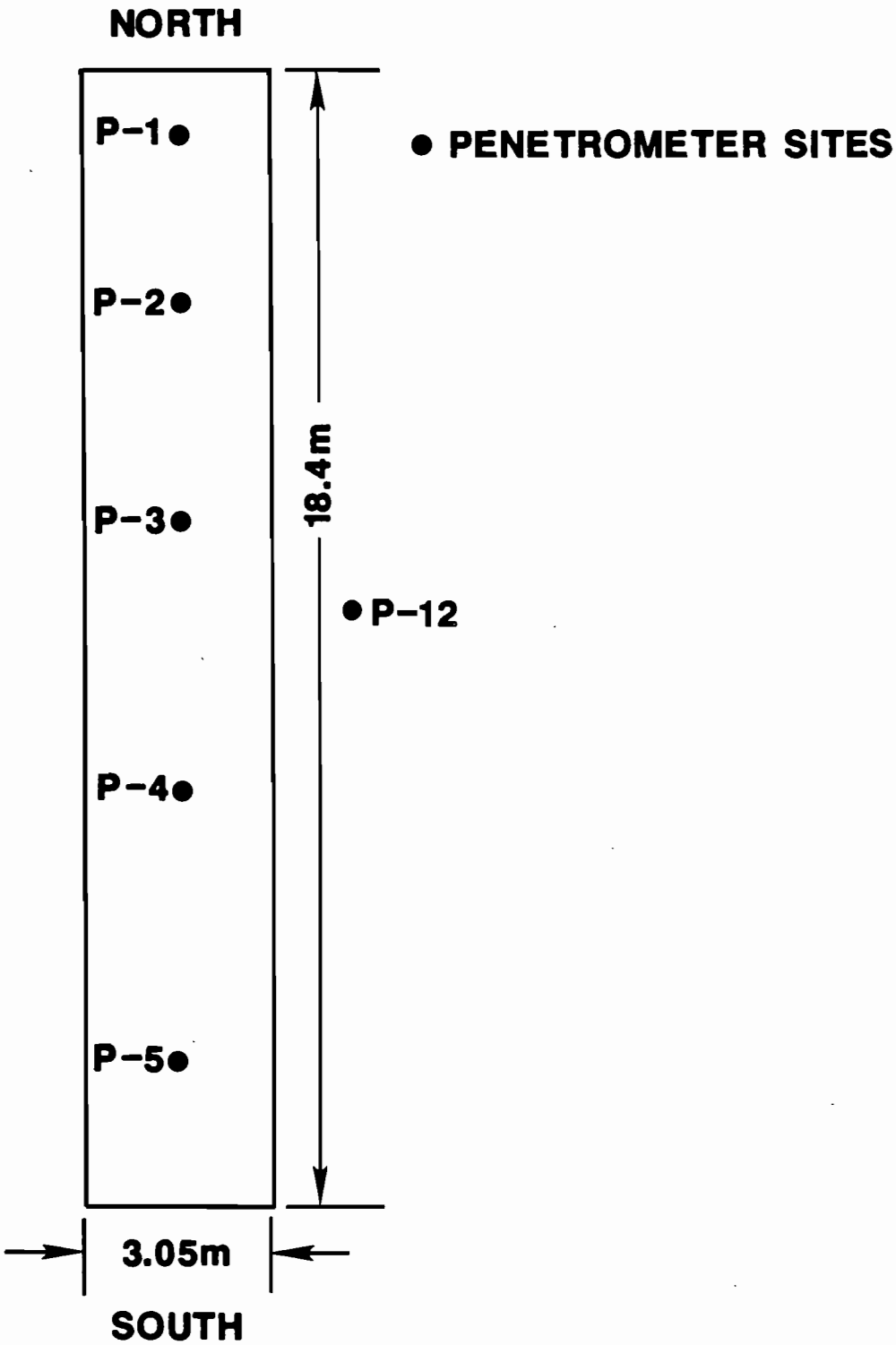

Fig. 11. Locations of penetrometer sites in ungrouted trench 152. Note additional site outside of trench in the undisturbed area between trenches.

