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Desert Research Institute
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ABSTRACT

The U.S. Department of Energy (DOE) is operating an environmental restoration program to characterize, remediate, and close non-Nevada Test Site locations that were used for nuclear testing. Evaluation of radionuclide transport by groundwater from these sites is an important part of the preliminary risk analysis. These evaluations are undertaken to allow prioritization of the test areas in terms of risk, provide a quantitative basis for discussions with regulators and the public about future work at the sites, and provide a framework for assessing data needs to be filled by site characterization. The Rio Blanco site in west-central Colorado was the location of the simultaneous underground detonation of three 30-kiloton nuclear devices in 1973. The devices were located 1780, 1899, and 2039 m below ground surface in the Fort Union and Mesaverde formations. Although all the bedrock formations at the site are thought to contain water, those below the Green River Formation (below 1000 m depth) are also gas-bearing, and have very low permeabilities. The transport scenario evaluated was the migration of radionuclides from the blast-created cavity through the Fort Union Formation. Transport calculations were performed using the solute flux method, with input based on the limited data available for the site. Model results suggest that radionuclides from the test are contained entirely within the area currently administered by DOE. This modeling was performed to investigate how the uncertainty in various physical parameters affect radionuclide transport at the Rio Blanco site, and to serve as a starting point for discussion regarding further investigation at the site; it was not intended to be a definitive simulation of migration pathways or radionuclide concentration values. Given the sparse data, the modeling results may differ significantly from reality. If needed, confidence in transport predictions can be increased by obtaining more site data, including ascertaining the amount of radionuclides which would have been available for transport (i.e., not trapped in melt glass or vented during gas flow testing), and the hydraulic properties of the Fort Union Formation.

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INTRODUCTION

The U.S. Department of Energy (DOE) and its predecessor agencies are responsible for nuclear weapons research and development as part of the national defense program. These activities include underground nuclear testing, and a small number of such tests have been conducted at sites distant from the Nevada Test Site (NTS). The Rio Blanco site is located in west-central Colorado, approximately 83 km northeast of Grand Junction (Figure 1). Project Rio Blanco was part of the Plowshare Program, and was designed to increase the natural gas production of a low permeability reservoir formation. The project consisted of the simultaneous detonation of three 30-kiloton nuclear explosives in a 2,134-m-deep well on May 17, 1973. The explosives were located at depths of 1,780, 1,899, and 2,039 m below land surface (bls).

DOE has implemented an environmental restoration program with the goal of characterizing, remediating, and closing the offsite nuclear test areas. An early step in this process is performing a preliminary risk analysis of the hazard posed by each site. These analyses will allow prioritization of the sites in terms of risk, provide a quantitative basis for discussions with regulators and the public about future work at the sites, and provide a framework for assessing data needs to be filled by site characterization. The Desert Research Institute (DRI) is tasked with performing hydrologic risk evaluations for the groundwater transport pathway. This report details the results of the groundwater-transport evaluation for the Rio Blanco Site in terms of radionuclide concentrations that could cross the site boundary. There are also predictions of distances past which radionuclide concentrations are expected to be below concentrations of regulatory concern. These results will be included with evaluations of risk due to surface sources at Rio Blanco to present a comprehensive site risk analysis in a separate report.

The basic scenario evaluated for this assessment is the groundwater transport of radionuclides introduced into the subsurface by the Rio Blanco nuclear detonations. This assessment strives to be as accurate as possible, but the lack of data requires that significant assumptions be made about release scenarios and several critical transport parameters. As a consequence of these limitations, the results of this modeling are meant to serve merely as a tool to guide further discussion and investigations, not as a definitve assessment of radionuclide migration at the Rio Blanco site. The analysis relies solely on unclassified data availible to the general public. Although this may increase the uncertainty of the source term data, and result in the lack of transport calculations for certain radionuclides present at the Rio Blanco site, these issues can be investigated more thoroughly, and with much greater accuracy, after the acquisition of further data regarding contaminant transport at the site. Measured values were used wherever possible, but given the lack of data, calculations were performed for ranges of certain parameters. The assessment can be made more realistic with the acquisition of additional site data.

METHODOLOGY

A screening tool approach outlined in Cvetkovic *et al.* (1992), Daniels *et al.* (1993), Andricevic *et al.* (1994), and Andricevic and Cvetkovic (1996) was used to model radionuclide transport from the Rio Blanco site. The employed modeling approach incorporates real physical phenomena, such

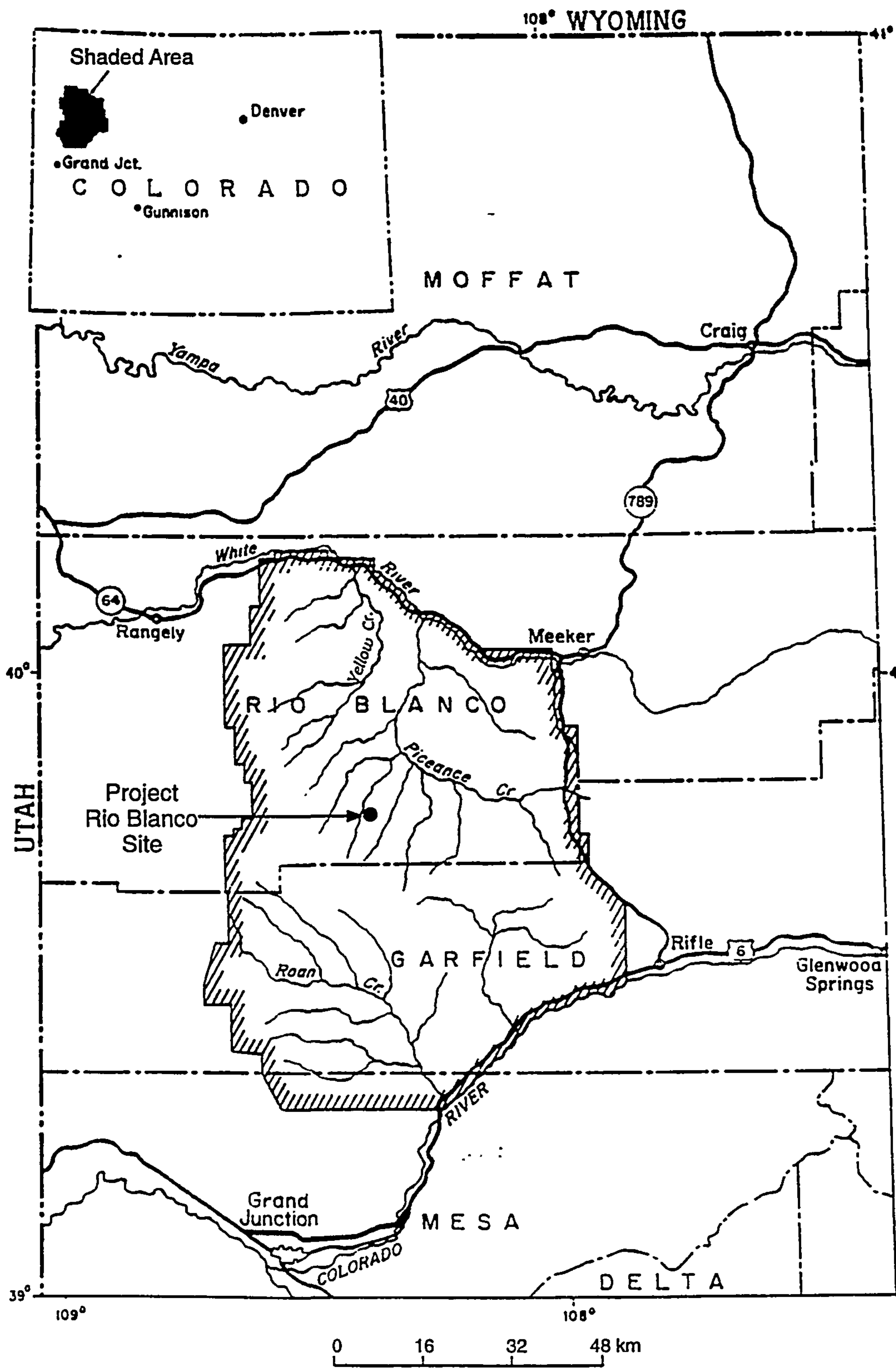

Figure 1. Rio Blanco site location map (from Coffin *et al.*, 1968).

as instantaneous and/or slow release from the source, advection, dispersion, sorption, mass transfer, and possible uncertainty in the model parameters. The output is the expected concentration profile as a function of time (e.g., concentration breakthrough curves) at the compliance point downgradient from the source, as well as the uncertainty around the expected concentration resulting from the natural hydrogeologic heterogeneity, in general, and from the spatially variable groundwater velocity, in particular.

