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Field demonstration of in situ grouting of radioactive solid waste burial trenches with polyacrylamide[*]

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ABSTRACT: Demonstrations of in situ grouting with polyacrylamide were carried out on two undisturbed burial trenches and one dynamically compacted burial trench in Soild Waste Storage Area (SWSA) 6 at Oak Ridge National Laboratory (ORNL). The injection of polyacrylamide was achieved quite facilely for the two undisturbed burial trenches which were filled with grout, at typical pumping rates of 95 L/min, in several batches injected over several days. The compacted burial trench, however, failed to accept grout at more than 1.9 L/min even when pressure was applied. Thus, it appears that burial trenches, stabilized by dynamic compaction, have a permeability too low to be considered groutable. The water table beneath the burial trenches did not respond to grout injections indicating a lack of hydrologic connection between fluid grout and the water table which would have been observed if the grout failed to set. Because grout set times were adjusted to less than 60 min, the lack of hydrologic connection was not surprising. Postgrouting penetration testing revealed that the stability of the burial trenches was increased from 26% to 79% that measured in the undisturbed soil surrounding the trenches. In situ permeation tests on the grouted trenches indicated a significant reduction in hydraulic conductivity of the trench contents from a mean of 2.1 x 10^{-3} to 1.85 x 10^{-5} cm/s. Preliminary observations indicated

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that grouting with polyacrylamide is an excellent method for both improved stability and hydrologic isolation of radioactive waste and its incidental hazardous constituents.

KEY WORDS: in situ grouting, polyacrylamide, radioactive waste, hydraulic conductivity, penetration resistance, stabilization, field demonstration.

INTRODUCTION

As part of a burial ground stabilization and closure technology demonstration project, a group of 19 burial trenches in Oak Ridge National Laboratory (ORNL) SWSA 6 was selected as a demonstration and test area. These 19 trenches are contained within a hydrologically isolated area of SWSA 6 and any effects of stabilization activities on site performance and groundwater quality would be separable from the influence of other waste disposal units in SWSA 6. To obviate the chronic problem of burial trench subsidence and to provide support for an infiltration barrier cap, five of the 19 trenches were dynamically compacted in July and August 1988. Dynamic compaction was achieved by repeatedly dropping a 4-Mg weight, with a 0.9 m^2 base, onto each trench from heights of 4 to 8 m. The penetration resistance of these five trenches was extremely low prior to compaction and was increased to a level equivalent to that of the undisturbed surrounding soil after compaction (1). Thus, dynamic compaction was found to be very effective in stabilizing burial trenches to the extent that no differential land surface settlement should be expected to compromise the foundation support of an infiltration barrier.

However, because of the large inventory of radioactivity in some burial trenches in SWSA 6, additional assurance of hydrologic isolation of trench contents from groundwater intrusion and/or percolation, beyond that provided by an infiltration barrier, may be warranted for particular trenches. In situ grouting is a technique for attaining hydrologic isolation of burial trench contents, regardless of infiltration barrier integrity or performance. Two in situ grouting field demonstrations have been completed previously at ORNL (2,3). Both of these demonstrations involved placing polyacrylamide grout into uncompacted burial trenches. Both were successful in changing the burial trenches from a condition of extreme permeability (e.g., 10^{-2} cm/s) and facile water intrusion to a condition of unmeasurable permeability ($<7 \times 10^{-6}$ cm/s). The long-term stability of the polyacrylamide grout has been established previously by measurement of low rates of microbiological decay (3). The inherent low permeability of neat polyacrylamide grout (i.e., 10^{-10} cm/s) has the potential to reduce radionuclide leaching to diffusion-controlled mechanisms. However, neither of the previous demonstrations addressed the problem of trench geotechnical stability nor, because of their limited scope, did they provide an adequate assessment of grout distribution and hydraulic properties within trenches. These demonstrations did establish that the costs of materials alone for in situ grouting with polyacrylamide were quite high, i.e., about $50,000 per typical (4 m x 15 m x 5 m deep) burial trench, due to the large amount of voids per trench and the cost of the acrylamide grout materials (about $530 m^{-3}). Dynamic compaction, in contrast, is a relatively inexpensive method to eliminate many of the large voids within a trench which potentially might result in a smaller residual void volume to be grouted. An additional benefit of dynamic compaction would be its ability to collapse voids within waste packages which may not be accessible during grout injection into an uncompacted trench.

The objectives of the present demonstrations were to evaluate the effectiveness of grouting in 1) reducing burial trench permeability, 2) improving trench stability against further surface subsidence, 3) avoiding groundwater contamination by the grout's toxic monomer, acrylamide, and 4) achieving hydrologic isolation of dynamically compacted trenches to the same degree experienced after grouting undisturbed burial trenches.

SITE SELECTION AND PREPARATION

The site selected for the demonstration lies on a small hillock in the northeast corner of SWSA 6 (Fig. 1). The site was selected based primarily on the following two criteria: (1) it was away from operational areas within SWSA 6 and would, therefore, not interfere with daily waste management activities or vice versa and (2) it was located entirely on high ground and was, thus, isolated hydrologically from any peripheral recharge areas which would complicate performing a site water budget and performance monitoring as part of the stabilization and closure evaluation. The water table at the site is at least 9 m below the bottoms of the trenches; they, therefore, remain unsaturated throughout the majority of the year in contrast to chronically or seasonally inundated trenches as is the case for other trench areas within SWSA 6.

Three trenches (numbers 6, 7, and 165) were selected for the polyacrylamide grouting demonstration. Grout was also injected into trench 8 which, because of partial sidewall collapse during its construction, showed hydrologic connection with trench 7. These specific trenches were selected for demonstration because of their proximity to several of the groundwater monitoring wells at the site such that any breakthrough of acrylamide might be observed with minimal migration. Trench 6 had been dynamically compacted in 1988 collapsing 66% of its water-accessible voids (1). The other trenches (7, 8, and 165) were undisturbed since their closure in 1972-74. Leachate and bottom soil samples from each of these trenches had been tested previously for compatibility with the polyacrylamide grout polymerization and no interferences were observed (1).

