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**In-Situ Stabilization of
Radioactively Contaminated
Low-Level Solid Wastes Buried
in Shallow Trenches—an Assessment**

H. S. Arora
T. Tamura
W. J. Boegly

ENVIRONMENTAL SCIENCES DIVISION
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ABSTRACT

ARORA, H. S., T. TAMURA, and W. J. BOEGLY 1980. In-situ stabilization of radioactively contaminated low-level solid wastes buried in shallow trenches - An assessment. ORNL/TM-7130. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 68 pp.

The potential effectiveness of materials for in-situ encapsulation of low-level, radioactively contaminated solid waste buried in shallow trenches is enumerated. Cement, clay materials, and miscellaneous sorbents, aqueous and nonaqueous gelling fluids and their combinations are available to solidify contaminated free water in trenches, to fill open voids, and to minimize radionuclide mobility. The success of the grouting technique will depend on the availability of reliable geohydrologic data and laboratory development of a mix with enhanced sorption capacity for dominant radionuclides present in the trenches. A cement-bentonite-based grout mix with low consistency for pumping, several hours controlled rate of hardening, negligible bleeding, and more than 170 kPa (25 psi) compressive strength are a few of the suggested parameters in laboratory mix development. Cost estimates of a cement-bentonite-based grout mix indicate that effective and durable encapsulation can be accomplished at a reasonable cost (about \$113 per cubic meter). However, extensive implementation of the method suggests the need for a field demonstration of the method.

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1. INTRODUCTION

1.1 Background

Radioactive waste materials, except high-level, transuranic, and liquid wastes, have routinely been buried in shallow trenches in the United States. The disposal operation has been commonly accepted as the most practical and economically feasible method. More than 100,000 m³ of solid radioactive wastes are generated annually at various U. S. Department of Energy (DOE) installations, in the weapons program, and in nuclear power generation (Steger 1977). Most of the commercial wastes are buried in privately licensed burial sites, whereas all those generated by governmental operations are disposed of at federally controlled reservations.

Recent Congressional hearings have indicated that minor quantities of radioactivity have been discharged from existing burial grounds (U. S. House of Representatives 1976). Risks associated with indiscriminate use of shallow land burial have highlighted the increasing interest and concern over these operations by several governmental agencies (General Accounting Office 1976, Webster 1976, NRC 1976, Rowe 1976, Wheeler et al. 1976). Public perception of the waste disposal problem has also contributed to the urgency of the situation and is reflected in increased governmental funding for waste management technology (Bradley and Lyons 1976). Although no evidence of injury to the public has been detected from the minimal releases that have occurred (Duguid 1977), concerns do exist about the long-term influence of low-level radiation on human health.

Extensive research has been conducted on isolation of high-level transuranic and liquid wastes. However, environmental evaluation and treatment of low-level solid wastes have received lower priority. The major objective of this report is to enumerate materials available for postburial isolation of solid wastes by in-situ encapsulation and to evaluate the effectiveness of this treatment. Emphasis is placed on disposal sites in the humid eastern United States (Fig. 1) with particular reference to the conditions at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee.

1.2 Perspective

Low-level solid wastes include such items as paper, clothing, plastic bags, building rubble, glass, and contaminated laboratory equipment and machinery. The level of radioactivity in typical waste for shallow land burial does not require shielding to protect personnel from radiation. Depending on its origin, the waste may contain almost any radionuclide although transuranic elements must be lower than 10 nanocuries per gram of waste. Plastic bags are used to pack most of the waste materials, but large machinery and building rubble are dumped directly into the trenches.

Solid waste disposal practices differ somewhat from one site to another (Horton and Corey 1976; J. R. Gissel, ORNL, personal communication). A typical shallow burial operation consists of digging trenches of varying dimensions and depths above the seasonal maximum groundwater elevation. Waste materials are dumped to within 1 to 1.5 m of the original soil surface, and the unlined trenches are backfilled

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Fig. 1. Locations of commercial and U.S. DOE low-level radioactive solid waste burial grounds in the humid region of the United States.

with the original overburden. One of the major functions of the cover is to impede infiltration of surface water, but the cover also restricts gas movement and reduces the fire hazard. A vegetative cover over the burial area is usually provided to control soil erosion, to enhance evapotranspiration, and to maintain an aesthetic appearance.

Acceptable hydrogeologic conditions are necessary to prevent radionuclide mobility from disposal sites. A fluctuating ground-water table, lateral movement of percolating water, and infiltration of rainwater are primarily responsible for radionuclide transport at humid-region burial sites (Wheeler et al. 1976, Duguid 1977). Seasonal water-table fluctuations occur in solid waste trenches in portions of disposal areas at ORNL. Also, ^{90}Sr is the dominant radionuclide present in the free-standing water of these trenches. Fractures in local Conasauga shale, pores in weathered clay, and waste disposal in lengthy trenches on gently sloping topography, resulting in a tilted bathtub effect, may be largely responsible for the radioactivity leaking from these solid waste disposal areas.

The natural ability of soils to exchange and adsorb a variety of radionuclides plays a major role in contaminant attenuation. Inherent in radioactive waste is the decay of radionuclides to innocuous levels depending on the half-life of the radionuclides present. Also, hydrologic dispersion tends to dilute and, thus, diffuse the environmental impact of contaminant releases. Despite these natural mitigating measures, radioactive waste disposal sites and their immediate watersheds will necessarily be "perpetual-care landfills" for the foreseeable future.

In consideration of the risks involved, much greater emphasis is being placed on developing corrective measures to arrest radionuclide releases. One corrective action that might yield a prompt response would be to pump the contaminated water from a trench into temporary holding containers, mix it with cement and other additives to obtain a slurry, and then pump the mix back into the trench. (Alternatively, separate disposal of the contaminated water and preparation of the slurry in fresh water would reduce radiation risks to field personnel.)

Slurry grouting has been used in construction projects to induce consolidation, improve soil strength, and reduce permeability. Grouting consists of injecting, under pressure, a variety of binder materials that solidify under controlled conditions. Grouting technology may possibly be adopted to immobilize radionuclides and to solidify stored wastes in situ.

2. IN-SITU ENCAPSULATION

Satisfactory immobilization of radionuclides in wastes can be carried out only with a clear understanding of the grouting process. Successful grouting is an artful blend of educated guesstimates and experience in soil mechanics, fluid mechanics, and engineering geology. A vast body of practical knowledge has been developed recently on grouting applications for preconstruction, construction, and postconstruction stages in wide-ranging geotechnical projects. Wider acceptance of grouting methodology has been achieved in Europe than in the United States (Herndon and Lenahan 1976).

