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**A CONCEPTUAL MODEL AND PRELIMINARY
ESTIMATE OF POTENTIAL TRITIUM
MIGRATION FROM THE BENHAM (U-20c)
SITE, PAHUTE MESA, NEVADA TEST SITE**

by

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ABSTRACT

U-20c is the site of a large below-water-table nuclear test near the Nevada Test Site boundary. A conceptual model of potential groundwater migration of tritium from U-20c is constructed and quantitatively evaluated in this report. The lower portion of the collapse chimney at Benham is expected to intersect 200 m of permeable rhyolite lava, overlain by similar thicknesses of low-permeability zeolitized bedded tuff, then permeable welded tuff. Vertical groundwater flow through the chimney is predicted to be minimal, horizontal transport should be controlled by the regional groundwater flow. Analytic solutions treating only advective transport indicate 1 to 2 km of tritium movement (95 percent confidence interval 0.7–2.5 km) within 5 years after test-related pressure-temperature transients have dissipated. This point lies at the axis of a potentiometric surface trough along the west edge of Area 20, Nevada Test Site. Within 25 years, movement is predicted to extend to 3 km (95 percent confidence interval 2–5 km) approximately to the intersection of the trough and the Nevada Test Site boundary. Considering the effects of radioactive decay, but not dispersion, plume concentration would fall below Safe Drinking Water Act standards by 204 years, at a predicted distance of 11 km (95 percent confidence interval 7–31 km). This point is located in the eastern portion of the Timber Mountain Caldera moat within the Nellis Air Force Range (military bombing range).

INTRODUCTION

The U-20c site on Pahute Mesa was the location of one of the largest announced-yield underground tests at the Nevada Test Site (NTS). Its proximity to the test site boundary and location below the water table make it an important site for investigation of hydrologic impacts of below-water-table nuclear testing. This study is a preliminary investigation of the potential for radionuclide migration from U-20c, using analytic solutions to estimate tritium plume dimensions given an idealized view of the site. The transport estimates made below are intended to provide a basis for conceptualizing potential groundwater transport at U-20c, and give an order-of-magnitude indication of the probable scale of tritium plumes at that site. These results can also guide future field investigations at U-20c and provide a basis for more detailed and accurate numerical simulations of transport from the site.

In describing the potential migration of radionuclides in groundwater at the NTS, analytical models (algebraic equations) are convenient tools for making preliminary estimates. Analytic solutions are relatively simple to apply and are most useful in making preliminary assessments at a site. In particular, they are useful for determining those locations most in need of environmental monitoring, and this study is a part of such an evaluation for Pahute Mesa. Previously, simple analytical models considering only horizontal flow and neglecting permeability variation were developed to estimate radionuclide migration at the NTS (Fenske, 1969). An important factor at Pahute Mesa is the potential for vertical flow through shot-generated rubble zones (collapse chimneys), allowing hydraulic communication between multiple aquifers. The solutions applied below allow for the effects of connection between previously isolated permeable zones (Brikowski, 1993a and 1993b). The U-20c site was chosen for investigation because groundwater movement there was expected to be influenced tremendously by vertical flow. As discussed below, an estimated low ratio of vertical to horizontal head gradients and presence of bedded tuff in the chimney indicate that vertical chimney flow will not be very important at U-20c; however, horizontal flow away from the lower chimney is expected to be rapid.

SETTING: BENHAM SITE

The Benham event was detonated in borehole U-20c on December 19, 1968 on Pahute Mesa in Area 20 of the NTS (Figure 1). The test occurred at a depth of 1,463 m below the surface, 822 m below static water level (SWL; Table 1) and had an announced-yield of 1.15 megatons (U.S. DOE, 1990). The site lies approximately 2 km from the NTS boundary.

The physical effects of underground nuclear testing include transient perturbations in temperature and pore fluid pressure, and a permanent change in the local permeability (Borg et al., 1976). The test instantaneously forms a roughly spherical cavity in the rock containing abundant radionuclides. The roof of the cavity soon collapses to form a rubble chimney that may extend to the surface, forming a subsidence crater (Houser, 1968). The rubble chimney may be permeable and if it intersects multiple aquifers, groundwater flow can occur through it after the pressure and temperature perturbations have dissipated. This flow can allow rapid migration of

Figure 1. Location of study site (after Erikson, 1991).

radionuclides into the surrounding aquifers. The geometry of such a system can be approximated as a cylindrical conduit connecting two aquifers (Figure 2). The Benham site is conceptualized below as such a system. To evaluate flow in that system, hydrologic parameters for the aquifers and chimney must be determined. Since post-shot data are unavailable

TABLE 1. PHYSICAL SETTING OF BENHAM SITE.

