ER-20-12: A Case Study of Corrective Action Investigation in a Challenging Environment-17236

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ABSTRACT

Low-level tritium was unexpectedly detected in 2010 in a monitoring well located more than three kilometers (km) downgradient of an area formerly used for underground nuclear testing. The approach used by the U.S. Department of Energy (DOE) to investigate potential sources for the tritium is an exemplary case study of corrective action investigation at the Nevada National Security Site (NNSS).

Multiple challenges presented themselves during the course of the investigation, ranging from difficulties associated with confirming the presence tritium within the well to a field site characterized by remote, rugged terrain, high elevation, inclement weather, great depths to groundwater, complex geology, and residual surficial contamination originating from the near-surface detonations of two large-scale nuclear plowshare tests. Limited resources required a judicious process for evaluating competing conceptual models. Timely communication of monitoring results to stakeholders and early involvement of regulatory authorities in the planning process were critical components of the overall investigation.

INTRODUCTION

The U.S. Department of Energy (DOE) Office of Environmental Management is responsible for characterizing subsurface radionuclide contamination originating from underground nuclear tests conducted on the Nevada National Security Site (NNSS). It is also responsible for developing and implementing corrective action strategies that mitigate risks to human health and the environment posed by the potential migration of these radionuclides via groundwater transport. Actions taken to address these obligations are conducted within a program called the Underground Test Area Activity (UGTA). This program has been actively characterizing the geology, hydrology, and radionuclide transport from underground nuclear tests since 1993.

Numerous challenges must be overcome to successfully investigate radionuclide transport from an underground nuclear test. These challenges are exemplified in a case study that documents the detection and identification of the source of a contaminant plume in the far northwestern corner of the NNSS in a region known as Pahute Mesa (Fig. 1). Pahute Mesa covers an area of approximately 630 km^2 and ranges in elevation from below 1,650 m on the northern and southern margins to

2,295 m in the eastern portion. Detailed investigations of the geology of Pahute Mesa were initiated during the late 1950s to evaluate the site and support efforts to contain underground nuclear tests. These investigations have shown that Pahute Mesa is underlain by six overlapping calderas (partially shown in Fig. 1) that