Success in immobilization of waste contaminants by grouting will depend on the availability of site-specific data, selection of an appropriate grout mix, intelligent design, and field operations by experienced personnel. Site investigations usually will entail collection of onsite data, augmented by available information from the literature. Information needed prior to injection design and material selection include:

- (1) general geology of the area and description of soil profile to a depth of several meters below the trench depth (occurrence of any fracture zones and bedding patterns should also be recorded);
- (2) grain size distribution, porosity, and pore size distribution of native soil material and solid waste materials;
- (3) radionuclide type and content in free-standing water and variability with depth, if any;

- (4) chemical analysis of trench waters (i.e., pH, electrical conductivity, and major solutes).
- (5) information on soil engineering properties including overburden material depth, unconfined compressive strength, Atterberg limits, and soil material passing through a 200-mesh sieve;
- (6) hydrologic properties of the basin with special reference to in-situ permeability, trench water level, and water-table fluctuations in the vicinity of trenches over a one-year period, and pump tests to determine the amount of pumpable water, recharge rate, and direction of flow of ground water; and
- (7) physical, chemical, and geometric characteristics of stored wastes and inventory of contaminant levels. Some of these data at DOE sites are available through Solid Waste Information Management System (SWIMS) data base (Duguid 1977).

A conceptual description of field operations, after initial survey and monitoring of hydrologic and site characteristics, includes (1) pumping contaminated water from the trenches, (2) mixing it with the grout mix developed earlier in the laboratory, and (3) injecting the grout slurry back into the same trench and is illustrated in Fig. 2.

2.1 Grout Mix Development Criteria

The properties of the grout mix and the solidified products for an effective in-situ treatment are described below. Most of these

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Fig. 2. Field injection for in-situ encapsulation of solid wastes.

considerations are not independent but are strongly interactive.

Standard laboratory tests for measuring these parameters usually are not available and major problems are encountered in laboratory simulation of grout operations in the field.

2.1.1 Control of grout mix consistency (viscosity)

The consistency of a grout mix is the measure of its ability to penetrate porous media. Some chemical grouts are Newtonian fluids possessing low average viscosity in initial stages followed by a rapid rise in viscosity. However, for a majority of grouts, the consistency gradually increases with time after mixing until gelation takes place (Fig. 3). Factors that control the rate of hardening of a grout slurry, such as temperature and additives, also significantly influence consistency. The optimum slurry consistency will vary with the grout system used and the specific application. Customary laboratory equipment can be used for measuring the viscosity of Newtonian grout fluids. Recommended test methods under ASTM Specification C187-74 (ASTM 1976) or American Petroleum Institute practice for testing oil-well cements (API 1977) can be used to measure the consistency of cement slurries.

2.1.2. Control of rate of hardening

The setting or hardening of a grout is the term applied to its change from a fluid to a solid phase. The time required for grout hardening cannot be judged precisely because the transformation from fluid to solid phase in most systems is gradual. Also, the rate of hardening in the formation may not be the same as that determined in the laboratory. Prevailing temperature and salts present in the

Fig. 3. Viscosity versus time for some chemical grouts (Adapted from Mitchell 1970).

groundwater affect the rate of hardening; however, the process can be easily manipulated by a variety of additives available for individual grout systems. For practical purposes, the rate of hardening in shallow trench grouting may not be critical, provided the grout remains in a pumpable fluid state for at least 1 h, or the time required to complete the injection operation.

2.1.3 Ease of mixing

Most chemical grouts are freely soluble in water and present minimal mixing problems. Ease of mixing is an important criterion for particulate grouts because of the radionuclide component of the slurry. A large number of wetting agents are available and should be employed when reduction of the consistency of a specified particulate grout mix is desired. Similar results can normally be obtained by decreasing the solid-to-liquid ratio in particulate grouts, provided bleeding can be prevented. Foaming problems that may arise during mixing can be controlled by adding appropriate defoaming chemicals.

2.1.4 Bleeding-control additives

Bleeding is essentially a sedimentation process wherein the solids settle in a plastic mass. In chemical grouting, syneresis is the term used for the separation of liquid from a gel. Liquid separation should not present problems for most chemical grouts except for insufficiently gelled or nonpolymerized parts of the grout which are not incorporated with the macromolecules.

Bleeding is sensitive to shear, chemical composition of the leachate, and grout blend. A grout formulation whose consistency, setting time, and strength characteristics remain essentially unaltered

over the expected range of chemical composition of leachates in trenches should be the aim of laboratory research and development. Bentonite clay has been successfully used as a bleed-control additive. A standard test method for measuring bleeding in cement pastes and mortars is available under ASTM Specification C243-65 (ASTM 1976).

2.1.5 Leachate retention and permeability of encapsulated waste

It is highly desirable to retain as an integral part of the solidified grout essentially all of the radionuclides present in the leachate. Any bleeding results in accumulation of radioactive fluid in pools which would be free to escape.

The permeability of the stored waste can be minimized by selecting formulations which yield an impervious grout. Ordinarily, it is not economically feasible to obtain an absolutely impervious mass. The overall watertightness of the stabilized mass will depend on the laboratory development of the grout mix, its consistency at the time of injection, the ease with which setting time can be regulated, and the shear strength which must be adequate to overcome degradation and dissolution upon contact with moving water.

2.1.6 Compressive strength

The final set strength of the pure grout is not a critical factor for in-situ stabilization of wastes in shallow trenches because the grout will not be exposed to extensive shear stresses. However, the hardened grout should resist hydrostatic forces that might tend to displace it. Hydrostatic pressures in shallow trenches are usually small, so low-strength grouts [at least 170 kPa (25 psi)] are acceptable provided required imperviousness is obtained.

Distinction should be made between the hardened strength of pure grout and that of the stabilized mass. The mechanical characteristics of most of the pure clay and chemical grout systems in the laboratory may be unrelated to the strength of the stabilized mass obtained in the field, and both kinds of measurements should be made to arrive at the most appropriate grout mix. A variety of measurements, such as unconfined compressive strength, triaxial strength, and flexure strength are used to characterize the strength and hardness of pure grouts and the grouted mass. A standard test to measure the compressive strength of cement mortars is available under ASTM Specification C109-75 (ASTM 1976).

2.1.7 Durability

Generally, experimental and field evidence on the durability of grouts is lacking because it is difficult to define the durability of grouts and appropriate conditions for their study. Most particulate grouts are expected to be reasonably durable over several decades. Portions of chemical grouts may be insufficiently gelled or polymerized during conversion from liquid to solid state; these portions will be more vulnerable to degradation by percolating water. Accelerated degradation may also be brought about by acidic ground water which may be encountered in humid environments.

2.1.8 Specific additives

The ability of most commonly used encapsulating agents to react chemically or to adsorb radionuclides is limited but might be enhanced by the incorporation of functional additives in the grout mix as

described in Section 2.4.1. Leaching rates are generally used to compare competing encapsulating processes for use in a particular situation. Preference should be given to grout systems that show maximum flexibility in incorporating most of the potential adsorbents without sacrificing the physical effectiveness of the grout.

