SENSITIVITY ANALYSIS OF THE LONG-TERM PERFORMANCE OF THE GROUT SYSTEM FOR THE DISPOSAL OF A LOW-LEVEL RADIOACTIVE WASTE STREAM AT HANFORD

D. G. Huizenga, W. T. Farris, R. L. Treat, A. H. McMakin
Pacific Northwest Laboratory
Richland, WA 99352

ABSTRACT

The U.S. Department of Energy is planning to design and construct a Transportable Grout Facility at the Hanford Site near Richland, Washington. The facility will combine grout-forming materials with low-level liquid radioactive wastes to produce solidified grout monoliths for near-surface disposal. Pacific Northwest Laboratory is conducting studies to verify that the process is workable and that the waste, as disposed of in grout, will provide long-term protection for people and the environment. The long-term performance of the grout disposal system is sensitive to several parameters that affect radionuclide release and transport (e.g., local climate, leach rate, and monolith integrity). The purpose of this analysis was to investigate variations in these parameters in order to evaluate several design options for the grout system, including the proposed design for the grout startup campaign. The analysis was performed by postulating several scenarios that included conditions that could potentially compromise the effectiveness of the grout system. The grout system's performance was then evaluated, under each set of conditions, to measure its ability to reduce the transport rate of contaminants to the biosphere.

INTRODUCTION

The U.S. Department of Energy and Rockwell Hanford Operations are planning to construct a Transportable Grout Facility (TGF) for use in disposing of liquid low-level radioactive waste (LLW). Oak Ridge National Laboratory and Pacific Northwest Laboratory are providing technical support for this project. The TGF is located near the geographical center of the 1475-km^2 Hanford Site in south-central Washington State. The disposal site will be located adjacent to the existing 200-East Area facilities that are currently used for waste processing and radioactive waste storage. The 200-East Area is an elevated plateau approximately 11 km west of the Columbia River and 45 km north of the nearest population center.

The TGF will immobilize thousands of cubic meters of LLW by solidifying the waste in cementitious grout. In this application, grout is a mixture of liquid wastes and grout-forming solids that include portland cement, fly ash, and clays. The TGF will convert the wastes to a grout slurry that will be pumped to near-surface disposal sites where it will subsequently harden into a solid matrix that immobilizes the contaminants. A protective overburden of soil or layers of soil and rocks will be placed over the hardened grout to further isolate the waste from the biosphere. Previous assessments of the operational characteristics of grout have shown that operational criteria such as grout rheology, angle of flow, compressive strength, maximum permissible temperature, and the minimization of development of free-standing liquid can be met.[1]

A variety of LLW streams have been identified as candidates for disposal in grout. A LLW generated at the Hanford Site "N Reactor" has been selected as the startup feedstream for grouting operations, which are scheduled to begin in late 1987. This initial grout feedstream contains two separate wastes in approximately equal proportions and is referred to as 50/50 Hanford Facilities Waste (50/50 HFW).

The primary purpose of this paper is to present the results of a sensitivity analysis that was used to evaluate the long-term performance of the 50/50 HFW grout disposal system over a wide range of simulated performance levels. The secondary purpose is to compare the results to applicable regulatory limits. The results of such an investigation may be used in the cost-effective design of the grout-disposal system. The grout disposal system was defined as the solidified monoliths, a layer of overburden, and characteristics inherent to the disposal site (e.g., the physical properties of the surrounding soil and depth of the soil to the unconfined aquifer).

To accomplish the sensitivity analysis, several hypothetical design options were investigated in terms of their abilities to provide long-term protection for people and the environment. A number of scenarios were postulated describing events that could lead to a reduction in the effectiveness of the grout disposal system. The impacts of each scenario were evaluated, and a relative comparison of performance was made based on the estimated measure of containment of certain radioactive and nonradioactive waste species. Figure 1 pictorially represents the grout disposal system and the contaminant transport pathways that were investigated, including the depiction of hypothetical future human activities at both onsite and offsite locations.

Description of Reference Waste Stream

The 50/50 HFW feedstream will be comprised of approximately equal volumes of two LLW streams. One stream, referred to as phosphate waste, is produced during periodic reactor decontamination campaigns using a commercial decontamination agent that contains phosphoric acid, citric acid, and other chemicals. The resulting waste, after treatment, is essentially a weak solution of trisodium phosphate. The other stream, referred to as sulfate waste, is produced during periodic regeneration of ion exchange resins that are used to remove radionuclides from the water in the spent fuel storage basins. Sulfuric acid is used to regenerate the cation exchange resin and sodium hydroxide is used to regenerate the anion exchange resin. Extensive rinsing of the resins produces a dilute sodium sulfate waste solution. Both sulfate and phosphate wastes are adjusted,