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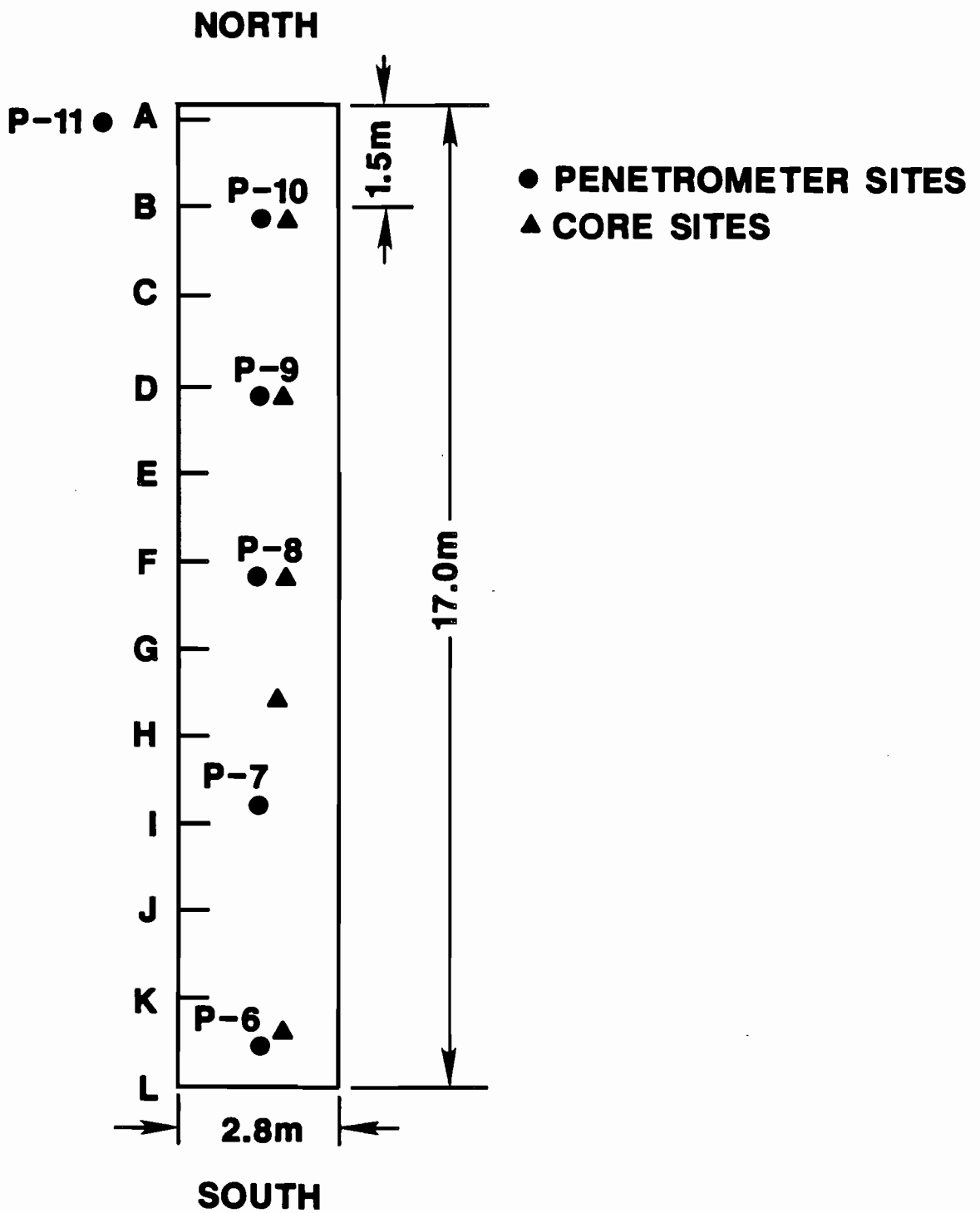

Fig. 12. Locations of penetrometer and coring sites in grouted trench 150. Note additional penetrometer site in undisturbed area between trenches.