Location Nevada State Coordinates	N 903,296 ft; E 556,215 ft
Detonated (yield = 1.15 megatons)	December 19, 1968
Surface elevation	1,914 m
Total depth, U-20c	1,463 m
Hole diameter	1.8 m
Working point (WP) depth	1,402 m
Rock Unit encountered at WP	Zeolitized bedded tuff
Static water level	1,273 m
Surface distance to major fault	1,750 m (West Boxcar Fault)
Surface topography	Flat for a radius of ~1,000 m; drops off to south-facing cliff ~2,400 m south of U-20c
Major Stratigraphic Units (below water table)	Tiva Canyon Tuff (Tpc) Bedded Tuffs of Paintbrush (Tbp) Tonopah Spring Tuff (Tpt) Calico Hills Formation bedded tuffs Tac(b) and lavas Tac(l)
Observation well	UE-20c
Nevada Coordinates of UE-20c	N 903,296 ft; E 556,215 ft
Distance from U-20c to observation well UE-20c	~180 m SE

regarding hydrologic parameters at U-20c, they must be inferred from lithology and phenomonological experience.

Pahute Mesa is part of the Silent Canyon Caldera, a structural depression resulting from volcanic caldron subsidence (Blankennagel and Weir, 1973). The majority of the mesa consists of Tertiary rhyolitic lava flows, air-fall tuffs, and welded and nonwelded ashflow tuffs. These volcanic units extend to depths of 4 km. In the southeastern section of the caldera, these volcanic units comprise the upper 600 m of the saturated zone. The geological surface map of the area (Figure 3a) shows the locations of surface faults, outcrops of stratigraphic units, and cross section line A-A'. Symbols used in Figures 3a and 3b are shown in Table 2a. The A-A' geological cross section (Figure 3b) is a fence diagram showing U-20c in relationship to several surrounding drill holes with similar stratigraphy. A generalized lithologic log of U-20c is presented in Table 2b.

Figure 2. Approximate flow pattern for Benham conduit/aquifer system in the presence of vertical and horizontal head gradients. Bold arrows represent uniform regional flow, fine arrows represent radial flow induced by the conduit (after Brikowski, 1993a).

Hydrogeology

Little hydrogeologic information is available for U-20c. Hydrogeologic properties at the site must be inferred by comparison with nearby boreholes where hydrologic investigations were carried out. These are U-20a-2 (Blankennagel and Weir, 1973) and PM-3 (U.S. DOE, 1991).

Figure 3a. Geologic map of the area near the U-20c site. A-A' is line of cross section shown in Figure 3b (after Howard and Wagoner, 1985). Geologic symbols given in Table 2a.

Three basic lithologies are present in the volcanic sequence at Pahute Mesa: rhyolitic lavas which tend to be highly fractured and permeable, welded tuffs which are moderately fractured and permeable, and bedded tuffs which are generally unfractured and relatively impermeable. Superimposed on the primary lithology is secondary alteration (zeolitization) which tends to seal pores and fractures when present, and is associated with low permeabilities. Hydrologic properties of the various lithologies present at U-20c are presumed to be similar to those at other

Figure 3b. A-A' geological cross section through U-20c. (l) indicates lava; (b) indicates bedded tuff; no indication implies welded tuff (after Howard and Wagoner, 1985; Santos, 1964). High permeability zone in UE-20d identified by Blankennagel and Weir (1973).

TABLE 2a. STRATIGRAPHY IN U-20c AND KEY TO SYMBOLS USED IN FIGURES 3a and 3b. DEPTHS ARE IN METERS (after Santos, 1964; Erikson, 1991).