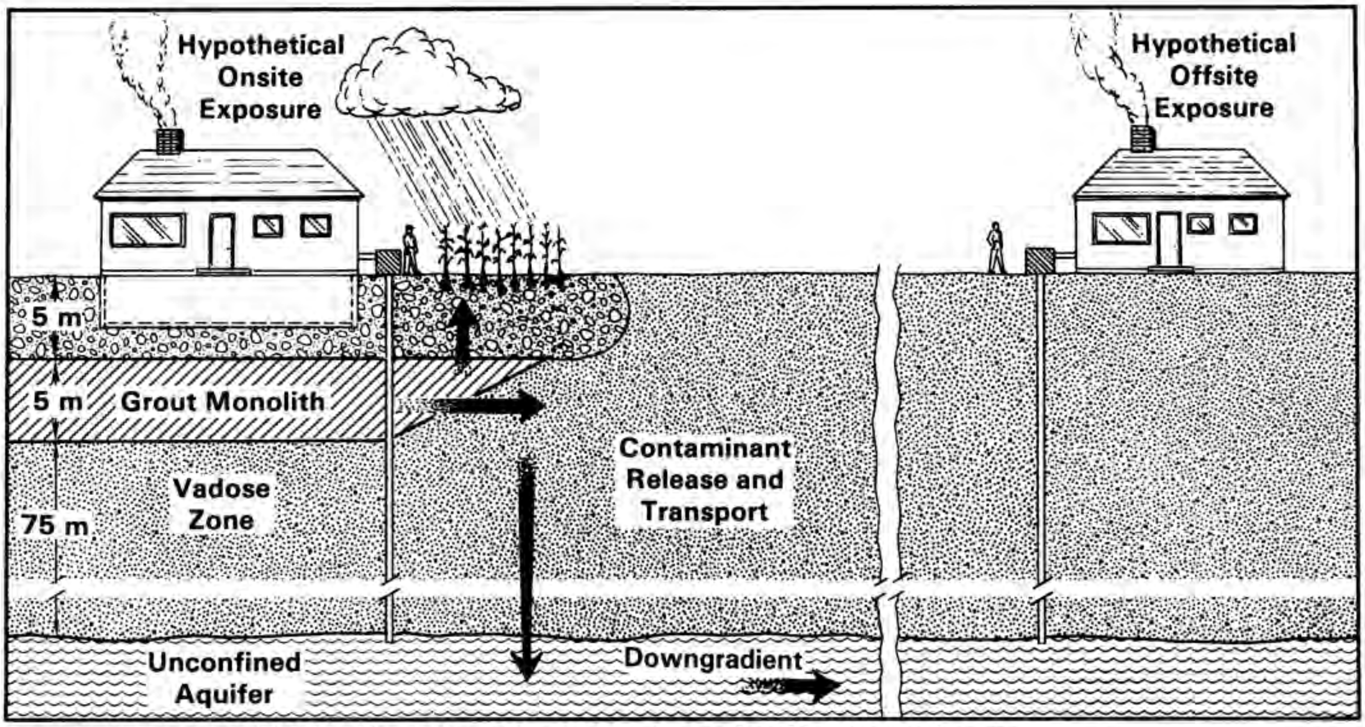


Fig. 1. Grout disposal system and associated hypothetical human exposure pathways that were analyzed.

according to tank-farm specifications, to a pH of 12 and a nitrite ion concentration of 0.011 molar. They are combined in a staging tank to be homogenized prior to disposal as grout.

The startup 50/50 HFW campaign will dispose of ~7.6 x 10^3 m^3 of 50/50 HFW liquid waste, resulting in the formation of two grout monoliths, each containing ~4.9 x 10^3 m^3 of grout. The primary radionuclides present in 50/50 HFW that contribute to long-term risk are cobalt-60, strontium-90, iodine-129, cesium-137, and plutonium-239. Because of its environmental mobility, transport of the nonradioactive nitrite ion, NO_2^-, was also investigated. Table I presents the expected concentrations of contaminants in the 50/50 HFW startup campaign. These concentrations were used as the source term for this analysis. The total transuranic (TRU) content is 0.06 nCi TRU waste per gram of grout.

TABLE I

Source Term For Grouted 50/50 Hanford Facilities Waste

Radionuclide or Chemical	Total Inventory	Concentration
^{60}Co	5.7 x 10^2 Ci	5.8 x 10^{-2} Ci/m^3
^{90}Sr	1.1 x 10^2 Ci	1.1 x 10^{-2} Ci/m^3
^{129}I	2.3 x 10^{-7} Ci	2.3 x 10^{-11} Ci/m^3
^{137}Cs	1.6 x 10^2 Ci	1.6 x 10^{-2} Ci/m^3
^{239}Pu	7.6 x 10^{-1} Ci	7.7 x 10^{-5} Ci/m^3
NO_2^-	3.9 x 10^9 mg	4.0 x 10^5 mg/m^3

DESCRIPTION OF SCENARIOS AND PARAMETERS

The long-term performance of the grout disposal system is measured in terms of its ability to mitigate the impacts of postulated natural and human-induced events that might compromise the effectiveness of the system. Several scenarios based on these events were formulated to evaluate the sensitivity of the 50/50 HFW grout disposal system to variations in selected parameters that could impact performance.

The scenarios fall into two major classes: one that measures potential offsite contamination of the unconfined aquifer, and five that estimate the onsite radiation impacts associated with hypothetical human activities that occur directly over the grout disposal site. The offsite impacts were simulated as they would occur from use of a domestic water well located downgradient of the grout disposal site. The choice of an offsite location is somewhat arbitrary, as the steady-state groundwater contamination levels change relatively little from the point of contaminant entry into the groundwater until the point of entry into the river. For the purposes of this analysis, the offsite location was chosen to be 5 km from the grout disposal site. The onsite scenarios take place at the grout disposal site assuming the absence of active and passive institutional control. Five onsite scenarios were postulated that lead to direct or indirect contact with the grout waste form. The following sections describe the scenarios and their associated parameters.

Offsite Scenario

The analysis of the offsite impacts was based on a scenario in which radionuclides and nitrites that were leached from the grout monoliths migrated through the vadose (unsaturated) zone to the unconfined aquifer and ultimately to the domestic well (Fig. 1). For this scenario, the sole pathway for exposure was through ingestion of the contaminated well water. An individual was assumed to consume 2 liters of water per day. The effects of varying the values of four different parameters were evaluated to establish the offsite performance of the grout disposal system. The four parameters evaluated were:

- groundwater recharge rate
- release mechanism
- monolith integrity
- moisture barrier performance

The following paragraphs describe the parameters in detail, including the major assumptions and parameter values.