Five grout delivery and/or trench fluid monitoring wells were inserted into each trench. Each trench was also surrounded by six 4.5-m-deep monitoring wells in the surrounding unsaturated undisturbed soil within 1.5 m of the known trench edges. These monitoring wells were placed in residual penetration test holes which were used to obtain penetration resistance measurements on the trenches and surrounding soil formation. Monitoring wells within trenches consisted of 3.66 m of screen, with 2.5 mm slots, which was threaded with flush-joints to 1.22 m of solid polyvinylchloride (PVC) pipe. Monitoring wells outside trenches were identical except that screens with 0.5 mm slots were employed. The larger slots were used for wells within trenches to avoid grout setting between slots spanned by residual fluids after daily batch injections. Well screen diameters were either 3.8 or 3.2 cm depending on which size a particular hole would accept to its full depth.

To avoid bringing highly contaminated soil and/or waste to the surface, which would have resulted during a standard penetration test (ASTM Penetration Test and Split-barrel Sampling of Soils D 1586-84), a nonstandard penetration test was devised which used a 63.5-kg (140-lb) drill-rig-mounted drop hammer to drive a 4.4-cm diameter drill rod into the soil. The end of the drill rod was fitted with a 5.1-cm diameter 60°-cone point and the rod was marked off in 30-cm lengths. At each nonstandard penetration site, the rod was hammered into the soil and the number of blows for each 30-cm depth were recorded. This nonstandard penetration is similar to the Dutch cone penetration test (DCPT) except that the test borehole was not augered out every 46 cm (18 in.) to relieve drill stem friction. Blow count values (penetration resistance) obtained by the DCPT have been found equivalent to blow count values (4) obtained with the standard penetration test.

FIELD GROUTING OPERATIONS

Field grout operations consisted of mixing the grout and catalyst solutions as they were pumped into a trench (Figure 2). Solutions of grout and catalyst were made up in 5,678 L (1,500 gal) seamless polyethylene tanks. Each tank was fitted with a 5-cm (2 in) diameter ball valve at its lower access port. One side of the valve was connected to the intake of a portable gasoline-powered centrifugal pump. A T-fitting with two valves was placed on the outflow of the pump to regulate fluid flow either for recirculation to the tank's top access port, when grout components were being dissolved in the tank, or for injection into a trench. The delivery lines from both the acrylamide (grout) and catalyst tanks contained water meters to record volumes injected and check-valves to prevent backflow and grout set within the hoses. The two lines (consisting of 2.5-cm diameter hose) were joined in a Y-fitting and the solutions mixed in a 2.5-cm diameter by 43-cm long static mixer containing an array of angled baffles (Cole-Parmer, Inc.). A bleed valve was also fitted to allow for line drainage, if necessary, and for line flushing at the end of each batch injection. The delivery line was then connected, with a manual shut-off valve, to the desired grout injection well head via quick-connect fittings to facilitate switching of injection wells if necessary. The entire arrangement of pumps, tanks, meters, and valves was placed within secondary containment consisting of a reinforced PVC liner with sidewalls maintained by air-inflatable pillows (Aero Tec Laboratories, Inc.).

A 10% acrylamide grout formulation was selected for the field demonstration as had been used in previous demonstrations. Into the grout tank was placed approximately 4,500 L (1,200 gal) of water pumped from the emergency waste basin to the north of the site (Fig. 1). Fifty double-lined bags, containing 22.7 kg (50 lb) of Q-1 Chemical Grout (Ques, Inc.) each, were then emptied into the tank followed by 30 L of triethanolamine and 1.14 kg of potassium ferricyanide. The tank was filled, as necessary, to its capacity, 5870 L (1,500 gal). Into the catalyst tank, previously filled with water, was placed 57 kg of ammonium persulfate. The solutions in each tank were then recirculated until all solids were dissolved, usually in about 30 min. The final formulation, based on a 1:1 mixture of the two solutions, would contain 10% acrylamide grout (9.5% acrylamide plus 0.5% methylenebisacrylamide), 0.3% triethanolamine, 0.01% potassium ferricyanide, and 0.5% ammonium persulfate. Personnel preparing the acrylamide grout solutions employed personal protective equipment including disposable water-resistant suits, double rubber gloves, and full-face respirators. Personal air samplers were also worn by all personnel to quantify exposure to possible fugitive dust emissions. Samples of the solutions were taken from each tank and mixed 1:1 (v:v) and the time for grout set measured to determine if the batch set time was less than the specification of 60 min maximum (Table 1).

Grout was delivered to a single desired injection well by routing flow from both pumps through the static mixer to the delivery hose. Grout delivery rates varied from 5 to 95 L/min with the lower flows occurring during final batches into trenches after previous batches had sealed up much of the available well screen in a particular well. Generally 2-4 hours were required for the delivery of each batch. One individual was assigned to monitor the flow meters of both grout delivery lines and record cumulative flow readings at 10 min intervals. Pump delivery rates were adjusted regularly to maintain a 1:1 mixture during delivery. During each batch delivery, an "as delivered" sample was taken from the line by interrupting flow at the wellhead and diverting it to a sample container; these samples were also monitored for set time and later analyzed for residual acrylamide, total solids, and ash-free solids (1) for verification of grout quality (Table 1). During injection, one individual was assigned to monitor the injection well for either leaks or backup flow around the well annulus. A leak containment collar, made of 40 cm high steel sheet with a beveled edge, was pushed into the ground around the injection well. Another individual was assigned to monitor levels of fluids and set grout (i.e., the depth to well bottom) within the injection trench at 10 min intervals during injections until grout had set within all intratrench wells. Fluid levels were measured using an electrical depth sounder (SoilInst, Inc.). Another individual was assigned to monitor fluid levels or confirm their absence in the six perimeter monitoring wells surrounding each grouted trench and in wells within surrounding burial trenches. Another individual was assigned to monitor water levels within the 15 permanent groundwater monitoring wells at the site. These readings were recorded hourly during injection periods and were continued until grout had set in all wells, usually about 1 hour after termination of injection. Following completion of a batch delivery, approximately 75 L of water was flushed through each tank line to the trench by switching the pump intake to water from a third storage tank. A residual of approximately 500 L remained in each tank due to the height (about 10 cm) of the port valve above the tank bottom. This residual volume was then included in the next batch and resulted in the increasing solids content of latter batches of grout. For the final batch, the tanks were tilted, when fluid levels were near the bottom, so that the contents were completely emptied.