Stratigraphy Symbol	Stratigraphic Group Unit	Group Depths (m)	Unit Depths (m)
Qa	Alluvium	0 - variable	
Tt	Thirsty Canyon Group	0 - 66	
Ttt	Trail Ridge Tuff (partially welded)		0 - 20
Ttr	Pahute Mesa Tuff (welded)		20 - 48
Ttp	Rocket Wash Tuff (rhyolitic)		48 - 66
Tm	Timber Mountain Tuffs	66 - 290	
Tma	Ammonia Tanks Tuff (bedded)		66 - 135
Tmr	Rainier Mesa Tuff (vitrophyre)		135 - 247
Tmrl	Rhyolite of "Pre-Rainier" Mesa		247 - 290
Tp	Paintbrush Group	290 - 930	
Tpb	Rhyolite of Benham		290 - 637
Tps	Rhyolite of Scrugham Peak		637 - 643
Tpc	Tiva Canyon Tuff (welded)		643 - 750
Tp(b)	Bedded tuffs of the Paintbrush Group		750 - 792
Tpt	Topopah Spring Tuff (rhyolitic)		792 - 930
Ta	Volcanics of Area 20	930 - 1463	
Tac(b)	Calico Hills Formation (bedded tuff)		930 - 1106
Tac(l)	Calico Hills Formation (lavas)		1106 - 1338
Tac(b)	Calico Hills Formation (bedded tuff)		1338 - 1463

sites at Pahute Mesa. Average values of hydrologic properties for these lithologies on Pahute Mesa will be assumed to represent the units at U-20c.

The Benham device was emplaced 822 m below SWL in zeolitized bedded tuffs. Figure 4 shows the stratigraphic sequence at U-20c and an estimation of the explosion-created cavity, chimney, and SWL. Overlying the zeolitized tuffs are two fractured rhyolite units (Tpt and Tac(l)) separated by a thin-layered zeolitized bedded tuff aquitard. The rhyolitic lavas are expected to have high permeabilities. Given an expected upward hydraulic gradient in this area (Blankennagel and Weir, 1973), a potential pathway for radionuclide migration at U-20c is up through the chimney and out into one of the upper lava or welded tuff units.

Once contaminants have entered the aquifers they will be carried by the regional flow, with some local velocity perturbations near the chimney. On Pahute Mesa, horizontal groundwater flow is generally southwestward toward Oasis Valley (Figure 5). A trough is present in the

TABLE 2b. GENERALIZED LITHOLOGIC LOG OF U-20c (after Santos, 1964; Erikson, 1991).

Symbol	Group Unit and Rock Type	Depths (m)
Tt	Thirsty Canyon Group moderately to densely welded ashflow tuff layered with vitric bedded tuff; large cooling joints near the surface	0 - 66
Tm	Timber Mountain Tuffs nonwelded to moderately welded ashflow tuff layered with vitric bedded tuff; mixture of minor to large cooling joints with large breakout	66 - 290
Tp	Paintbrush Group devitrified, nonwelded to slightly welded tuff layered with zeolitized bedded tuff	290 - 930
Ta	Volcanics of Area 20 Group partly zeolitized, devitrified, bedded tuff layered with lava flows; scattered cooling joints and lithophysae	930 - 1463

potentiometric surface and probably deflects groundwater flow southward, essentially along the NTS boundary toward the Timber Mountain Caldera moat. U-20c is located on the margin of the trough and exhibits relatively high head gradients oriented southwesterly. Gradients within the trough are considerably reduced and are directed almost due south.

Chimney radius and height at U-20c can be estimated using the maximum credible cavity radius (r_c), which can be estimated from depth-of-burial of the device using formulas presented by Glasstone and Dolan (1977). The Benham shot cavity has a maximum credible radius of 120 m, which would extend approximately 60 m upward into the Calico Hills lava unit, and the estimated chimney would extend ~600 m upward to just below the static water table at 641 m below the land surface (Figure 4). In the modeling presented here, the chimney is assumed to have a constant radius equal to the cavity radius. Radionuclides from the test are expected to be concentrated in the lower part of the chimney (Thordarson, 1987).

The analytic solutions require parameters characterizing the geometry and hydrologic properties of the system (Table 3). The hydraulic conductivity (K) and vertical head difference ($h_1^o - h_2^o$) were derived from the work of Blankennagel and Weir (1976); they reported a transmissivity range for rhyolitic lavas of 1.97×10^{-4} to 2.10×10^{-2} m²/sec, with an average of

Figure 4. Stratigraphic sequence of U-20c, static water level, and an estimation of the explosion-created cavity and chimney. The working point is approximate. Geological symbols are described in Table 2a (after Howard and Wagoner, 1985). Aquifers and aquitard are inferred from expected hydrologic characteristics based on lithology.

Figure 5. Potentiometric map of Area 20, Nevada Test Site (after DRI, 1991). Contours are 30 meters; arrows indicate general groundwater flow direction.

TABLE 3. INPUT PARAMETERS USED TO COMPUTE MIGRATION CONSTRAINTS FOR VERTICAL FLOW IN BENHAM CHIMNEY. CAVITY RADIUS IS MAXIMUM CREDIBLE VALUE (from Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; and NTS Site Characteristics Reports). Symbols are described in text. Expected value based on normal distribution.