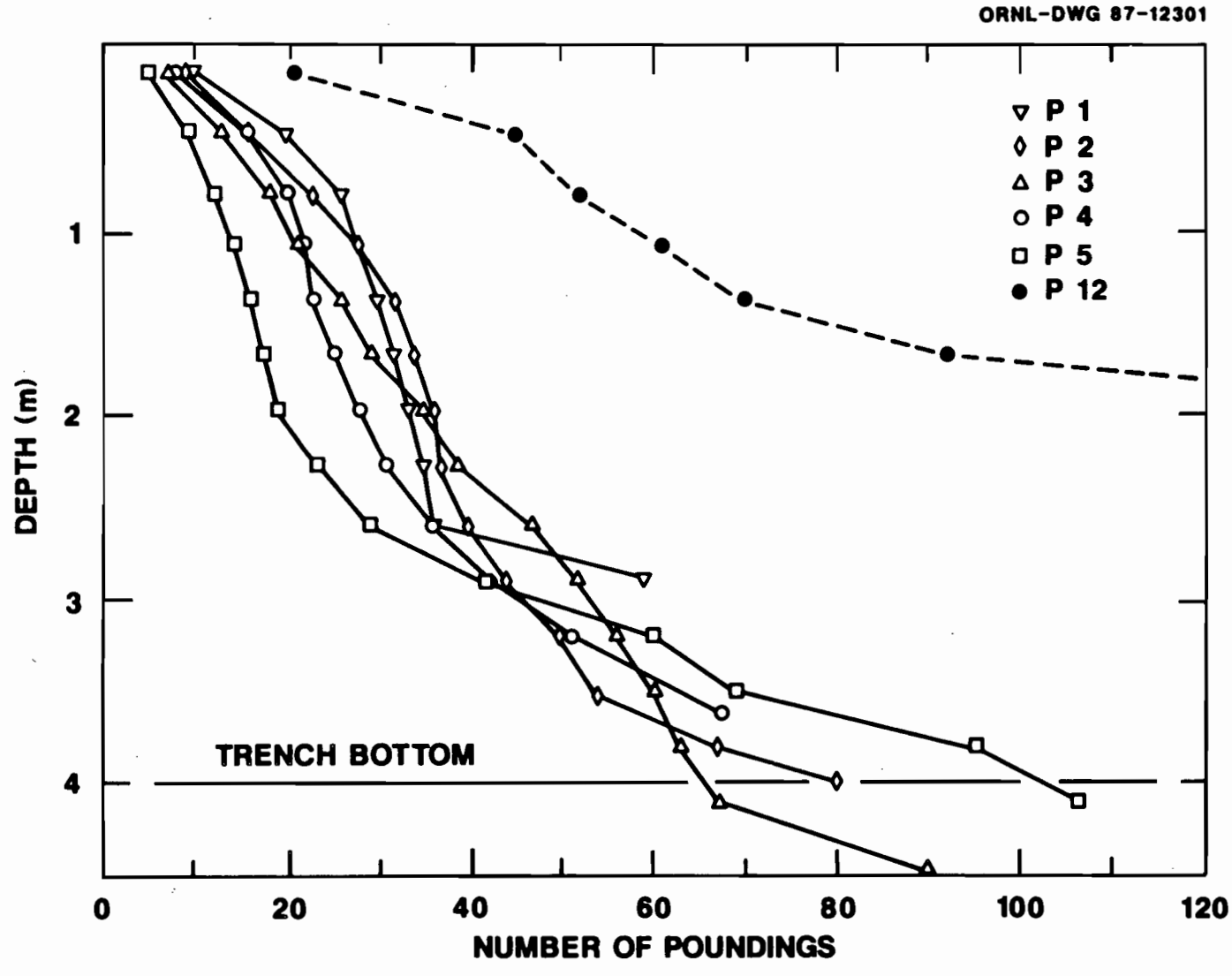

Fig. 13. Depth of penetration in ungrouted trench 152 as a function of number of poundings. Poundings refer to the number of drops required for a hammer weighing 140 lb (63.6 kg) lifted to 30 in. (76 cm) to penetrate 1-ft (30-cm) depth increments.