FIELD GROUTING RESULTS

The total volumes of grout delivered to each trench are summarized in Table 2. The volumes of various trenches were computed from their surveyed corner coordinates and their nominal depth of 4.57 m (15 ft). The total grout volume delivered was then expressed as a percentage of the total volume of the trench. Although none of these grouted trenches had their void volume measured directly prior to grouting, previous water filling tests on six other ORNL burial trenches found water-accessible voids accounting for an average of 20% (range of 8 to 30%) of total trench volume (1,5). Thus, the estimated grout capacity of trenches 7 and 165 was consistent with these previous measurements because the acrylamide grout is very similar in fluid properties to water. Perhaps not too surprisingly, trench 6, which had been previously dynamically compacted, accepted very little grout (1,500 L). All five of its access wells eventually refused grout delivery after initially accepting small volumes presumably due to access to minor voids. Once these voids had been filled, further grout delivery was refused. Thus, it appears that in situ grouting, as a technique to reduce residual permeability after dynamic compaction, is not feasible and, perhaps, not necessary. Therefore, the decision to pursue trench stabilization or trench hydrologic isolation will need to be made prior to site closure.

The response of fluids and set grout within trench 7 is depicted in Figure 3. The concomitant cumulative injected grout volume is plotted with the intratrench fluid hydrograph to demonstrate the time relationship between grout injection and fluid responses in other regions of the trench. The intratrench hydrograph was based on observations taken from monitoring wells within the trench most distant from the point of initial grout injections but was typical of all wells within both trench 7 and 165. Grout injections were started at the lower elevation end of the trench, i.e., the northern most access well. Although the slopes of the trench bottoms are not known, the elevation of the bottoms of the northern access wells was about 1 m lower than those in the southern end. Thus, there was apparently no fluid response in the southern access wells to the first batches of grout placed in the northern end of the trenches. However, once the level of grout fluids had risen during later injections, fluid responses were observed in direct and undelayed responses to grout injections. This response illustrates the high permeability and continuity within burial trenches which can be ascribed to their large voids. The trench response to grout fluids was very similar to that observed during water filling tests where water elevations rise uniformly within the trench during filling (5). Because of the relatively short time lag for grout to set, i.e. about 1 h, only a few instances, where fluid levels exceeded set grout levels, were observed during actual grout injection intervals. An apparent occurrence of unset grout fluids, persisting for several days within trenches, can be seen in Figure 3. However, this occurrence was an artifact of the delivery line washing procedures. When the delivery line was flushed with 75 L of water, this volume was delivered to the injection well diluting the grout within the well casing so that the resulting fluid would not set. However, the grout, which has been displaced around the well casings circumvallates this fluid resulting in a persistent standing fluid within the casing. Support for this interpretation is provided by the lack of persistent fluids levels in other access wells within the trench during the same interval.

The response of the water table to the grout fluid injections is depicted in Figure 4. Well 1 was used as a reference well because it was distant from the three trenches which received grout (Figure 1). Responses of other wells should be interpreted relative to this well to account for water table responses to rainfall during the 22 day interval over which grout injections were carried out. Although the water table was quite responsive to rainfall events during the interval of grout injections, it was unresponsive to the grout injections particularly when normalized to elevations in well 1. On a daily and hourly basis, which resolutions cannot be discerned from Figure 4, none of the proximate groundwater monitoring wells responded to grout injections. The time lag for hydrologic connection of the water table to the trenches had been established in previous water filling tests where changes in water elevations of several meters were observed within a day of fluid placement within the burial trenches.

About a month after completion of grouting of trenches 7 and 165, the nonstandard penetration tests were repeated on both trenches using five testing points per trench. In addition, further penetration tests were completed about five months later as part of the installation of in situ permeameters; this resulted in an additional 12 and 15 testing points in trenches 165 and 7, respectively. Prior to grouting, ten penetration tests were completed along longitudinal transects of each trench. A total of 12 penetration tests were completed on the soil formation immediately surrounding the grouted trenches as a reference for the ambient stability of the soil formation. Results of all these penetration tests are summarized in Figure 5. Prior to grouting, the inherent instability of the burial trenches was apparent in that the total number of blows required to reach 4.6 m (15 ft) was approximately one-fourth that required within the surrounding undisturbed soil formation. Following grouting, the cumulative number of blows to reach this same depth within a burial trench was increased by a factor of 3 over pregrouting conditions from 26% to 79% that of the undisturbed soil formation. This increase in penetration resistance is ascribed to filling of trench voids with polyacrylamide grout. Thus, grouting with polyacrylamide should afford a considerable increase in burial trench stability concomitant with the reduction in trench permeability.

Hydraulic conductivities of the waste burial trenches were determined before and after grouting (with newly installed wells) using a constant head pump-in test (6). The governing equation for deriving hydraulic conductivity of the material surrounding a well point was:

$$K = \frac{q \ln \{m L/D) + [1 + (m L/D)^2]^{1/2}\}}{2 \pi L H_z} \qquad \text{Eq. [1]}$$

where,

K = hydraulic conductivity in cm/s

q = rate of water acceptance in cm^3/s

L = length of screened section in cm

H_z = constant piezometric head in cm

D = diameter of well casing in cm

m = transformation ratio, assumed to = 1.