Parameter Values at Benham	Expected Value	Range	Variance*
K_1, K_2	1.2603×10^{-5} m/sec	10^{-3} to 10^{-7}	$2.778e-8$
K_c	3.7×10^{-8} m/sec	10^{-4} to 10^{-7}	$2.772e-10$
r_c	120 m	100 to 120 m	25
b_1	133 m	124 to 142 m	20.25
b_2	232 m	223 to 241 m	20.25
$z^1 - z^2$	176 m	167 to 185 m	20.25
$h_1^0 - h_2^0$	-7 m	-5 to -9 m	0.444
dh/dx	0.0176	0.0145 to 0.0230	$4.516e-6$
ϕ	0.03		

* Variance calculated from data distributions for conductivity (K) and dh/dx . Otherwise estimated from parameter range ($\equiv 4\sigma$).

4.6×10^{-3} m²/sec. The subsurface cavity created by a nuclear explosion is partly filled by the collapse of overburden, producing a rubble chimney extending upward from the point of detonation. Relatively competent rocks such as rhyolitic lava and welded tuff should yield increased hydraulic conductivity in the rubble-filled chimney over that in the wall rocks. A local horizontal gradient (dh/dx) was computed using hydraulic information from surrounding wells. The thicknesses of the aquifers and aquitards for Benham (Figure 4) were determined from site characteristic logs and NTS geological reports (Blankennagel and Weir, 1973; Blankennagel, 1967; Howard and Wagoner, 1985; Erikson, 1991).

Hydraulic conductivity of the chimney K (K_c) is calculated assuming a 60 percent increase in the permeability of the in-fill of the chimney (Claassen, 1978). The lithostratigraphic units at Benham are assumed to be equivalent to hydrostratigraphic units. Given this assumption, the most likely path for vertical flow in the Benham chimney is upward, with water entering the chimney from the Calico Hills lavas (Tac(l)) and exiting in the Topopah Spring tuff (Tpt) (Figure 4). If so, then the hydraulic conductivity in the chimney is a composite of the conductivities of the three units Tac(l), Tac(b) and Tpt. An average conductivity K_c for this entire interval (from 792–1338 m) can be computed (Freeze and Cherry, 1979):

$$K_c = 1.6 \cdot \left[\frac{484 \text{ m}}{\frac{170 \text{ m}}{K_1} + \frac{176 \text{ m}}{K_{\text{Tac(b)}}} + \frac{138}{K_2}} \right] = 3.70 \times 10^{-8} \text{ m/sec} \quad (1)$$

where K_1 and K_2 are the conductivities of the Tac(l) and Tpt units, and are given in Table 3. $K_{\text{Tac(b)}}$ is assumed equal to the average for ash fall tuffs given by Blankennagel and Weir (1973), 8.4×10^{-4} m/sec. The factor of 1.6 accounts for porosity increase in the rubble.

Conceptual Model of Potential Radionuclide Migration

Previous observations of radionuclide migration in and near below-water-table nuclear tests provide a limited basis for a conceptual hydrologic model at U-20c. Hydrologic properties of the formations intercepted by the rubble chimney are the most influential in determining the potential for radionuclide migration via groundwater. The Benham chimney is expected to encounter three basic lithologies (Figure 4). The shot cavity is likely to be bounded by low-permeability zeolitized bedded tuffs. Immediately above the original cavity, the chimney will intercept the Calico Hills rhyolitic lavas of presumed high-permeability. The presence of this permeable unit should allow ready interaction between the lower chimney and the surrounding groundwater. Above this 200-m-thick unit lie 200 m of zeolitized bedded tuffs similar to those at the cavity level. Finally, the upper 150 to 200 m of chimney should be surrounded by welded tuffs of similar or slightly lower permeability than the lavas. These contacts are expected to be displaced downward approximately one cavity radius during chimney collapse (Thordarson, 1987; Figure 4).

