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Multiple Pass Permeation Grouting to Encapsulate and Contain Radioactive Waste in a Predictable Fashion

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ABSTRACT: During the 1960s, trenches and wells were constructed for the disposal of liquid low-level radioactive waste (LLLW) in Melton Valley at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. Trenches 5 and 7 were the subject of a remedial in situ grouting program executed in 2005-2006 for the purpose of limiting migration of radionuclides from the site. Both trenches contained poorly (uniformly) graded coarse crushed stone backfill, in which approximately 34 million litres of LLLW per trench were disposed.

A multiple-pass, multiple-stage, multiple-hole permeation grouting program was carried out via driven, vertical, steel sleeve pipes inside the trenches, using five different types of stable, balanced, durable cement-based suspension grout mixes, with various rheological and set characteristics. A grout curtain was then constructed with acrylamide grout in the native soil around and below these trenches. Real time monitoring and assessment of the grouting parameters using CAGES was used to construct the end product.

The in situ grouting (ISG) program was highly successful in reducing the hydraulic conductivity of the grouted materials and the grouted soil “envelope” around the trenches to values well below the 1.0 x 10^{-5} cm/s target number. The work was performed safely, and without environmental insult.

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INTRODUCTION

Seepage Trenches 5 and 7 are located at Oak Ridge National Laboratory (ORNL) within the Melton Valley watershed, in Oak Ridge, Tennessee. ORNL historic missions, plutonium production during World War II, and nuclear technology development during the postwar era produced a diverse legacy of waste disposal areas in Melton Valley. After waste disposal operations ceased in Melton Valley, the DOE embarked on a program to hydraulically isolate the wastes interned within the waste management units.

The following sections detail the operational history of the trenches, results of previous investigations and remedial actions. A typical disposal trench cross-section is shown in Figure 1.

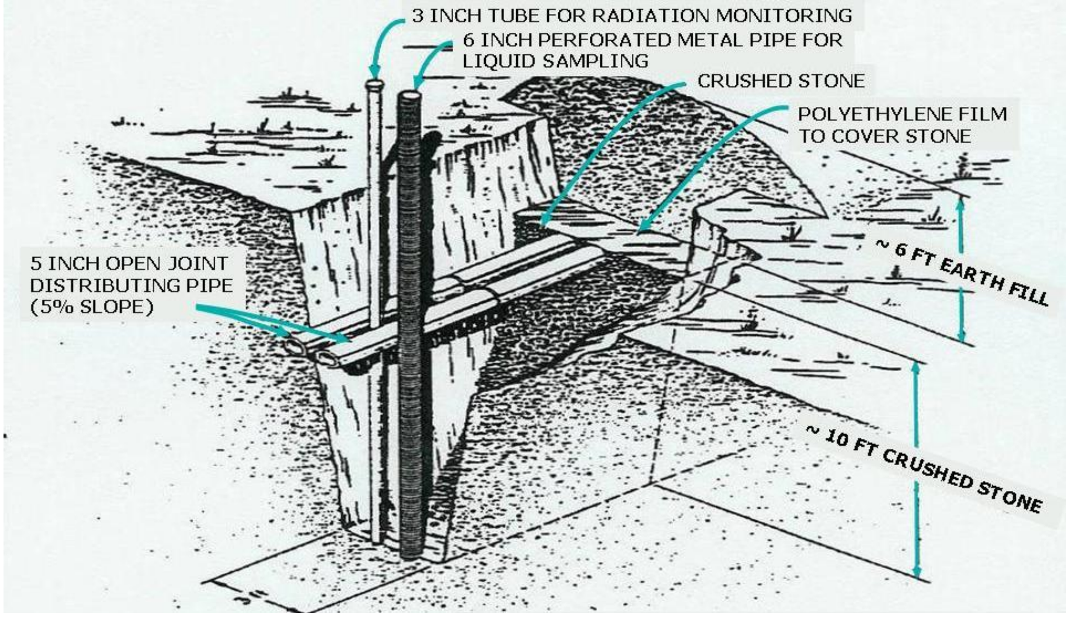

FIG. 1. Typical waste disposal trench design.