Three field techniques were used to collect the pregrouting water acceptance rates to calculate the hydraulic conductivity. In the first method, the time required for the well to accept 10 L of water was measured. In most of the intratrench wells, no measurable water level could be determined in the 25-40 s required to deliver this amount of water into the well casing. In order to use Eq. [1], the length of the intake section was assumed to be the entire slotted interval of the well casing and the piezometric head was assumed to be equivalent to that depth interval. In the second method, the acceptance rates of the acrylamide grout were used to calculate pregrouting hydraulic conductivities. In this case, the intake section was the entire length of the slotted interval or, in wells not used for injection until later batches, the fraction of the intake section which was free from set grout of previously injected batches. The piezometric head was taken as the entire height of the well casing below ground, usually 4.27 m, plus the additional height of grout in the delivery tank. The third method used water acceptance rates achieved in filling tests on trenches 2, 3, 4, 5, 6, and 151; the piezometric head and intake section were assumed to be the entire depth of uncased hole. The estimated hydraulic conductivities by these three methods were not significantly different resulting in a geometric mean of 2.10×10^{-3} cm/s which was based on 35 independent determinations. The average hydraulic conductivity of the undisturbed soil formation has been measured at 3.47×10^{-5} cm/s in previous studies (7). This two order of magnitude difference in the hydraulic conductivities of burial trenches and the surrounding soil is a significant factor in the frequent occurrence of standing or perched water within burial trenches at ORNL.

After grouting, in situ permeameters were inserted into penetration holes in trenches 7 and 165 extending to depths of 1.8, 2.7, or 4.3 m below ground. However, only the bottom 60 cm was screened with 0.5 mm slots with the remaining length being solid pipe. Thirteen such in situ permeameters were inserted into trench 165 while 15 were inserted into trench 7. An additional five permeameters, which were screened over the bottom 360 cm, were placed in both trenches 7 and 165 using the penetration test holes. Water acceptance rates were then measured for each permeameter using either a pour-in method to maintain a constant head near the top of the casing or a pump-in method using positive head and flowmeter. Equation [1] was used to compute the postgrouting hydraulic conductivities from these water acceptance rates as described above. Analysis of the characteristics of the different in situ permeameters indicated that the different depths of insertion had no effect on the measured hydraulic conductivity nor did the diameter of the permeameter (both 3.8 and 3.2 cm pipe was used). The geometric mean hydraulic conductivity of the population of measurements was 1.85 x 10^{-5} cm/s for 36 independent determinations. The distribution of hydraulic conductivities in the groups of pre- and postgrouting measurements is depicted in Figure 6. Although the mean hydraulic conductivity of 9.7 x 10^{-7} cm/s of the polyacrylamide grouted pilot-scale burial trench in the previous study (2) was an order of magnitude lower than that in the present study, the distribution of previous values was much narrower with eight out of nine values at or below the field detection limit of 7 x 10^{-7} cm/s. In that previous study, hydraulic conductivities were measured in well casings which had remained within the trench during grouting; whether those measurements could be ascribed to grouting of waste and trench contents or to grouting of well screen could not be determined. The present observations, however, are free from such possible artifacts because the in situ permeameters were not placed into the trenches until several months after grout had set. Thus, the hydrologic isolation of burial trench contents appears to have been achieved by in situ grouting with polyacrylamide. The regions of higher hydraulic conductivity within the trenches may be caused by the insertion of the permeameters into waste packages inaccessible to the grout or may be caused by grout fracturing by waste movement induced by penetrometer insertion. However, the determination of whether such higher hydraulic conductivities by grout segregation within the trenches or by failure of the grout polymerization in specific regions cannot be determined at present. Likewise, the persistence of the these hydrologic properties with time needs to be determined.

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Table 1. Polymerization and Set Times of Polyacrylamide Grout Used for Injections into Burial Trenches

Batch Number	Injection Date	Set Time (min)	Residual Acrylamide (μg/g)	Grout Solids (%)	Degree of Polymerization (%)
1	28Aug89	21	18.1	10.4	99.98
2	29Aug89	23	13.7	14.6	99.99
3	30Aug89	23	54.6	8.2	99.93
4	31Aug89	34	11.4	14.8	99.99
5	01Sep89	31	NA	NA	NA
6	06Sep89	34	10.9	14.5	99.99
7	07Sep89	34	11.3	13.2	99.99
8	08Sep89	30	14.5	14.0	99.99
9	09Sep89	35	7.5	13.3	99.99
10	13Sep89	43	7.4	15.4	99.99
11	14Sep89	40	24.0	13.7	99.98
12	15Sep89	35	8.9	16.2	99.99
13	18Sep89	41	22.1	14.9	99.99

NA = not analyzed.

Table 2. Polyacrylamide Grout Injection Summary

Trench Number	Grout Delivered (m^3)	Trench Area (m^2)	Trench Volume (m^3)	Fraction Grouted (%)
7	67.9	65.2	298.1	22.8
165	41.1	29.6	135.5	30.4
6 (Compacted)	1.5	57.6	263.2	0.6
8 (Partial Fill)	23.0	52.5	239.9	9.6

LIST OF FIGURE CAPTIONS

Fig. 1. Location of demonstration site for in situ grouting at the Oak Ridge National Laboratory showing location of burial trenches, topography, and groundwater monitoring wells.