The solute flux method is described in detail by Andricevic and Cvetkovic (1996), while important elements of the approach can also be found in Daniels *et al.* (1993) and Andricevic *et al.* (1994). The following summary is derived from these sources, but the reader is directed to these references for a detailed treatment of the method.

The contaminant migration process is described in the solute flux method through the Lagrangian concept of motion following a particle on the Darcy scale. In the absence of direct information on groundwater velocities near Rio Blanco, the mean velocity, $\overline{U}$, is calculated using Darcy's law:

$$\overline{U} = \frac{\overline{K}\,\overline{J}}{\overline{n}_e} \tag{1}$$

where $\overline{K}$ is the mean hydraulic conductivity, $\overline{J}$ is the mean hydraulic gradient, and $\overline{n}_e$ is the mean effective porosity. Hydrogeologic parameters such as K and n_e can be highly variable as a result of geologic heterogeneity. Numerous studies of the variability of hydraulic conductivity have concluded that conductivity is generally log-normally distributed (Freeze and Cherry, 1979; Hoeksema and Kitanidis, 1985). Thus, the natural logarithms of hydraulic conductivity data can be described by a normal distribution with a mean $\mu_{\ln K}$ and variance $\sigma^2_{\ln K}$. The variance represents the variability of $\ln K$ about its mean, and may range from near zero for homogeneous deposits to five, or higher, for extremely variable porous media (Hoeksema and Kitanidis, 1985). Because it is distributed in space, K usually has some degree of spatial correlation. The negative exponential function is often used to describe the K correlation structure because it is found to correspond to log K data and is easy to use. The correlation length of K, λ, represents the distance beyond which data points show weak correlation. The higher the value of λ, the greater the spatial continuity of K. When the log-normal distribution and the negative exponential covariance function are assumed, the heterogeneous, isotropic hydraulic conductivity field can be statistically characterized by three parameters: $\mu_{\ln K}$, $\sigma^2_{\ln K}$, and λ.

If the parameters on the right-hand side of the Darcy equation are log-normally distributed, then so is $\overline{U}$ and the estimate of the mean velocity is $\mu_{\ln U} = \mu_{\ln K} + \mu_{\ln J} - \mu_{\ln ne}$. The variance of the estimated mean U, $\sigma^2_{\ln U}$, can be calculated as the sum of the variances of the other parameters, if sufficient data are available. The estimation error in U, $\sigma^2_{\ln U}$, represents the magnitude of uncertainty in the estimate of U contributed by the estimation errors of K, J, and n_e. The magnitude of the uncertainty in the mean velocity, $\sigma^2_{\ln U}$, depends on the number of measurements used to estimate the parameters in the Darcy equation. In the case of independent measurements, $\sigma^2_{\ln U} = \sigma^2_{\ln u}/N$, where $\sigma^2_{\ln u}$ is the variance in the velocity field and N is the number of measurements. For spatially correlated measurements, σ^2_u is scaled by $N^{-1}[1+\bar{\varrho}(N-1)]$, where $\bar{\varrho}$ is an averaged spatial correlation between data points.

The solute flux method evaluates movement of a solute from the source to a plane perpendicular to the direction of flow. Aquifer heterogeneity is included and represented by the variance of log-hydraulic conductivity, $\sigma^2_{\ln K}$, and the hydraulic conductivity integral scale, λ. The combination of the spatial variability of aquifer properties and the uncertainty in the estimates of these properties causes the solute flux to be a random function described by a probability density function (PDF). The mean and variance of the solute flux are converted to the flux-averaged concentration needed for risk calculations by dividing by the groundwater flux, Q. The first two moments of the flux-averaged concentration are important in determining the total risk level. The larger the magnitude of variance in the flux-averaged concentrations, the larger the maximum potential risk.

HYDROGEOLOGIC SETTING

The geology and hydrogeology of the Rio Blanco site are described by many authors, including Ege *et al.* (1968), Cordes (1969), CER Geonuclear Corporation (1971), Coffin *et al.* (1971), Weir (1972), Knutson (1973a), Knutson (1973b), and Knutson (1975).

The Rio Blanco site is located in the Piceance Creek Basin, a large structural basin over 8,500 m thick, containing sedimentary rocks from Cambrian to recent age. Mineral resources in the Piceance Creek Basin include coal, oil, gas, and oil shale. Groundwater occurs in surficial alluvium found along major drainages, and in the Green River Formation (Figure 2). The Green River Formation is divided into three hydrologic units: the "A" subsystem, consisting of the Evacuation Creek Member and upper part of the Parachute Creek Member; the "B" subsystem, including the middle and lower parts of the Parachute Creek Member; and the Douglas Creek Member at the base of the formation, which is generally discontinuous and frequently contains gas (CER Geonuclear Corporation, 1971). The A and B subsystems are separated by the Mahogany Zone aquitard.

The transmissivity of the aquifers generally decreases with depth, with the alluvium being the most permeable and the Douglas Creek Member the least. Below the Green River Formation (Wasatch, Fort Union, and Mesaverde formations), rocks are frequently gas-bearing, have low permeability, and consist of discontinuous sandstone lenses within clay and shale. The units below the Green River Formation are not known to yield water to wells (Coffin *et al.*, 1975), and are not considered to constitute aquifers nor form viable groundwater systems (U.S. Atomic Energy Commission, 1972). In general, recharge to the bedrock aquifers occurs along the southern edge of the basin with groundwater flow northward through the center, eventually discharging into Piceance Creek, Yellow Creek, or the White River (Figure 1).

RELEASE SCENARIO

There are two potential sources for groundwater contamination by radionuclides at the Rio Blanco site: near-surface contamination from site activities (e.g., flaring during production testing), and subsurface contamination resulting from the radionuclides produced by the detonation.

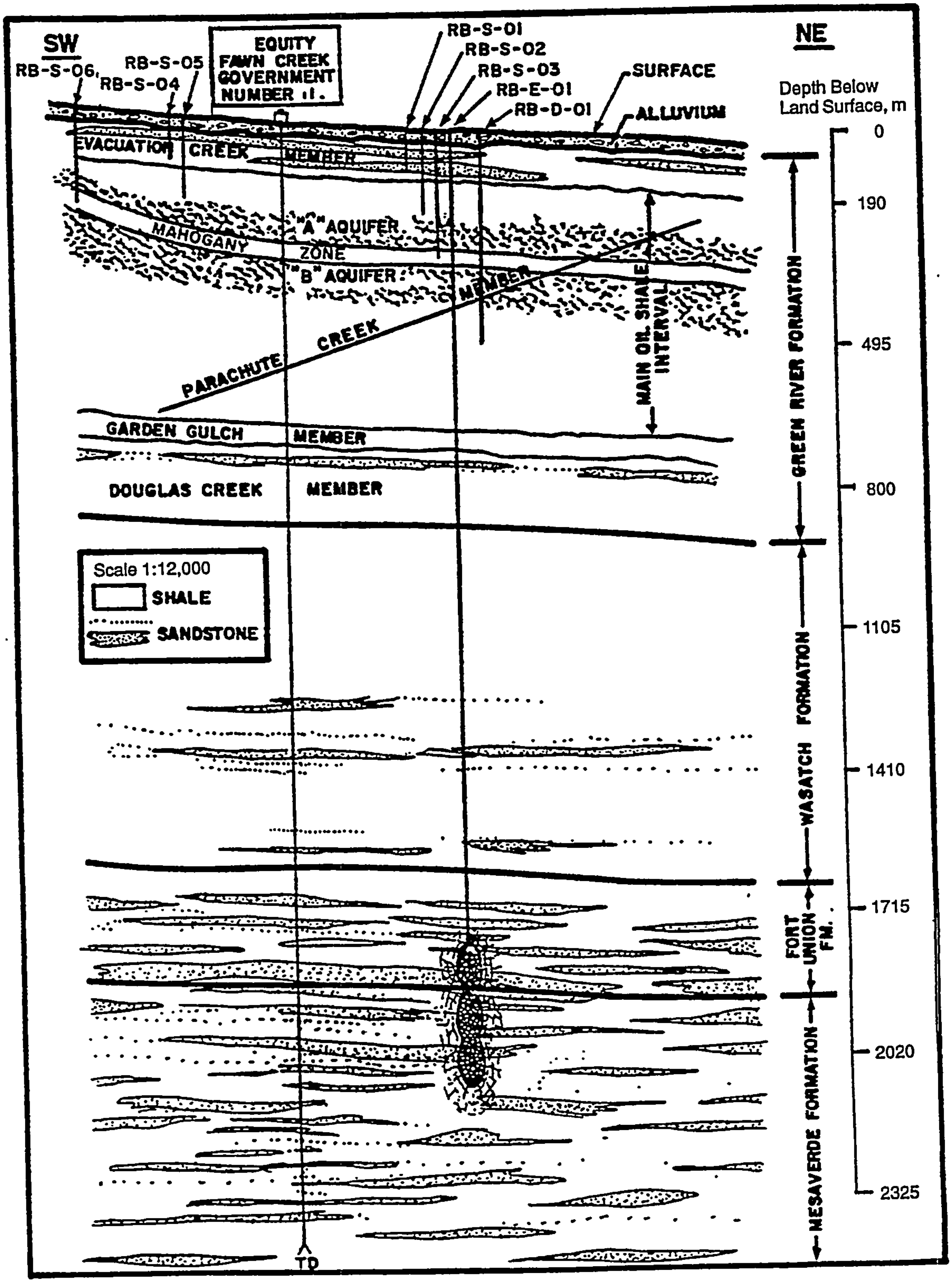

Figure 2. Stratigraphic cross section of the Project Rio Blanco site showing the locations and depths of pertinent wells (from CER Geonuclear Corporation, 1973).

