A Groundwater Flow and Transport Model of Long-Term Radionuclide Migration in Central Frenchman Flat, Nevada National Security Site – 11161

Edward M. Kwicklis*, Gregory Ruskauff**, Nicole DeNovio***, Naomi Becker* and Bill Wilborn****
*Los Alamos National Laboratory, Los Alamos, New Mexico 87545
** Navarro-Intera, LLC, Las Vegas, Nevada 89193
*** Golder and Associates, Redmond, Washington 98052
**** U.S. DOE NNSA NSO, Las Vegas, 89193

ABSTRACT

A set of groundwater flow and transport models were created for the Central Testing Area of Frenchman Flat at the Nevada National Security Site (formerly the Nevada Test Site), to investigate the long-term consequences of a radionuclide migration experiment that was done between 1975 and 1990. In this experiment, radionuclide migration was induced from a small nuclear test conducted below the water table by pumping a well 91 m away. After radionuclides arrived at the pumping well, the contaminated effluent was discharged to an unlined ditch leading to a playa where it was expected to evaporate. However, recent data from a well near the ditch and results from detailed models of the experiment by Lawrence Livermore National Laboratory (LLNL) personnel have convincingly demonstrated that radionuclides from the ditch eventually reached the water table some 220 m below land surface. The models presented in this paper combine aspects of these detailed models with concepts of basin-scale flow to estimate the likely extent of contamination resulting from this experiment over the next 1,000 years. The models demonstrate that because regulatory limits for radionuclide concentrations are exceeded only by tritium and the half-life of tritium is relatively short (12.3 years), the maximum extent of contaminated groundwater has or will soon be reached, after which time the contaminated plume will begin to shrink because of radioactive decay. The models also show that past and future groundwater pumping from water supply wells within Frenchman Flat basin will have negligible effects on the extent of the plume.

INTRODUCTION

Frenchman Flat is located in the southeast corner of the Nevada National Security Site (NNSS) where 100 aboveground and 828 subsurface nuclear tests were conducted between 1951 and 1992 [1]. Frenchman Flat itself was used for only 10 relatively small-yield subsurface tests between 1965 and 1971, making it a relatively minor testing area in terms of its contribution (0.14 percent) to the overall subsurface radionuclide inventory at the NNSS. However, the proximity of the testing areas in Frenchman Flat to NNSS boundaries has raised its perceived importance to a level higher than its percentage of the NNSS radionuclide inventory might otherwise suggest. Of the 10 tests in Frenchman Flat, seven tests were detonated in the Northern Test Area of Frenchman Flat and three were detonated in the Central Testing Area of Frenchman Flat (Fig. 1). All but one of the tests were emplaced in the unsaturated zone, although it is believed that even for the unsaturated zone tests some radioactivity following the detonation was initially emplaced beneath the water table. Of the unsaturated zone tests, only those located above saturated fractured tuffs or lavas (PINSTRIPE and MILKSHAKE, respectively) are expected to result in potentially significant contaminant transport [2]. This paper concerns groundwater contamination that resulted from a small (0.75 kt) nuclear device that was detonated on May 14, 1965 (CAMBRIC) beneath the water table in alluvium at borehole U-5e in the Central Testing Area of Frenchman Flat. A long-term experiment to measure radionuclide migration and breakthrough from the CAMBRIC nuclear test cavity was conducted between 1975 and 1990 during which time a total of about 17 million m^3 of groundwater was pumped at an average rate of 2,950 m^3/d from well RNM-2s located 91 m south of U-5e [3]. After sampling to characterize radionuclide concentrations in the groundwater, the pumped groundwater was discharged to an unlined ditch that extended approximately 1.6 km from RNM-2s to the normally dry Frenchman Lake playa. At the time, it was believed that the water would evaporate or else be safely isolated within the approximately 220 m thick unsaturated zone that exists beneath the ditch. However, analysis of the radionuclide breakthrough behavior at well RNM-2s and at well UE-5n located 106 m north of the ditch indicated that much of the water discharged into the ditch and playa percolated through the unsaturated zone and recharged the groundwater. Some of the recharge was eventually recirculated through well RNM-2s at later times during the experiment [4, 5]. The recharge water was characterized by high concentrations of mobile radionuclides such as ^{3}H and ^{36}Cl, but the concentrations of radionuclides that sorbed to sediments or which were originally incorporated in melt glass indicated little or no breakthrough of these radionuclides to the pumping well. Volatile radionuclides such as ^{85}Kr broke through at the pumping well, but were apparently lost through de-gassing when the water flowed down the ditch. Nevertheless, the experiment that was intended to investigate the risk posed by radionuclides in groundwater had the unintentional effect of spreading radionuclides across a much wider area of central Frenchman Flat than would otherwise have been likely given the small hydraulic gradients that exist naturally at the site.

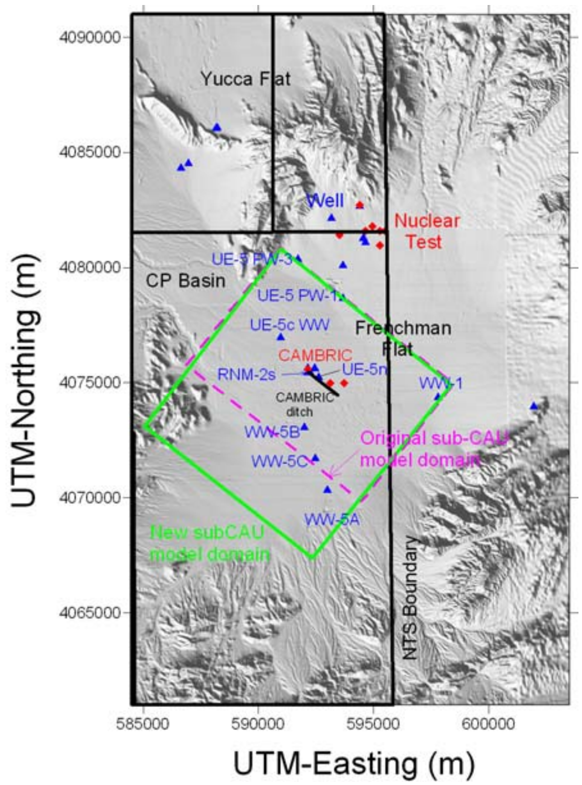

Fig. 1. Sub-CAU model domains with selected boreholes and test locations. The "new" sub-CAU model domain was used to investigate the impact of pumping from water supply wells WW-5A, WW-5B and WW-5C [2].

Building on past work, here we describe the development of groundwater flow and transport models for the Central Testing Area of Frenchman Flat that considers the long-term (1,000 year) effects of the contaminated groundwater that was discharged to the ditch and playa during the CAMBRIC RME. As described in project reports [2], these radionuclide contributions were subsequently combined with radionuclide contributions from the nearby nuclear tests WISHBONE and DILUTED WATERS, and with the less mobile part of the CAMBRIC inventory, using the techniques applied to tests in northern Frenchman Flat to calculate the total contaminant boundary for central Frenchman Flat [2]. However, these contributions to the total volume of contaminated water in Frenchman Flat were shown to be relatively minor compared to those arising from re-infiltration of contaminated water from the ditch and playa, and consequently will not be discussed here.

GEOLOGIC AND HYDROLOGIC SETTING

Geologic and geophysical data indicate that Frenchman Flat basin is an eastward tilted half-graben formed in Paleozoic carbonate rocks with significant vertical displacement along the splays of the Rock Valley Fault system along its southern, eastern and northern margins [6]. As the basin developed in the carbonate rocks, it was filled with lacustrine and volcanic sediments, ash-fall and ash-flow tuffs from the northwest part of the NNSS, lavas from the nearby Wahmonie volcanic center to the west of the basin, and finally by alluvial and playa deposits. Within Frenchman Flat basin, the shallower alluvium and tuff aquifers are separated from the underlying carbonate rocks by thick tuffaceous, lava-flow and sedimentary confining units that line the basin. These confining units become thinner as they rise up along the flanks of the basin and become more faulted where they cross the basin margins along the Rock Valley fault system.