Trench 5 History and Design

Trench 5, constructed in 1960 for the disposal of liquid low-level (radioactive) waste (LLLW), is approximately 90 metres long by 4.8 metres deep with a horizontal open-joint pipe installed on a 5% slope for distribution of the LLLW throughout the trench. Vertical pipes were installed within the trenches for radiation monitoring, liquid sampling, and water-level measurement. Based on the holding capacity, the volume of crushed stone in the trench is approximately 488 m^3. The trench is approximately 3.3 metres wide at the top of the crushed stone layer and approximately 5.7 metres wide at the ground surface.

Trench 7 History and Design

Trench 7, constructed in 1962, is located 300 metres east of Trench 5. Trench 7 was designed to contain three separate cells (trench segments) to prevent the loss of the entire disposal capacity of the trench if a geologic feature was encountered that caused excessive seepage. Ultimately, only cells 7A and 7B were constructed. Trench 7 is similar to Trench 5, with each cell being approximately 30 metres long and 4.8 metres deep. The volume of crushed stone within Trench 7 is estimated at 400 m^3.

PROJECT HISTORY AND OBJECTIVES

A sophisticated remedial grouting program was executed to encapsulate and contain the radioactive waste located in Trenches 5 and 7. Initially, an in situ soil vitrification program was contemplated to immobilize radioactive waste within the trenches to stop the migration of radionuclides.

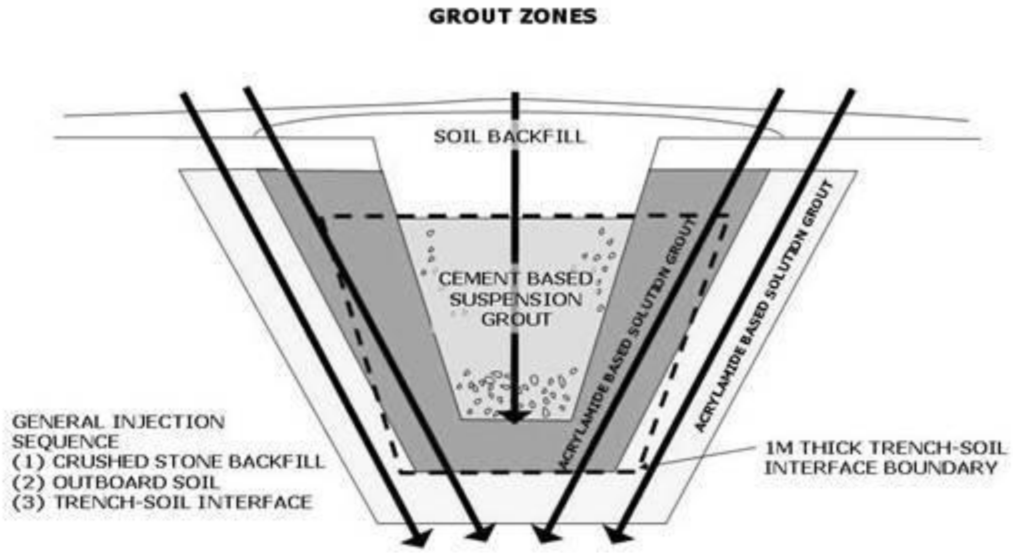

FIG. 2. Typical disposal trench cross-section showing grout pipes and injection sequence.

The design of the grouting program was based on the successful "in situ grouting" program of four radioactive waste disposal trenches in WAG 4 in 1996 (Huff et al. 1996 and Long et al. 1997). The original grouting program (Figure 2) consisted of injecting a durable and stable cement-based suspension grout into the pore space of the crushed stone backfill zone of the trenches via driven, vertical steel sleeve pipes.

Following the injection of the crushed stone matrix inside each trench, acrylamide-based grout was injected into the soils and fill surrounding each trench via two rows of battered oblique steel sleeve pipes located around the perimeter of the trenches, which also extended below the bottoms of the trenches.

The objectives of the remedial grouting program were to:

- Inject a durable, stable, cement-based suspension grout into the crushed stone matrix to contain and fixate the radioactive waste for more than 200 years.
- Inject the cement-based suspension grout in such a fashion that a sloped grout front would be established during the grouting process to ensure that the more concentrated radioactive waste remained in the bottom portion of the trenches and that no radioactive waste would be brought up to surface.
- Inject acrylamide solution grout to construct a 1-metre-thick grouted soil envelope around the perimeters and bottoms of the trenches to minimize the migration of radionuclides and fixate any radioactive material that had migrated into the soils adjacent to the trenches via fissures and fractures, during previous years. Acrylamide grout was selected because of its ability to permeate soils with fine fissures and fractures, its predictable set times, and its predicted durability of more than 200 years (Ref. Long, J., Huff, D., and A. Naudts).