Near-Surface Contamination

Flaring of gas released 7.53 x 10^{13} pCi of tritium and 8.9 x 10^{11} pCi of ^{14}C to the atmosphere (Colorado Department of Health, 1980), as well as isotopes of krypton, argon, and xenon that are not considered here because health effects are regulated for immersion of the human body in the gas, rather than ingestion (National Bureau of Standards, 1963). The amount of tritium released by the test was far less at Rio Blanco than at previous gas-stimulation tests, due to changes in the nuclear device design. During site cleanup operations in 1976, 482 soil samples were collected from areas of known or possible fallout or spills (Eberline Instrument Corporation, 1978). The criterion for release of the area from DOE control was that residual tritium concentration in soil water be less than 3.0 x 10^7 pCi/L, and all samples collected had concentrations far below that level. The highest tritium concentration measured in soil water was 762,000 pCi/L, measured in a sample collected near the flare line separator. Nine samples had concentrations above 300,000 pCi/L and 78 had concentrations greater than 30,000 pCi/L. Tritium was below detection (2,000 pCi/L) in 164 soil samples (Eberline Instrument Corporation, 1978). ^{137}Cs and ^{90}Sr were not detected above ambient concentrations resulting from worldwide fallout. Apparently, ^{14}C was not analyzed in the soil samples.

The fate of the tritium and possible ^{14}C in soil water is expected to be migration into either surface drainages or into the shallow groundwater system in the alluvium. In either case, the combined effects of radioactive decay and dilution would significantly reduce the tritium concentration, and dilution would reduce the ^{14}C concentration. Based on local meteorological conditions and operating plans, the maximum potential exposure from tritium in the flared gas was expected to be less than the concentration guidelines outside a distance of 305 m from the production well. Assuming deposition of the entire mass of flared tritium (7.53 x 10^{13} pCi) within a circle around the flare stack with a radius of 305 m, rapid dispersal of the mass within the upper 1 m of the root zone, and a volumetric water content of 0.15, a tritium concentration of 1.72 x 10^6 pCi/L in the soil water would result. Shallow groundwater at the site occurs 14.2 m bls (U.S. Atomic Energy Commission, 1972), and assuming annual recharge of 25.4 cm/yr (half of the annual precipitation), leads to a mean travel time to the water table of 57 yr (over four tritium half-lives). Considering the decay that occurs during this period, and the dilution that occurs when the water enters the fully saturated zone (assuming a total porosity of 0.3 leads to a dilution of one-half), suggests a concentration at the water table of 53,750 pCi/L. Using the same assumptions for ^{14}C, but neglecting decay because of the relatively long half-life, suggests the ^{14}C concentration entering the water table could be 10,000 pCi/L. Some of the flared tritium and carbon mass was undoubtedly dispersed far from the site by winds, and additional dilution and dispersion (and for carbon, possibly mineral precipitation and sorption) would occur during soil-water transport such that the expected concentrations are much lower. Once in the alluvial groundwater system, migration would be northward toward the White River at a groundwater velocity of 3.7 m/day (U.S. Atomic Energy Commission, 1972). The remainder of this report addresses the radionuclides created by the Rio Blanco test that were confined to the deep subsurface.

Subsurface Contamination

The three Rio Blanco detonations occurred simultaneously in the Fort Union and Mesaverde formations at depths of 1,780, 1,899, and 2,039 m bls (Figure 2). Each of the three devices was emplaced in conjunction with a unique noble gas tracer, and post-detonation gas production testing indicated that there was no connection between the upper chimney and the two lower chimneys. The uppermost cavity had a radius of 20 m, and production tests indicated that fractures which could affect permeability extended about 60 m laterally from the shot point (Toman, 1975). Assuming the extent of vertical fracturing is the same, the upper limit of nuclear fracturing would be 1,720 m bls. The bottom of the Green River Formation occurs 884 m bls (U.S. Atomic Energy Commission, 1972), so that there are over 835 m between the upper limit of fracturing and the bottom of the Douglas Creek Member of the Green River Formation, and over 1,216 m to the bottom of the B Aquifer Subsystem. Under these conditions, radionuclides from the Rio Blanco chimneys should not be in contact with mobile groundwater.

Tritium removed from the gas during flaring operations was injected into the Fawn Creek Government No. 1 well (Figure 2) between the depths of 1,716 and 1,851 m bls (Eberline Instrument Corporation, 1978). This horizon, within the Fort Union Formation, coincides with the upper fracture zone for the Rio Blanco test. In approving the permit for subsurface disposal into Fawn Creek Government No. 1, the Colorado Department of Health concurred that there was no natural movement of water within the Fort Union Formation and that there "will be no pollution resulting therefrom or that pollution, if any, will be limited to waters in a specified limited area from which there is no risk of significant migration..." (Colorado Department of Health, 1980).

Though the data suggest that the Fort Union Formation does not constitute an aquifer, the possible migration of material from both the injection and the nuclear test through the Fort Union is considered here as the only viable migration pathway, because fracturing did not extend beyond the Fort Union. The model used to simulate radionuclide movement for this report can only account for transport via a single given phase (i.e., water, gas, etc.); since this report is concerned with waterborne transport of radionuclides, it was assumed that the Fort Union Formation is fully saturated with water, and this water transported the entire source mass of radionuclide for each scenario used. This assumption was made despite abundant evidence of the presence of natural gas in the Fort Union Formation in the area of the Rio Blanco site (CER Geonuclear Corporation, 1971). Migration from only the upper Rio Blanco cavity is evaluated, as the three chimneys were found to have no pressure connection during formation testing in the top chimney via the emplacement/re-entry well, RB-E-01 (U.S. Atomic Energy Commission, 1974; Toman, 1975). The radionuclide source for each of the three shots is the same, and the migration modeled here would thus be identical for each separate cavity.

The Environmental Statement (U.S. Atomic Energy Commission, 1972) for Project Rio Blanco includes an analysis of a seepage model to evaluate containment issues for the test. To generate a "maximum credible" event (a planning concept to assure safety under all conditions, even those considered highly improbable), leakage of gas from the nuclear chimney to the atmosphere through the emplacement well annulus outside the 27.3-cm casing was postulated (Figure 3). The scenario requires the formation of a continuous series of cracks through the grout-filled annulus. This scenario was also submitted to define the upper limits of aquifer contamination (Knutson, 1973b), with the hydrologic scenario involving radioactive gas entering the Green River Formation aquifer system (specifically the B subsystem) by gas leakage through the annulus.

The gas seepage scenario described above is not considered here to be a viable event. The Environmental Statement (U.S. Atomic Energy Commission, 1972) that discussed seepage was defining the worst possible situations that could arise as the basis for formulating operational plans and related safety plans. The scenario as presented in the original Environmental Statement (U.S. Atomic Energy Commission, 1972) and described in more detail by Knutson (1973b) was amended in an addendum to the Environmental Statement (U.S. Atomic Energy Commission, 1973) after a more rigorous analysis by Lessler *et al.* (1972). Lessler *et al.* (1972) refined the seepage model originally presented by Pastore (1971), limiting open-void flow to regions that could credibly undergo shear fracturing, spalling, or were found on geophysical logs to have poor cement-to-casing bonds. The revised calculations result in a reduction of radiation exposures from the gas seepage event by about a factor of ten (U.S. Atomic Energy Commission, 1973), while still representing a conservative scenario that is not expected to occur. Despite this significant change in the seepage scenario considered for the maximum credible incident, the hydrologic release scenario was not revised because the maximum concentrations calculated in the original Environmental Statement were already a factor of 20 below the radioactivity concentration guides in place at that time (U.S. Atomic Energy Commission, 1973).