Groundwater Recharge Rate

The first parameter evaluated was groundwater recharge rate. The climate of the site, soil characteristics, and vegetation affect the rate at which meteoric water percolates through the vadose zone (recharges the aquifer) and carries contaminants to the unconfined aquifer. To quantify the effect of the groundwater recharge rate on the performance of the grout disposal system, two average annual recharge rates were analyzed. Values of 0.5 and 5.0 cm/yr were chosen to bridge expected recharge rates under drier and wetter conditions at the disposal site. The lower end of this range is thought to represent recharge rates typical of present day drier climatic conditions (15 cm/yr precipitation) and the upper end is representative of a hypothetical wetter climate (30 cm/yr precipitation).[2]

Release Mechanisms

Mechanisms that immobilize wastes in grout include chemical precipitation, adsorption, mineralogic reaction, and simple physical encapsulation in the grout pores. Because these mechanisms are not completely effective and may diminish in effectiveness over time, contaminants will eventually migrate to the surface of the grout monolith where they could be released to the surrounding soil. Several models have been postulated for the release of contaminants from cementitious waste forms such as grout.[3,4,5] Two of these models were applied in this study. One, a constant-release model, was selected to provide a release rate that was independent of time. In contrast, the semi-infinite plane, diffusion-controlled release model was selected to represent a release rate that decreases with time. This model is thought by many researchers to most realistically predict the contaminant release rate from cementitious waste forms.[3,4] In preliminary laboratory leaching tests conducted at PNL in support of this investigation, the nitrite ion had the highest rate of release from simulated 50/50 HFW grout relative to other contaminants known to be present in 50/50 HFW grout. Thus, as a conservative approach, it was assumed that all radionuclides were released congruently with the nitrite ion.

For the constant-release model, it was assumed that the monolith releases a contaminant at a rate that is constant with time until the monolith is totally depleted of that contaminant. Based on preliminary PNL leach studies, a constant leach rate of 1×10^{-6} g/cm²·day was used for all contaminants in this analysis. The mathematical equation governing this release is[5]:

$$FR = \frac{L \cdot A \cdot t}{m} \qquad (1)$$

where:

FR = fraction released
L = leach rate, g/cm²·day
A = surface area, cm²
t = time, day
m = mass, g

In contrast, the semi-infinite plane diffusion model yields a release rate that diminishes as a function of time. This model is routinely used in transport analyses to describe the release from cementitious waste forms and is supported by the American Nuclear Society. The equation that describes this type of release rate is[6]:

$$FR = 2 \frac{A}{V} \left(\frac{D_e t}{\pi} \right)^{\frac{1}{2}} \qquad (2)$$

where:

FR = fraction released
A = surface area, cm²
V = volume, cm³
D_e = effective diffusion coefficient, cm²/sec
t = time, sec

In this study, an effective diffusion coefficient of 2×10^{-10} cm²/sec was used, based on preliminary NO_2^- release data that PNL generated in support of this analysis.

A third type of release model was used when simulating the complete structural failure of the grout monolith; at which time the grout is assumed to behave like soil. In this case, the contamination release rate would be solely a function of sorption characteristics and would be independent of a surface-area-to-volume ratio. Release and transport under these conditions were investigated as a worst case and are described in the next section under the assumptions corresponding to a disintegrated monolith.

Monolith Integrity

Because release rates that are determined by both the constant-leach model and the semi-infinite plane diffusion-release model are a direct function of surface area, the ability of the grout monolith to resist fracturing greatly affects the rate at which the grout releases contaminants to the surrounding soil. To gauge the sensitivity of the grout system to changes in surface area, three different forms of monolith integrity were studied: a disintegrated monolith, a partially fractured monolith, and an unfractured monolith (Fig. 2).

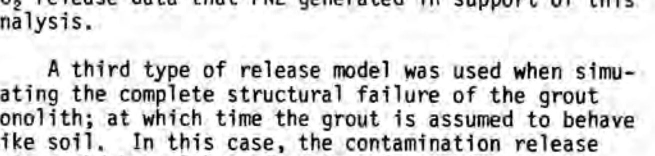


Fig. 2. Monolith integrity.

As mentioned above, a disintegrated monolith was modeled as an extreme case in which the grout matrix was given no credit for immobilizing the waste. In this case, the grout monolith was modeled as having the physical properties of soil. The release of the contaminants was assumed to be governed by the species' sorption properties coincident with Hanford soil. Contaminant transport rates were defined in terms of the species' distribution coefficient value, K_d. The K_ds used were 0, 0.6, 0, 26, 20, and 0 mL/g for cobalt-60, strontium-90, iodine-129, cesium-137, plutonium-239, and nitrite, respectively.[7] The combination of a disintegrated monolith with sorption-controlled release represents the extreme situation (worst case) and was evaluated to provide a highest bound of release rate.

In the second form of monolith integrity, the monolith was assumed to fracture from forces resulting from thermal expansion, lithostatic pressure, and subsidence. The monolith was postulated to crack into cubes whose sizes were determined by the thickness of the monolith at each cube's location and by stresses calculated to occur within the grout monolith. This method yielded cubes ranging from 1.4 to 500 cm on a side. This resulted in a range of surface-area-to-volume ratios of 4.3 to 0.012 cm^{-1} for 1.4- and 500-cm cubes, respectively. Each cube was assumed to release its contaminants at a constant rate in one case and at a diffusion-controlled release rate in another.

In the final monolith-integrity case, the monolith was assumed to remain as a whole without any fracturing. This monolith was assumed to have a surface-area-to-volume of 0.0076 cm^{-1} based on preliminary monolith design specifications. Both the constant- and diffusion-release models were applied in this case as well.

Moisture Barrier Performance

The rate of contaminant transport to the unconfined aquifer could be greatly reduced by the presence of a surface barrier which would, by design, prevent percolating recharge water from directly contacting the grout monolith. Although a moisture barrier is not thought to be necessary for the safe disposal of 50/50 HFW, and it is not included in the current design, an investigation of moisture-barrier performance was included for the purposes of conducting a thorough sensitivity analysis.

A conceptual moisture barrier has been proposed and may be composed of a soil layer directly over the monoliths, followed by a layer of basalt riprap and another layer of soil.[8] This top soil layer would be seeded with shallow-rooted indigenous plants to enhance evapotranspiration (Fig. 3). Although such a barrier has not been tested, it is assumed that a fully functional barrier prevents surface water penetration. Because this assumption rules out percolating surface water from directly contacting the grout, contaminant release is governed by the rate at which contaminants diffuse away from the monolith to the edge of the barrier, where they eventually come in contact with water percolating to the unconfined aquifer. Based on the diffusion rate of the nitrite ion, transport from the monolith to the edge of the barrier (10-m distance) is estimated to require ∿5000 years.