2.1.9 Reducing migration potential

The distribution coefficient (K_d) values of radionuclides of concern in different soils are the major indicators of radionuclide migration potential. These values are strongly influenced by the pH of the medium and other soil properties described later in Section 2.4.1. Chemical grout formulations vary from strongly acidic (urea formaldehyde grout) to strongly basic (sodium silicate grout) and can be used advantageously by proper material selection to enhance adsorption (raise K_d).

2.1.10 Control of nonpumpable contaminated fluid in trenches

It is virtually impossible to pump out all of the contaminated water that accumulates in waste trenches. The selected grout formulation should have the ability to imbibe additional water without losing its overall effectiveness as an immobilizer of pumped leachate and to encapsulate the waste. The heat treatment of bentonite and illite (Tamura 1966) or hydrophobic film covering of bentonite (van Leeuwen 1940) may help provide the capacity of these materials to rehydrate slowly, and to immobilize nonpumpable fluid.

Additional operational criteria for selecting grouting materials include (1) low cost and easy availability, (2) nontoxicity and

noncorrosiveness, (3) radiation stability, (4) absence of biodegradation, (5) personnel safety, and (6) minimum heat generation during solidification.

2.2 Grout Classification

The vast number of grouts preclude easy classification. Two general types are recognized: particulate and nonparticulate (chemical). These are described below.

2.2.1 Particulate-type grouts

The particulate-type grout materials include clay, cement, lime, soil, and additives. Penetration ability is limited by the relatively large particle size of their components. Groutability ratio refers to the ability of particulate grouts to penetrate a geologic formation. Mitchell (1970) reported the following groutability ratio for successful grout penetration in soils.

$$\text{groutability ratio} = \frac{(D_{15})_{\text{soil}}}{(D_{85})_{\text{grout}}} > 25,$$

where $(D_{15})_{\text{soil}}$ is the diameter of soil particles at the 15 percent size fraction obtained from a grain size curve (particle diameter vs percent size fraction) of the soil to be grouted and $(D_{85})_{\text{grout}}$ is the diameter of grout particles at the 85 percent size fraction obtained from a grain size curve of the grout material. For example, cement grouts (D_{85} approximately 40 μm) would not penetrate a sand formation (D_{15} approximately 200 μm) because the groutability ratio is less than 25. Much greater strength and stability can be achieved with particulate grouts than with nonparticulate ones. Properties and

uses of individual particulate grout materials are reported later in this report.

2.2.2 Nonparticulate (chemical) grouts

A majority of chemical grouts are Newtonian fluids and tend to exhibit constant viscosity at all rates of shear. Chemical grouts are relatively expensive in terms of material cost but offer several distinct advantages including absence of particulate material, very low viscosity, and well-controlled gel times. Emulsion and resin grouts, considered to be chemical grouts in this report, are the most expensive types, but possess higher ability to penetrate and lower consistency in comparison with particulate grouts. Figure 4 shows the ranges of grain size over which different grout systems can be applicable.

Chemical grouting technology has advanced considerably in recent years. Several excellent treatises on various aspects of chemical grouting have recently appeared in the literature (U. S. Department of the Army 1973; Bowen 1975; Herndon and Lenahan 1976; Tallard and Caron 1977a, 1977b). Reviews by Lambe (1962), Skipp and Renner (1963), and Mitchell (1970) also discuss the characteristics and uses of chemical grouts. Numerous proprietary commercial chemical grout systems are available under trade names in this country; selected properties of some of these grouts are listed in Table 1.

Grout injection of chemicals includes single- or two-shot systems. In the single-shot system, all grout ingredients are premixed prior to injection, which provides a better control of the grouted matrix radius and completeness of grout penetration since the gel time can be reliably controlled. Higher strengths can often be obtained

Fig. 4. Soil grain size ranges over which different grout types are useful (Adopted from Herndon and Lenahan 1976).

Table 1: Properties of currently used grouts

Grout material	Catalyst Material	Unconfined compressive strength PaPa (psi) of grouted soil	Viscosity (kPa s)	Setting time (min.)	Toxicant ^a	Pollutant ^b
<u>Silicate base</u>						
Low concentration	Bicarbonate	70 - 340 (10-50)	1.5	0.1 - 300	No	No
Low concentration	Halliburton Co. Material	70 - 340 (10-50)	1.5	5 - 300	No	No
Low to high concentration	Siroc-Diamond Shamrock Chemical Co.	70-3,450 (10-500)	4-40	5 - 300	No	No
Low to high concentration	Chloride-Joosten process	70-6,900 (10-1000)	30-50	0	No	No
Low to high concentration	Ethyl Acetate Soletanche & Halliburton	70-3,450 (10- 500)	4-40	5 - 300	No	No
Low to high concentration	Rhone-Progil 600	--	--	--	--	--
Low to high concentration	Geloc - 3 H. Baker Co.	70-3,450 (10- 500)	4-25	2 - 200	No	No
Low to high concentration	Geloc - 3X	70-1,700 10- 250	4-25	0.5- 120	No	No
<u>Lignin base</u>						
Blox-All	Halliburton Co. Material	30 - 600 (5 - 90)	8-15	3 - 90	Yes	Yes
TDM	Cementation Co. Material	340-3,450 (60- 500)	2-4	5 - 120	Yes	Yes
Terra Firma	Intrusion Co. Material	70- 340 (60- 500)	2-5	10 - 300	Yes	Yes
Lignosul	Lignosul Co. Material	70- 340 (10 50)	50	10-1,000	Yes	Yes
<u>Acrylamide base</u>						
AM-9C	DMAPN and ammonium or sodium Persulfate	70-3,450 (50 - 500)	1.2-1.6	0.1-1000	Yes	Yes
<u>Formaldehyde base</u>						
Urea-formaldehyde	Halliburton Co. Material	Over 6,900 (over 1,000)	10	4-60	Yes	Yes
Urea-formaldehyde	American Cyanamid Co. Material	Over 3,450 (over 500)	13	1-60	Yes	Yes
Resorcinol Formaldehyde	Cementation Co. Material	Over 3,450 (over 500)	3.5	--	Yes	Yes
Tannin - Para-formaldehyde	Borden Company MQ-8					
Geoseal MQ-4 & MQ-5	Borden Company Material					
<u>Unsaturated Fatty Acid Base</u>						
Polythixon FRD	Cementation Co. Material	Over 3,450 (over 500)	10-80	25-360	No	No

^aA material which must be handled using safety precautions and/or protective clothing.^bPollutant to fresh water supplies contacted.^cAlso available from grouting companies under trade names of PWG or Injectite-Q.