An additional problem with the seepage scenario relates to downhole pressure relationships. The only possible conduit for gas migration from the chimney to the overlying aquifers is through the annulus between the surrounding formations and the 27.3-cm casing (Figure 3). Leakage within the 27.3-cm casing would be contained by that casing, and prevented from impacting groundwater (a small gas leak was noted at the surface from the annular space between the 27.3 cm and 17.8 cm casing strings, but was thought to be a result of pressurizing a crack in that annulus from the gas pressure built up within the wellhead during formation testing, not a leak from the shot horizon (Eberline Instrument Corporation, 1978)). Knutson (1973b) evaluates formation pressures and concludes that gas moving through the fractured cement annulus could not exit until it reached the B aquifer subsystem. The basis of this conclusion appears to be the observation that all zones between the shot horizon and the B aquifer are at pressures greater than that approximated for pressure within the annulus (Figure 4). The pressure model presented by Knutson (1973b) can also be interpreted as prohibiting any transport of gas from the chimney to the B aquifer. The pressure indicated for the Basal Sand in the Wasatch Formation (over 1.52×10^1 MPa in Figure 4) is higher than that estimated for the Rio Blanco cavity (the first production test began at 1.38×10^1 MPa and only built back up to 1.14×10^1 MPa; a second pressure build-up period only recovered to 9.93 MPa after 494 days shut-in) (CER Geonuclear Corporation, 1975). This higher pressure zone, or any of the others identified on Figure 4, presents a pressure barrier between the shot horizon and the Green River Formation aquifers. Any continuous cracks in the emplacement hole annulus would provide

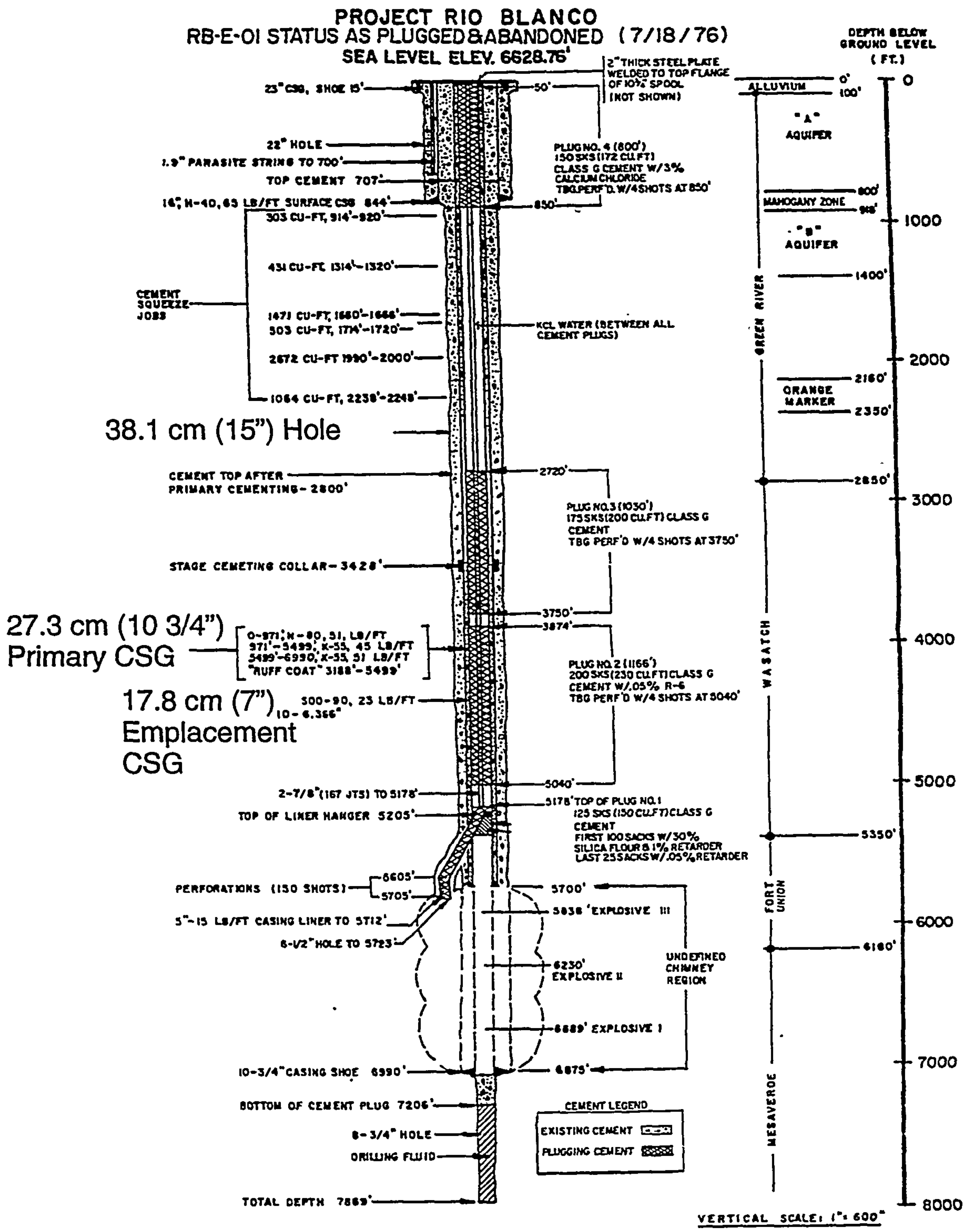

Figure 3. Schematic diagram of the emplacement well (RB-E-01) after plugging (modified from DOE, 1978). Note the locations of the 38.1-cm hole, the 27.3-cm casing, and the 17.8-cm casing. This diagram is schematic, and shows an idealized rendering of the chimneys, which were found to have no pressure connection during gas flow testing (U.S. Atomic Energy Commission, 1974; Toman, 1975).

a conduit for migration both upward and downward from the Basal Sand unit, rather than from the emplacement horizon upward.

Given the conditions described above, the migration of radionuclides from the Rio Blanco test and from the injection of radionuclides in Fawn Creek Government No. 1 is only considered possible through the Fort Union Formation. The seepage model discussed above, though not considered viable, is also evaluated for migration from the upper Rio Blanco cavity alone simply because that scenario was presented in the original Environmental Statement (U.S. Atomic Energy Commission, 1972). The scenario, as described by Knutson (1973b), is based on gas migration from the upper cavity through the annulus of well RB-E-01, thereby placing gaseous ^3H into the B aquifer of the Green River Formation, where it can be transported through the groundwater system.

DATA

The specific conceptual model evaluated in this hydrologic assessment is that of groundwater flow transporting radionuclides from the upper Rio Blanco nuclear chimney through one of two pathways: 1) horizontal flow through the Fort Union Formation surrounding the test, or 2) horizontal flow through the B aquifer subsystem after transport in the gas-phase up the annulus between the emplacement well casing and the borehole. Migration of the radionuclides injected into Fawn Creek Government No. 1 well through the Fort Union is also evaluated.

By virtue of describing the solute flux through the Lagrangian concept of motion (following a particle on the Darcy scale), the analytical solution is actually independent of the transport medium, relying simply on the assigned transport properties. The only assumption required is that the particle trajectory not deviate significantly from the mean flow direction. This assumption is imbedded in the first-order approximation used to derive the arrival time moments of the moving plume (see Dagan *et al.*, 1992). The method allows for matrix diffusion, but due to the absence of evidence that the process is significant, it was not included in the calculations. The parameters used for the transport calculations are discussed in detail below. In some cases, lack of data requires that significant assumptions be made regarding the appropriate input values. Parametric uncertainty in all of the hydraulic properties can be included through uncertainty in the estimate of the mean velocity, but because data were estimated, sensitivity analyses were performed on parameter ranges instead.

Source Terms

Fort Union Formation

No complete listing of radionuclide production for the Rio Blanco test is available, though there is some information about radionuclides that would be released in the natural gas during flaring operations. The total tritium production for the three devices used in the Rio Blanco test is reported as less than 3.0×10^{15} pCi (CER Geonuclear Corporation, 1975). The tritium production of the upper shot is thus estimated as 1.0×10^{15} pCi, and this value is used for migration from the test through the Fort Union Formation. This mass is known to be an overestimation, because over 2.0×10^{14} pCi