In the vicinity of Frenchman Flat, precipitation gages with records spanning up to 50 years show that average precipitation is about 13 to 15 mm/yr [7]. The low rates of precipitation combined with an extremely high rate of potential evaporation lead to estimates of net infiltration and recharge rates that are close to zero on the basin floor to as much as several millimeters per year in the hills bordering the basin [7]. Tyler et al. [8] interpreted unsaturated-zone borehole chloride profiles measured in three boreholes in northern Frenchman Flat as indicating that recharge near two of the boreholes had not occurred in over 100,000 years and, near the remaining borehole, that recharge had not occurred in at least the last 25,000 years. The near-absence of modern recharge in Frenchman Flat groundwater is also inferred from corrected groundwater carbon-14 age dates, which indicate an absence of groundwater with ages less than 8,000 years [9]. Thus, most of the groundwater in the basin is inferred to have infiltrated during past pluvial climates that existed prior to about 10,000 years ago.

Hydraulic head data from the alluvium in Frenchman Flat show that differences in water levels are small (less than 5 m) throughout the Frenchman Flat basin. The data show an overall north-to-south or northwest-to-southeast gradient between the northernmost wells and the wells along the southern edge of Frenchman Lake playa; however, there is almost no difference in heads between the northern and central parts of the basin, and most of the head loss occurs in the vicinity of the playa. Water-level data for the volcanic aquifers from wells along the perimeter of the basin in Frenchman Flat do not show meaningful differences either among themselves or with nearby alluvial heads when measurement uncertainty is accounted for, making flow directions within this aquifer also somewhat uncertain. However, hydraulic heads in Control Point (CP) Basin, adjacent to northwest Frenchman Flat and separated from it by the Cane Springs Fault, are approximately 110 m higher than those in Frenchman Flat, suggesting that CP Basin is a potential source for some of the groundwater in Frenchman Flat. Sparse water-level data from the Paleozoic carbonate aquifer in the vicinity of Frenchman Flat also show relatively little variability within and adjacent to the Frenchman Flat basin. Hydraulic heads in the carbonate aquifer are about 7 m lower than heads in the overlying volcanic and alluvial aquifers in the vicinity of the Northern Testing Area. There is thus an overall drop in head between the shallower alluvial and volcanic aquifers and the deeper carbonate aquifer that creates the potential for downward drainage in the Frenchman Flat basin. Fig. 2a shows the simulated hydraulic heads in the Frenchman Flat basin based on a model calibrated to the available head data [9]. Particle tracks originating at the test locations show the expected trajectory of test-generated radionuclides and the hydrostratigraphic units traversed by the particles (Fig. 2b).

The central part of the Frenchman Flat basin contains a dry playa that is approximately 210 m above the regional water table, based on the depth to groundwater at nearby wells. Given the present depth to groundwater, it is unlikely the playa discharged groundwater even under the wetter climate that prevailed at the end of the Pleistocene. At present, the playa floods periodically following storms, but it appears that the floodwater remains on the playa surface until it evaporates without producing significant infiltration. Nonetheless, due to continuous ponding from the CAMBRIC RME for 16 years in the northwest part of the playa with little opportunity for evapotranspiration (ET) to remove previously infiltrated water, it is likely that some of the water that flooded the northwest section of the playa has recharged the water table.

PAST ANALYSES

Radionuclide Breakthrough

The 16-year long CAMBRIC RME was a significant effort to understand the distribution of radionuclides within and adjacent to the CAMBRIC cavity and their mobility in alluvial groundwater at the NNSS [3, 10, 11]. A great deal of emphasis in both this paper and in past studies is placed on the breakthrough of ^{3}H at RNM-2s because ^{3}H becomes part of the water molecule as ^{3}HHO and moves conservatively with groundwater, and because most of the ^{3}H is incorporated into groundwater within the cavity rather than being sorbed to the alluvium or incorporated into the melt glass. Thus, ^{3}H provides a benchmark against which other more reactive radionuclide species or species incorporated into the melt glass can be compared. The decay-corrected ^{3}H concentrations within the CAMBRIC cavity (sampled by well RMS-1) decreased significantly by pumping at RNM-2s between 10.3 and 26.3 years, during which time breakthrough of ^{3}H occurred at RNM-2s. Sometime at around 28 years, measurements of ^{3}H at UE-5n began to show significant increases in concentrations as water that infiltrated through the CAMBRIC ditch began to reach the groundwater and flow laterally away from the ditch because of the recharge mound that developed [5].

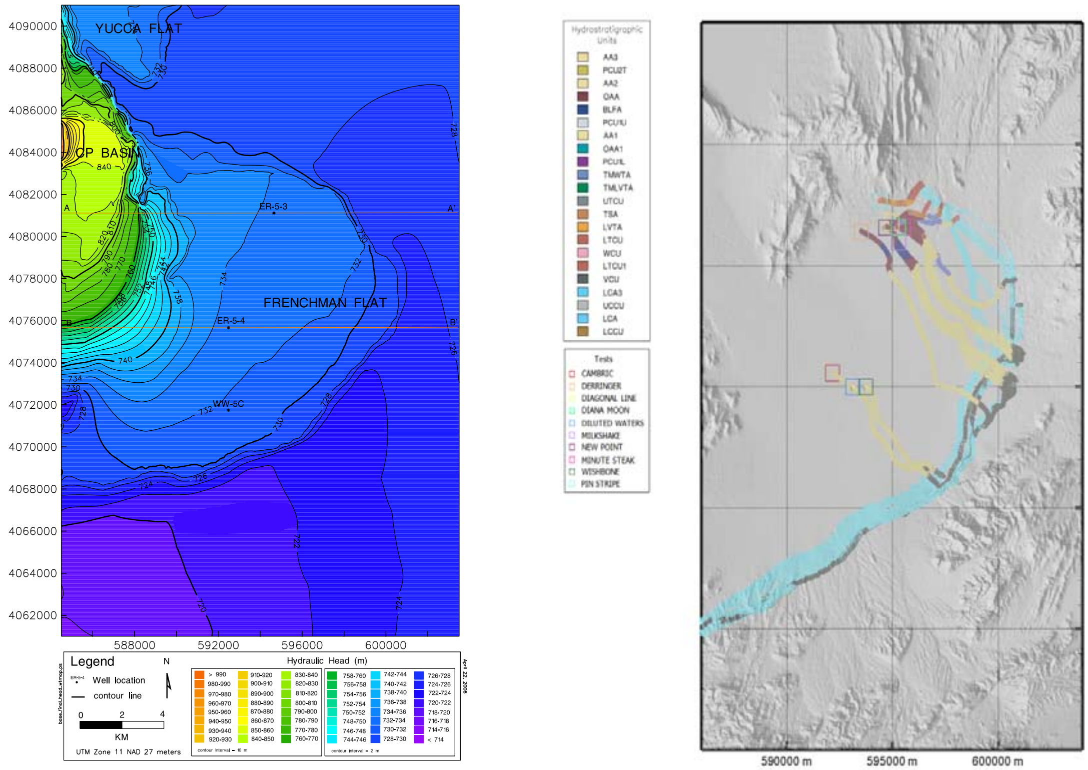

Fig. 2. Results from the BASE-USGS basin-scale CAU model (a) simulated steady-state heads and (b) particle trajectories from the test locations color-coded by hydrostratigraphic unit [9].

Peak breakthrough of ^{3}H at RNM-2s occurred at about 15 years after the CAMBRIC detonation. Similar peak arrival times at RNM-2s are evident for ^{85}Kr, ^{36}Cl, ^{129}I, and ^{99}Tc, suggesting that, like ^{3}H, these species move unretarded with the groundwater [2, 5]. In contrast, for highly sorptive species such as ^{90}Sr, little or no breakthrough occurs at RNM-2s, and the decreases within the cavity that occur in response to pumping appear to be buffered by desorption of the radionuclides from the sediment [5].