Source: Herndon and Lenahan 1976.

using the two-shot process in which one solution containing the base material (e.g., sodium silicate) is injected, followed by a separate injection of a second reactant system (e.g., calcium chloride). Only limited penetration of grout can be achieved by this process.

Six major groups of chemical grout systems are in use today. They include (1) silicates, (2) acrylamides, (3) urea-formaldehydes, (4) lignin sulfonates, (5) polyphenolics, and (6) resins and emulsions. The choice of which grout system to use depends on field conditions and job specifications. The first five groups are soluble in water and are frequently used for grouting of fine sands. Synthetic polymer resins consist of materials that may or may not be soluble in water, and they generally have a consistency too high to satisfy completely the Newtonian character of a chemical grout.

2.3 Grouting as a Functional Barrier

In-situ stabilization can be successfully employed to establish chemical and/or physical barriers against radionuclide transport from shallow trenches. Use of clay minerals and other sorbents as inexpensive precipitating and adsorbing agents for radionuclides appears to be very promising. Physical encapsulation of wastes provides retardation of radionuclide migration by lowering the porosity and permeability of the stabilized mass.

2.3.1 Chemical barrier

Clay minerals and other additives can be easily incorporated into the grout mix. The ion exchange and adsorption properties of these materials can be used to retain radionuclides. Ion exchange is a

reversible process by which ions are exchanged between solid and liquid phases, whereas adsorption is an increase in concentration or an accumulation of a specific ion species on the solid phase, caused by ion exchange or other reactions. The exchange sites normally originate as a result of isomorphous substitution of lower charged ions for highly charged ions. Exchange sites also may occur due to ionizable sites, generally hydrogen, present at the edges of clay minerals (commonly occurring in kaolinite), as well as on surfaces of hydrous oxides (commonly occurring in iron, aluminum, and manganese hydrous oxides).

The electrical charge due to isomorphous substitution on clay surfaces is constant over a wide pH range. In comparison, the electrical charge due to ionization of hydrogen varies more or less with the pH and with the total counter-ion concentration of the liquid phase. The cation-exchange capacity of soil increases with rising pH and vice versa (Deshpande et al. 1964).

The variable ion-exchange capacities of clay minerals, the variable concentration of stable ions in waste leachate, and the very low concentration of radionuclides relative to stable-ion content make it difficult to derive a generalized equation to depict ion-exchange reactions. The law of mass action has been used to relate the K_d values for measuring the adsorption of radionuclides by these materials. The K_d , defined as the ratio of the radionuclide in the adsorbed phase and in the solution at equilibrium,

$$K_d = \frac{(Sr-X_2)}{(Sr^{2+})}, \quad (2)$$

may be derived in the following manner by use of exchange of strontium on a sodium clay:

$$K_{Na,Sr} = \frac{[Sr-X_2] (Na^+)^2}{(Sr^{2+}) [Na-X]^2}, \quad (4)$$

where

$K_{Na,Sr}$ = ion exchange selectivity or equilibrium constant,

X = exchanger (clay),

[] = concentrations,

() = activity.

In a system where the Sr^{2+} (exchange ion) is present in trace quantities relative to sodium ions, the clay remains essentially sodium-saturated (nearly equal to the cation exchange capacity) and Na-X may be treated as a constant. Substituting K' for $K_{Na,Sr} \cdot [Na-X]^2$, we obtain

$$K' = \frac{[Sr-X_2] (Na^+)^2}{(Sr^{2+})}. \quad (5)$$

One may combine Eqs. (2) and (5), assuming $[Sr-X_2] = (Sr-X_2)$, to form

$$K_d = \frac{K'}{(Na^+)^2} \quad (6)$$

As Eq. 6 implies, a log-log plot of K_d values for several clay minerals commonly found in natural formations as a function of sodium concentration yields a straight line with -2 slope (Fig. 5). Because the K_d is an experimentally determined quantity which is dependent upon the conditions under which it is determined, there can be as many K_d 's as there are combinations of radionuclides, kinds of sorbents, and chemical components in the waste. Hence, K_d values determined in the laboratory cannot simulate actual field conditions. Additional details of K_d 's and their determinations are available in the literature (Tamura 1972, Grove and Rubin 1976, Reeves et al. 1977).

Adsorption of radiostrontium, the predominant radionuclide in trench waters, by most naturally occurring clay minerals is much lower than the adsorption of radiocesium (Tamura 1972). Ion exchange is the principal mechanism of strontium adsorption by soils components. Since the chemical behavior of calcium is very similar to that of strontium and since calcium is abundant in most natural systems, it readily replaces traces of strontium and causes radiostrontium to migrate.

The strontium K_d values of several clay minerals and other materials in natural waters at two pH levels are presented in Table 2. The natural water in these studies contained strontium, calcium, and magnesium ions in concentrations equal to ORNL's low-level liquid water with 1 ppm sodium concentration. These data show that the K_d values

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Fig. 5. Influence of NaNO₃ concentration on strontium sorption by montmorillonite and hydrobiotite (Adapted from Tamura 1967).

Table 2. Distribution coefficients (K_d) of selected materials for strontium in natural water^a

Material	Size or area	Distribution coefficient (ml/g)	
		pH 7.5	pH 10
Montmorillonite	< 2 μm	506	
Illite	< 2 μm	117	760
Kaolinite	< 2 μm	55	257
Limonite	6.8 m^2/g	39	1,240
Heat-treated limonite	93 m^2/g	1,200	24,000
Alumina	230 m^2/g	2,100	34,000
Hydrobiotite	< 50 m	440	
Muscovite	< 50 m	82	
Biotite	< 50 m	48	

^aAdapted from Tamura (1972).

with limonite heated to 600°C), surface area (values increase with increase in surface area), and pH (enhanced adsorption at higher pH). In addition, the K_d values are also influenced by the equilibrium ionic concentration of the solution (Fig. 5). Recent data obtained at ORNL on local Conasauga shale confirm some of these findings (B. P. Spalding, personal communication).

Illite and K-hydrobiotite exhibit a high affinity for trace levels of radiocesium (Tamura and Jacobs 1960). Clay mineral structure was observed to be the dominant factor in radiocesium sorption. Formation of favorable sites for retention at higher cesium concentrations was observed with natural hydrobiotite. Heat treatment to 600-700°C has been found to improve radiocesium sorption for smectitic clays and most illites (Tamura 1966). Zeolitic minerals, clinoptilolite (Ames 1961) and mordenite (Berak 1962), have also been reported to show high selectivity for cesium.

In addition to natural clay minerals, synthetic materials like ion exchange resins and fly ash may be used to retain radionuclides. Fly ash has been used, in part, to improve strontium retention in the hydrofracture cementitious mix at ORNL (Tamura 1967).