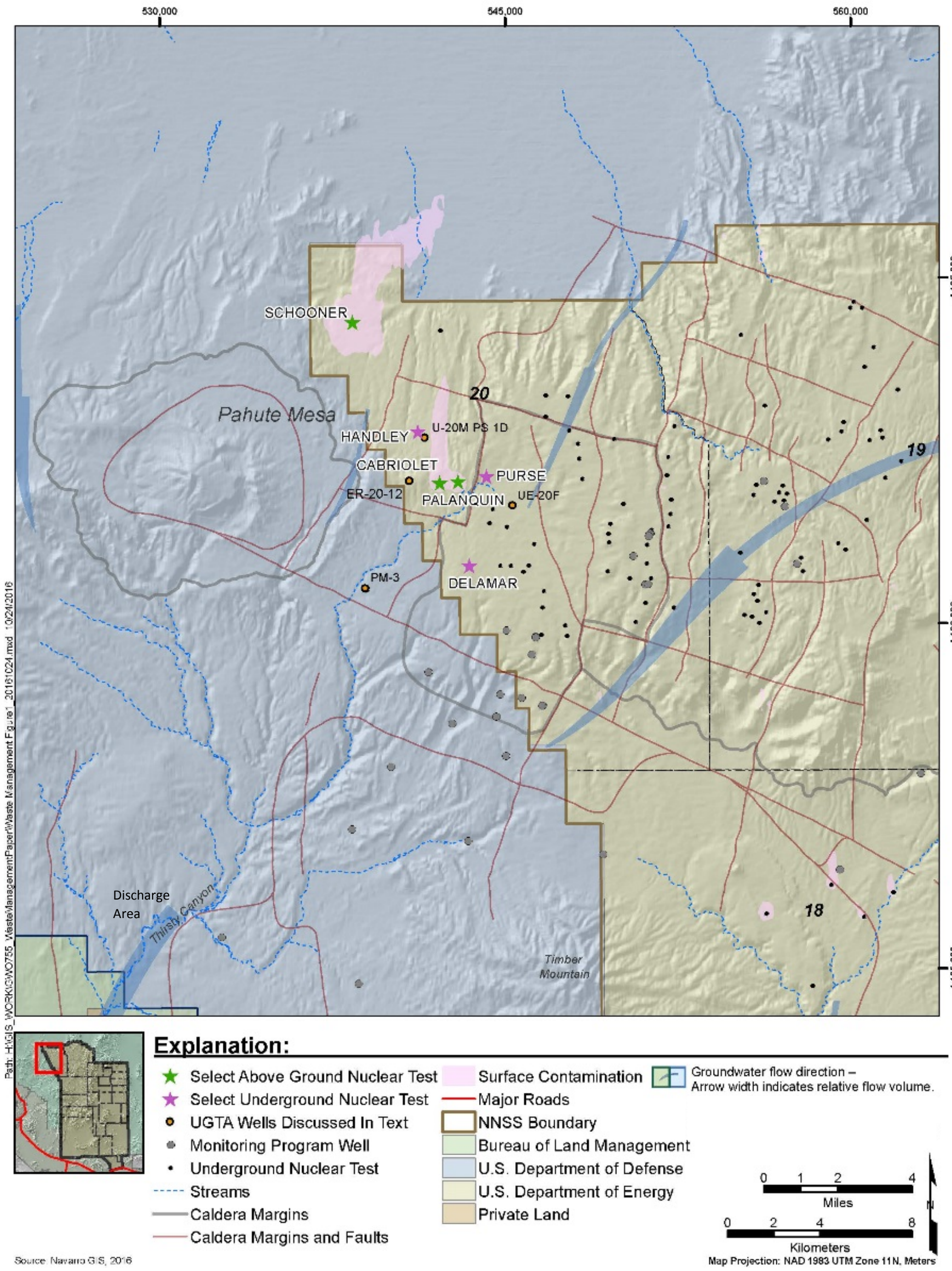

Fig. 1. Location map Showing Study Area, Boundaries of the NNSS, Locations of Nuclear Tests [1], Locations of Monitoring Wells, Major Geologic Structures [2], Groundwater Flow Directions [3] and Discharge Areas [4].

erupted a complex assemblage of lava flows, welded tuffs, and bedded tuffs between 15 and 9 mega-annum (Ma) [5]. The assemblage of Tertiary volcanic rocks is exceedingly thick. The deepest borehole on Pahute Mesa (UE-20f) encountered Tertiary volcanics throughout its entire depth of 4,171 m [6]. Extensional tectonics have resulted in the presence of multiple north-south trending normal faults that offset the Tertiary volcanic rocks within the area. Hydrologic investigations were initially conducted to better understand the presence and occurrence of groundwater so that shafts could be mined to support the underground nuclear testing program. An extensive number of wells were drilled in the area to identify the depth to water, transmissivities, and hydraulic gradients [6]. The depth to groundwater ranges from 263 m in the northwestern part of Pahute Mesa to 715 m in the eastern portion [6]. Groundwater gradients indicate that flow is to the southeast toward discharge areas near Beatty, Nevada. The most permeable units in the subsurface tend to be lava flows and welded tuffs, which are units that are dominated by fracture flow. Nonwelded ash-fall tuffs, which are zeolitized at or below the water table, tend to act as aquitards [7].

The first underground nuclear tests at Pahute Mesa were conducted in 1965 and the last test was conducted in 1992, with a total of 82 tests being conducted at Pahute Mesa (Fig. 1 [1]). Pahute Mesa is the location of some of the largest underground nuclear tests conducted on the NNSS. Approximately 60 percent of all radioactivity deposited in the subsurface of the NNSS as a result of underground nuclear testing (1.65 x 10^{18} Becquerel (Bq) as of September 30, 2012) can be found in Pahute Mesa, with 45 percent of the total activity being located in western Pahute Mesa [8].

Geologic and hydrologic characterization of groundwater flow and radionuclide transport continued under the auspices of the UGTA activity after underground nuclear testing ceased in 1992. Two rounds of characterization efforts have been conducted. The initial round of characterization was principally performed from 1999 to 2007 and consisted of the drilling, hydraulic testing, and geochemical sampling of eight wells; resistivity, electromagnetic, and gravity geophysical surveys; geologic mapping; recharge studies; geochemical flow path and radiochemical source term analyses; and tracer tests, colloid studies, and laboratory studies of matrix diffusion [9]. Data from these characterization activities were analyzed and used to create a large-scale numerical model of groundwater flow and radionuclide transport for the area of interest (Fig. 2).