Carbon-14 was not measured at RNM-2s during the course of the RME, but measurements at RNM-1, RNM-2s and UE-5n in the early 2000s suggest it was transported to RNM-2s during the RME. However, most of the ^{14}C appears not to have reached UE-5n, suggesting that much of the ^{14}C in the RNM-2s discharge may have sorbed to surficial sediments or been lost by isotopic equilibration with the atmosphere as it flowed in the ditch. There is evidence that minor amounts of $^{239,240}Pu$ and ^{137}Cs were transported conservatively to RNM-2s during the CAMBRIC RME, presumably because of sorption to colloids [2, 5]. However, the peak concentrations of these radionuclides were less than 10^{-4} times the regulatory limits for alpha- and beta-emitting radionuclides (15 pCi/L and 4 mrem/yr, respectively), and so $^{239,240}Pu$ and ^{137}Cs would not have contributed significantly to groundwater contamination over the next 1,000 years.

Water Balance

Water loss rates measured using flumes at various locations in the CAMBRIC ditch during the RNM-2s multiple-well aquifer test (MWAT) in 2003 showed that about 40 percent of the RNM-2s discharge either infiltrated or evaporated along the 1,100-m-long section of the ditch that was monitored, with about 30 percent lost along the 339-m-long upper reach between 3 to 442 m and roughly 10 percent lost through the lower reach between 442 and 1,100 m [12]. If the average loss in these two reaches (40 percent) is extrapolated over the entire 1.6-km length of the ditch, then about 58 percent of the RNM-2s discharge is estimated to have infiltrated or evaporated along the ditch and 42 percent is estimated to have reached the playa. The absence of seasonal trends in these seepage data and in earlier data collected during the course of the CAMBRIC RME in the mid-1980s suggests that within-channel evaporation was a minor factor in the overall variability of the flow loss measurements [13]. Because transpiration by salt-cedar, cattails and other mixed wetlands vegetation that grew along the ditch is expected, an attempt was made to estimate the transpiration losses from vegetation around the ditch and playa during the course of the CAMBRIC RME [14]. These estimates were based on the measured seepage losses, the width and area of the vegetated zones adjacent to the ditch and playa as determined from aerial photos, measured transpiration losses at analogous settings in Nevada, and numerical modeling. The modeled transpiration losses had a pronounced seasonal component due to the strong seasonal controls on potential ET; however, on an annual basis, transpiration losses from the root zone ranged from 5 to 21 percent of shallow infiltration beneath the ditch and between 22 to 71 percent of shallow infiltration in the playa [14].

Flow and Transport Modeling

A highly detailed and comprehensive flow and transport model of the CAMBRIC RME was developed by Carle et al. [5] to better understand the details of radionuclide release from the CAMBRIC cavity, capture by the RNM-2s pumping well, infiltration through the ditch and playa to the water table, and the subsequent spreading and partial recirculation of radionuclides by the pumping well. This detailed model also considered the initial radionuclide distribution within the CAMBRIC cavity, the permeability structure of the cavity/chimney system, the partitioning of different radionuclides between the melt glass, collapse debris, and a highly detailed alluvial hydrostratigraphy to simulate the breakthrough of specific radionuclides at pumping well RNM-2s. The model demonstrated that once radionuclides had reached the water table, they were either recirculated through RNM-2s during the RME or spread laterally away from the ditch and playa as a result of groundwater mounding beneath these areas.

The transport models by Carle et al. [5] indicated that ^{3}H, ^{14}C, ^{36}Cl, ^{39}Ar, ^{85}Kr, ^{99}Tc, ^{129}I, U-isotopes, and ^{237}Np are likely to have reached well RNM-2s during the CAMBRIC RME. However, of these, only ^{3}H, ^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I and U are likely to have been dispersed in groundwater beneath the ditch and playa at high enough concentrations to affect the location of the contaminant boundary, which defines the volume of groundwater within which there is a 5 percent or greater likelihood that the EPA Safe Drinking Water Act (SDWA) standard for alpha- and beta-emitting radionuclides is exceeded. Volatile radionuclides like ^{85}Kr (and by analogy, ^{39}Ar) are thought to have de-gassed from the groundwater to the atmosphere when it flowed down the ditch, based on their very low concentration relative to ^{3}H at well UE-5n. Other radionuclides were either too strongly sorbed, sequestered in the melt-glass fraction, or too small a part of the radionuclide inventory to be important for the ditch and playa source term [5].

PRESENT MODELING APPROACH

Although the short-term effects of re-infiltration of the recycled water from the CAMBRIC RME have been assessed in the earlier studies cited above, these earlier studies did not consider the long-term (1,000-year) migration of the contaminated water once the effects of groundwater mounding beneath the ditch had dissipated and steady groundwater flow had been re-established. Agreements with the Nevada Department of Environmental Protection (NDEP) stipulate that the likely extent of contamination over the next 1,000 years will be estimated. Moreover, the earlier models were forced to estimate steady-state flow directions from locally noisy hydraulic head data, whereas the present model has flow directions consistent with those of a larger basin-scale flow model [9] that is based on more regionally extensive head data and boundary conditions. The present model, referred to as the sub-CAU model throughout the remainder of this paper, combines aspects of the basin-scale Corrective Action Unit (CAU) models and earlier models of radionuclide capture and dispersal reported in Tompson et al. [4] and Carle et al. [5] to create a relatively simple model of radionuclide dispersal and migration that is consistent with basin-scale concepts of flow yet has sufficiently fine grid resolution to calibrate and test local-scale aspects of flow and transport from the ditch. To ensure compatibility in overall flow directions between the basin-scale models and the corresponding sub-CAU models, boundary conditions applied at the lateral boundaries and bottom of each of the sub-CAU models were derived by linearly interpolating the hydraulic heads from the nearest eight nodes of the corresponding CAU model onto the nodes along these boundaries. This process captured not only the lateral head gradients and flow directions but also any vertical gradients associated with faults and the basin boundaries.

The sub-CAU model described in this paper is a highly simplified representation of the models described in Carle et al. [5] in that it does not attempt to account for radionuclide capture from the CAMBRIC cavity by the RNM-2s pumping well nor does it attempt to directly simulate radionuclide migration through the unsaturated zone to the water table. Instead, it uses both the measured radionuclide concentrations at the pumping well and inferences regarding unsaturated travel times provided by the Carle et al. [5] models to create water and radionuclide input functions that are applied at the water table surface in the model beneath the ditch and bermed portion of the playa. Like the model of Carle et al. [5], it also takes advantage of a multiple-well aquifer test (MWAT) done in 2003 and observations of radionuclide arrivals at well UE-5n to calibrate and test the model before making long-term predictions of radionuclide transport.

Model Domain and Grid

The sub-CAU model domain is shown in Fig. 1 along with the locations of the nuclear tests and selected wells for reference. The model domain extends approximately 9.2 km in the NW-SE direction, 6.4 km in the SW-NE direction and is 0.5 km thick, extending from the water table elevation (734 m) to 222 m relative to sea level. Although most of model volume contains alluvium, volcanic rocks are present near the northwestern boundary and both volcanic and carbonate rocks are present along its southeastern boundary. Major faults associated with the Rock Valley Fault system were assumed not to propagate upward from the carbonate rock into the tuffs and alluvium in both the CAU and sub-CAU models; nonetheless, their presence in the underlying carbonate rocks and their influence on heads in the overlying alluvium and tuffs is represented through the hydraulic heads that were mapped onto the sides and bottom of the sub-CAU model from the larger scale CAU model.