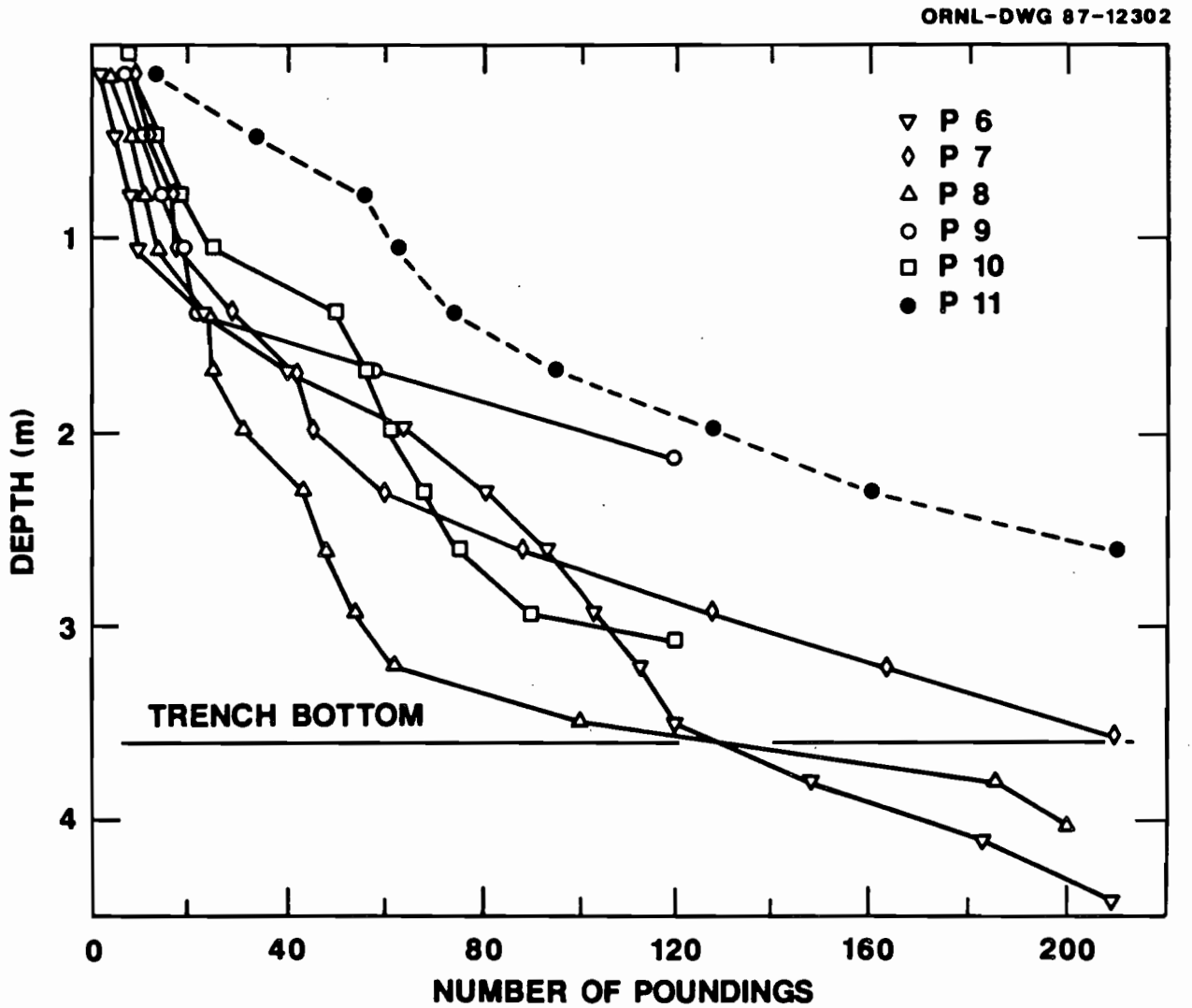

Fig. 14. Depth of penetration in grouted trench 150 as a function of number of poundings. Refer to Fig. 13 for explanation of poundings. Note change in abscissa scale from Fig. 13.

undisturbed material outside of trench 150 (as with trench 152) shows the compact nature of the formation.

If one considers the readings for P-8 in the grouted trench, it appears that this area is lacking in grout. The number of strokes required to penetrate to the bottom is in the range observed for the ungrouted trench. When attempts were made to obtain cores from the grouted trench, the site adjacent to P-8 reflected this ease in penetration.

Coring sites were selected to be close to the penetrometer site. This was possible for four of the five sites, the exception being the site next to P-7. In Fig. 14 the core sites are shown; the core sites are approximately 0.7 m away from the penetrometer site when depicted as being alongside. The site near P-7 is located 6 ft (1.8 m) to the north of P-7.

In obtaining cores, it was initially decided to take 24-in. (61-cm) core segments since the Shelby tubes and split spoon samplers came in these lengths. Later when it was found that the desired length of core and the actual recovered cores had very little relationship, the fixed depth was abandoned. Table 18 lists the depth of coring as measured by the tube penetration, the length of core retrieved, the number of poundings administered for the depth increment, and general remarks about the character of the core.

It became obvious that the technique used to obtain cores left much to be desired. In order to drive the sampling tube into the ground, the same pounding technique was used as in the penetrometer