The hydrologic system at U-20c can be considered to consist of two fractured-rock aquifers (lava and welded tuff) separated by a bedded tuff aquitard/aquiclude, and connected by a rubble chimney. Few fractures should be present in the bedded tuff, even within the rubble chimney, making it a relative barrier to vertical movement of water and contaminants inside and outside of the chimney (e.g., Faultless site; Thordarson, 1987). This is borne out by the calculation of the average chimney conductivity from 792-1338 m depth of 3.7×10^{-8} m/sec, three orders of magnitude lower than the anticipated conductivity of the lavas and welded tuffs. Without vertical flow in the chimney, the bulk of the radionuclides produced by the Benham test should move only in the lower, Calico Hills rhyolitic lavas. Chimney in-filling is generally thought to limit potential radionuclide migration; this mechanism may not have been very effective at U-20c. Presence of the high-permeability lavas suggests that chimney in-filling with groundwater could have taken place relatively quickly. Rapid in-fill has been observed at the Cheshire site where cavity and chimney were formed in the same unit of rhyolitic lavas present at U-20c (Erikson, 1991). With the presence of the bedded tuff seal in the chimney, water levels need only to have risen to the base of the seal before lateral migration of radionuclides out of the chimney could take place. Conversely, the large yield of the Benham device likely produced a large dewatered zone around the working point, increasing the time required for in-fill.

The permeability distribution postulated for the Benham chimney implies that features of the regional groundwater flow should dominate transport at this site. The presence of a trough in

the potentiometric surface 1 to 2 km west of U-20c means that groundwater velocity magnitude and direction change dramatically downgradient from U-20c. Transport is expected to be rapid in a southwesterly direction from U-20c to the axis of the trough, then much slower in a southerly direction toward Timber Mountain Caldera. The conceptual model adopted here for post-shot hydrologic phenomena at U-20c assumes that the Calico Hills rhyolitic lavas contain a large, well-connected reservoir of groundwater, and that the chimney walls pose no barrier to hydraulic connection with the lower chimney. In this case, in-fill of the lower chimney should have proceeded relatively quickly, allowing lateral migration of soluble radionuclides via the regional groundwater flow. Presence of a relatively high horizontal head gradient in this area (Table 3) also suggests relatively quick in-fill, and rapid migration of radionuclides from the site.

Estimation of Radionuclide Migration at Benham

Analytic solutions are the most easily applied tools for estimating transport at poorly-characterized sites such as U-20c, and several analytic approaches can be taken for this setting. Vertical flow in the chimney is thought to be important at several Pahute Mesa sites since vertical gradients are relatively high and chimney permeability is often likely to be high. At sites where bedded tuffs are intersected by the chimney, vertical flow past the tuffs is unlikely. At U-20c, where permeable rocks are probably present only in the lower chimney and in the rubble filling the shot cavity, vertical flow between aquifers is unlikely to be important. In such a case, solutions developed to include the impact of vertical chimney flow (Brikowski, 1993a and 1993b) are still valid, with appropriate inputs for chimney conductivity. An alternative is to apply solutions considering only horizontal flow in the presence of a cylindrical inhomogeneity (Wheatcraft and Winterberg, 1985). For transport beyond a few cavity radii away from the chimney, solutions for movement of a body of groundwater from a well can be applied (Bear and Jacobs, 1965) and the impact of heterogeneity in hydraulic conductivity can be included (Pohlmann and Andricevic, 1993). Each of these solutions will yield similar results for advective transport via regional flow, i.e., in all but the nearest regions to the chimney. The solutions of Brikowski (1993b) are applied below. Transport is modeled beginning at the time when the system has returned to a quasi-steady state (when in-filling is complete or the water rises to a low permeability barrier in the chimney).

Interestingly, the ratio of anticipated vertical to observed horizontal head gradients in the vicinity of U-20c is likely to minimize the influence of vertical chimney flow no matter what rock type is present in the chimney. Horizontal gradients are two or more times the expected magnitude of vertical gradients, strongly encouraging horizontal rather than vertical flows. Given this fact and uncertainty about U-20c chimney materials, a maximum possible conductivity is assumed below, treating the chimney as if it were filled entirely with rubblized rhyolitic lava ($K_c = 2.02 \times 10^{-5}$ m/sec). Given the parameter values summarized in Table 3, the vertical groundwater flux through the chimney can be computed as follows. Several assumptions are made in applying these models. Flow is treated as one-dimensional (vertical) in the chimney; two-dimensional (horizontal) in the parallel aquifers; along the intersection of

chimney and aquifer head is constant; and transport mechanisms are nondispersive and nonreactive (except for first-order radioactive decay).