An analysis of the modeling results indicated that parametric uncertainty was significant enough to warrant an additional round of characterization and modeling. A second round of characterization activities was initiated in 2009 and continues to this day. Characterization activities include the drilling, hydraulic testing, and geochemical sampling of 10 new wells; refined water-level and hydraulic gradient analyses; 16 multiple-well aquifer tests; radionuclide source-term analysis; fracture analysis; and simplified modeling to reconcile boundary fluxes and recharge with known groundwater discharge [10].

Routine monitoring of the hydrologic system has been ongoing since the early 1970s under the auspices of several different programs, including the Environmental Protection Agency's Long-term Hydrologic Monitoring Program and the DOE's Routine Radiological Environmental Monitoring Program (RREMP). One of the wells routinely monitored for the presence of tritium is Well PM-3. Well PM-3 was originally drilled in 1988 to characterize the geology and hydrology of an extra-caldera environment west of the NNSS (Fig. 1). The sparse water levels in this

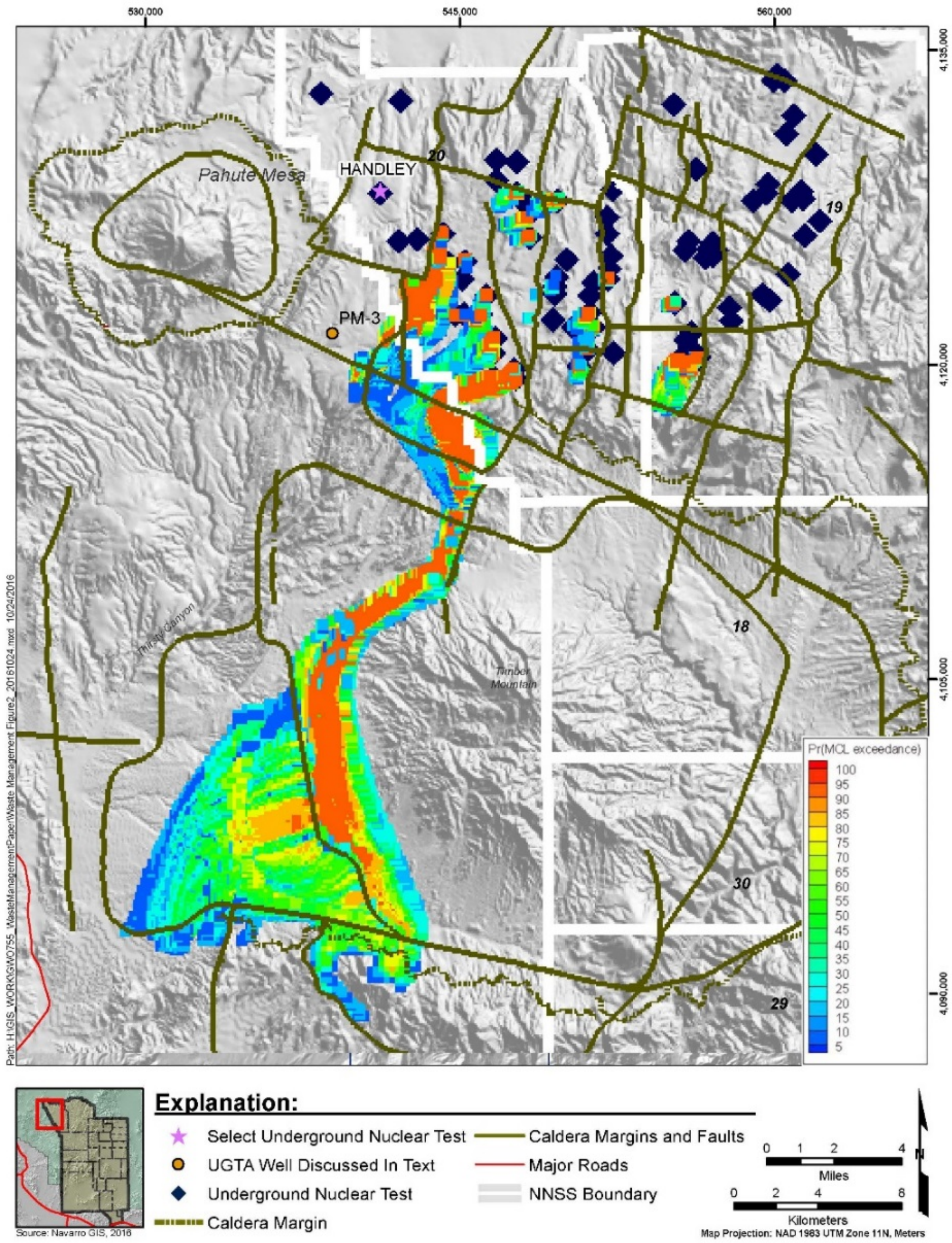

Fig. 2. Map Showing an Ensemble of Contaminant Transport Results after 50 years as forecasted by the Phase I Model. Colors Represent a Frequency (in terms of percent) that a Given Model Node Exceeded the Maximum Contaminant Level for Alpha Particles, Beta Emitters, or Uranium [11].