2.3.2 Physical barrier

The velocity of the radionuclide of concern relative to the ground-water velocity, called the retardation factor, K_f , in a formation is generally used as a measure of sorption in modeling radionuclide migration. The K_f is based on physical parameters of the medium and the K_d value as:

$$K_f = 1 + \frac{\rho}{\theta} K_d \quad , \quad (7)$$

where ρ = bulk density and θ = porosity. When there is no sorption, K_d equals 0 and the minimum value for the K_f is 1. Since in-situ stabilization provides both a physical barrier (by reducing porosity and moisture content in the stabilized mass) and a chemical barrier with an enhanced K_d (by proper grout mix selection), the treated mass would retard the transport of dissolved species with respect to ground-water movement. The degree of retardation would be a function of the grout properties and the success of the field injection.

3. TREATMENT MATERIALS

In-situ stabilization of buried waste in trenches can be achieved with a variety of materials, several of which are commonly used for grouting in civil engineering practice. Potential treatment materials for low-level radioactive waste management are described below.

3.1 Cement and Additives

3.1.1 Portland cement

Portland cement is the basic component for particle bonding and is by far the most extensively used material for grouting purposes. Cement-based grouts are useful for both imperviousness and strength. Portland cement also has been used routinely as a solidifying agent for radioactive liquid wastes for more than two decades, but its use as an encapsulating agent for low-level solid wastes has been limited. With greater emphasis on prevention of contaminant releases, it is becoming increasingly evident that Portland cement will play a major role in radioactive waste management. Active cement solidification research programs for waste encapsulation have been or are currently in progress in this country (Table 3).

A typical Portland cement consists of calcium silicate, calcium aluminate, alkalies, and free lime. Four types of Portland cement -- types I through IV -- meet ASTM specifications and are commercially available; the higher the number, the higher the sulfate resistance and the higher the price. Type I is ordinary cement, and type II is rapid-hardening cement. Type III is much more finely ground than type I

Table 3. Summary of active or potential waste management applications of cement-based components in the United States

Application	Organization	Reference
1. Solidification of power plant liquid wastes	Commercial firms	Colombo and Neilson (1976) Heacock and Riches (1974)
2. Hydraulic fracturing of liquid wastes	CRNL	deLaguna et al. (1968) Moore et al. (1977)
3. Encapsulation of concentrated salts	Fanford Engineering and Development Laboratory	Lerch (1977)
4. Encapsulation of transuranium wastes	Savannah River Plant	Stone (1977)
5. Encapsulation with polymer-coated cements	Erookhaven National Laboratory	Kukucka and dePuy (1972)
6. Liners of waste canisters	DOE installations	
7. Mixes for radioactive sludges	CRNL	Moore, J. G. (personal communication)
8. In situ stabilization	CRNL	Arora (unpublished data)

and is slightly slower in rate of strength development, but it has other restrictions on the chemical composition. Type IV is a low-heat cement in which the chemical composition has been adjusted to reduce the heat of hydration. Its rate of strength development, though not its ultimate strength, is lower than that of ordinary cement. Portland cement of each of these types conforms to the respective physical and chemical requirements under ASTM Specifications C150-76 (ASTM 1976). Certain optional physical and chemical requirements also are designated in these specifications. The setting and hardening of Portland cement is a complex process because of the presence of several anhydrous compounds which, when brought in contact with water, decompose and transform to hydrated compounds (Table 4).

Solidified Portland cement is not an impervious material in the strict, technical sense. Leaching rates are used as a measure of radionuclide mobility from the solidified product. These rates are commonly determined by measuring the fraction of a given radionuclide constituent that leaches from the solidified product over a period of time. A specified leach rate test is used for this purpose (Hespe 1971).

Numerous additives have been incorporated in cement to obtain a variety of desired physical properties of the mix and the end product (Table 5). Certain salts retard the set when used in small amounts but accelerate it when larger amounts are added. For example, the addition of very small amounts of CaCl_2 (less than 1%) retards setting; the addition of larger amounts produces an accelerated set. In some cases, the addition of over 3% CaCl_2 causes a flash set.

Table 4. Summary of reactions of cement minerals

Products in dry cement	Hydration products at atmospheric temperatures and pressures
Tricalcium silicate ($3\text{CaO} \cdot \text{SiO}_2$)	$1.5\text{CaO} \cdot \text{SiO}_2 \cdot 1.0 \text{ to } 2.5 \text{ H}_2\text{O} + \text{Ca}(\text{OH})_2$
Dicalcium silicate ($2\text{CaO} \cdot \text{SiO}_2$)	
Tricalcium aluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$)	
Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}$
Alkalies ($\text{Na}_2\text{SO}_4 + \text{K}_2\text{SO}_4$)	$+ 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O} + \text{KOH and NaOH}$
Tetracalcium aluminoferrite ($4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$) or as ($6\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3 \cdot 2\text{CaO} \cdot \text{Fe}_2\text{O}_3$)	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}$
Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)	$+ 3\text{CaO} \cdot \text{R}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$
Calcium hydroxide ($\text{Ca}(\text{OH})_2$)	
Magnesia (MgO)	$\text{Mg}(\text{OH})_2$
Free lime (CaO)	$\text{Ca}(\text{OH})_2$

R = Al or Fe

Source: American Petroleum Institute (1959).

Table 5. Influence of commonly employed additives on the physical properties of cement

Property	Additive					Diatomaceous earth	Calcium chloride
	Bentonite	Pozzolan	Lignosulfonates	CMHEC			
Density Decrease Increase	Z	X	X			Z	X
Water required Less More	Z	X	Z			Z	
Viscosity Decrease Increase	X	X	Z			X	X
Thickening time Accelerated Retarded	X	X	Z	Z		X	Z
Setting time Accelerated Retarded	X	X	Z	Z		X	Z
Early strength Decreased Increased	X	X	Z	Z		X	Z
Final Strength Decreased Increased	X	X	X	Z		Z	
Durability Decreased Increased	X	Z				X	
Water loss Decreased Increased	Z		X	Z		X	

X Denotes minor effect.

Z Denotes major effect and/or principal purpose for which used.
Carboxymethyl hydroxyethyl cellulose

Source: American Petroleum Institute (1959)

Pozzolans are another group of additives for Portland cement. These are materials that, although not cementitious in themselves, contain constituents that will combine with lime at ordinary temperatures in the presence of water to form stable insoluble compounds possessing cementitious properties. The natural pozzolans comprise volcanic tuffs, diatomaceous earths, zeolites, and hydrated oxides of aluminum. Synthetic pozzolanic materials, such as fly ash, may be used for as much as 50% replacement of cement. These materials can combine with hydrated lime and produce a durable and economical grout.