Two hypothetical failure conditions of the moisture barrier were modeled, representing, in one case, barrier disruption as a result of human activities and, in the second case, simply a partially ineffective barrier (see Fig. 3). First, in the case of a disruptive-barrier failure, a hole (or holes) was postulated to occur in some part of the barrier 500 years after disposal. As a result of postulated funneling effects, precipitation was assumed to pass through this hole(s) at an enhanced infiltration rate of 5.0 cm/yr, while the recharge rate adjacent to the disposal site remained at 0.5 cm/yr. In this failure case, 10% of the grout monolith was modeled as being exposed to direct leaching by the constant- and diffusion-release models.

The second failure condition is referred to as a functional barrier failure. The barrier was assumed to fail, soon after disposal, from wind erosion, seismic activity, or poor barrier construction. The moisture barrier was assumed to fail such that 50% of the waste was leached at an infiltration rate of 0.1 cm/yr beneath the barrier. As with the disruptive barrier-failure case, the climatic recharge rate adjacent to the site was assumed to be 0.5 cm/yr.

For the final barrier condition, no moisture barrier was assumed to be present. Instead, 5 m of Hanford soil were assumed to be placed over the grout monoliths for final closure. (This is consistent with the reference depth of overburden for the design of the 50/50 HFW disposal system.) Two recharge rates were modeled for this case (0.5 cm/yr and 5.0 cm/yr), simulating both climatic conditions.

Onsite Scenarios

The analysis of the onsite impacts was based on five scenarios that involve hypothetical human intrusion onto the 50/50 HFW grout disposal site. Intrusion was postulated to occur at various future times in the absence of active institutional control at the Hanford Site. Although 50/50 HFW grout is a LLW disposal system, in keeping with the spirit of Environmental Protection Agency (EPA) guidance that calls for no reliance on active institutional controls for more than 100 years after disposal of high-level or transuranic wastes, control of the grout site was assumed to be absent 100 years following disposal.[9]

Government control of the Hanford Site is planned to continue indefinitely; as long as it does continue, these scenarios and the associated impacts are not

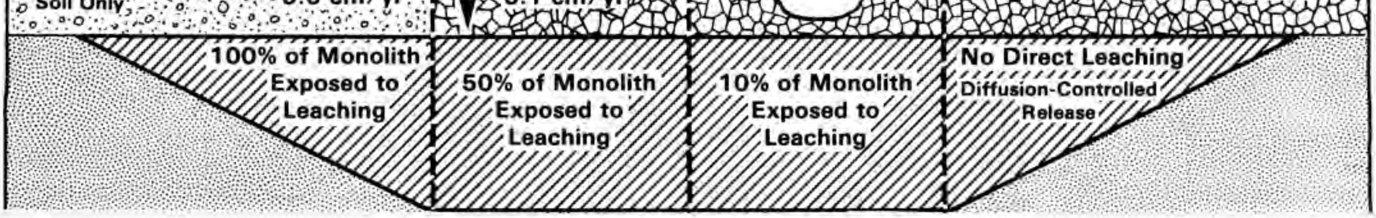


Fig. 3. Assumptions corresponding to simulation of moisture barrier performance.

reasonable. However, in keeping with the overall purpose of conducting a sensitivity analysis, the results of intruder activities are deterministically presented and no attempt was made to estimate the probability of when, or even if, an event might actually occur. Evaluation of the five postulated intruder scenarios can therefore most accurately be viewed as providing information that would be useful when conducting a cost-benefit analysis regarding the depth of overburden necessary to ensure that public health and safety is provided for and that regulatory requirements are satisfied.

The scenarios evaluated in this report parallel those developed in support of National Environmental Policy Act (NEPA) documentation that provides evaluation of several options for shallow-land disposal of low-level radioactive wastes.[10] The five scenarios evaluated were based on the following activities:

- home gardening
- well drilling
- post-drilling habitation
- shallow excavation
- post-excavation habitation.

The goal of the onsite analyses was to determine how radiological impacts varied in response to various assumed depths of soil overburden that could be placed over the 50/50 HFW grout disposal site. To accomplish this, the five scenarios were evaluated assuming three different depths of overburden. In addition to analyzing the current design depth for the 50/50 HFW disposal system (5 m of soil), a depth of 2 m and a depth greater than or equal to 15 m were also analyzed. An overburden depth of 2 m represents a soil cover depth consistent with that recommended for other types of LLW disposal sites at Hanford, while a disposal depth greater than 15 m was assumed to sufficiently preclude most heavy construction activities.[10]

The following paragraphs describe the five hypothetical intruder scenarios in detail, including the major assumptions and parameter values that differentiate one from another.

Home Gardening

In the absence of active institutional control and where passive controls such as warning markers and public records are absent or ignored, it is conceivable that people could eventually reside over the grout disposal site. In the home gardening scenario, people were postulated to grow crops over the grout monoliths for either domestic or animal consumption. The roots of these crops were assumed to penetrate into the grout, resulting in contamination of human and animal food supplies. In addition to the ingestion pathway, it was assumed that the residents were exposed to external radiation from the buried monolith. (Direct human contact with the waste form, e.g., via basement construction activities, was analyzed in other scenarios.)

In this scenario, the quantity of root mass contacting the waste was assumed to be a function of the depth of overburden. With less overburden, more roots would be in contact with the waste and more radionuclides would be subsequently transported to the surface. The percentages of roots assumed to contact the waste were 10, 1, and 0% for soil overburdens of 2, 5, and 15 m, respectively.[11] In other words, with a 2-m overburden, 10% of a given plant's roots were assumed to penetrate to the monolith, but only 1% reach the monolith that has a 5-m overburden. None of the roots penetrate to the monolith that has a 15-m overburden. The maximum annual total-body radiation dose to an individual over a 50-year period of settlement was estimated.