area suggested that Well PM-3 was on the western limb of a trough in the potentiometric surface, which was originally interpreted as being upgradient of underground nuclear tests on the NNSS [12]. Single well aquifer tests indicated that the hydraulic conductivity of the formations intersected by this well were moderate (1.1 x 10^{-6} m/s [13]).

Tritium monitoring results for Well PM-3 are shown in Fig. 3. The initial samples collected in the late 1980s were from the open borehole before it was completed into an upper (PM-3-2) and lower (PM-3-1) piezometer in 1992. Completion zones were selected based on their relatively greater transmissivity [13]. A gap of 10 years in sample collection occurred before the well was resampled in 1999 as part of the UGTA's initial round of characterization efforts on Pahute Mesa. An analysis of tritium activity from samples bailed on December 10, 1999, indicated a high-level of activity (9,842 Bq/l). Knowledge of the sampling process identified that the likely source of tritium was a contaminated bailer. This was confirmed by a second round of sampling conducted a month later that resulted in the nondetection of tritium (<10.4 Bq/l).

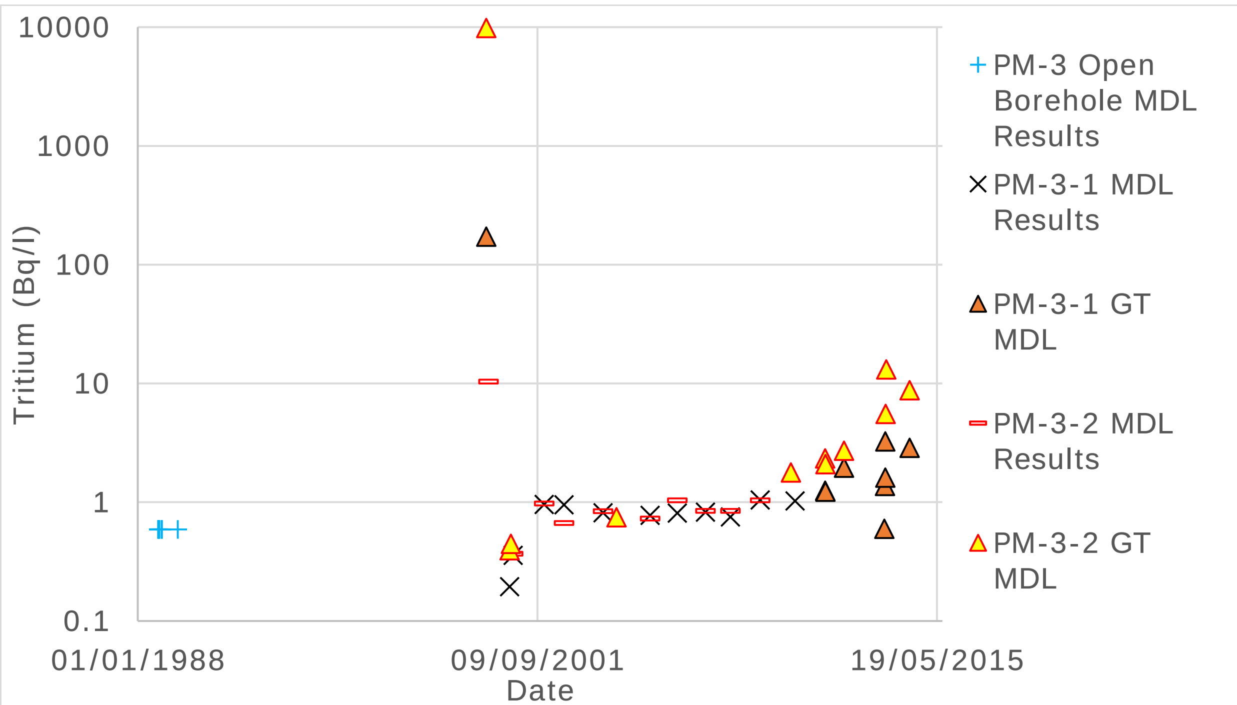

Fig. 3. Time Series of Well PM-3 Tritium Activity (Open Symbols Indicate Sample Results Were Less Than the Minimum Detection Level (MDL). Closed Symbols Indicate Sample Results were Greater Than the Minimum Detection Level (GT MDL) (modified from [14]).