measurements. On several occasions the Shelby tube would be crumpled upon contact with hard objects. These techniques are more suited for soft-soil-type material than the brittle cementitious grouts. A rotating coring system would be preferred but this would have required a separate permit (introducing water during drilling) and time did not permit changing the method.

Nonetheless cores were obtained as listed in Table 18. The cores are labeled C-6 through 10 to correspond to the penetrometer sites although C-7 is somewhat removed from P-7. The best core recovery appears to be C-8, which was also the easiest to recover as evidenced by the number of poundings required to obtain the segments. Interestingly this site required the least number of poundings to penetrate to the trench bottom; in fact, its behavior was similar to penetrometer readings obtained in the ungrouted trench (Fig. 13). As expected, the recovered core was composed nearly completely of cover-type material. Figure 15 is the top two segments from P-8. Although grout was found in the bottom of the second increment, its thickness was extremely narrow. Note also in Fig. 15 that the top 57 cm of the core is well preserved; this was rather typical of the surface segment, which was almost exclusively soil cover material. In Fig. 16 the three segments of the core from C-9 are shown. The middle section shows a length of soil bounded by grout on both sides. As expected for a particulate-type system, the soil pores are too small to admit the particles; the soil segment remained soft and pliable. The lowest section is almost pure grout; this is reflected not only by the clumps