The basin-scale flow and transport models for Frenchman Flat [9] considered various combinations of geologic structural models and recharge models in order to test the sensitivity of the model results to geologic and recharge uncertainty. However, many uncertain aspects of geologic structure pertained to features that are not present in the sub-CAU model domain. Likewise, the different recharge models tended to produce similar estimates of recharge beneath the central part of Frenchman Flat (< 1 mm/yr). Therefore, the sub-CAU models for the Central Testing Area described in the paper focus on alternative models that span a range of assumptions regarding if, and how strongly, permeability in the alluvium decreases with depth due to increasing overburden pressure [2]. This is an important but highly uncertain aspect of the larger-scale models that affect the lateral and vertical extent of contamination. The sub-CAU models described in this paper are based on three combined hydrostratigraphic framework models (HFMs) and recharge models developed for the Frenchman Flat basin as a whole [9]. These models are designated BASE-USGS, BASE-USGS (NODD), and DISP-USGS, where the first part of the name indicates the HFM component and the second part of the name indicates the recharge component [9]. (The BASE-USGS (NODD) model is a variation of the BASE-USGS model that treats alluvial permeability as constant with depth, but is otherwise the same.) Each of the three models was discretized with a spatially variable grid that had finer resolution around the ditch and playa areas and around wells that were used to calibrate and test the sub-CAU models (wells ER-5-4, UE-5n, RNM-1, RNM-2s, and RNM-2). The resolution is approximately 4 x 4 x 4 m near the ditch and increases in steps by factors of two to a maximum of 128 x 128 x 128 m near the bottom and lateral boundaries of the model. The 2,042,361 finite elements contained in the mesh result in 357,856 nodes and associated volumes.

The heat, flow and mass-transport code FEHM (Finite Element Heat and Mass Transfer) [15] uses the geometric information associated with the tetrahedral finite elements mesh to create control volumes centered on the nodes that form the corners of the tetrahedra. Actual flow and transport calculations are performed on the control volumes using integrated finite difference techniques.

Model Inputs to the Ditch and Playa

The hydrologic source term (HST) models of Carle et al. [5] demonstrated that during and following the CAMBRIC RME, radionuclide-bearing groundwater pumped from RMN-2s re-infiltrated beneath the ditch and playa and affected groundwater quality throughout central Frenchman Flat. The sub-CAU models attempt to account for these processes through the application of the appropriate boundary conditions at the water table, without explicitly simulating the capture of radionuclides from the CAMRIC cavity or simulating unsaturated-zone transport processes. These boundary conditions were based on outputs from the HST models, observed radionuclide breakthrough at RNM-2s, expected radionuclide ratios, and mass-balance considerations for both water and radionuclides.

The recharge function used to approximate the mass flux of water at the water table beneath the ditch and playa has a shape and temporal distribution similar to the recharge function presented in [5] for recharge beneath the ditch. However, the total mass beneath the curve was adjusted to account for the total mass of water pumped from RNM-2s during the CAMBRIC RME (approximately 16.9 x 10^9 L), with 56 and 44 percent applied beneath the ditch and playa, respectively, at any point in time. These estimates of the distribution of recharge beneath the ditch and playa are based on flume studies that measured flow losses in the ditch during the RNM-2s MWAT. Recharge beneath the ditch was applied to a 20-m-wide zone at the water table centered on the ditch. Recharge in the playa was confined to the northwest section of the playa that had been isolated with berms. The simulations presented in this paper assume that all of the water pumped from RNM-2s reaches the water table. Although ET losses undoubtedly occurred, based on the presence of phreatophytes along the ditch, this worse-case scenario was adopted in the interest of conservatism and to limit possible issues of contention with reviewers and regulators.

Tritium breakthrough at RNM-2s during the CAMBRIC RME formed the basis for estimating the concentrations of ^{3}H and other mobile radionuclides in the recharge water beneath the ditch and playa. To simulate the ^{3}H concentrations in the recharge water, the measured ^{3}H concentrations at RNM-2s were decayed an additional 3½ years and applied to the recharge water beneath the ditch and playa. To simulate mobile radionuclide species with much longer half lives, the ^{3}H breakthrough at RNM-2s was decay corrected to time zero (May 14, 1965), and the undecayed ^{3}H mass arriving at RNM-2s was shifted an additional 3 ½ years relative to RNM-2s breakthrough and applied to the recharge water. Thus, mobile, non-decaying radionuclide species were assumed to have concentrations in the recharge water identical to the ^{3}H concentrations that would have been measured if ^{3}H did not decay and have a total mass equal to that of the initial ^{3}H source (2.08 moles), as estimated from the RNM-2s ^{3}H breakthrough curve. The concentrations of these other radionuclide species (^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I and U) over the simulation period are estimated in a post-processing step using the ratio of these radionuclides in the published unclassified radionuclide inventory [16] for Frenchman Flat relative to ^{3}H undecayed to time zero [5]:

$$RN_{RNM\text{-}2s} = (RN/{}^3H)_{Bowen} \cdot {}^3H_{RNM\text{-}2s} \qquad \text{(Eq. 1)}$$

where $RN_{RNM\text{-}2s}$ is the estimated concentration of radionuclide RN arriving at RNM-2s, $(RN/{}^3H)_{Bowen}$ is the ratio of the concentrations of radionuclide RN to ^{3}H at time zero estimated from [16], and $^3H_{RNM\text{-}2s}$ is the undecayed ^{3}H concentration arriving at RNM-2s during the CAMBRIC RME.

This approach was taken because the measured breakthrough of several radionuclides of interest (e.g., ^{4}C, ^{99}Tc, and U) at well RNM-2s was non-existent or inadequate for the purpose of estimating their concentration in recharge beneath the ditch and playa. A comparison between the concentrations estimated as input at the water table with equation (1) and available measurements at RNM-2s during the CAMBRIC RME (Fig. 3) shows that the estimates produced with equation (1) overestimate the arrival concentrations at RNM-2s, and therefore also tend to overestimate the concentrations of radionuclides other than ^{3}H at the water table beneath the ditch. This approach, although approximate, was adopted in order to provide worst-case estimates of contamination beneath the ditch and playa.

The models explicitly simulate ^{14}C because its half-life (5,730 years) is small enough that significant decay of the initial inventory (11.4 percent) occurs over the 1,000 year simulation period. The half-lives of the other mobile radionuclide species are in excess of several hundred thousand years, and the small amount of radioactive decay that would have reduced the concentrations of these species in the groundwater is ignored. An additional approximation is that each of these radionuclide species moves conservatively with ^{3}H. This assumption ignores the fact that the partition coefficients (K_d's) for some of these species (e.g., U) are non-zero, and thus the movement of these slightly sorbing species will be retarded somewhat relative to ^{3}H. These approximations also ignore the fact that a significant fraction of some of these radionuclides is probably incorporated into the melt glass, and hence not immediately available for transport out of the CAMBRIC cavity.

Table I shows the half-lives, initial radionuclide abundances estimated to be in the CAMBRIC cavity, fraction of the radionuclide incorporated in the melt glass, and the ratio of each radionuclide to ^{3}H at time zero (t_0) (based on the Bowen et al. [2001] inventory for Frenchman Flat) for each of the radionuclides considered in the simulations. For

^{36}Cl, ^{129}I and ^{99}Tc, the breakthrough of these radionuclides was complete enough that peak concentrations and peak arrival times at RNM-2s could be estimated (see Fig. 3). As noted by Carle et al. [5], the average radionuclide inventory calculated by [16] for Frenchman Flat tends to overestimate the CAMBRIC-specific inventory calculated by Hoffman et al. [10] for lighter radionuclides. Nonetheless, in the interest of understanding the maximum possible extent of the contaminant boundary in central Frenchman Flat, the Bowen et al. [16] derived estimates were used in this study. As will be demonstrated, the conservatism inherent in this approach had little or no effect on extent of contamination as defined by the SDWA limits.

Table I. Parameters Used in Post-processing Simulation Results (Based on [5]).