Injection of cement grout is feasible if the permeability of the deposit is higher than 5.0×10^{-4} cm/s. Water-to-cement ratios of 0.5:1 to 5:1 are commonly used in grouting. The lower the ratio, the less likely will be cement segregation and filtering, but injection will be more difficult. A variety of intrusion aids are available to facilitate cement grout injection (e.g., Ca-lignosulfonate, AM-9, sodium silicate). Extensive information on cement-based commercially developed solidification and grouting processes is reported in the literature; however, exact formulations are unavailable because such information is considered proprietary by the vendors.

3.1.2 Sodium silicate-based cement

Flexibility in the rate of setting and hardening of cement can be attained by the addition of sodium silicate. Portland cement mixes reportedly have strong bonding properties when combined with sodium silicate; strengths in excess of 7600 kPa (1100 psi) and set times of about 10 to 600 s are possible. Extremely short set times are useful

for cutoff of flowing water or water under pressure. A Portland cement-sodium silicate grout slurry can be injected more easily than Portland cement mixtures alone, because apparently the cement particles are lubricated by the silicate.

Sodium-silicate-based cement is gaining popularity for encapsulating radioactive liquid wastes generated at commercial power plants because of its ability to produce a quick set with no free water. It readily solidifies boric acid solutions from pressurized-water reactors which set poorly in cement alone. Sodium silicate also provides a significant reduction (about 30%) in the solidified volume of liquid wastes in comparison with cement without additives (Richardson 1976). Improvement was obtained in physical properties, shelf life, chemical tolerance, shipping efficiency, and amount of water remaining in the product. In addition, the estimated cost of silicate-base cement was less than that of conventional cement solidification for power plant liquid wastes (Heacock and Riches 1974).

3.1.3 Other cements

Although special cement formulations may have limited applications for in-situ treatment of low-level solid wastes, it is worthwhile to mention the following types, all of which may be applied in combination with Portland cement.

1. Slag cement from a blast furnace is an economical material with enhanced sulfate resistance.
2. Expanding cements are useful for filling large voids.
3. High-alumina cements with carborundum have high thermal conductivity.

4. Lumnite cements harden quickly and consist of a calcium aluminate variety which can be used for emergency plugging of leaks.
5. Air-entrained cement is lightweight.

3.2 Clay Minerals and Soil

Clay mineral and soil-water slurries are the cheapest materials available and have been used in grouting for decades (Greenwood and Raffle 1963). Clay grouts may be valuable in filling large voids which are expected in solid waste trenches and in encapsulating the waste. However, pure clay and soil grouts are difficult to inject, there is no cementing action, and the permeability reduction in the treated formation may be relatively small. Soil-cement grouts in which the volume of soil is four to six times the volume of loose cement have been commonly used for strength development (Mitchell 1970). Some of the most commonly used materials and those of potential use for waste disposal operation are described below.

3.2.1 Bentonite

Bentonite is a micaceous clay mineral belonging to the smectite mineral group. It occurs naturally in several parts of the country. The ion-exchange and specific sorption capacities of bentonite play a major role in retaining mobile radionuclides. The quality of bentonite used in grouting determines its injectability and effectiveness. Generally, a bentonite clay with high exchangeable sodium and high pH, coupled with minimal mineralogical impurities is ideally suited for admixing purposes in waste management. Large swelling capacity and

high fluidity make bentonite clay an ideal grout material (Jones 1963). Sodium-saturated bentonite has also been extensively used as a drilling mud (van Olphen 1963) and for improving the workability of cement (Bowen 1975).

Set times of bentonite grouts are not well defined, and the strength development is slow (Mitchell 1970). Undisturbed bentonite suspensions will gel thixotropically when at rest, but the process can be reversed by agitation. The sol-gel transformation may be repeated indefinitely. The compressive strength of the clay slurry can be improved by adding cement.

Chemical additives such as sodium silicate and deflocculating agents such as sodium polyphosphate are often used to facilitate bentonite dispersion, suspension, and penetration. Deflocculating agents or organic complexing chemicals are, of necessity, admixed with bentonite if the mix water has a high salt content or if the ground to be treated is highly saline. Bentonite clay admixed with patented deflocculating agents is commercially available (Clem 1976).

Cohesion of bentonite gel in the ground may possibly be increased by delaying its hydration. Relatively higher amounts of bentonite could possibly be injected in this manner by covering the clay with hydrophobic film or by heat treatment as mentioned earlier. Injection of bentonite clay slurry in shallow waste trenches to cover the bottom, sidewalls, and interstitial space between waste components may go a long way toward reducing the migration potential of radionuclides from the buried waste.

3.2.2 Other clay minerals

In addition to smectitic clays, several other clay minerals have been employed or hold promise for improving cement slurry characteristics or enhancing radionuclide retention of a grout mix. Attapulgite was found to resist flocculation and to permit a reduction of cement content in the mix (deLaguna et al. 1968). The role of clay minerals in radionuclide retention has already been described in Section 2.4.2.

3.2.3 Lime

Hydrated lime slurries have been used effectively for in-situ strength improvement in soils (Lundy and Greenfield 1968, Ingles and Neil 1970). As with Portland cement, lime reacts with clay minerals or other fine pozzolanic components such as hydrous silica in soils. The resulting product is a water-insoluble gel of calcium silicate.

Lime imparts alkalinity, which neutralizes acidic wastes and may be expected to increase the K_d values of radionuclides and thus reduce their migration potential. However, the large amount of soluble Ca in the lime-treated soil could well enhance radiostrontium migration. Fuller and Korte (1976) report that soils high in natural or admixed lime are highly effective in immobilizing trace elements such as cadmium and nickel.

3.3 Nonparticulate (Chemical) Grout Materials

Chemical grout systems include materials which are soluble in water and polymer resins which may or may not be soluble in water.

These fluids are highly versatile for penetrating and stabilizing soil formations; however, the treatment costs are among the most expensive.

3.3.1 Sodium silicate-base chemicals

Sodium silicate injections, one of the first chemical grout systems used, originated in Germany in the early 1920's. In-situ stabilization can be achieved by injecting sodium silicate and a gelling agent into the buried waste, causing the silicic acid gel to encapsulate the waste. Sodium silicate can be applied in a two-shot process in which the silicate is injected into one hole, and calcium chloride is then injected into a neighboring hole to obtain a flash reaction. In recent years, a single-shot injection (Malmberg process) consisting of the premixed silicate solution and gel control chemicals described below has been preferred. Sodium silicate is one of the least expensive chemical grout systems. It is nontoxic, and the alkalinity and high soluble sodium content imparted by sodium silicate is expected to enhance adsorption resulting in radionuclide immobilization.