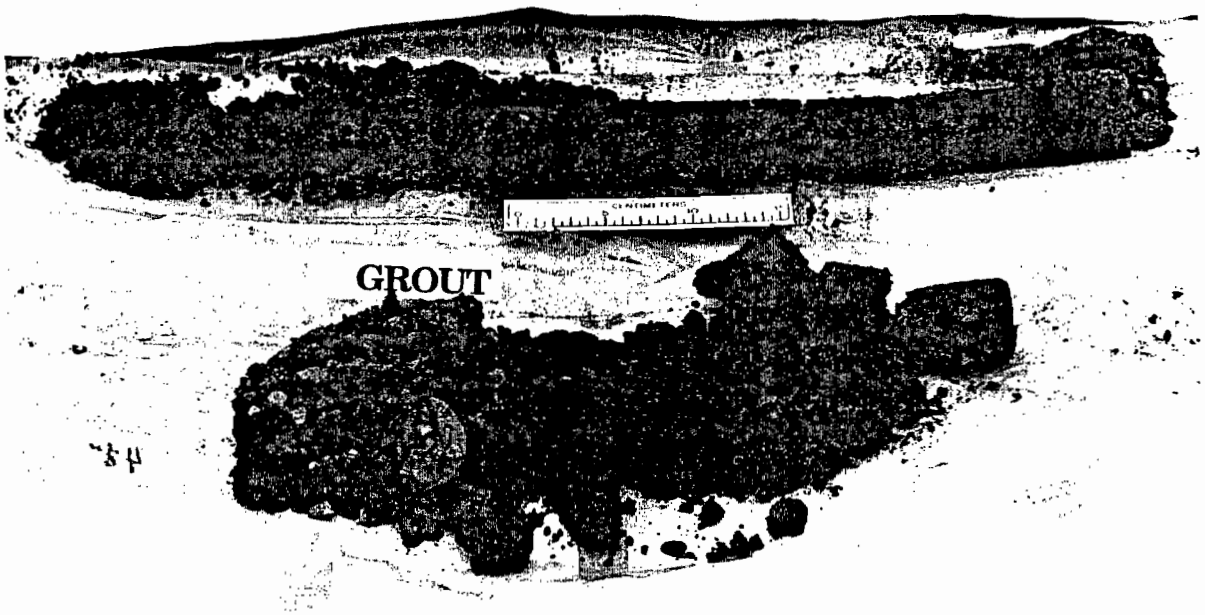

Fig. 15. Recovered core from site C-8. Upper portion of core shows typical surface material of soft pliable soil; lower portion shows small amount of grout at the deeper end.