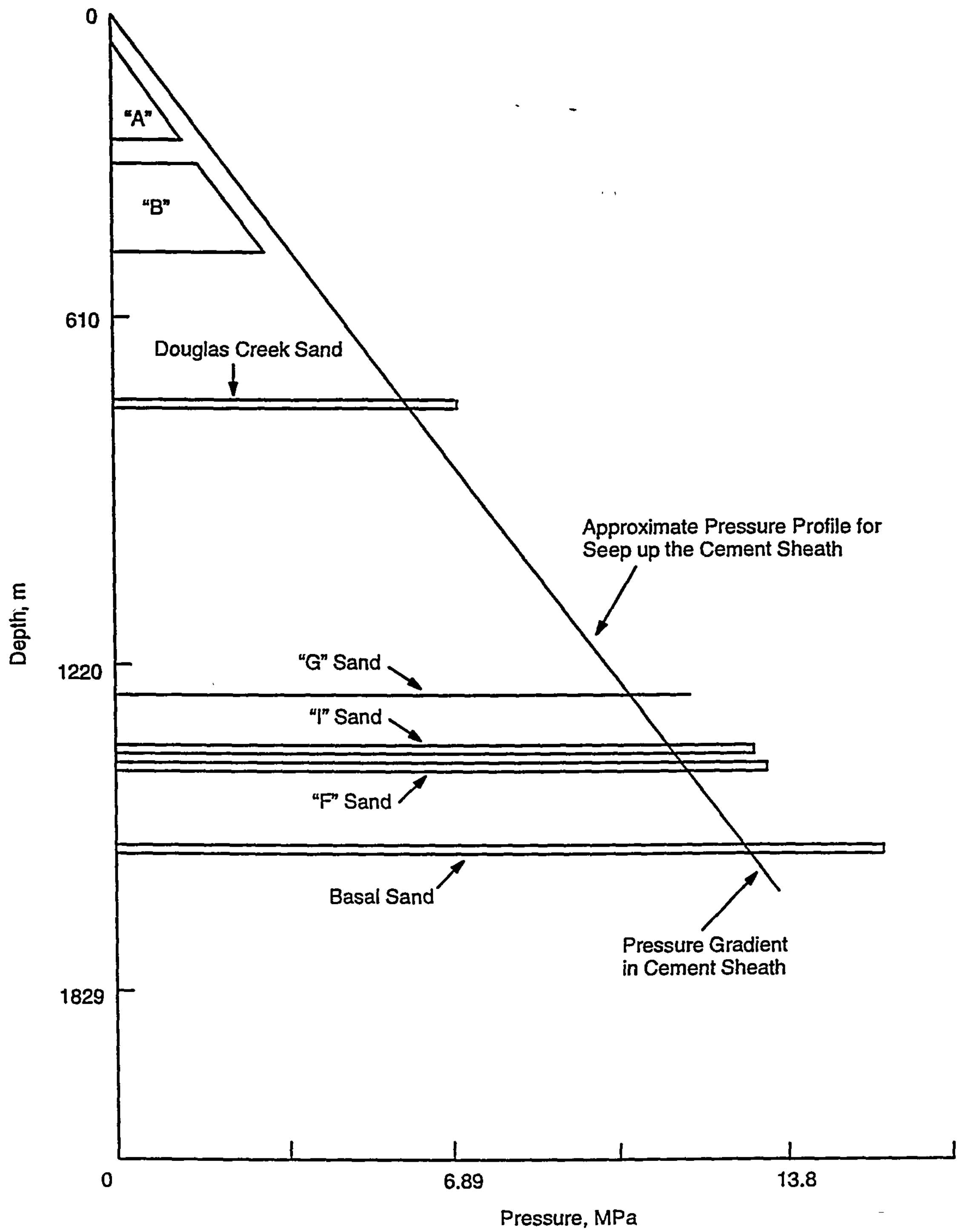

Figure 4. Postdetonation formation pressures at the Rio Blanco site (from Knutson, 1973b), with the horizontal bars representing pressure in the units indicated. The upper limit of device-induced fracturing estimated by Toman (1975) is 1,719 m below land surface.

of tritium were produced from the upper cavity during gas production testing (CER Geonuclear Corporation, 1975), and were thus unavailable for subsurface transport. Without any declassified data on other radionuclides, production values for two isotopes of concern to human health, ^{90}Sr and ^{137}Cs, were estimated using a generic relationship between isotope production and device yield. The relationships used were as follows: 1.5 x 10^{14} pCi of ^{90}Sr produced per kiloton yield and 1.8 x 10^{14} pCi of ^{137}Cs produced per kiloton yield (Borg *et al.*, 1976). Using a yield of 30 kilotons (CER Geonuclear Corporation, 1975) results in a production estimate of 4.5 x 10^{15} pCi of ^{90}Sr and 5.4 x 10^{15} pCi of ^{137}Cs. It should be remembered that these numbers are crude estimates, and that the Rio Blanco devices had a design significantly altered from standard nuclear devices that further reduces the confidence in the application of a generic relationship to this situation. The amount (if any) of unburned nuclear fuel (including isotopes of Pu, U, and H) remains classified. Given the purpose of this document as a planning tool, and the importance of public access to acheiving that purpose, no clasified data are included in the analysis. This results in a possible underestimation of nuclides included in the unburned nuclear fuel, and an uncertainty in the activation and fission products that can be reduced in future transport calculations using classified data.

For the migration of the radionuclides injected into the Fort Union via Fawn Creek Government No. 1, the masses injected in the well were used as the source terms. These were 2.78 x 10^{14} pCi of tritium, 4.33 x 10^9 pCi of ^{137}Cs, and 1.02 x 10^9 pCi of ^{90}Sr (Colorado Department of Health, 1980).

B Zone

As described above, a scoping calculation is performed for the gas seepage migration scenario described in the project Environmental Statement (U.S. Atomic Energy Commission, 1972), though the scenario is not considered physically possible. The scenario considers instantaneous migration of gas upward through the emplacement well annulus and out into the B aquifer subsystem. As a scoping effort, only tritium migration was considered, and the source was limited to tritium in the gas phase. With the majority of tritium in either the liquid phase or confined in melt material, the total tritium in dry gas was reported as 4.8 x 10^{13} pCi (Toman, 1975). This entire mass was used as the source at the B aquifer, though this is an overestimation due to the known presence of tritium in the cavity gas, as indicated by the presence of tritium in gas during production testing.

Attenuation Factors

As discussed by Smith *et al.* (1995), there are a number of factors that complicate the release function of various radionuclides from an underground test: heterogeneous spatial distribution (in melt matrix, on surfaces, etc.), solubility, sorption, and colloid formation. Smith *et al.* (1995) emphasize the importance of time in evaluating the transition from radiologic to hydrologic source term because the relative importance of the radionuclides changes during decay. All of these factors are essentially unknown for the Rio Blanco test.

Given the lack of data on sorption of various radionuclides on rocks from the Rio Blanco site, it was decided to model the transport of radionuclides as being unretarded. Although this assumption is appropriate in the case of ^3H, it should be considered highly conservative for the other nuclides considered, ^{90}Sr and ^{137}Cs. As an example, K_d values for ^{90}Sr and ^{137}Cs reported by Nork and Fenske (1970) for a variety of geologic media range from 0.19 to 2,450 mL/g, and 0.027 to 2,640 mL/g, respectively.

Discharge Mixing Areas

The discharge mixing area is the cross-sectional size of the contaminant plume as it passes the control plane. It is used in conjunction with the average velocity and porosity to estimate the volume of groundwater which contains radionuclides.

For each model run, the discharge mixing area was calculated by estimating the transverse width of the resultant plume at the desired distance, and multiplying this value by the thickness of the Fort Union assumed to be transporting radionuclides. The thickness of the Fort Union through which transport occurred was assumed to be that of the cavity plus the fractured zone around it (120 m (Toman, 1975)) for the calculation of transport from the nuclear detonation. The thickness of the Fort Union for the migration from Fawn Creek Government No. 1 was assumed to be 60 m, the lowest estimated diameter of injection (CER Geonuclear Corporation, 1975). For the case of the migration through the B aquifer, tritium was assumed to leak through the entire section of the formation adjacent to the well annulus (228 m).

To calculate the width of the plume at any given point downgradient, the formula

$$W = w_o + 2\sqrt{2D_t t} \qquad (2)$$

was used, where W is equal to the downstream plume width, w_o is the initial transverse source width (120 m for the Fort Union cavity release scenario, 60 m for the Fort Union injection scenario, and 0.8 m (the width of the emplacement well borehole) for the Green River Formation scenario), D_t is the transverse hydrodynamic dispersion coefficient of the aquifer (assumed to be 1 m^2/yr), and t is the time of transport. The two terms in this equation represent the initial source width and the amount of transverse dispersion and diffusion that occurs during transport to the control plane.

Because each source was larger than the correlation scale (18.3 m, as discussed below) in at least one dimension, assuming a point-source model would eliminate any diffusion on a scale smaller than that of the correlation scale, resulting in increased concentration values because the area in which the radionuclide mass is contained is kept artificially small. For this reason, a version of the solute flux model which incorporates source size into its calculations (Cvetkovic *et al.*, 1992) was used to perform all the modeling described in this report. Other offsite nuclear test area hydrologic assessments (Earman *et al.*, 1996a; 1996b) were able to use the point source model because the source size was considered small relative to the correlation scale. It should be emphasized that neither the source size nor the correlation scale are known values; they are simply estimates, based on the estimated source diameters and the general relationship of correlation scale to transport distance, respectively.