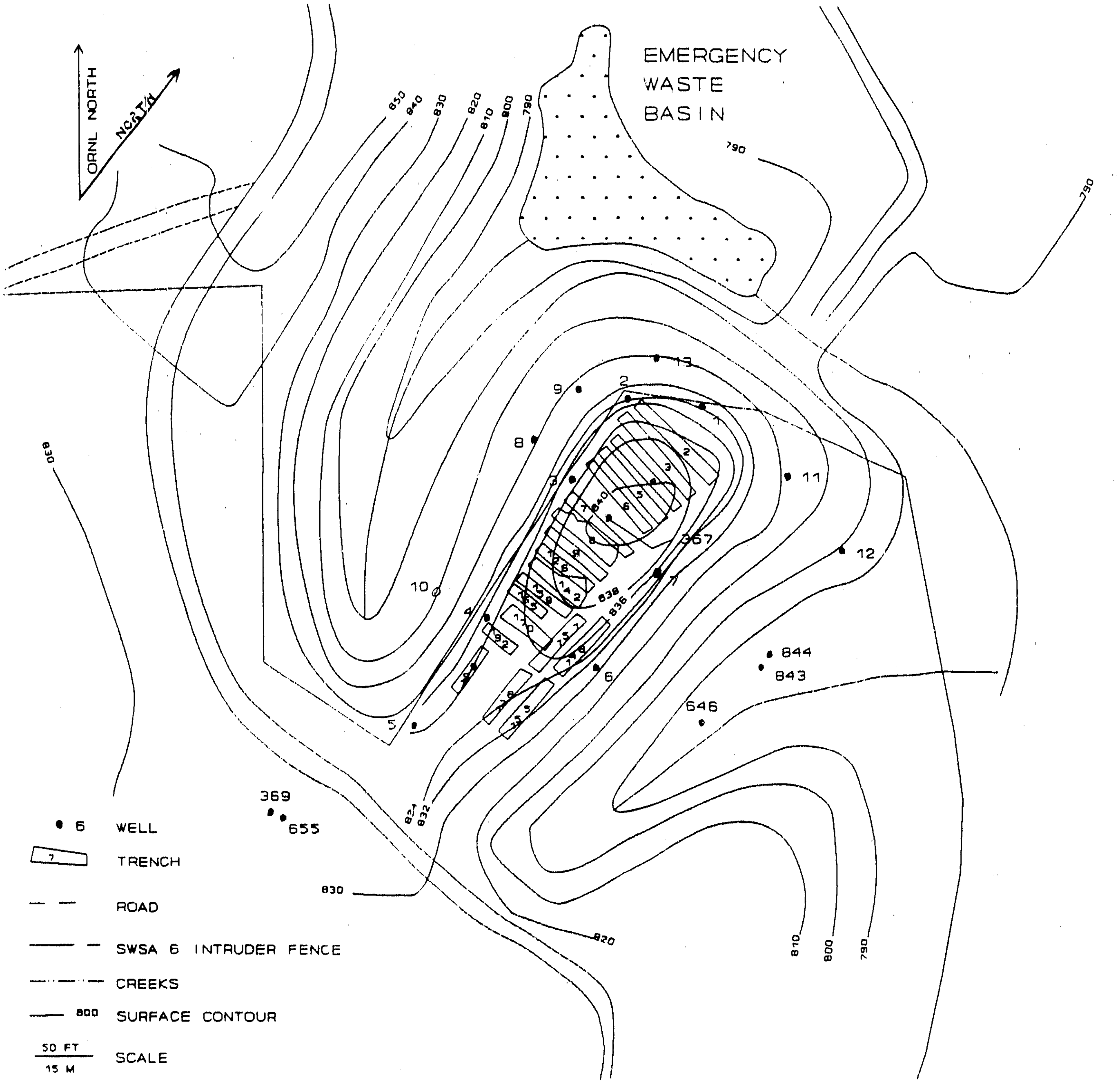
Fig. 2. Arrangement of fluid handling equipment employed for mixing and injecting polyacrylamide grout into radioactive solid waste burial trenches.

Fig. 3. The elevation of fluids and set grout in a monitoring well within ORNL solid waste burial trench 7 during and after in situ grouting with polyacrylamide.

Fig. 4. Groundwater elevations within permanent monitoring wells and rainfall at the demonstration site during the period of polyacrylamide grout injections into burial trenches 6, 7, 8, and 165. (See Fig. 1 for locations of wells relative to grouted trenches.)

Fig. 5. Penetration resistance of two radioactive solid waste burial trenches before and after in situ grouting with polyacrylamide relative to the surrounding undisturbed soil formation.

Fig. 6. The distribution of hydraulic conductivity measurements within two radioactive solid waste burial trenches before and after in situ grouting with polyacrylamide.