- Reduce the geometric mean of the residual permeability (hydraulic conductivity) values of the grouted end product inside and in the envelope adjacent to the trenches to 1 x 10^{-5} cm/s or lower (a readably achievable value at least one order of magnitude lower than the average permeability of the surrounding marginally-groutable native soils). Application of this grouting technology satisfied the regulatory requirement for "treatment of the waste." Because the remedial design included a large multilayered cap designed to eliminate surface water infiltration and lower the groundwater table in the vicinity of the trenches, it was not necessary to achieve a very low permeability to meet remedial action objectives for groundwater.

TRIAL GROUTING PROGRAM

Prior to grouting the trenches, a trial grouting program was conducted on a small-scale trench constructed within the same geology, referred to as the construction verification trench (CVT). The purpose of the CVT was to confirm that the design objectives could be met and to make the necessary adjustments to the grouting procedures, equipment, grout mixes, injection pressures, injection sequencing and waste management prior to performing the grouting operations in Trenches 5 and 7.

The original grouting program was re-designed during the fall of 2005, and in December 2005, the CVT was grouted via the driven sleeve pipes, using a series of cement/fly-ash based suspension grouts followed by the acrylamide grouting of the soil around and below the CVT. There were 3 to 5 grouting passes performed via each sleeve pipe.

The grouting operation was monitored and assessed in real time. The gel and set time of the grouts were extended. The challenge was that the gravel in the trench had to be 100% grouted and only via the CAGES monitoring system (Ref. 3 and 5) could the grouting engineer derive that the mission was accomplished. Bringing water or grout to surface would have brought the grouting project (Trenches 5 and 7) in jeopardy.

Following the grouting of the CVT, the trench and the native soils were excavated to visually inspect the end-product. The exhumation revealed a perfectly and completely grouted crushed stone matrix.

GROUTING THE CRUSHED STONE MATRIX WITH CEMENT-BASED SUSPENSION GROUT

Grout Formulations and Quality Control Requirements

Laboratory tests were performed to develop a series of cement-based suspension grout formulations suitable for the injection of the CVT and trenches. These grout formulations had specific rheological and set characteristics to facilitate multiple grouting passes and to completely fill the crushed stone matrix. By subjecting the same formation to multiple grouting passes, the pores were more completely filled and the originally injected grout (with delayed gel and set time) was densified (as long as it did not reach initial set - i.e. for 72 hours) through pressure filtration. This resulted in a considerably lower matrix permeability of the grout, closer spacing between the particles, and hence a more durable end product.

In order to obtain the requisite durability, a pozzolan was included in each grout formulation. For this project, class F fly-ash, an artificial pozzolan, was selected to transform the calcium hydroxide that is formed within the primary ettringite of the grout matrix into secondary ettringite. The latter is the key to durability of cement based suspension grouts (discovered by the Romans 2000 years ago, but still not well understood by some grouting practitioners today).

The addition of class F fly-ash also slowed down the hydration process and hence reduced the thermal shrinkage. Pre-hydrated biopolymer solutions were used to reduce the pressure filtration coefficient to less than 50 x 10^{-3} $\text{minute}^{-1/2}$ and hence prevent "dry-packing" of the grout. The superplasticizer was used to lower the viscosity and cohesion of the grout.

The following cement-based suspension grout formulations were prepared and injected in Trenches 5 and 7 through the vertical sleeve pipes based on the encountered conditions.

Tabl 1. Cement-based suspension grout formulations used to grout the trenches.

Grout Ingredients	**Mix A**	**Mix B**	**Mix C**	**Mix D**	**Mix E**
Water (kg/m^3)	257.0	357.0	453.8	388.7	367.0
6% Bentonite Slurry (kg/m^3)	321.3	295.6	258.1	258.2	290.0
1% Diutan Gum Solution (kg/m^3)	64.3	56.8	46.8	38.9	52.8
Napthalene Suphonate (kg/m^3)	9.0	7.1	6.0	12.6	8.5
Class F Fly Ash (kg/m^3)	449.8	355.0	297.7	97.2	233.0
Type II Portland Cement (kg/m^3)	449.8	355.0	297.7	923.1	474.0
Delvo Stabilizer (kg/m^3)	9.0	3.5	0	1.5	4.5

Grout Spread/Hole Spacing

The spacing of the grout holes was based upon the distance a suspension grout can travel under a given pressure through the medium to be grouted with a given in situ hydraulic conductivity. It was known that the trenches contained coarse, open-graded, angular limestone gravel, approximately 37.5 to 50mm in size.