Because the value for D_t was estimated from aquifer characteristics, a sensitivity analysis was performed to determine how changes in the discharge mixing area resulting from changes in the transverse hydrodynamic dispersion coefficient would alter model results for tritium transport. Values of 0.1 m^2/yr and 10.0 m^2/yr were used for D_t in the sensitivity analysis.

Distance to Control Planes

Drilling exclusion areas are in place around the emplacement (RB-E-01) and waste injection (Fawn Creek Government No. 1) wells at the Rio Blanco site. In the case of RB-E-01, drilling is prohibited within a 30.5-m radius between ground surface and a depth of 457 m; between 457 and 2,286 m bls, drilling is prohibited within a 183-m radius (DOE, 1978). Drilling below a depth of 1,615 m is prohibited within a 183-m radius of Fawn Creek Government No. 1 (DOE, 1986). As all the groundwater transport scenarios evaluated in this report take place below the depths at which the drilling exclusion boundary is 183 m from the source, this value was used as the distance to the control plane in every case.

Correlation Scale

The correlation scale (also known as the integral scale) is the distance beyond which two measurements of hydraulic conductivity tend to exhibit weak correlation. A large value suggests a system with a high degree of spatial correlation, and has the net effect of extending the path length of higher conductivity conduits. Hoeksema and Kitanidis (1985) report a range for correlation scales of transmissivity in consolidated rock aquifers of 1,400 to 44,700 m (mean of 17,400 m), but these values refer to aquifer-wide properties, and it has been shown that the correlation scale increases systematically with increasing overall scale. Analysis of correlation and overall scales for a number of well-characterized sites revealed a predictable relationship of the correlation scales being approximately ten percent of the overall scale (Gelhar, 1993).

The correlation scale, λ, used in all scenarios was 18.3 m, one-tenth of the distance to the control plane. Because of the uncertainty in this value, a sensitivity analysis was performed to determine how changes in the correlation scale would alter the model results for tritium transport. Values of 36.6 and 91.5 m (two and five times the base value) were used for λ.

Effective Porosities

Fort Union Formation

An effective porosity of 13.5 percent (0.135) was assumed for the Fort Union, based on the median total porosity reported for the reservoir (CER Geonuclear Corporation, 1973). The median porosity was based on an analysis of logs and cores from a number of wells in the Rio Blanco area. It should be noted that this value is reported to represent total porosity, as opposed to effective porosity. In spite of this fact, the value of 0.135 was used, because no value for effective porosity is reported in the available literature. The uncertainty in effective porosity is incorporated in the overall uncertainty in mean velocity, discussed in the following section.

B Zone

An effective porosity of 15 percent (0.15) was used for the B aquifer, based on the estimate of Weir (1972).

Mean Groundwater Velocity

Fort Union Formation

The mean groundwater velocity used in the transport calculations was 3.02 x 10^{-3} m/yr. The mean velocity was calculated from values for aquifer hydraulic conductivity and effective porosity, in conjunction with the regional hydraulic gradient. The partially water-saturated nature of the Fort Union Formation at the site made the selection of the parameters from which this value was calculated a difficult task.

As previously described, the low permeability of the Fort Union prevented any pumping tests to determine aquifer properties such as transmissivity. Permeability values to gas based on production tests in Fawn Creek Government No. 1 and Scandard Draw No. 1 (located almost 10 km to the east) vary from 0.016 to 0.059 millidarcies (CER Geonuclear Corporation, 1973). Permeability values can be converted to hydraulic conductivity values, but there are several underlying assumptions to this process, most notably that the pore spaces in question are completely saturated with water. The Fort Union is estimated to be only 60 percent saturated with water (CER Geonuclear Corporation, 1973). Although the underlying assumptions are obviously not met in this case, in the absence of any values for hydraulic conductivity, it was decided to estimate the conductivity values by using the standard conversion formula on the permeability data. The reported permeability values are thus assumed to be equivalent to a range in hydraulic conductivities of 1.4 x 10^{-5} and 4.9 x 10^{-5} m/d. The conductivity of 4.9 x 10^{-5} was used in an effort to select values yielding higher groundwater velocities.

An effective porosity of 0.135 was used in the mean velocity calculation. As described above, this value is reported as representing total porosity, but was used in the absence of any data for effective porosity. A hydraulic gradient of 0.019, reported by Weir (1972) based on potentiometric surface data provided by Coffin *et al.* (1971), was used for the Fort Union Formation.

Migration is assumed to occur laterally from the cavity and surrounding fractured region. The mean fracture diameter of 120 m was thus used as the thickness of the Fort Union in which the radionuclides from the shot were released, and through which migration occurred.

B Zone

A mean groundwater velocity of 3.78 m/yr was used for the B aquifer, as reported by Weir (1972). This value is based on a hydraulic conductivity of 0.0815 m/d, a hydraulic gradient of 0.019, and an effective porosity of 0.15.

Estimation Error

The solute flux model includes an estimation error in mean velocity to account for uncertainty in the assigned mean velocity due to uncertainties in mean effective porosity, mean hydraulic conductivity, and mean hydraulic gradient. The lack of data did not allow calculation of these uncertainties at the Rio Blanco site. Instead, sensitivity analysis for the velocity value was used to examine the effects resulting from an estimation error. It is important to stress that the sensitivity analysis addresses the uncertainty in the mean velocity. The range of velocities in the flow field is incorporated through the spatial variability in hydraulic conductivity and would be expected to be much larger than the uncertainty in the mean.

In the case of the Fort Union Formation, a velocity for the sensitivity analysis was generated by using an effective porosity value of 0.03, and keeping all other parameters constant. This was done because the value for n_e was based on a reported value for total porosity, and the low permeability exhibited by the Fort Union is not typical of a sandstone with such a high effective porosity. The value of 0.03 was arbitrarily chosen to represent an effective porosity value that might account for the low permeability values reported for the Fort Union. This resulted in an estimated mean groundwater velocity of 0.014 m/yr. For the B aquifer, the scenario modeled in the base case is thought to be extremely unlikely, and is presented only for comparison to the calculations in the Environmental Statement (U.S. Atomic Energy Commission, 1972). As a result, no sensitivity analyses were performed for that scenario.

Spatial Variability in Hydraulic Conductivity

It is known that hydraulic conductivity varies through space due to geologic variability. The variability in K creates flowpaths with both higher and lower mean velocities than those calculated using the mean K, and results in spreading of a contaminant plume along the direction of flow. The spreading is noted at the control plane as early arrivals in advance of the bulk of the contaminant mass, and a "tail" of trailing arrivals behind the bulk of the mass. The early arrivals caused by spatial variability in hydraulic conductivity are particularly important when considering transport of a decaying solute such as tritium because the mass of contaminant decreases with time. A large variance allows more variation in K about the mean value, and thus results in a distribution of velocities that can include much faster flowpaths than the mean. A lower variance restricts the spreading about the mean.

In the absence of any spatially distributed data for hydraulic conductivity at the Rio Blanco site, a value of 0.3 was used for the variance in the natural logarithm of hydraulic conductivity ($\ln K$) for both the Fort Union Formation and the B aquifer. This value is the median value for consolidated aquifers, as reported by Hoeksema and Kitanidis (1985). Because of uncertainty in the variance value, a sensitivity analysis was performed to determine how changes in the variance would alter the model results for tritium transport. A value of 0.704, the highest value of $\ln K$ cited by Hoeksema and Kitanidis (1985) for a sandstone aquifer, was used for the Fort Union Formation sensitivity calculations.

RESULTS

The results of the transport calculations are shown in Table 1. The model results for radionuclide migration through the Fort Union suggest that ^{3}H, ^{90}Sr, and ^{137}Cs all decay below 10^{-45} pCi/L (the approximate lower limit of calculation for the solute flux model) before reaching a drilling exclusion boundary, both in the case of migration from the cavity, and migration from the waste injection point. These values are not only far below the U.S. Environmental Protection

TABLE 1. RESULTS OF GROUNDWATER TRANSPORT CALCULATIONS FOR RADIONUCLIDES PRODUCED BY THE RIO BLANCO TEST. No retardation was assumed for the calculations, though ^{90}Sr and ^{137}Cs are expected to be strongly sorbing. The concentrations presented are the peak values in the mean breakthrough curves at the Rio Blanco drilling exclusion boundary. For reference, nuclide concentrations causing a 4 mrem/yr dose rate (as per 40 CFR 141.16 (EPA, 1976)) and their required detection limits are also presented. The values described as "sensitivity case" for each scenario are those suggested by the solute flux model for a test of model sensitivity to simultaneous changes in model parameters (velocity, correlation scale, variance (ln*K*), and the transverse hydrodynamic disperion coefficient), each of which would result in higher transport velocities.