Silicic acid-containing compounds, primarily sodium silicate, have found numerous applications for waterproofing and consolidation in geotechnical engineering. The chemical composition of syrupy sodium silicate used for grout applications is defined in terms of the weight ratio Na_2O to SiO_2 , the general formula is $\text{Na}_2\text{O} \cdot n\text{SiO}_2$ (8.9% Na_2O ; 28.7% SiO_2).

Diverse chemical compounds have been used to induce gelation of sodium silicate: soluble salts, acids, polyvalent cations, and organic

reagents. A flash set can be triggered by soluble salts of calcium, magnesium, barium, and zinc and by inorganic acids such as HCl or H_2SO_4 . Sodium bicarbonate, sodium aluminate, ammonium salts, and calcium hydroxide have been used to provide controllable gel time. Several proprietary chemicals have also been employed to improve gel-time control and to strengthen mechanical properties. These include hydrolyzable esters, aldehydes, amides, and acid chlorides (Caron 1967) and sequestering agents (Williams 1966). The polymerization of sodium silicate, which is initiated with the lowering of pH by these chemicals, is also affected by dilution and temperature. Water, sodium salts, reagents anions, and unpolymerized silicic acid are trapped within the gel structure upon polymerization.

Pure silica gel has a tendency to undergo syneresis during which time the gel expels free water and other soluble ingredients upon contraction. The stability of the silicic acid gel decreases with time, and its resistance to water erosion depends on the gelling agent used (Tallard and Caron 1977a). Susceptibility to leaching is inherent in the nature of silicic acid gel, which will eventually alter its waterproofing capabilities.

3.3.2 Acrylamide-base chemicals

The best known proprietary acrylamide-base gelling system, AM-9, has five components: the base materials, reactant, initiator (or catalyst), inhibitor, and water. The base material is a mixture of two organic monomers -- 95% acrylamide and 5% N-N-methylene bisacrylamide. Several reactants and mixtures of reactants may be used. The most

commonly used reactant is B -dimethyl aminopropionitrile (DMAPN) followed by the inhibitor, potassium ferricyanide (KF) which provides a means for delaying gelation predictably. Finally, a redox catalyst, usually ammonium persulfate (AP), is used as an initiator or catalyst for the reaction. An exothermic polymerization cross-linking reaction that produces an elastic gel product takes place abruptly as shown earlier in Fig. 3. Water is trapped between the cross links. Excellent field procedures and gel charts with different concentrations of chemical are provided in the manufacturer's manual (Fig. 6).

The AM-9 chemical grout is injected as a single-shot; its low viscosity (1.5 to 2.5 kPa•s) allows penetration into fine geologic formations. Also, the formation chemistry exerts little or no influence on gelation. Special precautions are necessary in the handling and use of the system because of its toxic components. It is a low-strength chemical grout and is one of the most expensive.

3.3.3 Lignin-base chemicals

Lignin, the major noncarbohydrate constituent of wood, has a complex chemical composition. Lignin sulfonate, light tan to dark-brown in color, is a waste residue produced during the production of cellulose from wood pulp by the sulfite process. The residue, which is not a well-defined product, is concentrated to a syrupy liquid or powder for use as a grout. It is marketed under the trade name 'Rayonier' in this country. Soluble lignin sulfonate is polymerized by oxidation with hexavalent chromium salt. Potassium or sodium dichromate is also added. An acid salt such as aluminum sulfate is

Fig. 6. Gel time versus temperatures of AM-9 grout.

used as an accelerator. Many hydroxyl or carboxyl groups of the lignite molecule show affinity for the silicate surface and are thus suitable for forming strong bonds with soil particles. Higher solid strengths of grouted mass are obtained in comparison with classical sodium silicate gels (Caron 1963).

Because hexavalent chromium is toxic, precautions must be taken while mixing it with lignin sulfonate. Chromium ions may leach and contaminate ground water unless precautions are taken to precipitate any soluble chromium ions.

3.3.4 Urea formaldehyde-base chemicals

Urea formaldehyde has been used for rock grouting; however, wider use is lacking due to its high viscosity. The solidifying material in the grout is a viscous, water soluble emulsion containing partially polymerized monohydroxy methyl urea and dihydroxy methyl urea. Solidification of the aqueous solution of urea formaldehyde can be achieved by a variety of acidic catalysts, most commonly a weak acid salt such as sodium bisulfate. Acids such as hydrochloric or acetic and other acidic materials such as aniline hydrochloride are also used. The pH of the mixture of waste and urea formaldehyde must be lowered to 2 or less for initiating polymerization, which indicates that a large amount of acid catalyst will be required for alkaline wastes to prevent premature polymerization. The cross-linking process starts within 5 min after the addition of the catalysts, and polymerization is usually complete in about 30 min.

A number of commercial nuclear power generating plants use the urea formaldehyde solidification process to encapsulate radioactive

liquid wastes and sludges, but its usefulness for shallow land burial has not been established. The urea formaldehyde ingredients are commercially available from several chemical suppliers under various trade names, including Cyanaloc, Casco resin, and Tiger Lock (Colombo and Neilson 1976). Urea formaldehyde grouts are strong enough to be suggested as a substitute for cement slurry. The effectiveness of urea formaldehyde can be enhanced by adding clay minerals, which will increase the retention capacity for predominant radionuclides present.

The resistance of urea formaldehyde polymer to most chemical attacks is good. The polymer, however, is decomposed by strong acid or alkalis (Colombo and Neilson 1976); it also exhibits susceptibility to biodegradation. In addition, radioactively contaminated water (0.5 to 1 vol %) is usually released after the polymerization reaction. Very little information is available on the long-term integrity of the polymer.

3.3.5 Phenolic-base chemicals

Phenolic gels are obtained by the polycondensation of phenol with an aldehyde. Acid catalysts usually are adopted to initiate condensation reactions at ambient temperature. Recently, resorcinol, (1:3 dehydroxy benzene), formaldehyde, and catalysts, which react in an alkaline medium, have been marketed for use as grouts (Tallard and Caron 1977a).

The choice of catalyst and the proportion used can affect considerably the speed of the reaction and also the properties of the final product. The viscosity is usually low (about 1.5 kPa•s) and

remains almost constant up to the point of setting. The raw materials used for these grouts are toxic and should be handled by experienced personnel.

3.3.6 Synthetic resin grouts

Synthetic resin grouts are nonaqueous materials which have not found extensive engineering applications because of their high viscosity and cost and because their long-term performance has not been verified. Some of these materials have been studied for encapsulation of radioactive wastes prior to burial. However, information on their usefulness for in-situ stabilization of shallow trenches is not available. Resin grouts are mostly two-component systems consisting of solutions of resin-forming chemicals that combine with a catalyst to form a tough plastic mass. Gel times can be adjusted by varying the amount of the hardening reactant, by adding or deleting filler material, and by controlling the temperature, especially the initial temperature. Resin grouts retain their initial viscosity throughout most of their fluid life and pass through a gel stage before hardening. A large amount of heat is generally given off by resins upon solidification and curing. Major synthetic resin grouts include epoxy, polyester, and polyurethane materials.