Well Drilling

Drilling, either for water wells or for mineral exploration, is a potential mechanism for inadvertently bringing buried grout directly to the earth's surface. In this scenario, it was assumed that the drill rig was assembled over a grout monolith and that a 0.3-m-diameter drill hole penetrated through 5 m of grout. (The reference design thickness of the HFW grout monolith is 5 m.) Drilling through the waste form itself was assumed to take 1 hour. During this time, the driller was assumed to breathe suspended contaminated dust with a mass loading of 1×10^{-4} g/m^3 of air.[12]

In this scenario, the drilling activities resulted in 0.35 m^3 of grout being brought to the surface where it was mixed with nonradioactive surrounding soil. The exhumed grout was mixed with soil and evenly distributed over a 100-m^2 plot of land to a depth of 0.15 m. The driller was assumed to spend 40 hours working in the immediate vicinity of the exhumed waste. An annual total-body radiation dose to a member of the drill crew was calculated for this scenario.

Post-Drilling Habitation

In this scenario, the distribution of radionuclides in surface soils, caused by drilling activities, created a source of radiation exposure to people living on or near the disturbed site. The same volume of grout that was brought to the surface in the drilling scenario was postulated to be evenly distributed onto a 2500-m^2 plot of land to a depth of 0.15 m. People living in the contaminated environment were assumed to be exposed to direct radiation from the redistributed drill tailings, as well as from inhalation of airborne contamination and ingestion of contaminated garden and animal products.

Twenty-five percent of the individual's diet was assumed to come from garden products grown in contaminated soil. The individual was assumed to spend 2000 hr/yr outside, exposed to dust and surface contamination. A mass loading factor of 1×10^{-4} g/m^3 was used for suspension of contaminated dust into the air. As in the home-gardening scenario, the maximum annual total-body radiation dose to an individual over a 50-year period of settlement was estimated.

Shallow Excavation

The shallow excavation scenario was postulated to occur in conjunction with activities associated with the construction of a home. These activities might include emplacement of water mains, sewage lines and the digging of a basement. These excavations are typically confined to the top few meters of soil, with a typical depth associated with basement construction of about 3.5 m.[13] For conservatism, the shallow excavation scenario assumed a maximum excavation depth of 5 m.

The workers excavating into a HFW monolith were considered to be surrounded by contaminated material and consequently exposed to external radiation and contaminated dust. The excavator was assumed to be directly exposed to the grouted waste. The individual was assumed to work in the area for 80 hours breathing contaminated dust that was suspended at a mass loading of 1×10^{-2} g/m^3 of air for the 2-m case and 1×10^{-4} g/m^3 for the 5-m case. An annual total-body radiation dose was calculated for a member of the excavation crew.

Post-Excavation Habitation

The post-excavation scenario follows directly from the excavation activities described above. People were postulated to live in a home constructed over the site and to consume food from a small garden that was grown in contaminated soil. The scenario is similar to the home-gardening scenario and to the post-drilling habitation scenario, but in this case more contaminated material is mixed with the surrounding soil.

For the case of a 5-m excavation into grout buried 2 m deep, 60% of the excavated material was assumed to be waste. The resident was assumed to spend 2000 hr/yr outside exposed to contaminated suspended dust and soil and to obtain 25% of his or her annual vegetable intake from the contaminated garden. Because this scenario's activities were not considered reasonable at disposal depths greater than or equal to 5 m of soil overburden, no impacts would be expected for the 5- and 15-m depths of overburden. As in the other habitation scenarios, a maximum annual total-body dose to an individual was calculated for a 50-year period of continuous residence.

RESULTS AND ANALYSIS

Various calculational computer codes were applied in this sensitivity analysis to calculate radiation doses and contamination levels in the groundwater. The Variable Thickness Transient Groundwater Flow Model was used to estimate the movement of contaminants from the disposal site to offsite locations.[14] The radiation dose evaluation codes DITTY and ONSITE/MAXI1 were used to assess the offsite and onsite radiological impacts, respectively.[15,16]

Offsite Impacts

The effects of release mechanisms and monolith integrity on the rate of release of contaminants from grout are depicted in Figs. 4 and 5. (Figure 5 is an enlargement of a portion of Fig. 4.) For the totally disintegrated monolith, the rate of release is essentially instantaneous; therefore, its release curve falls on the vertical axis in both figures. In order to determine the concentrations of radionuclides in the groundwater, the release rates shown in Fig. 4 were analyzed under the two recharge rate conditions (0.5 and 5.0 cm/yr).[6] This analysis identified iodine-129 as the only radionuclide that would migrate to the 5-km well, due to its long half-life and mobility in the groundwater. Figure 6 shows the iodine-129 activity simulated to be present in groundwater at the 5-km well as a function of time. The peaks of the curves represent points of maximum activity. These points serve as bases for calculating dose to man from ingestion of contaminated well water. Table II shows the maximum doses to critical organs under all parameter conditions, and gives the corresponding time after disposal at which the maximum doses occur. These results are compared in the following sections to show the sensitivity of the grout disposal system under various parameter settings.