The flux (Q_c) through the chimney in the presence of vertical and horizontal hydraulic gradients is (Brikowski, 1993a)

$$Q_c = \frac{(h_2^0 - h_1^0) + (dh_1/dx - dh_2/dx)\beta}{(\alpha_c - \alpha_1 - \alpha_2)} \quad (2)$$

where dh_1/dx is the horizontal head gradient in Aquifer 1 and (r_0, θ_0) is the location of the known vertical head difference $h_1^0 - h_2^0$ between the two aquifers. The alpha (α) parameters are a path-length weighted measure of the resistance to flow in each part of the system and are defined by

$$\alpha_i = \frac{\ln(\hat{r}_0)}{2\pi T_i} \quad (3)$$

$$\beta = r_0 \cos \theta_0 (1 - \hat{r}_0^2) \quad (4)$$

$$\hat{r}_0 = \frac{r_c}{r_0} \quad (5)$$

$$\alpha_c = \frac{z_1 - z_2}{k_c \pi r_c^2} \quad (6)$$

where z_1 and z_2 are the elevations of Aquifers 1 and 2 and T_i is the transmissivity of the i th aquifer (Figure 2). Using "expected" values for Benham (Table 3) the chimney flux calculated using (1) is +0.0159 m³/sec, indicating upward vertical flow in the chimney.

Since there is uncertainty associated with the parameter values used in this calculation, a better approach is to include the effects of this uncertainty. For applications where parameters are uncertain, but where first and second statistical moments are known (expected value or mean and variance), the first two moments of the final solution can be estimated. In general terms, for an algebraic function g of N uncorrelated random variables X :

$$E[g(X_1 \dots X_N)] \approx g(m_{X_1} \dots m_{X_N}) + \frac{1}{2} \sum_{i=1}^N \frac{\partial^2 g}{\partial X_i^2} \bigg|_{m_x} \cdot \text{Var}[X_i] \quad (7)$$

$$\text{Var}[g(X_1 \dots X_N)] \approx \sum_{i=1}^N \left(\frac{\partial g}{\partial X_i} \right)^2 \bigg|_{m_x} \cdot \text{Var}[X_i] \quad (8)$$

where $E[\cdot]$ is the expected (mean) value, and $\text{Var}[\cdot]$ is the variance (Benjamin and Cornell, 1970, p. 184). The expressions on the right are Taylor's Series approximations, truncated after the third and second terms, respectively. Higher order terms are functions of higher order statistical moments of the parameters. The partial derivatives in eqs. (6) and (7) are evaluated using the mean values (m_{X_i}) of the parameters X_i . Recall that the standard deviation $\sigma = \sqrt{\text{Var}}$,

and that a 95 percent confidence interval is given by 2σ . Using eqs. (6) and (7), the mean and variance of Q_c for Benham are $E[Q_c] = 0.0173 \text{ m}^3/\text{sec}$, and $\text{Var}[Q_c] = 2.83 \times 10^{-3}$.

General expressions developed by Brikowski (1993b) describe the location of the stagnation point (farthest upgradient migration), injection front (extent of contaminated water), and downgradient breakthrough time (time to first contaminant arrival) given this value. The stagnation point and water divide is where flux from the chimney is exactly balanced by the regional flux. It also designates the divide between water that has flowed through the chimney (potentially contaminated) and uncontaminated regional groundwater. These features are most easily described using a dimensionless flux ratio, $\hat{Q}_c$, the ratio of vertical chimney flux to horizontal regional groundwater flux passing through the intersection of chimney and aquifer, defined for the i th aquifer as

$$\hat{Q}_c = \frac{(-1)^{i-1} Q_c}{2\pi r_c b_i q_0} \quad (9)$$

where b_i is thickness of the aquifer. For $|\hat{Q}_c| \leq 2$, regional flux dominates even the near-field in the discharge aquifer. For Benham, $E[\hat{Q}_c] = 0.7791$, $\text{Var}[\hat{Q}_c] = 0.1272$ indicating that regional flux controls transport throughout the discharge aquifer (even with the assumption that the chimney has high permeability throughout).

When $|\hat{Q}_c| < 2$, two stagnation points are present, located on the perimeter of the chimney. On the upgradient side of these points, the chimney recharges, discharging to the downgradient side; a weak source/sink is created and a narrow water divide is formed. Given $\hat{Q}_c$ as calculated above for Benham, these points lie at angles $\pm \theta_s$, where $E[\theta_s] = 66.6^\circ$ and $\text{Var}[\theta_s] = 2.15^\circ$ as given by