The length "L" that a particular cement-based suspension grout (a Binghamian fluid, with a cohesion C) will travel under a given pressure "P" through channels with average diameter "2R" is given by Lombardi's equation (Naudts 1996):

$$L = \frac{P \times R}{2 \times C} \qquad (1)$$

The theoretical grout spread of the various grout formulations was calculated to be in the 10 to 20 metre range in ideal conditions, based on the known size of the crushed stone backfill within the trenches. Since the viscosity and cohesion of the grouts do not remain constant over time, and since it was not known how the disposal of the liquid radioactive waste over the years had impacted the in situ hydraulic conductivity of the crushed stone backfill, and since the diameter of the pore spaces amenable to grouting would be reduced with successive grouting passes, a conservative hole spacing (between the sleeve pipes) of 3.75 metres was selected.

Grouting of Trenches 5 and 7 - Overview:

The cement-based suspension grouting operation of the CVT and Trenches 5 and 7 was conducted by Washington Safety Management Solutions through its subcontractors, Layne GeoConstruction and Miller Drilling Company. The cement-based suspension grout work was performed on consecutive single shifts.

In order to minimize displacement of radionuclides concentrated at the bottom of each trench, the packers were systematically set well above the bottom of the trench. The packer on the down gradient end of the trench was generally at a higher elevation than the other ones in order to maintain a sloping grout front. This method ensured that the sloping grout front engulfed the stones at the leading edge, displacing any contaminated groundwater, and encapsulating the waste in the bottom of the trench. A sloping grout front was easily established during the first hours of grouting and maintained during the remainder of the grouting operation. This grout front was continuously monitored via instrumentation placed in monitoring wells installed in the trench for this purpose. The displaced groundwater was subsequently absorbed by the hydrating grout.

Most vertical sleeve pipes (and the crushed stone matrix around them) were grouted during 3 to 4 consecutive days of grouting. This allowed for the most critical, lower portion of the trench to be subjected to pressure filtration for several days in a row, creating a very dense, competent and durable grout.

Typically, the apparent Lugeon value (using grout as a test fluid) only nominally increased during the first grouting pass. When performing the second grouting pass in the same horizon via the same sleeve pipes, the apparent Lugeon value was typically reduced by a factor of 8 to 30. During the execution of the 4 to 5 grouting passes, spread over several days, the apparent Lugeon value gradually dropped to zero.

Specifics of the Grouting of Trench 7

A total of 71 m^3 of cement-based suspension grout was injected in the southern segment of Trench 7, also referred to as Trench 7A. This first trench segment was predominantly grouted in a void filling mode quite similar to the grouting operation conducted at the CVT. Based on the apparent permeability values recorded by the real-time monitoring system, the in situ hydraulic conductivity value of the crushed stone matrix of the trench was lower than the permeability value obtained in the CVT. This provided evidence that the crushed stone matrix had been impacted by the disposal of the liquid waste during its years in service.

After completing the injection in the first trench segment, grouting continued in the northerly section of Trench 7, also referred to as Trench 7B. During the first injection day, the grout level quickly rose 1.2 metres in the southern end of the trench without establishing a sloping grout front. It became apparent that a “baffle” prevented the grout from moving freely within the trench. The grout level in the southern half of this trench continued to rise until this southern portion of the trench was substantially filled, while no grout migrated to the northern part of this trench. Once the grout crested over this “baffle”, the “baffle” seemed to erode or dissolve. Based on these encountered conditions, adjustments were systematically made to the grout formulation to ensure a complete filling of the crushed stone matrix. The formulations with the highest solids content were predominantly used for grouting the lower portions of the trench, where the highest concentration of radionuclides was present. From the second grouting pass onwards, the grouting mode indicated a permeation grouting trend, whereby the apparent Lugeon value gradually decreased with time from 5 x 10^{-2} cm/s to zero. This rather low initial hydraulic conductivity value was yet another indication that the crushed stone matrix had been affected by the liquid wastes and suspended solids from the days the trench was used as a disposal system for the liquid radioactive waste.