Radionuclide	**Half-Life (years)**	**Abundance in radiological source (moles)**	**Fraction originally in melt glass**	**Molar ratio relative to ^3H at t_0 [a]**	**Molar ratio relative to ^3H at peak break-through at RNM-2s**	**Time of peak arrival (years) [b]**	**Moles per 4 mrem/yr**
^3H	12.3	2.80	0	1	1.0	15.7	6.88e-13
^{14}C	5,730	0.107	0	0.0382	---	---	3.21e-11
^{36}Cl	301,000	0.75	50	0.2679	0.0036	14.8	5.89e-10
^{99}Tc	213,000	0.0696	80	0.02486	8.9e-7	15.9	5.36e-10
^{129}I	15,700,000	0.0199	50	0.0071	5.0e-4	17.2	4.39e-11
U (all isotopes)	Variable ($>10^5$)	120.7	90	43.11	---	---	1.26e-7 [c]

[a] Based on the average radionuclide inventory for Frenchman Flat (Bowen et al. [16]), as reported by Carle et al. [5], Tables 3.1 and 4.9
[b] Time since May 14, 1965
[c] U is an alpha-emitter and has a regulatory limit of 30 µg/L

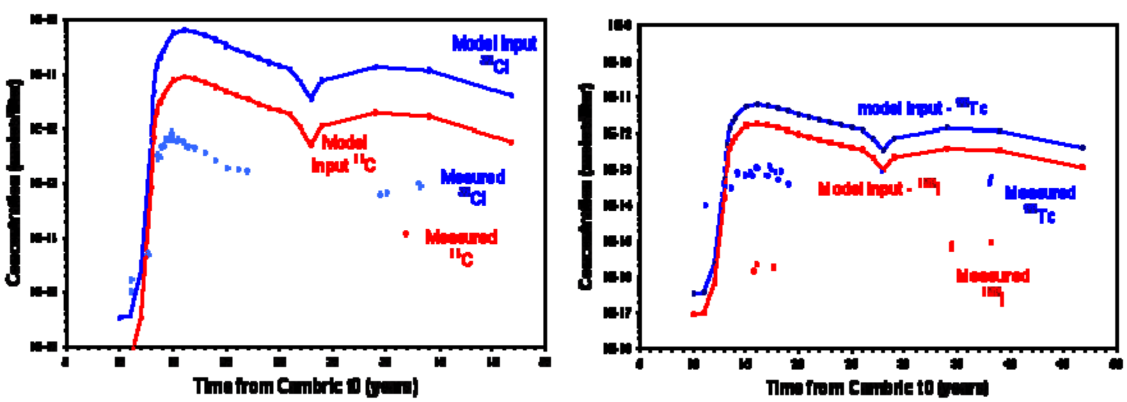

Fig. 3. Comparison of measured concentrations at RNM-2s with assumed FEHM input. (Note that no carbon-14 (^{14}C) was measured at RNM-2s during the CAMBRIC RME, so comparison between observed breakthrough and assumed input is limited to a single measurement after the RME was concluded).

MODEL CALIBRATION AND TESTING

To increase confidence in long-term model forecasts of the extent of contamination from the CAMBRIC ditch, the models were first calibrated against the results of multiple-well aquifer tests that were conducted in 2003 using RNM-2s as the pumping well. The hydraulic properties identified from calibration to the MWAT were further tested by comparing simulated and measured head changes at well UE-5n before, during and after the CAMBRIC RME during the 50-year period between detonation (May 14, 1965) and the year 2015. Assumptions concerning the recharge and radionuclide input functions at the water table beneath the ditch were checked by comparing simulated and measured ^3H increases at well UE-5n during the same time period.

Calibration to RNM-2s MWAT

A 75-day MWAT was conducted from April 26, 2003, to July 10, 2003, by pumping well RNM-2s at a nominal rate of 37.8 l/min (600 gpm) [7]. Water-level recovery monitoring continued until September 10, 2003, for the wells in central Frenchman Flat. Wells RNM-2s, RNM-2, RNM-1 and ER-5-4 showed a distinct response to pumping, whereas there was no discernible response at observations wells ER-5-4, ER-5-4 #2, or UE-5n.

Re-calibration of the three sub-CAU scale models of the Central Testing Area was completed using PEST v.11 [17] to optimize estimates of the hydraulic parameters of the alluvial aquifer (AA), including (1) reference permeability (k_0) at land surface, (2) anisotropy (k_v/k_h) (3) specific storage (S_s) and (4) specific yield (S_y). Calibration data were compared against simulated head measurements at the nodes nearest to the mid-points of the open screened intervals. PEST adjusted the aforementioned model parameters until differences between the measured and simulated drawdowns were minimized.

In the initial calibration results for each of the three sub-CAU models, the match of the models to the data was much better for the RNM-1, RNM-2 and ER-5-4 (piezometer) zones than for the deeper ER-5-4 zone, a result that prompted a decision to de-weight the observations from the latter interval in order to better capture the head changes at the three shallower observation points [2].The estimated k_0 value for the DISP model is higher (log $k_{AA} \approx -9.7$ m^2) than that of the BASE (log $k_{AA} \approx -10.96$ m^2) or NODD (log $k_{AA} \approx -11.46$ m^2) models because the permeability depth decay parameter (λ) values for the AA are larger for the DISP model (5.60e-3 m^{-1}) compared to the BASE (1.93e-3 m^{-1}) or NODD (0.0 m^{-1}) models. Because most of the observations used to constrain the model calibration are in the shallow part of the saturated zone, the reference permeabilities at land surface must be higher when the rate of depth decay is stronger in order to produce similar estimates of permeability in the shallow part of the flow system.

A comparison of the calibrated permeabilities for the sub-CAU models to those estimated by Carle et al. [5] from the same data set showed that the permeabilities in both models are similar in the shallow part of the saturated-zone (220 m to 700 m depth). The main difference between the models is the fine-scale permeability structure used in [5] which was predicated on sediment textural variations observed in UE-5n.

The permeabilities of the re-calibrated sub-CAU models were also compared against the permeabilities of the parent CAU models. In all cases except the BASE model, the sub-CAU models have one to two orders-of-magnitude higher permeabilities than the parent models. For the BASE model, the sub-CAU model has a permeability that is about three times higher than the corresponding CAU model. Because head gradients along the boundaries of the sub-CAU models are fixed by the heads in the parent CAU models, these permeability increases will result in fluxes through the sub-CAU models that will be proportionately higher than those through the corresponding volumes of the CAU models. At steady-state, however, the dominant flow direction in each of the sub-CAU models continues to be toward the southeast, as determined by the boundary conditions mapped from the simulated heads in the parent CAU-scale models.

Model Testing Using Data from Well UE-5n

Simulations of flow and radionuclide transport were carried out for the 50-year period beginning May 14, 1965, and extending until May 2015. This time frame encompassed the period of transient flow arising from RNM-2s pumping during the CAMBRIC RME and the re-infiltration and recharge of RNM-2s discharge through the ditch and playa. The simulations for this period explicitly incorporate the effects of RNM-2s pumping and recharge beneath the ditch and playa using the recharge and radionuclide input functions described previously to account for the dispersal of radionuclides in groundwater. In this section, sub-CAU model results for this period are compared to data from UE-5n to further evaluate model performance.

As illustrated by the results for the BASE model, the sub-CAU models reproduce the observed head changes at UE-5n reasonably well (Fig. 4a), but tend to predict faster and higher ^3H breakthrough at UE-5n than was actually observed (Fig. 4b). Similar behavior relative to the UE-5n data was observed for the DISP-USGS and BASE-USGS (NODD) models [2].