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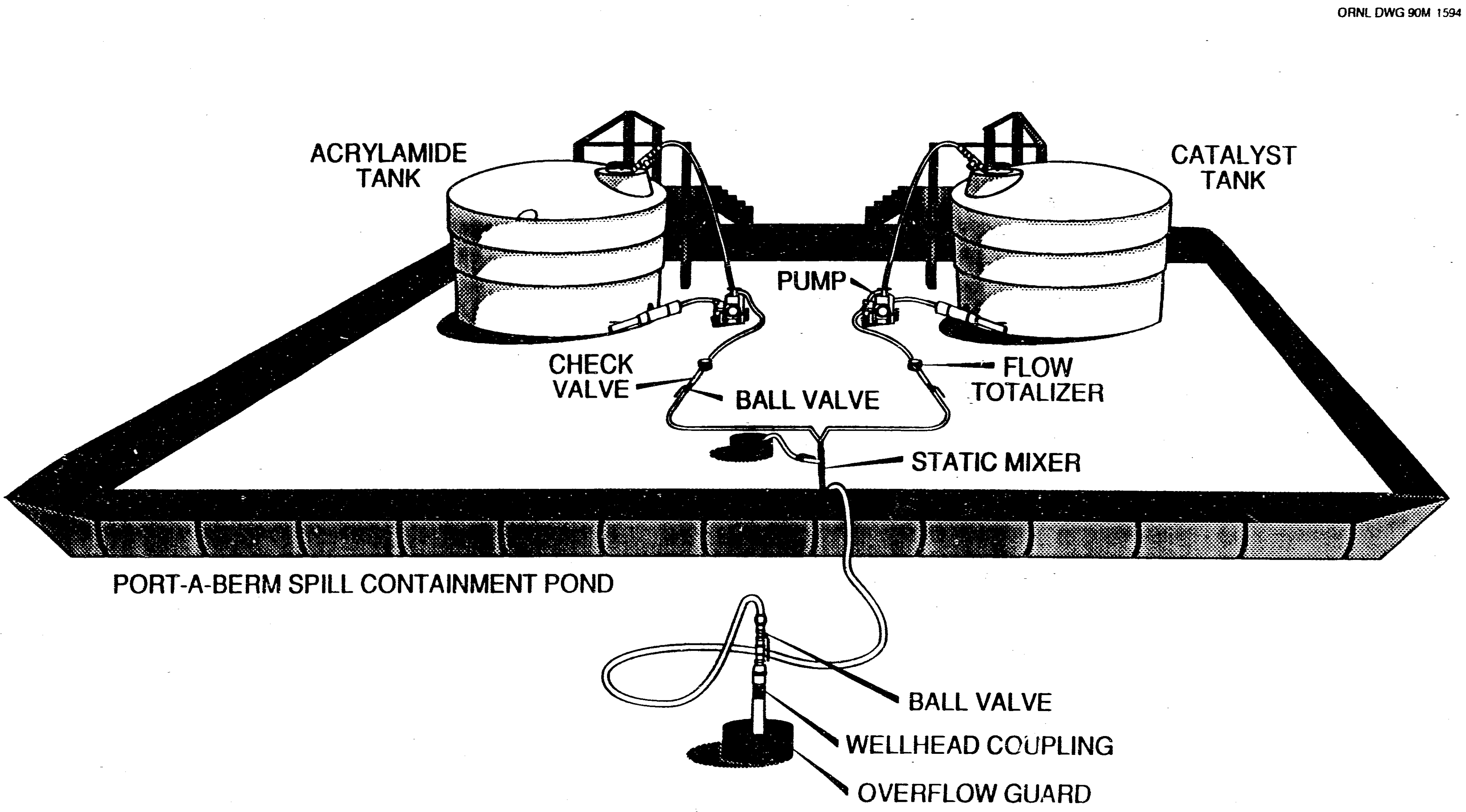

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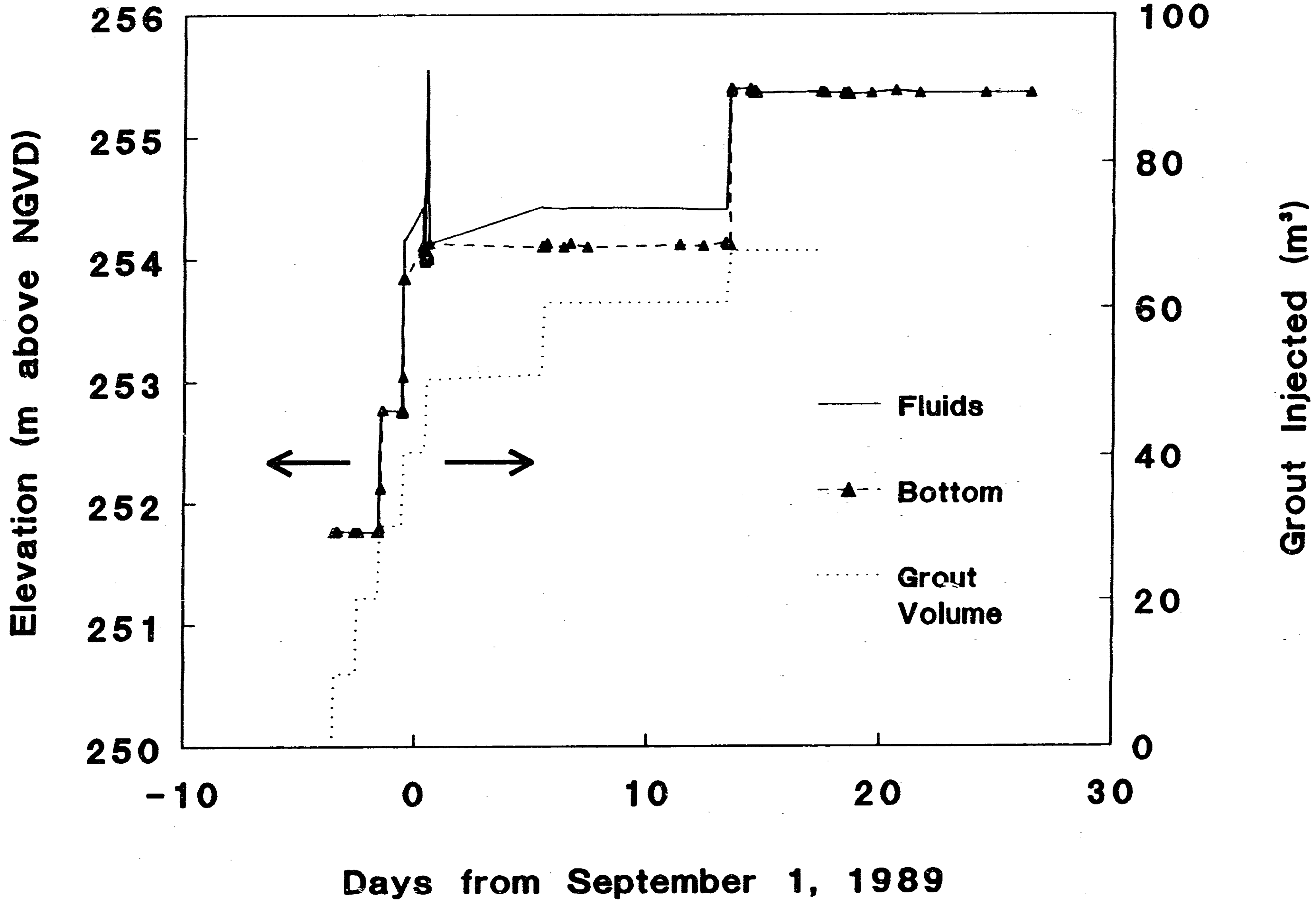