Once the northern portion of Trench 7B started to become pressurized, the well levels in the southern part of the trench started to rise again. The presence of an open-jointed, vitrified clay LLLW distribution pipe, on top of the trench, facilitated the migration of grout back towards the south until virtually the entire trench was under a pressure of approximately 1.6 metres of grout-column. In total, 80 m^3 of cement-based grout were installed in Trench 7B. Each zone in the trench was grouted four to five times using the same sleeve pipe causing a major densification of the grout before it cured.

Based on the well level readings, virtually no perched groundwater was encountered in Trench 7B. The small amount of perched groundwater remaining in shallow pockets in the trenches was readily absorbed by the grout; hence, the presence of contaminated groundwater did not impact the grouting operation.

Specifics of the Grouting of Trench 5

Prior to grouting, it was discovered that Trench 5 contained a significant volume of perched groundwater. It was clear, based upon water level data, even before the grouting operation started, that this trench contained “baffles” extending several feet above the bottom of the trench and that they were rather impervious. Furthermore, the sleeve pipe driving log reflected more consolidated subsurface conditions in the areas coinciding with the locations of the “baffles”. The presence of these “baffles” were confirmed during the grouting operation as the grout level had to rise 1.6 to 2.2 metres above the bottom of the trench before grout spilled over into the “next compartment” within the trench. The hydraulic conductivity of the crushed stone matrix in Trench 5 was lower than the value obtained for Trench 7. Even within Trench 5, the hydraulic conductivity varied greatly, due to the presence of the “baffles”. The hydraulic conductivity values recorded during grouting (using grout as a test fluid), revealed that these “baffles” had a considerably lower hydraulic conductivity than the rest of the trench (often 1 to 2 orders lower). It was noted that the evolution of the apparent Lugeon value via the grout pipes located between these “baffles” revealed a gradual increase of the apparent Lugeon value with time, which seemed to indicate that the grout-jetting action weakened or dissolved these “baffles”. Due to the lower hydraulic conductivity encountered in Trench 5, the cement based suspension grouts with lower cohesion and viscosity were predominantly used to grout this trench.

The perched, contaminated groundwater present in the bottom of the trench was either displaced or absorbed during the grouting process. Only during grouting of the most northerly portion of the trench was there water floating on top of the grout, over a short section of the trench. This water was gradually absorbed by the grout or displaced into the surrounding soils during the last day of grouting, until the grout level was established to be at least 0.3 to 0.6 metres above the level of the crushed stone matrix in the trench.

Grout was always (except during the first few hours of grouting) injected below the surface of the grout front. Each zone was grouted several times during 3 to 4 consecutive days at systematically increasing pressures. This multiple pass approach was a major and key component of the grouting program. The grouting operation of Trench 5 took seven days to complete, during which almost 255 m^3 of grout were injected. The grouting operation of Trench 5 was a showcase on how professional grouting should be conducted when the conditions (permeability) vary along the trench.

GROUTING THE SOILS SURROUNDING THE TRENCHES WITH ACRYLAMIDE SOLUTION GROUT

The acrylamide grouting operation was performed by WSMS through its subcontractors, Miller Drilling Company and Rembco Geotechnical Contractors (Rembco) and included a rigorous safety program implemented in accordance with the grouting manufacturer's recommendations. The acrylamide grout was prepared as a two component system. The final composition of the acrylamide solution grout (per volume basis) consisted of:

- Water
- Triethanolamine solution
- Ammonium persulfate
- Dye (Blue and Red)
- 40% Acrylamide solution
- 1% Potassium ferricyanide solution (KFe)
- Sodium bicarbonate (Baking soda)

Throughout the grouting operation, the gel time of the acrylamide grout formulation was adjusted by systematically reducing the amount of KFe introduced into the A-component based on above-ground ambient temperature and "feedback" from the assessment of the grouting data as the operation was unfolding. Quality control tests were performed on each batch of grout prepared to determine the temperature and gel time of the grout to ensure that the grout would meet the requirements set by the Grouting Engineer.