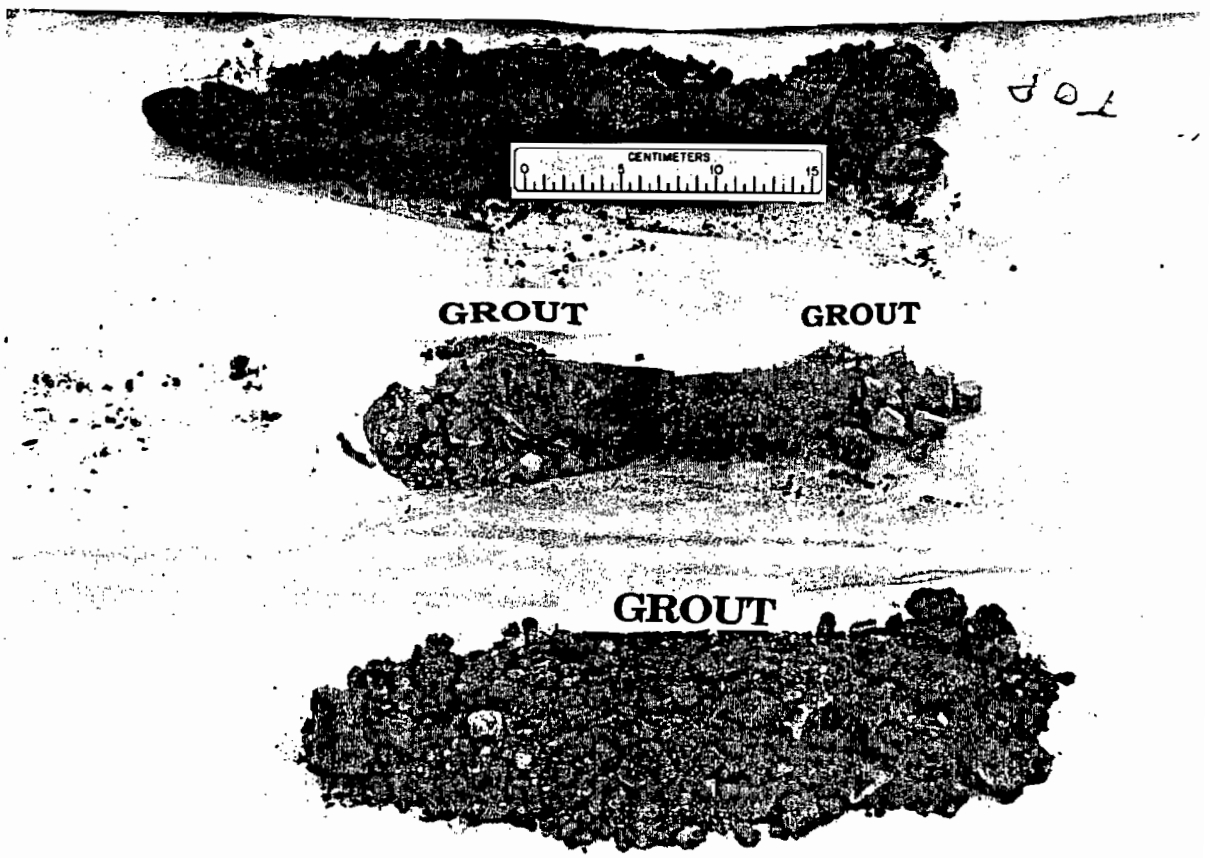

Fig. 16. Revered core from site C-9. Note soil bounded by grout material in the middle portion of core. Cores were fragmented when grout was encountered, resulting in brittle broken pieces.

Table 18. Core recovery from five sites within trench 150
(See Fig. 12 for site locations)

Core No.	Depth (cm)	Core recovery (cm)	Poundings[a]	Remarks
C-6	0-71	49.5	10	Soil core
	71-142	0	109	Shelby tube collapsed to 29 cm from original 60 cm
	142 +	0	25	Split spoon sampler encountered metal object; no penetration
C-7	0-127	61	15	Soil core
	127-198	0	69	Shelby tube deformed at end not allowing core to enter
	198-259	48	139	Used split spoon sampler; grout present
	259-325	10	49	Bottom of core is very wet
C-8	0-61	57	9	Split spoon sampler penetrated relatively easily; small amount of grout at bottom of segment 2 and top of segment 3; bottom segment very moist
	61-122	48	7	
	122-183	44	14	
	183-244	28	7	
C-9	0-61	43	15	Soil core
	61-122	32	21	Grout present
	122-180	38	150	Grout present; stopped coring due to excessive poundings administered
C-10	0-61	28	13	Soil core
	61-122	7.5	24	Evidence of grout
	122-183	10	37	Unusual grey-black color and brittle
	183-244	5	9	
	244-305	20	12	Coring ceased due to encountering impenetrable object

[a] Poundings refer to the number of times a 63.6-kg (140-lb) weight suspended at 30 in. (76 cm) is dropped to penetrate one foot (30 cm) depth.

of grout but by the high number of strokes required to penetrate the zone. On the other hand, the middle section with significant amount of grout required only a few more poundings than the surface soil zone to penetrate the 2-ft depth.

5.5. LESSONS LEARNED AND RECOMMENDATIONS

Initially, there were two major considerations in pursuing this project. The first was to use a particulate grout to stabilize formerly filled waste trenches and mitigating migration of radionuclides out of the trenches. The second objective was to accomplish this task on a scale and with equipment that would demonstrate the practicality of such a treatment. In pursuing the second objective, it became apparent that the equipment, which had been used to grout the asbestos-filled trench with lime-fly ash grout, would not be available. The following comments are offered regarding the injection based on the substituted equipment actually used in the project.