$$\theta_s = \arccos\left(\frac{\hat{Q}_c}{2}\right) \quad (10)$$

The water divide separates water that has flowed through the chimney from the regional groundwater that has not. For $|\hat{Q}_c| < 2$, the water divide intersects the chimney margin at the stagnation points. Water divide for Benham is calculated by determining the value of streamfunction ψ at the stagnation points, then plotting the downgradient portions of those streamlines (see expressions in Brikowski, 1993b). For Benham, including consideration of uncertainty, the value of streamfunction at the stagnation points ψ_{divide} is characterized by $E[\psi_{\text{divide}}] = 7.206 \times 10^{-5}$ and $\text{Var}[\psi_{\text{divide}}] = 2.744 \times 10^{-10}$. Defining a "95 percent confidence" plume as the area enclosed by $\psi_{\text{divide}} + 2\sigma$, the width of the plume at 1 km downgradient is nearly 1 km (Figure 6). The maximum plume width (ignoring dispersion) is $\sim 1,077 \text{ m}$ as calculated by:

$$w = 4\pi r_c |\hat{Q}_c| \quad (11)$$

Figure 6. Water divide with 95 percent confidence interval (dashed line) for the Benham site. Dashed line encloses the area that is expected to contain the tritium plume with 95 percent probability.

An arrival time curve for points downgradient can also be computed (Brikowski, 1993b). This curve plots the initial arrival of contaminated water released from the chimney, since dispersion is ignored. Downgradient movement of tritium in the aquifer will be chiefly controlled by the regional groundwater flow, and given the assumption of uniform regional flow, the arrival curve will be a straight line approximated by $x = V_{\text{pore}} * t$. Slightly more rapid transport than predicted by this expression will occur near the chimney, owing to its slightly higher conductivity and the flux entering the chimney from below. While assumption of constant regional groundwater velocity is reasonable within 1 to 2 km of U-20c, clearly gradient direction and magnitude changes dramatically at the potentiometric trough west of U-20c (Figure 5). An approximate breakthrough curve can be constructed for this situation, assuming high uniform velocity for the first 2 km of travel, then lower velocity for the remainder of the travel path. A gradient in the southern part of the potentiometric trough is difficult to estimate owing to the lack of observation points in the Timber Mountain Caldera (Figure 5). A value implied by contours given for the Timber Mountain Caldera in Waddell et al. (1984) will be used here, $|\nabla h| \approx 3.33 \times 10^{-3}$. Using the travel time expressions given in Brikowski (1993b) and allowing for reduced velocity 2 km from U-20c, the front of the tritium plume would be

expected to move 2.7 km downgradient in 25 years (Figure 7). Considering the effect of parameter uncertainty, the front of the plume could be located somewhere between 2.3 and 5.3 km downgradient with a 95 percent certainty at 25 years. The length of the 95 percent confidence region is primarily a function of uncertainty in the effective porosity of the aquifer. If in-filling required less than one year at the Benham site, 25 years would represent the year of publication of this document. Note that the Timber Mountain Caldera wall lies somewhere near the intersection of the NTS boundary and the potentiometric trough axis. Lithologic and hydrostratigraphic relations are unknown within the moat. Rocks similar to the Calico Hills rhyolitic lavas will be assumed to continue south of this boundary, although this is in fact highly unlikely.

Similar breakthrough calculations can be made for other time periods. The plume front is predicted to reach the potentiometric trough axis at ~5 years, the 95 percent confidence region for front location extends from 775 to 2,450 m (2,543 to 8,038 ft) (Figure 8). The total "lifetime" of the plume can be estimated. Assuming that post-shot groundwater concentrations of tritium

Figure 7. Expected value of arrival time curve with 95 percent confidence interval (shaded area) for the Benham site. Plume concentrations expected to decay to below Safe Drinking Water Act Standards in 204 years (marked by "Decay Limit").

Figure 8. Calculated plume dimensions for Benham site. Times are years after chimney in-fill, central line is expected location of the plume front, shading indicates 95 percent confidence interval. Effects of dispersion are not included, making the indicated plume much narrower and somewhat longer than the actual plume is likely to be.

at Benham are similar to those observed at Cheshire (Erikson, 1991), 204 years would be required for concentrations to decline to below Safe Drinking Water Act standards (20,000 pCi/l). The plume front computed using the above procedures is expected to lie 10.6 km downgradient at 204 years, and should lie between 7.1 and 31.1 km with 95 percent confidence. Beyond this time and these distances, concentrations in the plume will be below 20,000 pCi/L.