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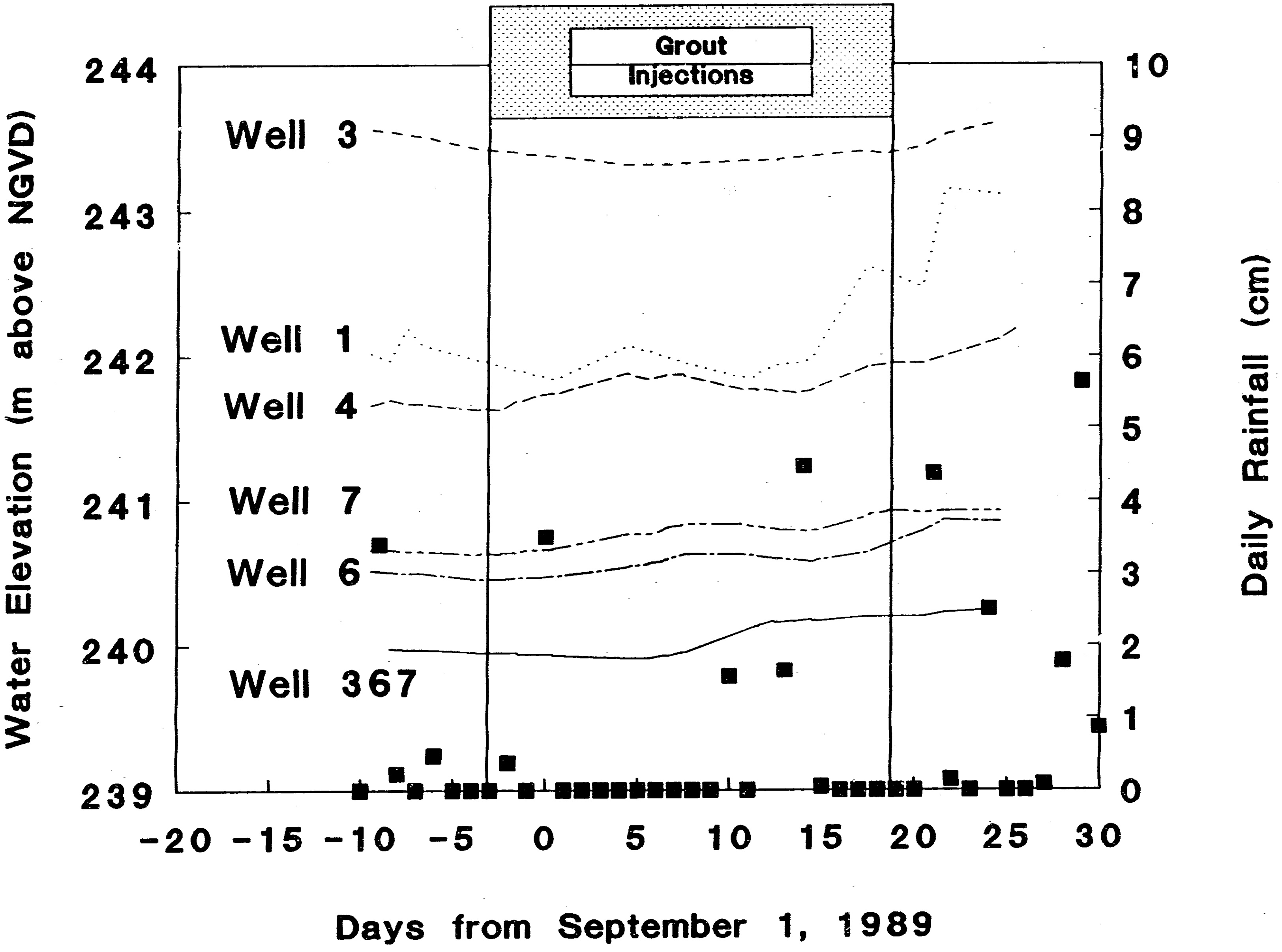

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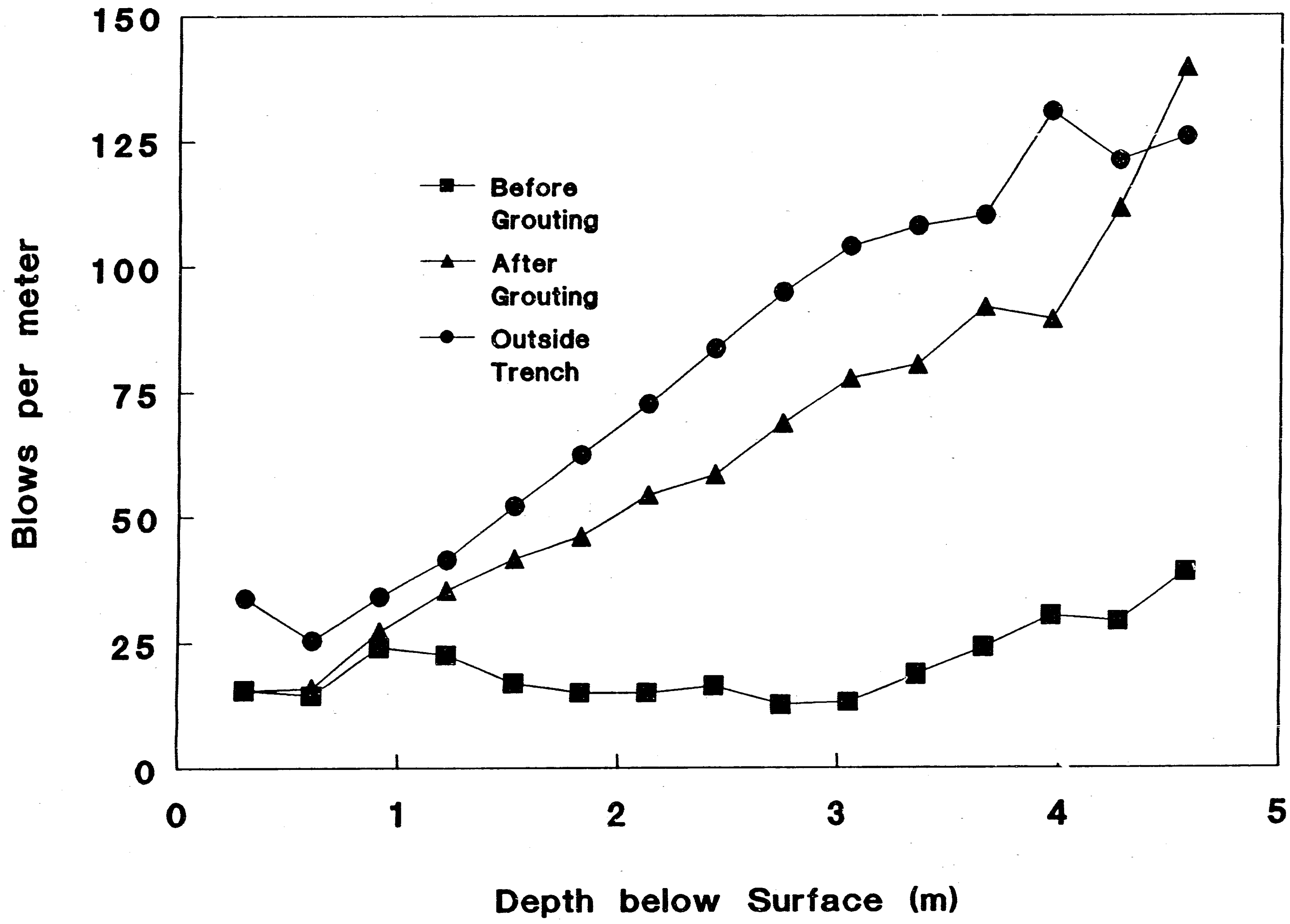