1. The accessible voids in the shallow land trenches can be grouted with particulate grout having a cement base.

2. Monitoring wells cannot be relied upon to indicate the level of particulate grout because the cement grout will not penetrate the well screen opening (0.01 in.).

3. Following a single point injection to saturation of a given area, immediate attempts to grout in the same area usually pushed grout out of the previously used hole or a previous breakthrough zone. A better strategy would be to allow the grout to set before attempting to

continue injecting. An alternative technique could involve holes located on the side of the lance rather than at the bottom. For holes on the bottom, the grout tends to follow the same path when the lance is raised.

4. Casings of 2-in. (5-cm) Schedule 80 pipe are too large to be easily driven into the backfill of the trench. Smaller pipes would allow easier insertion; a hydraulically driven system may be more efficient in this type of operation as was demonstrated during the asbestos trench test. Another option would be to use the Holegator with a standard drill rod.

5. The concrete mixing truck was effective in preparing the slurry. A recirculating tank mixer originally planned did not produce a consistent smooth slurry and took much longer to prepare.

6. On the average, the grout take was 6.1 gpm (23 L/min), but only an average of 1154 gal/d (4370 L/d) was injected. Thus only about 40% of an 8-h workday was used in grout injection. The remainder of the time was used in mixing the grout, driving and pulling the lances, and cleaning up. The hydraulic system mounted on a truck or the modified fork lift would greatly facilitate the insertion and removal of the lances; a larger mixing tank would also extend the actual injection operation.

7. An injection should be continued as long as the take is satisfactory. Non-Newtonian flow systems exhibit thixotropic properties and, once at rest, require excess shear to reinduce fluidity. If stoppage is required, then the lance should be removed and the system cleaned.

8. Penetrometer measurements offer an economical method of assessing the distribution of grout. It would be desirable to perform the test before and after grouting to ascertain changes and thereby obtain a more definitive estimate of grout distribution.

9. No grout returning to the surface was contaminated. Removing the surface 1 ft of cover served to confine any breakthroughs and made detection easy. Breakthroughs between trenches were more difficult to see because tall grass concealed the grout.

10. Cores recovered from the grout trench were in poor condition wherever grout occurred. A rotary drilling system to recover cores may be superior for core recovery but further information on waste and cover soil contamination is needed for safety before drilling water is introduced by this method of coring.

11. Although the simple lance technique was quickly learned and used to grout the trench, existing mobile equipment, such as shown in Fig. 10, should be more economical. Previous testing with a truck-mounted unit and a larger-capacity mixer injected 7500 gallons in one day; a similar system could be advantageously utilized for this type of application and should result in reduced unit costs, especially for large-scale projects.

6. CONCLUSIONS

A trench containing solid low-level radioactive waste identified as No. 150 in the 49 trench area of SWSA 6 was selected for grouting. Initial studies had made this the suspect trench in contributing to a ^{90}Sr seep located in the westerly direction of the trench and made it the candidate trench for grouting. A cement-based grout was formulated that had the desired properties of less than 50 mPa•s for pumpability and setting without phase separation. The final blend was successfully injected into the trench; the volume injected was 8,081 gal (30,585 L), which was 109% of the accessible void volume based on water injection tests. The injection operation was labor intensive and although the equipment used did perform the required operations, the excessive time spent in driving the lance into the ground, pulling the lance out of the ground, and the slow injection rate due to using a single lance all suggested that a more mechanized and multiple lance system should be employed if future injections are planned.

The injected grout reduced the accessible void volume by three orders of magnitude. Although the effect at the seep cannot be assessed at this time, the concentration of ^{90}Sr found in one permanent monitoring well within the grouted trench was reduced by approximately two orders of magnitude. Water injection tests before and after grouting revealed that the conductivity was reduced on the average by two orders of magnitude.

Cement-based grouts can also play a role in reducing subsidence; however, the mode of application into the trench has to be improved to

reduce manpower requirements and increase injection rates. Mechanized units do exist in the private sector but availability is not yet known.

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