DISCUSSION

This study sought to make a preliminary assessment of the potential for radionuclide transport from the Benham site (U-20c). Evaluation of hydrostratigraphic relations at U-20c indicates a unit of expected high permeability intercepts the lower chimney, and is likely to provide a ready pathway for transport away from the site. Vertical flow in the chimney is expected to be minimal, both because horizontal hydraulic gradients greatly exceed expected vertical gradients there, and owing to the presence of a presumed low-permeability unit at the mid-level in the chimney. Given this setting, horizontal transport can be estimated using a variety of techniques. The analytic solutions used above were developed for cases where vertical chimney flow is important, but are equally applicable for horizontal flow cases. Applying the solutions, a narrow plume of large horizontal extent is predicted. If the experience at Cheshire is applicable to the Benham site (in-fill complete in less than one year; Erikson, 1991), chimney in-fill was likely to be rapid and horizontal transport begun relatively soon after the test. If so, the solutions above predict the front of the tritium plume from Benham to have traveled 2 to 3 km to date, to the trough in the potentiometric surface west of U-20c. Ignoring the effects of dispersion, a tritium plume could extend 7 to 30 km from the site before concentrations drop below Safe Drinking Water Act standards.

Transport of nonreactive species is affected primarily by advection and dispersion. Dispersion strongly influences plume width and concentrations within the plume, while advection primarily controls plume orientation and breakthrough times. Breakthrough times and general plume location predicted above should therefore be relatively reliable, within the limitations of the various assumptions made. Implied concentrations will be unreliable, but in the case of the 204-year time to "safe" concentrations at least give an indication of probable maximum plume length. Dispersion effects will cause actual plume width to be considerably larger than indicated in Figure 8 and cause it to widen downgradient, and reduce concentrations from those implied here.

Transport of nonsorbing radionuclide species (primarily tritium) from U-20c seems likely. The lower chimney intersects the laterally extensive Calico Hills rhyolitic lavas (Figure 3b). This unit was tested in hole U-20a-2 (near the Cheshire site) by Blankennagel and Weir (1973) and found to be highly permeable. Higher in the section, the Tiva Canyon tuff (Tpc on Figure 3b) was found to have high permeability as well in hole UE-20d. The presence of intervening bedded tuffs between these units in the Benham chimney should keep groundwater and radionuclides from migrating upward into the Tpc unit. The expected high permeability and horizontal extent of the Calico Hills lavas indicates that in-fill of the lower Benham chimney

and tritium migration from that zone should have been rapid. The radionuclides are likely to remain confined to the deep Calico Hills lava aquifer.

CONCLUSIONS

Development of a conceptual model for tritium migration from the Benham chimney suggests relatively rapid movement away from this site, confined to a deep rhyolitic lava aquifer. Preliminary quantitative evaluation of this model using analytic solutions indicates expected movement to 3 km (very near the NTS boundary) 25 years after chimney in-fill was complete. Total plume length, defined by the expected limit of concentrations exceeding Safe Drinking Water Act, is not expected to exceed 10 km (this figure is highly uncertain and neglects dilution caused by chemical dispersion). Uncertainty in input parameters, particularly in effective porosity, results in a considerable range of predicted travel distance.

These results confirm the suspicion that the Benham site is one of the most likely tests to have resulted in off-NTS migration of radionuclides in groundwater. If this migration occurs, it should be limited to the deep rhyolitic lava aquifer on the NTS (upper Calico Hills lavas) and unknown units off-NTS in the Timber Mountain Caldera. Expected off-NTS movement is southward just outside the NTS boundary. Environmental monitoring studies aimed at characterizing this plume will likely be most successful if carried out in the potentiometric surface trough shown in Figure 5, which should localize the predicted narrow plume from U-20c. A recommended monitoring site for contaminant migration from U-20c and other areas in Area 20 is near the intersection of southwestward flow from U-20c and the potentiometric surface trough (slightly east of ER-20-1; Figure 5). If the conceptual model outlined above is correct, rapid migration from U-20c should have reached this point, but may have moved little along the trough axis.

The analytic solutions used above are highly simplified and are intended only to illustrate the essence of the transport consequences of the conceptual model presented here. Since only the process of advection was treated, important physical controls on plume development and concentrations were neglected. While this report gives a general indication of probable post-in-fill plume development at Benham, it is not intended for nor should it be used as the basis for determination of regulatory compliance regarding groundwater contamination. Future studies using more detailed analytic or numerical models, guided by this work, will be required for such determination.

This study indicates a strong possibility of off-site migration of tritium from Benham, albeit in a direction parallel to the NTS boundary in an area designated as a military bombing range. While public hazard is not indicated by this study, the Benham site warrants further field and theoretical investigation.

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