3.3.6.1 Epoxy resins. The most common epoxy resins are derived from the action of varying proportions of epichlorohydrin on bisphenol A 2,2-bis(4-hydroxyphenol) propane. These resins, which can be hardened by amines, polycarboxylic anhydrides, monocarboxylic acids, or a variety of other catalysts (Tallard and Caron 1977a), exhibit the

following characteristics: (1) resistance to acids, alkalies, and organic chemicals; (2) curing without volatile by-products; (3) curing without the application of external heat; (4) acceptance of various thickening agents such as bentonite; and (5) ability to combine with various fillers to obtain desired properties in both hardened and unhardened states.

3.3.6.2 Polyester resins. A variety of polyester resins are commercially available for solidification purposes. They are obtained by combining a polyacid (mostly an unsaturated diacid such as maleic or fumaric) with a polyalcohol. Polymerization is obtained through the addition of catalyst (peroxide type) and a promoter that accelerates the decomposition of the peroxide into free radicals. As high as 10% shrinkage may occur upon hardening in some polyester resins.

Compressive strengths in excess of 90,000 kPa (13,000 psi) have been attained with these resins. The rate of curing is influenced by resin volume, ambient temperature, and heat dissipation. The long-term behavior of polyester resins can be considered good if sheltered from ultraviolet rays. More details on the properties and behavior of polyester resins are available in the literature (Tallard and Caron 1977a).

3.3.6.3 Polyurethane resins. A polyurethane material results from the polymerization reaction of an isocyanate and a compound containing hydroxyl groups, such as polyalcohol. The isocyanate radical also reacts directly with water, releasing CO_2 and leading to a cellular structure such as

Setting time can be shortened by the use of an amine or prolonged by the use of an acid.

Vinson and Mitchell (1972) developed polyurethane-foam plastics that form in the soil after their injection. The technique proved successful in the laboratory for both dry and saturated sands. The system yielded foam densities of 0.4 to 0.8 g/cm³ in the soil pores, effectively making a medium-grained sand impermeable. Compressive strengths of samples of treated material were well in excess of 700 kPa (100 psi). These investigators claim that the cost of materials for this polyurethane grout system is comparable to that of other chemical grout systems. Similar development of a polyurethane-foam grout using proprietary liquids has been recently reported for plugging boreholes (Black 1977).

4. ECONOMIC CONSIDERATIONS

A sizable initial outlay is required merely to evaluate the radionuclide inventory and transport mechanisms from leaky trenches and to collect necessary geohydrologic data at a given disposal site. Although the necessity of long-term isolation of radioactively contaminated wastes suggests the utilization of cement-base particulate grouts, some of the nonparticulate grouts like sodium silicate-base gels hold promise for emergency situations.

The relative cost of commonly employed grout systems indicates the high cost of chemical grouts in comparison with the cost of a cement-based grout (Table 6). Cost estimates for in-situ stabilization are optimally determined by experience and include the cost of materials, labor, equipment rental, drilling, radiation safety measures, and decontamination of equipment. Most cost comparisons for grouting are based on cubic meters of soil or waste grouted. A recent estimate for in-place cost of soil grouting with cement was \$20 to \$50 per cubic meter (Herndon and Lenahan 1976). This translates to a cost estimate of \$2700 to \$6500 for grouting an average-size trench of 15 x 3 x 3 m (SWDA 6 at ORNL) but does not include the cost of site investigations and other incidental costs outlined above.

The cost escalation due to radiation safety measures is not available but may not be excessive in view of the fact that most of the grout contractors are well aware of the hazards involved in the injection of toxic compounds used in chemical grouting and train their field personnel accordingly. In addition, radiochemical analyses of

Table 6. Cost comparisons of various chemical grouts in relation to the cost of Portland cement grout

Type of grout	Basic cost (in relative dollars)
Portland cement	1.0
Silicate base (15% sodium silicate)	1.3
Lignin base	1.65
Silicate base (30% sodium silicate)	2.2
Silicate base (40% sodium silicate)	2.9
Urea formaldehyde resin	6.0
Acrylamide (AM-9)	7.0

Source: Herndon and Lenahan (1976)

trench water samples at ORNL indicate that exposure from gamma emitters is not a serious hazard. Most of the hazards are associated with potential equipment failure during the pumping out and injection process and the possibility of rupturing the overburden shale during injection. These hazards are common in all such operations and do not seem very serious because the field personnel are experienced in coping with such hazards. Nonetheless, a backup system for pumping, monitoring by health physics personnel, and the training of field operators on the risks involved in working with contaminated materials would undoubtedly raise the cost of in-situ encapsulation of these trenches. A more realistic rough estimate for the treatment of an average trench, without allowance for site investigations and laboratory costs for grout mix development and post-treatment evaluation, may be placed at \$15,000 to \$20,000.

Potential economic liabilities as a result of radionuclide transport from leaking solid waste trenches cannot be reliably estimated. In-situ encapsulation of these wastes seems to provide a safe alternative to minimize or prevent radionuclide releases to the environment at a reasonable cost. However, feasibility studies in the field are required to establish the effectiveness of the method.

5. SUMMARY AND CONCLUSIONS

Shallow land disposal of low-level radioactively contaminated solid wastes will probably be necessary for the foreseeable future. Development of corrective methodology for existing trenches with known or anticipated seeps is needed. These corrective measures must be very stringent to allay public concern about the nuclear industry as a whole and waste management practices in particular. A reliable and lasting treatment is essential because of the long time required for some radionuclides in the waste to become innocuous.

Grouting technology has potential applications in low-level solid wastes management. Grouting has been successfully employed for quick water shut-off, increasing strength, and imparting consolidation in varied civil engineering projects. Numerous treatment materials such as cement, clays, and several gelling fluids are currently available to immobilize the radionuclides in leachate solution and to encapsulate solid wastes. Geohydrologic data from the field site and the laboratory development of a suitable grout mix are required for successful field application of the treatment. Incorporation of specific radionuclide sorbents in combination with selected encapsulating agents should further minimize the risk of radionuclide releases to the environment.

Although a variety of chemical and synthetic resin grout systems used in the construction industry may have applications for in-situ stabilization of buried solid wastes, their high cost and unknown longevity restrict their use to emergency situations.

Cement-bentonite-based grouting, however, appears to be an economically feasible method of in-situ encapsulation of solid waste trenches (costing about \$113 per cubic meter of waste grouted); however, extensive field implementation requires further evaluation in pilot studies.

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