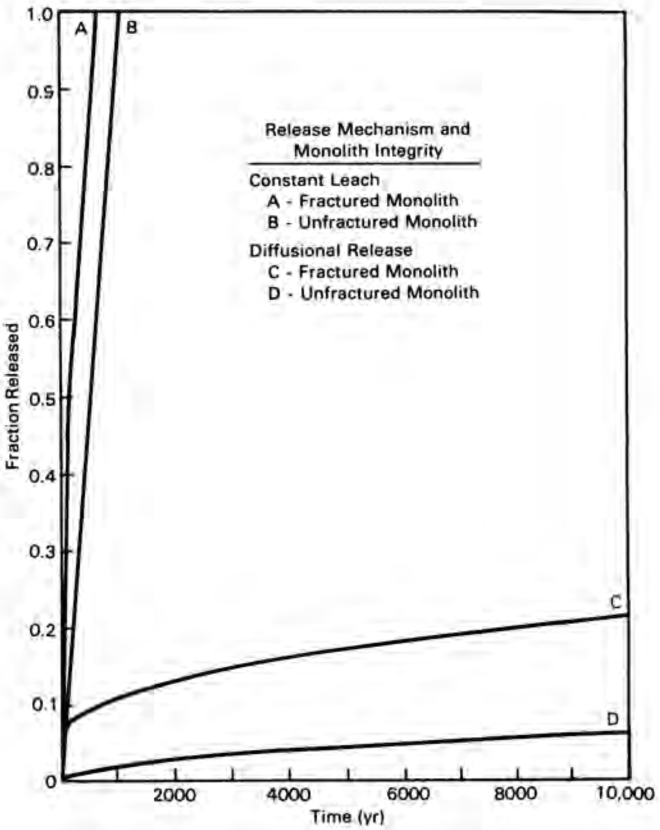
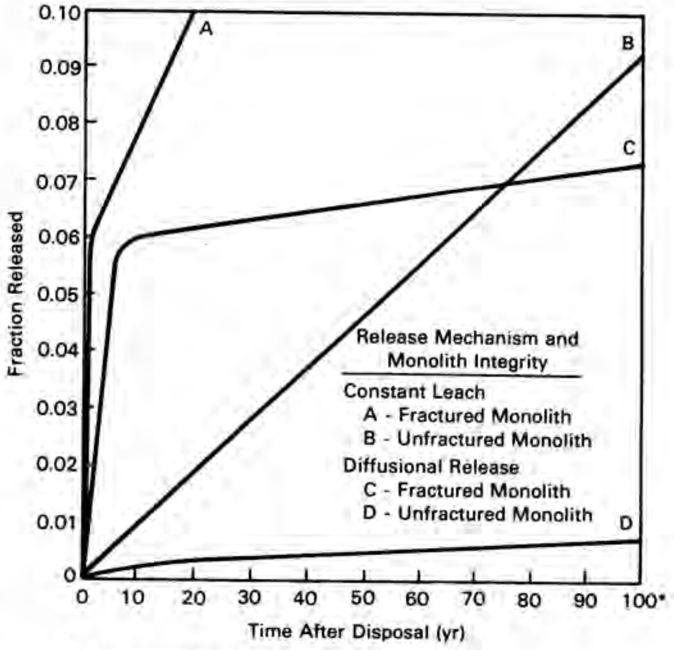


Fig. 4. Estimated contaminant release rates for grouted 50/50 Hanford Facilities Waste.

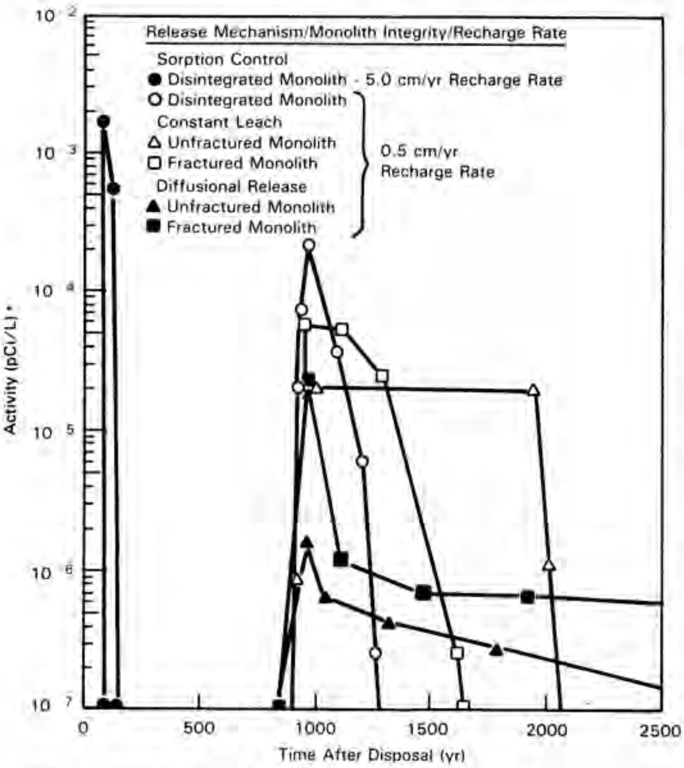


*Note expanded scale relative to Figure 4

Fig. 5. Estimated contaminant release rates for grouted 50/50 Hanford Facilities Waste (to 100 years).

Release Mechanisms

The grout system's response to the mode of release can be seen by comparing the no-barrier/unfractured-monolith cases under the conditions of both constant and diffusional release in Table II. By comparing these two cases, the effects of barrier performance, monolith integrity, and recharge rate are eliminated. This comparison shows that doses calculated using the constant-release model are as much as 14 times higher than doses calculated using the diffusion-release



*For comparison purposes, the maximum permissible concentration of iodine-129 in public drinking water is 1 pCi/L as per EPA-570/9-76-003

Fig. 6. Estimated groundwater concentration of iodine-129 at a hypothetical well located 5 km downgradient from the grout disposal site for 50/50 Hanford Facilities Waste.

model. However, there is little difference between the two cases regarding the time at which the maximum doses occur.

Monolith Integrity

The sensitivity of the system to the integrity of the monolith can be seen by comparing the no-barrier/constant-release case and the three monolith integrity types. The same comparison can be made with the no-barrier/diffusion-release case and the three types of monolith integrity. Recall that the disintegrated case is governed only by the sorptive properties of soil. This comparison shows that the fractured monolith yields doses approximately 2 to 16 times higher than those of an unfractured monolith, while the disintegrated case yields doses 7 to 120 times higher than in the unfractured case. The time of maximum dose is similar in all cases.