The acrylamide grouting operation took place via eight battered sleeve pipes at a time. The grout was distributed to the sleeve pipes via eight injection ports on the grout manifold fabricated for this application. All the basic grouting parameters (flow and pressure) for the acrylamide grouting operation were electronically measured, recorded and assessed in real time for each of the eight injection lines.

Acrylamide grouting commenced on the down gradient end of each trench. The outer row of holes was injected first followed by the inner row of holes. Each sleeve pipe was injected in two grout zones and injected at least three times. This first grouting pass was performed in the lower half of the sleeve pipe. The inside portion of the sleeve pipe in turn was pumped empty and the second injection pass was performed by positioning a single packer 1.8 metres below surface, therefore, injecting typically all the sleeves available on the sleeve pipe. The second injection pass was performed at a slightly higher pressure the day after the first pass was completed or after the hole/zone had been "rested" for at least 5 to 6 hours. If a zone did not refuse during the second acrylamide grouting pass after 5 hours, the hole was left to rest for 5 hours and re-injected again.

This procedure was followed until each sleeve pipe refused. Some zones required six grouting passes before refusal was eventually obtained.

The typical pre-grouting permeability (hydraulic conductivity) value of the "soil" around the trenches was in the order of 5 to 30 x 10^{-5} cm/s. These were soils that were marginally injectable. Hence the need for many grouting passes via the same sleeve pipes to accomplish the target value for the residual permeability. Based on the original construction records for the trenches, it was discovered that there were areas along the trenches that had been excavated during the construction process and backfilled with remolded soils (fill), which explained the higher permeability values encountered in some locations.

Because of the presence of fill and pockets of gravel within the “1 metre zone” around Trenches 5 and 7, the theoretical grout quantities for acrylamide were exceeded substantially. It was in these areas that often as many as six grouting passes were required to completely fill the soil/gravel matrix. Where the “native soil” was encountered, however, the estimated pore space was rather realistic. Note that the “native soil” was not granular in nature (the native soil was actually decomposed rock and its permeability was governed by fissures within the impervious matrix and not governed by matrix permeability). A total of 626 batches (600 litres per batch) of acrylamide grout were prepared for the acrylamide grouting program conducted at Trenches 5 and 7. This translated to a grand total of approximately 356 m^3 of acrylamide grout injected.

POST GROUTING IN SITU HYDRAULIC CONDUCTIVITY TESTING

In situ hydraulic conductivity tests (IHCT’s) were conducted on 68 designated sleeve pipes installed during the driving operation for verification purposes. These verification pipes, referred to on this project as “check pipes”, were configured identically as the sleeve pipes used for grout injection. The only difference between the sleeve pipes and the check pipes was that the latter were NOT grouted during the grouting operation.

Prior to performing the IHCT, each sleeve on each check pipe was opened or “fracked” with water to gain access to the formation. Once this task was completed, the IHCT was performed on each sleeve using a pressure pot, set on a weigh-scale, to determine the injection rate. For each sleeve tested, the in situ hydraulic conductivity value (k-value) was calculated.

With the IHCT values of each zone tested, the geometric mean was calculated for each trench both for the grouted crushed stone matrix and 1-metre-thick soil envelope around and below the trenches. All in situ hydraulic conductivity values obtained met the design criterion of 1 x 10^{-5} cm/s or less. The geometric mean of the grouted crushed stone matrix was 1 x 10^{-7} cm/s, while the geometric mean for the grouted soil was 2 x 10^{-6} cm/s. Based on an average initial (pre-grouting) in situ hydraulic conductivity value of 1 x 10^{-2} cm/s for the crushed stone in the trenches and 2 x 10^{-4} cm/s for the soil adjacent to the trenches, the permeability values of these formations were reduced by approximately five orders of magnitude for the stone-filled trench and two orders of magnitude for the adjacent native soil. The use of multiple-injection passes and long set times proved to be the key elements in successfully reducing the permeability inside the trench and in the surrounding grouted soil envelope.

CONCLUSIONS

This project demonstrates that professionally-executed, low-pressure permeation grouting can be executed safely and effectively as a means of source control for liquid radioactive wastes disposed in burial trenches. Without drilling and without bringing contaminated material to surface, driven sleeve pipes facilitated a multiple pass grouting program, which was the key to the construction of an end product with very low residual permeability. When combined with other hydraulic isolation methods, such as landfill capping, remedial action objectives for groundwater may be achieved without requiring the grouted media have a very low permeability.

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