Nuclide	Base–Case Peak Mean Concentration at the Boundary (pCi/L)	Base–Case Peak Mean Concentration Plus 2σ (pCi/L)	Sensitivity Case Peak Mean Concentration at the Boundary (pCi/L)	Sensitivity Case Peak Mean Concentration Plus 2σ (pCi/L)	Sensitivity Case Time of Arrival of Peak Mean Concentration at Boundary (yr after 1969)	Concentration causing 4 mrem/yr Dose Rate (pCi/L)	Detection Limit required in 40 CFR 141.25 (pCi/L)
Fort Union Formation, Radionuclides Released from Cavity							
^{3}H	<CL	<CL	4.10×10^{-13}	1.59×10^{-6}	274	2.0×10^{4}	1.0×10^{3}
^{90}Sr	<CL	<CL	2.32×10^{-7}	8.82×10^{-3}	522	8.0×10^{0}	2.0×10^{0}
^{137}Cs	<CL	<CL	4.64×10^{-7}	1.45×10^{-2}	538	2.0×10^{2}	2.0×10^{1}
Fort Union Formation, Radionuclides Injected via Fawn Creek Government No. 1							
^{3}H	<CL	<CL	2.13×10^{-13}	1.71×10^{-6}	274	2.0×10^{4}	1.0×10^{3}
^{90}Sr	<CL	<CL	9.85×10^{-20}	7.28×10^{-16}	522	8.0×10^{0}	2.0×10^{0}
^{137}Cs	<CL	<CL	6.95×10^{-19}	4.22×10^{-14}	538	2.0×10^{2}	2.0×10^{1}
B Aquifer Subsystem of the Greeen River Formation, Radionuclides Transported through Emplacement Well Annulus							
^{3}H	6.50×10^{4}	9.91×10^{4}	NA	NA	40*	2.0×10^{4}	1.0×10^{3}

CL=calculation limit for the solute flux model (approximately 10^{-45} pCi/L)

*=This value (40 yr) represents the time of arrival of the peak mean concentration for the base–case scenario, as no sensitivity case scenario was modeled

Agency (EPA) concentrations for human consumption, they are also well below EPA-required detection limits (see Table 1). The main factor causing the values to be so low is the mean groundwater velocity, which results in a mean transport time to the control plane of approximately 60,000 yr, thus allowing decay to greatly reduce radionuclide concentrations.

In the case of the B aquifer subsystem of the Green River Formation, model results suggest a peak mean tritium concentration of 6.5×10^4 pCi/L 183 m northeast of SGZ (Figure 5). It cannot be overemphasized that the B aquifer scenario on which these results are based is highly implausible, and is presented here merely because it was discussed in the Environmental Statement (U. S. Atomic Energy Commission, 1972).

Sensitivity Analyses

As discussed earlier, the lack of hydrogeologic data from the Rio Blanco site could cause large discrepancies between model results and reality. To address this issue for migration through the Fort Union Formation, sensitivity analyses were performed. The scenario involving tritium transport up the well annulus to the B aquifer is considered to be so unlikely that no sensitivity analyses were performed for comparison to the base values.

The concentration values predicted by the base-case scenarios were below the model's calculation limit for all three radionuclides considered, thus, sensitivity analyses based on changes to individual parameters produced extremely low values as well. A combined sensitivity analysis was also conducted for each radionuclide, where changes in the mean groundwater velocity, the correlation scale of hydraulic conductivity, the variance of hydraulic conductivity, and the transverse hydrodynamic dispersion coefficient were all considered simultaneously. The models for each radionuclide were re-run using values of 0.014 m/yr for the mean groundwater velocity (determined by recalculating the base-case velocity using a porosity value of 0.03), 91.5 m for λ (five times the base value), 0.704 for ln$K$ (the highest value for a sandstone reported by Hoeksema and Kitanidis (1985)), and 0.1 m^2/yr for D_t (one-tenth the original value).

Given these hydraulic parameters, mean tritium concentration 183 m northeast of surface ground zero was computed to see how it differed from the $<10^{-45}$ pCi/L value initially predicted. The results of these runs (shown as the "Sensitivity Case" values in Table 1) suggest that in no case would an individual radionuclide's peak mean concentration exceed 1.0×10^{-7} pCi/L at a drilling exclusion boundary. It must be emphasized that this "combined sensitivity" approach models an extremely unlikely scenario, and results in highly conservative estimates for radionuclide concentrations that are not likely to represent conditions at the Rio Blanco site. Although the "combined sensitivity" method used here does not allow the determination of the sensitivity of the calculated concentration to individual model parameters, it does strongly suggest that radionuclide concentrations at the Rio Blanco drilling exclusion boundaries are below detection limits, because none of the modeled peak mean concentrations plus two standard deviations at the drilling exclusion boundary exceeds 2.0×10^{-2} pCi/L.

DISCUSSION

The EPA-promulgated regulations in 1976 regarding radionuclides in community water systems through 40 CFR 141, the Primary Drinking Water Regulations. Part 141.16 describes the maximum contaminant levels for beta particle and photon radioactivity from man-made radionuclides in community water systems. Although no community water systems currently exist downgradient of the Rio Blanco site, and neither the Fort Union nor the B aquifer contain potable water, Part 141.16 provides a useful basis of comparison for the radionuclide concentrations calculated in the previous section.

The drinking water regulations actually limit the combined concentration of beta particle and photon radioactivity from man-made radionuclides to that producing less than an annual dose equivalent to the total body or any internal organ of 4 mrem/yr. Thus, the concentration limit for an individual radionuclide is influenced by the presence or absence of other radionuclides. For instance, the average annual concentration of ^{3}H assumed to produce a total body dose rate of 4 mrem/yr is 20,000 pCi/L and the concentration of ^{90}Sr assumed to produce a dose rate of 4 mrem/yr to bone marrow is 8 pCi/L. Those values would be the concentration limits only if either tritium or ^{90}Sr were the only man-made beta or photon emitter in the water (above detection). If both ^{3}H and ^{90}Sr are present, or if they are present with any other beta or photon emitter, the maximum concentration limits for each will be lower such that the combined dose rate remains below 4 mrem/yr.

The concentration limits where more than one radionuclide is concerned are obviously non-unique. For ease of reference, the 20,000 pCi/L guideline referred to for tritium is based on it being the only radionuclide present. It should be recognized that the release scenario considered for this study would result in the introduction into the Fort Union of several other long-lived radionuclides, the presence of which would change the overall concentration guidelines. In addition, the results presented here are based on available data, which are extremely sparse. If the available values for transport parameters are not an accurate representation of conditions at the site, the results presented here could deviate significantly from reality.

The scenarios examined for this report suggest that the migration of radionuclides in groundwater through the Fort Union Formation poses little or no risk of exceeding regulatory guidelines, as all modeled peak mean concentrations and peak mean concentrations plus two standard deviations for ^{3}H, ^{90}Sr, and ^{137}Cs are lower than the calculation limit (approximately 10^{-45} pCi/L). These results are for migration from only the uppermost cavity, because it is presumed to be most accessible from the surface and there is a lack of connection with the lower two cavities. However, considering all three cavities together would only multiply the results by a factor of three, so that concentrations would still be many orders of magnitude below regulatory detection limits.

Even if all the major aquifer characteristics used in the model are underestimations of the actual values at the Rio Blanco site, the highly conservative "combined sensitivity" analyses suggest that the peak mean concentrations and peak mean concentrations plus two standard deviations for ^{3}H, ^{90}Sr, and ^{137}Cs are all orders of magnitude below their respective detection limits. It should be emphasized that these values are the result of combined sensitivity analyses for parameter values that were initially conservative, and are thus likely to be greater than the actual concentrations present at the site. In addition, it is important to note that this report examines only the groundwater transport of radionuclides, and that other possible migration scenarios, such as gas-phase transport, were not considered.

Although the model results for tritium transport in the B aquifer subsystem of the Green River Formation suggest possible exceedence of EPA standards at the drilling exclusion boundary, these results are based on a migration hypothesis that was never documented, and is thought to be extremely unlikely. Groundwater and surface water have been monitored annually in the Rio Blanco area since 1977 by the EPA as part of the Long-Term Hydrologic Monitoring Program (LTHMP). Low tritium concentrations (60 pCi/L) are routinely observed in spring and creek samples, reflecting global fallout levels. Three of the wells monitored are located immediately downgradient of the emplacement well, and are completed in the Green River Formation. Well RB-S-03 samples water from the A aquifer subsystem, and wells RB-D-01 and RB-D-03 sample from the B aquifer subsystem. If gas seepage into the B aquifer occurred, either as described by Knutson (1973b), or as presented above, the wells monitored by the LTHMP are in reasonable positions to intercept a plume. Though a few analyses conducted prior to 1988 indicate tritium concentrations slightly above the general detection limit of 10 pCi/L (the highest being a value of 25 ± 7 pCi/L in RB-D-01 in 1986 (EPA, 1987)), they are always preceded and followed by non-detections that suggest no trend of contaminant migration (Figure 5). The model predicts rapid transit times and relatively high concentrations that are not supported by the monitoring well data (Figure 6), further indicating the implausible nature of the seepage scenario.