The simulated head responses at well UE-5n shown in Fig. 3a are complex and reflect (1) the onset of pumping from RNM-2s at 18.9 l/s (300 gpm) after 10.4 years, (2) the doubling of the pumping rate at RNM-2s to 37.8 l/s (600 gpm) at 12.3 years, (3) the arrival of recharge beneath the CAMBRIC ditch at about 16.7 years, and (4) the cessation of RMM-2s pumping at 25.5 years. (Note that all times in Figs. 4a and 4b refer to the number of years after the CAMBRIC detonation – May 14, 1965.) The steep rise in simulated water levels at UE-5n after roughly 25.5 years reflects the mounding that takes place beneath the ditch once pumping from RNM-2s had stopped. Each of the three models accurately reproduces the measured peak water table rise of about 0.7 m at UE-5n at about 26.8 years, as well as the gradual recession and return to ambient heads by the end of the 50-year simulation period (May 14, 2015). The rise of up to 1 m evident in the UE-5n head data between 13.7 and 24.6 years during a period when the models indicate that water level should be declining is difficult to explain. This period (roughly spanning the 1980s) could have been a time of poorly documented testing activities involving UE-5n. Alternatively, Wilson et al. [18] summarized evidence that a single large ponding event added a recharge volume of roughly 63,000 m^3 to the nearby WISHBONE crater sometime between the time the test was conducted (February 18, 1965) and 1997 when two boreholes were drilled to characterize moisture conditions beneath and adjacent to the crater. However, based on unsaturated-zone modeling of this hypothesized infiltration event, recharge was not predicted to have reached the water table before the mid 1990s (Wilson et al., 2000). Therefore, this hypothesized ponding event in the WISHBONE crater is probably unlikely to have caused the water-level increases observed at UE-5n throughout the 1980s.

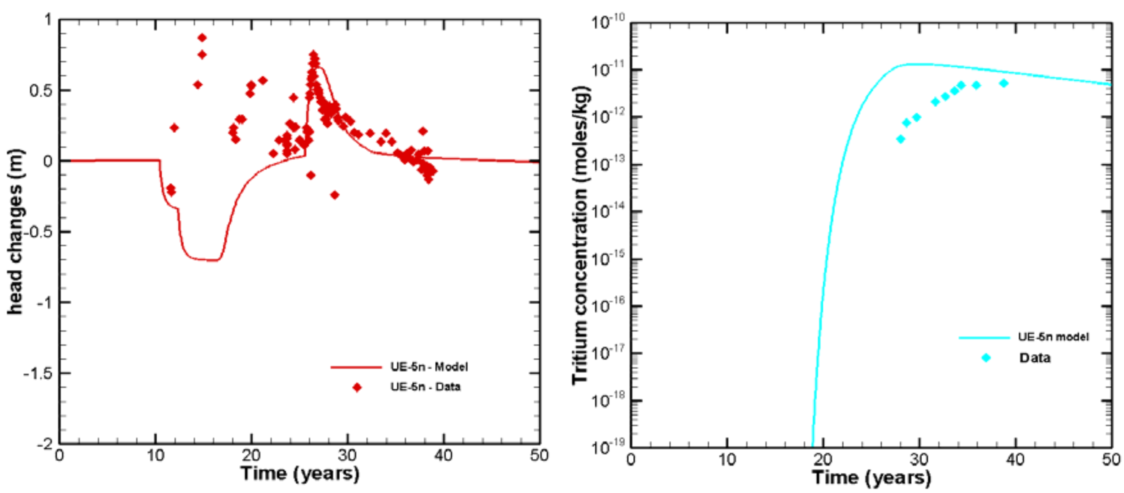

Fig. 4. Comparison of measured and simulated results for well UE-5n (a) head changes and (b) tritium breakthrough[2].

The simulated ^{3}H breakthrough for each of the sub-CAU models is similar to that shown for the BASE-USGS model in Fig. 4b. The simulated ^{3}H breakthrough for each of the 3 models occurs roughly 5.5 years before the measured breakthrough and overpredicts measured peak ^{3}H concentrations by a factor of about two in the BASE and NODD models, and by a factor of three to four in the DISP model. The early arrival and relatively high peak concentrations of ^{3}H in the simulations may be the consequence of several assumptions underlying the development of the ^{3}H input function for the ditch and playa recharge: (1) unsaturated-zone travel times are 3.3 years, (2) no additional dispersion of the RNM-2s ^{3}H source occurs in the unsaturated zone, (3) all of the water pumped from RNM-2s recharges the water table, with 56 percent of the pumped water recharging beneath the ditch, and (4) recharge enters the saturated zone along a 20-m-wide band centered around the ditch. Longer residence times in the unsaturated zone, more dispersion in the unsaturated zone, or lower recharge rates beneath the ditch because of ET (or more flow down the ditch to the playa) are each model changes that would have the expected effect of either lowering the peak concentrations or delaying the simulated peak ^{3}H arrival at UE-5n. However, rather than explore the effects of all these assumptions, the simulated early arrival and high peak ^{3}H concentrations at UE-5n were accepted as providing a reasonable upper bound on the magnitude, rate and extent of likely radionuclide contamination arising from the CAMBRIC RME source. In each of the 3 sub-CAU models, the total mass of undecayed ^{3}H and other long-lived radionuclides was 2.1 moles, or approximately 100 percent of the ^{3}H source term at time zero estimated from the breakthrough of ^{3}H at RNM-2s.

A comparison of the effect of different assumed widths for the recharge zone around the ditch showed almost no difference in the simulated head changes or ^{3}H breakthrough at UE-5n for 20-m and 60-m-wide recharge zones, illustrating that the UE-5n data alone do not provide meaningful constraints on the width of the recharge zone beneath the ditch [2].

The simulations done with the BASE-USGS model were also used to evaluate when hydraulic heads near RNM-2s and beneath the ditch had returned to their long-term following the CAMBRIC RME. The results showed that drawdowns near RNM-2s had recovered and that the groundwater mound beneath the ditch had dissipated by August, 2002 or roughly 12 years after the CAMBRIC RME had ended (November 1990). The estimated extent of the ^{3}H changed relatively little between 2002 and 2015 once head gradients returned to their steady-state values. In addition, the short half-life of ^{3}H (12.3 years) tended to cause the plume to shrink, even as ambient groundwater flow carried the plume to the southeast [2].

RADIONUCLIDE TRANSPORT CALCULATIONS FROM 2015 TO 3015

Extent of the Contaminant Boundary

The three sub-CAU models (BASE-USGS, BASE-USGS [NODD] and DISP-USGS) were used to simulate the transport of radionuclides from the ditch and playa over the 1,000-year period extending from 2015 to 3015. For initial conditions, these simulations used the final head and radionuclide concentrations at the end of the 50-year period produced with the 20-m-wide infiltration zones around the ditch. Whatever small residual head changes near the ditch and playa returned to steady-state during this time. The same tracers (^{3}H, ^{14}C and a non-decaying tracer) were used for this period of the transport analyses as for the first 50 years following the CAMBRIC nuclear test.

The contribution of ^{3}H,^{14}C, ^{36}Cl, ^{99}Tc, and ^{129}I to the contaminant boundary for radionuclides that decay by beta emission is shown for the BASE-USGS model in Fig. 5 for various times during the 1,000-year period starting in 2015. The contour interval in these plots is exponential and extends from the regulatory threshold of 4 mrem/yr to three orders of magnitude below this threshold. Only the parts of the model domain where the dose is colored red exceed the regulatory limit for beta-emitting radionuclides. This limit defines the extent of contaminated groundwater (the contaminant boundary) within the context of the regulatory framework. As shown in Fig. 5, the part of the plume exceeding 4 mrem/yr is at its maximum extent in 2015. By 2115, no groundwater in the Central Testing Area of Frenchman Flat will result in a dose exceeding 4 mrem/yr. The reason for this is that the dose from beta-emitting radionuclides is dominated by ^{3}H, which has a half-life of only 12.3 years. Radioactive decay of ^{3}H causes the part of the plume that exceeds the regulatory limit of 4 mrem/yr to shrink, even as ambient groundwater flow carries the plume downgradient toward the southeast. Plots of individual radionuclide concentrations shown in [2] for the BASE-USGS and the other sub-CAU models show that only ^{3}H ever exceeds the 4 mrem/yr standard for beta-emitting radionuclides, even immediately after the CAMBRIC RME. Likewise groundwater U concentrations never exceed the regulatory limit of 30 micrograms/L even though the simulations do not take credit for the fraction of the U that was incorporated in the melt glass (Table I) nor do they take credit for sorption of U on the alluvium.