Moisture Barrier Performance

System sensitivity to barrier performance is most evident when comparing the disintegrated/sorption-release case under the four barrier-performance conditions. Here the doses increase 3000 times from the fully functional barrier case to the no-barrier case. The time after disposal at which the maximum doses occur ranges from 300 years for the disruptive barrier failure case to 5100 years for the fully functional barrier case. The times of maximum dose for the functional barrier failure and the no-barrier cases are 4400 and 1100 years, respectively. These widely different times of maximum dose are indicative of the effectiveness of the barrier to alter the rate of travel of contaminants in the vadose zone. Once the contaminants reach the aquifer, their travel times are essentially the same. It is interesting to note that when the barrier is fully functional, the doses are totally insensitive to monolith integrity and release mechanism. This is due to the fact that diffusion from beneath the barrier is the mechanism that controls contaminant transport.

Groundwater Recharge Rate

Doses are reported in Table II for all parameter configurations using a 0.5-cm/yr recharge rate (except in the two cases indicated). The response of the disposal system to a change in recharge rate was determined to be a function of both travel time in the vadose zone and the dilution achieved once a contaminant reaches the unconfined aquifer. Results for the 5.0-cm/yr recharge case are reported for conditions representing the overall upper and lower performance levels. In the disintegrated/no-barrier case, the dose calculated for the 5-cm/yr recharge case is greater than that of the 0.5-cm/yr recharge case. This is because with the higher recharge rate, the contaminants are swept to the 5-km well before some of the short-lived radionuclides (e.g., strontium-90) have decayed. In contrast, for the fully functional barrier/diffusion-release case, the 5.0-cm/yr recharge case gives a slightly lower dose than for similar conditions at a 0.5-cm/yr recharge rate. Here the contaminant travel times to the well are comparable, hence similar decay, but the dilution is greater at the higher recharge rate, resulting in the lower dose. In general, however, the radiological results were found to be relatively insensitive to the range of recharge rates studied.

Overall Sensitivity and Performance

The overall sensitivity of the grout disposal system can be seen when a comparison is made between the best- and worst-parameter configurations. For the case of the no-barrier/disintegrated condition at a 5.0-cm/yr recharge rate, the dose is 5000 times that of the fully functional barrier case with diffusion release, an unfractured monolith, and a 5.0-cm/yr recharge. Although the hypothetical well is not a source of drinking water for the general public, for comparison purposes, all radiological results at the well are shown to be below the EPA primary drinking water standard of 4 mrem/yr provided in 40 CFR 141.[17]

The radiological transport analyses were also applied to the hazardous chemical of interest, nitrite. The hypothetical concentration of nitrite in the groundwater ranges from 2×10^{-3} mg/L to 3 mg/L, which is also below the EPA primary drinking water standard of a maximum permissible concentration level of 33 mg/L.[17]

Onsite Impacts

The dose impacts associated with inadvertent onsite intrusion were calculated for the five scenarios previously described. Radiation doses were calculated at four future times: 100, 500, 1000 and 10000 years following disposal. The doses are presented in Table III and are discussed in the following sections.

Home Gardening

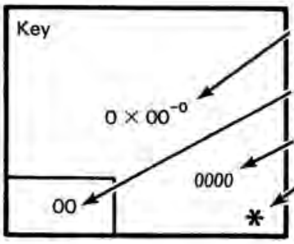
The radiation doses presented in column A of Table III for the home-gardening scenario are shown to be a direct function of the depth of soil overburden. The doses for the overburden depths of 5 and 2 m, which are initially from the ingestion of crops

TABLE II

Estimated Offsite Performance of Grouted 50/50 Hanford Facilities Waste

Release Model

	Sorption Control	Constant Release		Diffusional Release	
Monolith Integrity	Disintegrated	Fractured	Unfractured	Fractured	Unfractured
Fully Functional Moisture Barrier	3×10^{-7}; 1.5; 5100	3×10^{-7}; 1.5; 5100	3×10^{-7}; 1.5; 5100	3×10^{-7}; 1.5; 5100	2×10^{-7}; 1; 5100 * 3×10^{-7}; 1.5; 5000
Disruptive Barrier Failure	6×10^{-5}; 300; 300	2×10^{-5}; 100; 400	7×10^{-6}; 35; 300	4×10^{-6}; 20; 300	4×10^{-7}; 2; 300
Functional Barrier Failure	1×10^{-4}; 500; 4300	7×10^{-5}; 350; 4500	4×10^{-5}; 200; 4900	8×10^{-6}; 40; 4300	1×10^{-6}; 5; 4400
No Moisture Barrier	6×10^{-4}; 3000; 1000 1×10^{-3}; 5000; 300 *	2×10^{-4}; 1000; 1200	9×10^{-5}; 450; 1200	8×10^{-5}; 400; 1000	5×10^{-6}; 25; 1100



Annual dose to thyroid in mrem/yr (For comparison purposes, the maximum limit established in 40 CFR141 is 4 mrem/yr)

Indicates magnitude of the dose relative to the smallest reported dose (i.e., all doses are divided by 2×10^{-7}, the dose reported in the upper right hand corner of the figure)

Year after disposal at which maximum dose occurs

Indicates groundwater recharge rate of 5.0 cm/yr; all other doses calculated at groundwater recharge rate of 0.5 cm/yr

contaminated with strontium-90, decline steadily for the first 500 years as the strontium-90 decays. After 500 years, the doses result primarily from ingestion of plutonium-239. Because plutonium-239 is a radionuclide with a long half-life, the doses remain relatively constant throughout the remaining time studied. As described previously, the roots are not expected to penetrate to a depth of 15 m. As a result of this assumption and with the shielding provided by 15 m of soil, no impacts are projected for these conditions.

When comparing the doses at equal times from the 2- and 5-m cases, the results can be seen to be directly proportional to the fraction of roots contacting the grout monoliths. Hence, the doses associated with the 5-m case are 1 order of magnitude lower than those estimated for the 2-m overburden case. All of the doses are below the 500 mrem/yr total-body dose limit established for a member of the general public in DOE Order 5480.1A, Chapter 11.[18]

Well Drilling

The annual total-body radiation doses to an individual that result from drilling activities are presented in column B of Table III. The doses are dominated by external exposure to cesium-137 within the first 500 years, after which time inhalation of dust contaminated with plutonium-239 produces the majority of the dose.