CONCLUSIONS

The results of this study suggest that radionuclides from the Rio Blanco devices are likely contained entirely within the Fort Union and Mesaverde formations in the areas currently administered by DOE. These results were based on conservative assumptions, most notably that the Fort Union is water saturated, and that the entire mass of radionuclides produced by the test migrated out of the cavity and into the Fort Union. These results are based on extremely sparse data, and as a result, may differ significantly from reality. The results are meant to serve as the basis for discussion of possible transport scenarios and the need for further investigations at the Rio Blanco site, not as definitive estimates of migration pathways or radionuclide concentrations. Although a release scenario is proposed by Knutson (1973b) for migration of radionuclides along the well annulus from the uppermost cavity to the B aquifer subsystem of the Green River Formation, formation pressure data from the site, the assumptions underlying this scenario (Lessler *et al.*, 1972), and radionuclide monitoring in the B aquifer suggest that the likelihood of such migration is extremely unlikely.

The most critical factors affecting the transport calculations are the degree of water saturation of the Fort Union, and the amount of radionuclides released into the Fort Union by the nuclear detonations. If greater confidence in the calculations is needed, additional information on the hydraulic properties of the Fort Union Formation would be necessary, along with information on

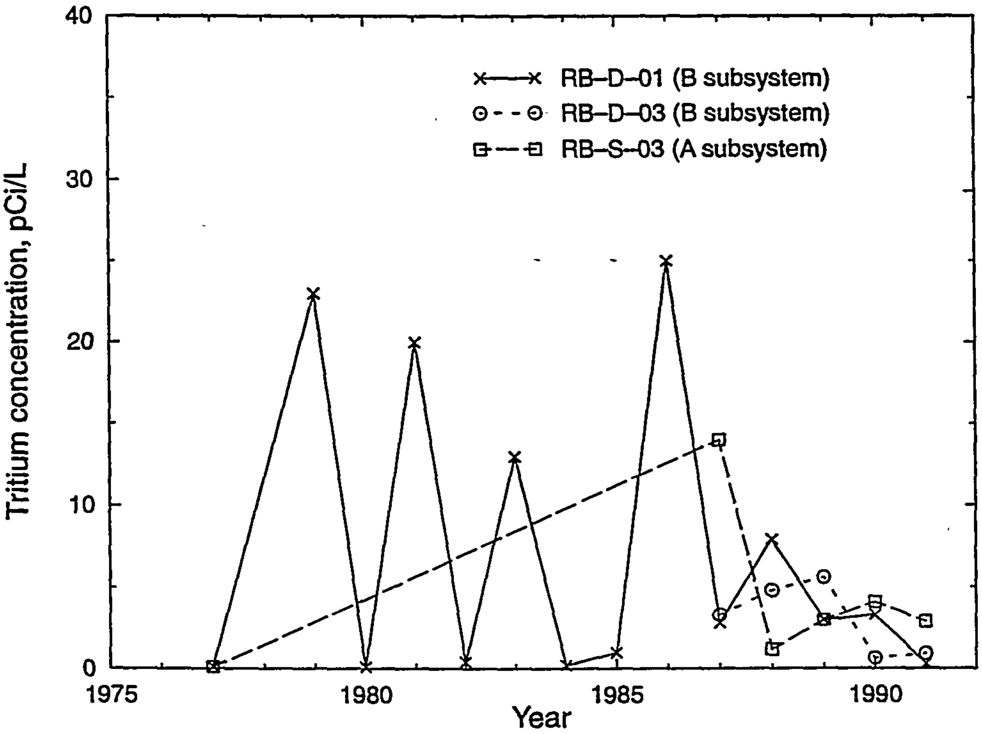

Figure 5. Tritium monitoring data from the Long-Term Hydrologic Monitoring Program conducted by the EPA (EPA, 1992). Despite the erratic data from well RB-D-01 prior to 1988, no migration through the Green River Formation is indicated.

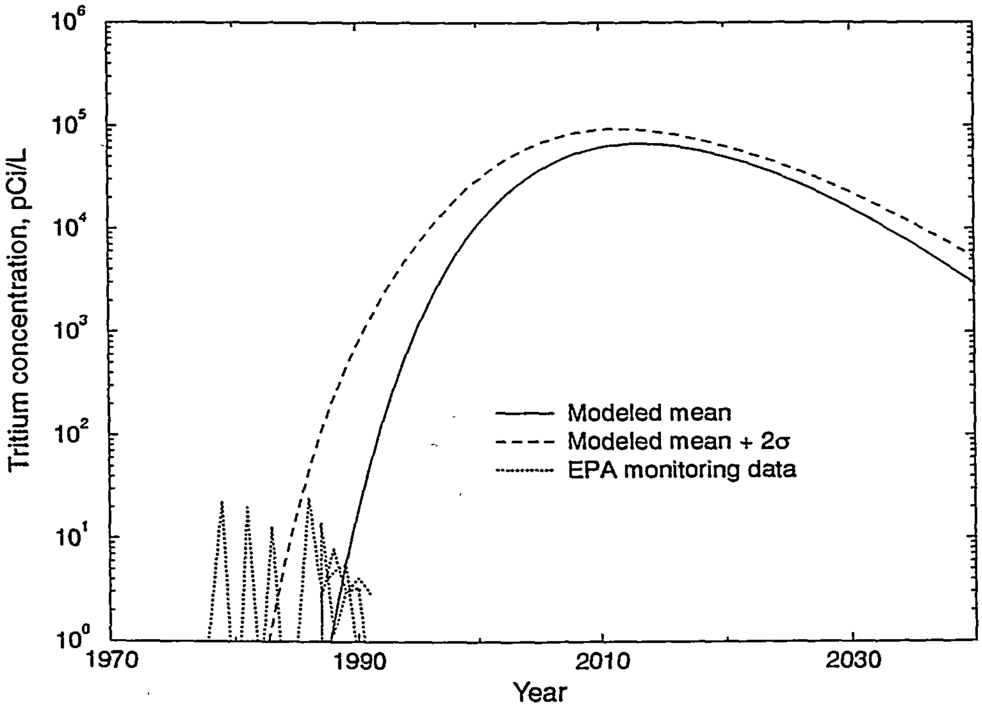

Figure 6. Modeled tritium concentrations at the drilling exclusion boundary that would result in the B aquifer subsystem of the Green River Formation from gaseous transport via the RB-E-01 annulus from the upper Rio Blanco chimney compared to tritium concentrations from monitoring wells in the Green River Formation downgradient of the test point.

the extent of fracturing surrounding the cavities and the likely disposition of the radionuclides that were produced (gas phase, liquid phase, or solidified in melt products). The radionuclide source term is an additional uncertainty in the calculations presented here, and can be addressed by considering classified data in future models.

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Janet Appenzeller-Wing
Environmental Restoration Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

Bob Bangerter
Environmental Restoration Division
Nevada Operations Office
U.S. Department of Energy
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Las Vegas, NV 89193-8518

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Las Vegas, NV 89193-8518

Frank Di Sanza, Director
Energy Technologies Division
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P.O. Box 98518
Las Vegas, NV 89193-8518

Doug Duncan
Hydrology Program Manager
Environmental Protection Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

Virginia Glanzman
U.S. Geological Survey
Box 2506, MS 913
Denver Federal Center
Denver, CO 80225

Paul Gretsky
International Technology Corporation
4330 S. Valley View
Suite 114
Las Vegas, NV 89103

Kenneth Hoar, Director
Environmental Protection Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

Roger Jacobson
Desert Research Institute
Water Resources Center
P.O. Box 19040
Las Vegas, NV 89132-0040

Marjory Jones
Desert Research Institute
Water Resources Center
P.O. Box 60220
Reno, NV 89506-0220

Jim Kannard
Bechtel Nevada Corporation
P.O. Box 98521
Las Vegas, NV 89193-8521

Randy Laczniak
U.S. Geological Survey
Water Resources Division
6770 S. Paradise Rd.
Las Vegas, NV 89119

Paul Liebendorfer
Division of Environmental Protection
State of Nevada
Capitol Complex
Carson City, NV 89710

Frank Maxwell
Environmental Restoration Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

Charles E. McWilliam, Director
Defense Projects Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

Steve Mellington, Director
Environmental Restoration Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

Leslie A. Monroe
Environmental Protection Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193–8518

Peter Sanders
Environmental Restoration Division
Nevada Operations Office
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

David K. Smith
Isotopes Sciences Division
Lawrence Livermore National Laboratory
P.O. Box 808, M/S L231
Livermore, CA 94550

Doug Trudeau
U.S. Geological Survey
Water Resources Division
6770 S. Paradise Rd.
Las Vegas, NV 89119

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