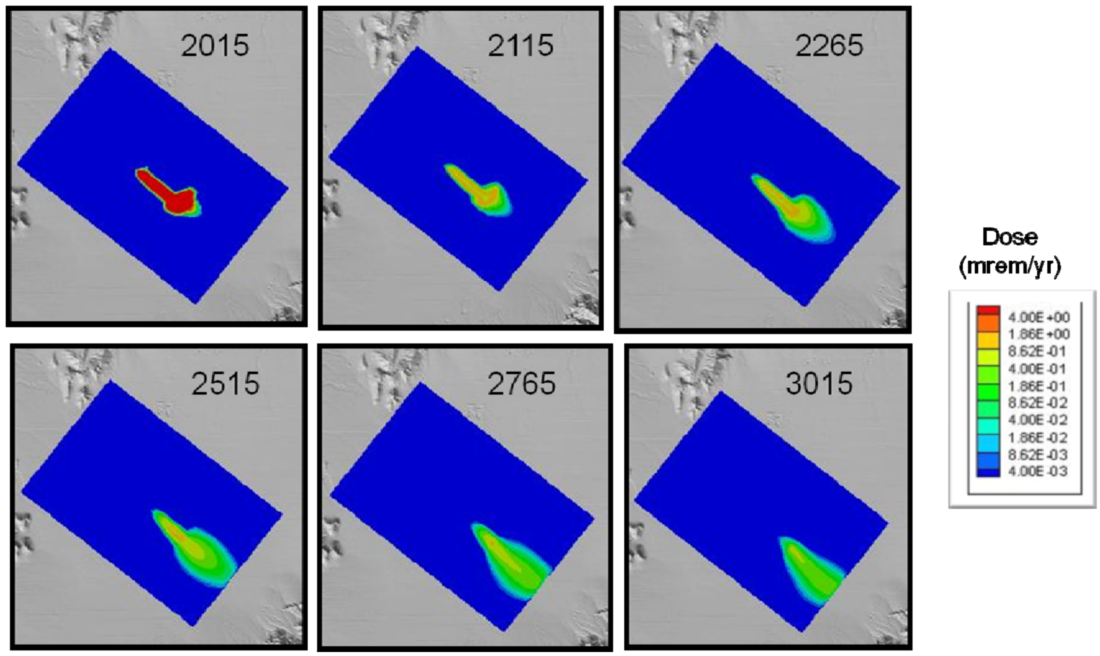

Fig. 5. Dose contribution from beta-emitting radionuclides ^{3}H, ^{14}C, ^{36}Cl, ^{99}Tc, and ^{129}I at various times calculated with the BASE-USGS model.

A comparison of the results obtained with the BASE-USGS models and the other sub-CAU models shows that differences in the extent of contaminated groundwater defined by the 4 mrem/yr regulatory standard are small. Because of the radioactive decay of ^{3}H, the extent of the 4 mrem/yr boundary depends almost entirely on the groundwater concentrations of ^{3}H at early times (2015 to 2065), before differences in the shallow groundwater velocities and boundary heads have had a chance to exert a large effect on plume migration distances.

Effects of Numerical Dispersion in the BASE-USGS Model

The computational mesh is very refined (4 x 4 x 4 m) in the area of the ditch and playa, but coarsens by factors of two until it is eventually 128 x 12 8x 128 m in the downgradient area southeast of the playa. To address possible concerns that dilution because of numerical dispersion (rather than radioactive decay of ^{3}H) is limiting the downgradient migration of the plume, the simulation with the BASE-USGS model was re-run with the radioactive decay of ^{3}H turned off. Without the benefit of radioactive decay, a plume with ^{3}H concentrations equivalent to or greater than a dose of 4 mrem/yr would migrate toward and eventually reach the southeast boundary of the model [2]. This indicates that it is indeed radioactive decay of ^{3}H rather than grid effects that limit the downgradient migration of the plume.

Investigation of the Effects of Groundwater Withdrawals for Water Supply on ^{3}H Plume Migration in Central Frenchman Flat

Concerns over the effects of past, present and future groundwater withdrawals for water supply on ^{3}H plume migration rates and trajectories in central Frenchman Flat prompted the development of a new model to address this issue. Consequently, the original sub-CAU model used in the simulations shown in Fig. 1 was extended to the southeast by several kilometers in order to encompass water supply wells WW-5a, WW-5b and WW-5c (Fig. 1) and thereby allow the possible effects of pumping from these wells to be investigated.

Between 1975 and 1990, groundwater withdrawals from WW-5b and WW-5c were overshadowed by water withdrawals from well RNM-2s during the RME. For these 16 years, well RNM-2s pumped more or less continuously at 37.8 l/s, or roughly 1,200,000 m^3 per year. Based on the proximity of well RNM-2s to the CAMBRIC ditch and its much larger pumping rates, the effects of RNM-2s pumping and the subsequent re-infiltration of RNM-2s discharge dominate the transient head response in the vicinity of the ditch [2]. Simulations done with and without pumping from water supply wells also show that the extent of the ^{3}H plume associated with CAMBRIC RME discharge is unaffected by pumping from water supply wells WW-5a, WW-5b and WW-5c between 1965 and 2015, assuming present-day (2008) rates continue until 2015. Likewise, the possible effects of long-term pumping from water supply wells WW-5b and WW-5c on the ^{3}H plume migration over the next 1,000 years were investigated by comparing the simulated ^{3}H plumes both with and without pumping from the water supply wells. For the 1,000-year period between 2015 and 3015, pumping rates were assumed to be the average pumping rates for the years 1998 to 2008 (124,227 m^3/yr at WW-5b and 80,191 m^3/yr at WW-5c). A comparison between the simulated ^{3}H plumes with and without pumping [2] shows that there are no significant differences in ^{3}H plume behavior for the 150 years between 2015 and 2165, after which time the ^{3}H concentrations are well below the SDWA standard (20,000 pCi/L, or $6.88 \cdot 10^{-13}$ moles/L). The contaminant boundary, which is defined completely by ^{3}H in central Frenchman Flat, is therefore also expected to be unaffected by long-term pumping from water supply wells WW-5b and WW-5c, assuming these wells pump at no more than their recent historic rates.

SUMMARY AND CONCLUSIONS

A set of sub-CAU models was created for the Central Testing Area of Frenchman Flat that integrate various aspects of the basin-scale CAU-models for Frenchman Flat [9] and transient HST models for the Central Testing Area [5]. The sub-CAU models were used to simulate the transport of radionuclides re-introduced into groundwater beneath the CAMBRIC ditch and Frenchman Lake playa during and after the 16-year-long CAMBRIC RME. The sub-CAU models use a range of assumptions about the presence and strength of permeability depth decay in the AA that correspond to those made in the BASE-USGS, BASE-USGS (NODD), and DISP-USGS CAU-scale models on which the sub-CAU models are based. To ensure consistency in flow directions between the corresponding CAU and sub-CAU models, boundary conditions for the sub-CAU models were determined by interpolating steady-state heads from nodes in the parent CAU model onto nodes along the sub-CAU model boundaries. Enhanced grid refinement around the CAMBRIC ditch and playa, and around wells involved in the CAMBRIC RME or the RNM-2s MWAT allowed the sub-CAU models to be recalibrated using data collected during the MWAT and tested against data collected during and after the RME. The re-calibrated sub-CAU models had higher AA permeabilities and generally, less anisotropy than the corresponding CAU models.