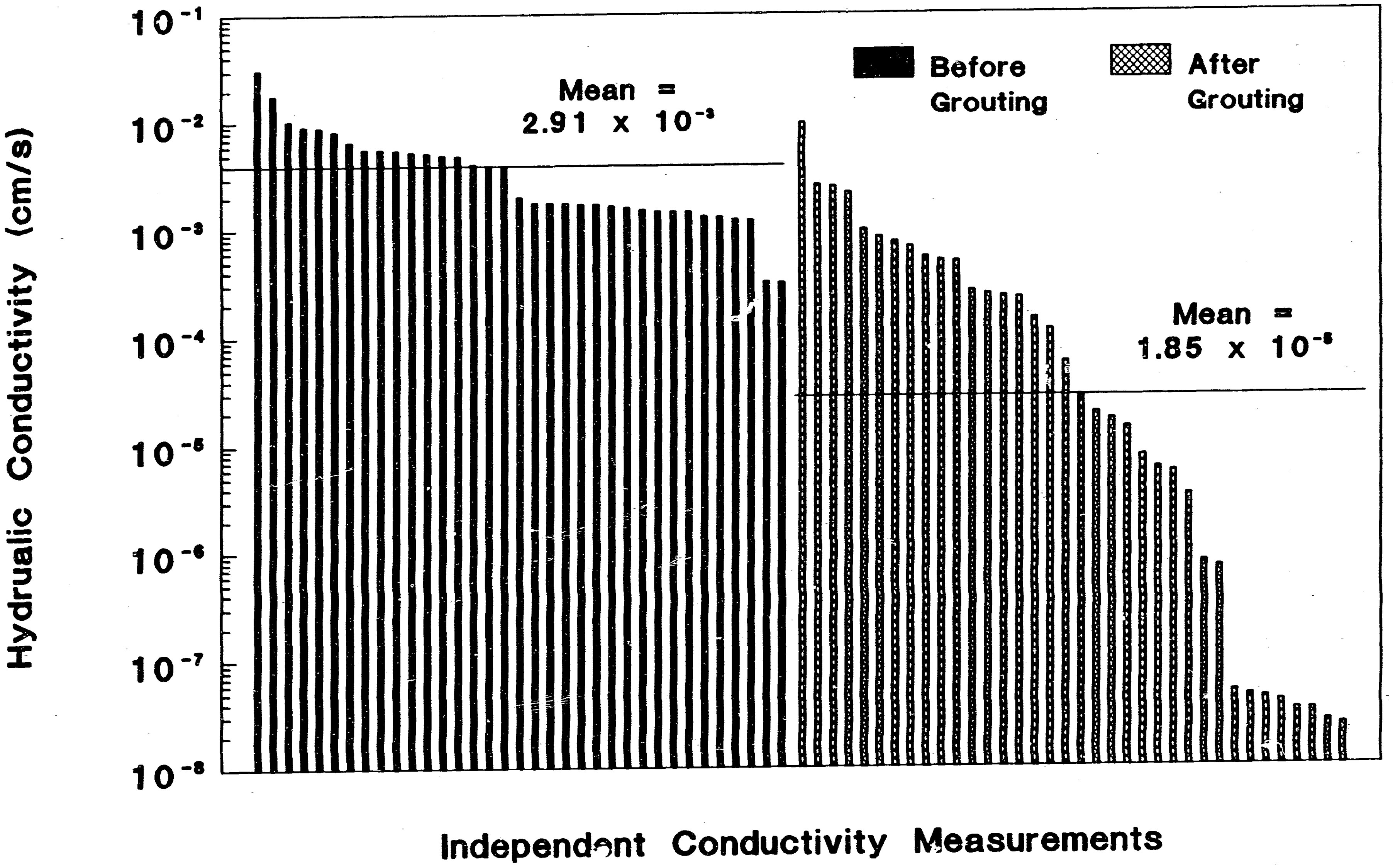

Fig. 6. The distribution of hydraulic conductivity measurements within two radioactive solid waste burial trenches before and after in situ grouting with polyacrylamide.

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