The doses are shown to be independent of the depth of soil placed over the grout monoliths. This is consistent with the assumption that, in each case, the drilling operation completely penetrated through the 5-m reference height of the monolith. Hence, an equal volume of grout was exhumed, irrespective of the depth at which the grout was encountered. At all the times investigated, the annual total-body doses are less than 1% of the annual dose obtained by exposure to natural background radiation (100 mrem/yr).

Post-Drilling Habitation

Maximum annual total-body doses to individuals living on lands contaminated with drill tailings are presented in column C of Table III. At 100 years following disposal, the dose received would primarily result from ingesting foods contaminated with strontium-90, with a small contribution from external exposure to cesium-137. From 500 years on, the dose

TABLE III

Onsite Performance of Grouted 50/50 Hanford Facilities Waste

		A	B	C	D	E
Depth of Soil Overburden	Years After Disposal	Home Garden (dose, mrem/yr)	Drilling (dose, mrem/yr)	Post-Drilling Habitation (dose, mrem/yr)	Shallow Excavation (dose, mrem/yr)	Post-Excavation Habitation (dose, mrem/yr)
2-m Soil Cover	100	5×10^{2}	2×10^{-1}	5×10^{0}	3×10^{1}	6×10^{3}
	500	3×10^{-2}	2×10^{-5}	7×10^{-4}	5×10^{-2}	1×10^{1}
	1,000	1×10^{-3}	1×10^{-7}	5×10^{-4}	5×10^{-2}	1×10^{1}
	10,000	1×10^{-3}	1×10^{-7}	4×10^{-4}	4×10^{-2}	8×10^{0}
5-m Soil Cover	100	5×10^{1}	2×10^{-1}	5×10^{0}	3×10^{1}	0
	500	3×10^{-3}	2×10^{-5}	7×10^{-4}	3×10^{-3}	
	1,000	1×10^{-4}	1×10^{-7}	5×10^{-4}	5×10^{-4}	
	10,000	1×10^{-4}	1×10^{-7}	4×10^{-4}	4×10^{-4}	
≥15-m Soil Cover	100	0	2×10^{-1}	5×10^{0}	0	0
	500		2×10^{-5}	7×10^{-4}		
	1,000		1×10^{-7}	5×10^{-4}		
	10,000		1×10^{-7}	4×10^{-4}		

The doses in this table may be compared to average annual background radiation levels of ~ 100 mrem/yr

is produced by inhaling dusts contaminated with plutonium-239. As with the drilling scenario, the doses are independent of the depth of soil overburden. At 100 years, the doses are 5% of the natural background radiation dose; after 500 years, the doses decrease to less than 1% of the background level.

Shallow Excavation

Column D of Table III shows annual total-body doses to an excavator as a function of time of excavation. No impacts are projected for the case of at least 15 m of overburden. This corresponds with the scenario assumption that the most probable inadvertent excavation would be confined to a maximum depth of 5 m.

Doses were projected for the 2- and 5-m cases and are shown to be independent of the depth of overburden for excavations occurring 100 years after disposal. In each case, the dose is dominated by direct radiation from cesium-137. At later times, the doses become primarily a function of inhalation of plutonium-239. At these later times the doses for the 5-m case are two orders of magnitude below those for the 2-m case due to the reduced mass-loading of contaminated material into the air.

All doses calculated for this case are shown to be well below the total-body dose limit of 500-mrem/yr for a member of the general public, which is established in DOE Order 5480.1A, Chapter 11.[18]

Post-Excavation Habitation

For this scenario, impacts are projected to be reasonable only for the 2-m depth of overburden. Excavation activities were not postulated to bring materials to the surface for redistribution from depths greater than 5 m and, therefore, no impacts were projected for the reference 5-m depth or for the 15-m case. The doses for the 2-m depth case are first dominated by ingestion of garden crops contaminated with strontium-90, and, for intrusions after 500 years, become controlled by inhalation of plutonium-239.

At 100 years, the projected dose (6000 mrem/yr) would exceed the 500-mrem/yr limit for a member of the general public. Because of strontium-90's 30-year half life, this dose would rapidly diminish with time and would reach the limit after about 210 years following disposal. However, it must be reiterated that government control of the Hanford Site is planned to continue indefinitely. Such control will preclude excavation and its subsequent impacts. Moreover, the reference case (5-m depth of overburden) essentially precludes any adverse post-excavation impacts as a result of a 5-m deep excavation.

CONCLUSIONS

The long-term performance of the 50/50 HFW grout-disposal system was determined to be sensitive to several parameters inherent to the shallow-land disposal of cementitious waste forms. The results of this sensitivity analysis yield the following major conclusions:

- Offsite (groundwater) impacts show a range of over three orders of magnitude between maximum and minimum performance levels.
- The impacts of hypothetical onsite intrusion activities, with the exception of those associated with the drilling scenarios, are directly related to the depth of overburden placed over the disposal site.

- The radiation doses calculated for all intruder scenarios are a strong function of the time of the intrusion event for the first 500 years following disposal, after which the impacts remain essentially constant.

Within the constraints of the parameters and their assumed values, this study has shown that the 50/50 HFW grout disposal system adequately provides for the long-term health and safety of the public, even at minimum performance levels. A measure of the level of performance can be seen by comparison with regulations as follows:

- Consumption of groundwater postulated to contain radionuclides released from 50/50 HFW grout results in a radiation dose at least 1000 times below EPA limits.[17] (Note: Because groundwater beneath the Hanford Site is not used as a source of public drinking water, the comparison to EPA standards is provided for perspective only.)
- All onsite radiation doses that result from postulated intrusion onto the 50/50 HFW grout disposal site with the reference 5-m depth of overburden in place, result in doses well below those limits contained in DOE Order 5480.1A.[18]

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