The sub-CAU models did not attempt to model the breakthrough of radionuclides from the CAMBRIC cavity to pumping well RNM-2s explicitly. Rather, the sub-CAU models focused on the dispersal of radionuclides into groundwater beneath the CAMBRIC ditch and Frenchman Lake playa by using recharge functions in which radionuclide concentrations were estimated from observed breakthrough curves at RNM-2s, mass-balance considerations, and the results of HST modeling. Only radionuclides that were observed to break through at RNM-2s during the CAMBRIC RME, or which, in the absence of measurements, were predicted to break through based on HST modeling were considered in the sub-CAU models. The radionuclides either directly or indirectly included in the simulations were ^{3}H, ^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I and U. Other radionuclides either did not break through at RNM-2s or broke through at concentrations that were too low to warrant inclusion in the sub-CAU models. The impact of less mobile radionuclides in the CAMBRIC cavity as well as radionuclide contributions from the WISHBONE and DILUTED WATERS tests on the contaminant boundary was investigated in a separate modeling step and found to be minor [2]. In the models summarized here, only ^{3}H, ^{14}C and a non-decaying tracer were explicitly simulated in the sub-CAU models. The concentrations of ^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I and U were estimated from the undecayed ^{3}H breakthrough at RNM-2s and scaled in a post-processing step using the molar ratio of individual radionuclide species to ^{3}H listed in the unclassified radionuclide inventory for CAMBRIC at time zero (May 14, 1965) [5].

Simulations were carried out for a 50-year transient flow period extending from 1965 to 2015 followed by a 1,000-year steady-state flow period extending from 2015 to 3015. The maximum extent of the contaminant boundary is likely to be dominated by groundwater ^{3}H concentrations between 2015 and 2065. After this time, radioactive decay will reduce ^{3}H concentrations to levels that cause the dose from mobile, beta-emitting radionuclides to drop below the regulatory threshold of 4 mrem/yr. In fact, without ^{3}H, the concentrations of other longer-lived, non-sorbing beta-emitters (^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I) do not result in a dose that exceeds this threshold at any time. Likewise, U concentrations are not high enough to exceed the regulatory threshold for U (30 µg/L) at any time during the 1,000-year compliance period.

The fact that ^{3}H will define the contaminant boundary, and the likelihood that the maximum extent of contaminant boundary will be reached before 2065, makes differences in the flow fields less important than might be expected for defining the contaminant boundary. Small differences in the flow directions and the permeability structure of the models affect transport significantly only at late times (250 to 1,000 years), long after ^{3}H has decayed well below its regulatory threshold. Present and expected future water withdrawals from water supply wells in Frenchman Flat were shown to have a negligible impact on the distribution of contaminated groundwater, in part because of the effect of radioactive decay on the concentration of ^{3}H in the groundwater.

REFERENCES

1. U.S. DEPARTMENT OF Energy, NEVADA OPERATIONS OFFICE. *United States Nuclear Tests, July 1945 through September 1992,* DOE/NV--209, Rev. 15. Las Vegas, NV (2000).
2. NAVARRO NEVADA ENVIRONMENTAL SERVICES, LLC. *Phase II Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada,* N-I/28091-004, Rev. 1. Prepared for the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office. Las Vegas, NV (2010).
3. BRYANT, E.A. *The Cambric Migration Experiment*, A Summary Report, LA-12335-MS. Los Alamos, NM: Los Alamos National Laboratory (1992).
4. TOMPSON, A.F.B., D.K. SMITH, G.B. HUDSON, and J.R. HUNT. "Analysis of Radionuclide Migration through a 200-m Vadose Zone Following a 16-Year Infiltration Event." In *Advances in Water Resources*, Vol. 29, pp. 281-292 (2006).
5. CARLE, S.F., R.M. MAXWELL, G.A. PAWLOSKI, D.E. SHUMAKER, A.F.B. TOMPSON, and M. ZAVARIN. *Evaluation of the Transient Hydrologic Source Term for the Cambric Underground Nuclear Test at Frenchman Flat, Nevada Test Site*, UCRL-TR-226916. Livermore, CA: Lawrence Livermore National Laboratory (2007).
6. BECHTEL NEVADA. *A Hydrostratigraphic Framework Model and Alternatives for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Clark, Lincoln, and Nye Counties, Nevada*, DOE/NV/11718--1064. Prepared for the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office. Las Vegas, NV (2004).
7. STOLLER-NAVARRO JOINT VENTURE. *Phase II Hydrologic Data for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada,* S-N/99205--032, Rev. 0. Prepared for the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office. Las Vegas, NV (2004).
8. TYLER, S.W., J.B. CHAPMAN, S.H. CONRAD, D.P. HAMMERMEISTER, D.O. BLOUT, J.J. MILLER, M.J. SULLY, and J.M. GINANNI "Soil-Water Flux in the Southern Great Basin, United States: Temporal and Spatial Variations Over the Last 120,000 Years." In *Water Resources Research*, 32: 1481-1499 (1996).
9. STOLLER-NAVARRO JOINT VENTURE. *Phase II Groundwater Flow Model of Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nye County, Nevada*, S-N/99205--074. Las Vegas, NV (2006).
10. HOFFMAN, D.C., R. STONE, AND W.W. DUDLEY, JR. *Radioactivity in the Underground Environment of the Cambric Nuclear Explosion at the Nevada Test Site*, LA-6877-MS. Los Alamos, NM: Los Alamos Scientific Laboratory (1977).
11. HOFFMAN, D.C. "A Field Study of Radionuclide Migration." In *Geologic Storage*, S. Fried (ed.) pp. 149-166. Washington, DC: American Chemical Society (1979).
12. MIZELL, S.A., J.J. MILLER, and R.H. FRENCH. "Effect of Soil Condition on Channel Transmission Losses During Ephemeral Flow Events, Part 2," EWRI 2005: Impacts of Global Climate Change. In *Proceedings of the 2005 World Water and Environmental Resources Congress*, May 15-19. Anchorage, AK (2005).
13. ROSS, W.C., and S.W. Wheatcraft. *A Two-Dimensional Simulation of Tritium Transport in the Vadose Zone at the Nevada Test Site*, DOE/NV/10162--21. Las Vegas, NV: Desert Research Institute (1994).
14. BIGGS, TRENT, A. ALY, and G. RUSKAUFF. "CAMBRIC Ditch Water-Balance Analysis Site." In *Phase II Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada,* N-I/28091--004, Rev. 1, Appendix A. Prepared for the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office by Navarro Nevada Environmental Services, LLC. Las Vegas, NV (2010).

15. ZYVOLOSKI, G.A., B.A. ROBINSON, Z.V. DASH, and L.L. TREASE. *Summary of Models and Methods for the FEHM Application – A Finite Element Heat and Mass-Transfer Code*, LA-13307-MS. Los Alamos, NM: Los Alamos National Laboratory (2003).
16. BOWEN, S.M., D.L. FINNEGAN, J.L. THOMPSON, C.M. MILLER, P.L. BACA, L.F. OLIVAS, C.G. GEOFFRION, D.K. SMITH, W. GOISHI, B.K. ESSER, J.W. MEADOWS, N. NAMBOODIN, and J.F. WILD. *Nevada Test Site Radionuclide Inventory, 1951-1992*, LA-3959-MS. Los Alamos, NM: Los Alamos National Laboratory (2001).
17. DOHERTY, J. *PEST: Model-Independent Parameter Estimation, User's Manual*, Version 11. Watermark Numerical Computing: Brisbane, Australia (2008).
18. WILSON, G.V., D.M. ELY, S.L. HOKETT, and D.R. GILLESPIE. "Recharge from a Subsidence Crater at the Nevada Test Site." In *Soil Scientist Society of America*, Vol. 4: 1570-1581 (2000).

DOE/NV--1339