Samples have been bailed from the well on roughly an annual basis since 1999. Most results were below detection. A low-level detection occurred in two samples collected from the upper piezometer in the fall of 2000 (0.4 Bq/l). These results were marginally above their detection limit and were thought to represent residual tritium in the well left over from the contaminated bailer. A second low-level detection (0.7 Bq/l) occurred in a sample obtained from the upper piezometer in 2004, but it was not confirmed by analyzing a duplicate sample collected that same day [15]. Tritium was again detected in the upper piezometer in 2010 (1.8 Bq/l). This time, the detection was confirmed by analyzing the field duplicate [16]. Tritium activities of these samples were a factor of two greater than the detection limits. These results generated a great deal of interest within DOE because of the distance of the monitoring well to the closest underground test (7 km). It was decided that the well would be sampled in 2011 by both the RREMP and UGTA. Samples were collected and the analysis revealed that there was detectable tritium within both the upper and lower piezometers (2.3 and 1.3 Bq/l, respectively [17]). Confirmation of tritium within the well initiated a series of events that ultimately led to the identification of the source of the tritium.

EVALUATION OF OPTIONS

The detection of low-level tritium in this well was surprising. Previous conceptions based on sparse water-level data had groundwater in this well originating from the north or northwest [13] rather than the north-northeast as depicted in Fig. 1. Previous modeling efforts [11] indicated that water emanating from the underground nuclear tests would generally flow to the east of Well PM-3 and that the rates of contaminant transport were negligible (Fig. 2) because of the moderate hydraulic conductivities reported for the units in this area [13].

The first action taken in response to the detection of low-level tritium in Well PM-3 was to report the results and notify stakeholders. The results were reported in the Annual Site Environmental Reports [15, 16, and 17]. The DOE verbally notified the Nevada Division of Environmental Protection (the regulatory authority for the UGTA), a presentation regarding the matter was given to the Nevada Site Specific Advisory Board (a board consisting of citizen volunteers that provides DOE's Office of Environmental Management with independent advice and recommendations), and notifications were posted at town hall style meetings held in the downgradient communities. Informal updates were also provided to the Nevada Division of Environmental Protection on an as-needed basis to keep them updated and to provide a forum for their input if they so desired.

The DOE requested a report that summarized the available hydraulic and geochemical data from Well PM-3 [14]. The report reviewed underground tests in the area and concluded that the likeliest source of tritium in Well PM-3 was the Handley underground nuclear test given its relative position within a recent reinterpretation of the potentiometric surface [3], similarities in water chemistry with water in Well PM-3, and a depth of burial for Handley such that radionuclides generated by the underground test were injected directly into the saturated zone. The report also noted several requirements that needed to be satisfied for this conclusion to be valid, namely that an extensive (greater than 7 km long) high permeability pathway needed to exist between the source and receptor coupled with an average linear groundwater velocity of approximately 170 m/yr (which would be the fastest observed groundwater velocity on the NNSS if confirmed). The report recommended the following: continued monitoring of Well PM-3 using enriched tritium and the need to purge Well PM-3 to improve the representativeness of the samples.

The piezometers at Well PM-3 are 7.3 cm in diameter, which necessitates the use of slim-hole pumping technology. Arrangements were made to acquire a sucker rod pump to develop and sample the well. The two piezometers were purged and sampled during August 2013 [18]. An extensive suite of geochemical parameters were collected, including water-quality parameters, major ions, trace elements, stable and radioactive isotopes, and noble gases. An analysis of the samples indicated that tritium activities within the upper and lower piezometer had increased to 13.1 and 5.6 Bq/l, respectively (Fig. 3), and that C-14, and possibly Cl-36 activities, were greater than the levels typically detected in uncontaminated wells at Pahute Mesa. A report documenting the results [18] identified several additional alternative sources for the tritium observed in the well. These include drilling fluids lost in the well in 1992 when the well was being recompleted, localized infiltration near the wellhead carrying atmospherically derived tritium down the well annulus (which is open from 28.3 to 403.3 m bgs), and enhanced infiltration of runoff from a nearby ephemeral channel whose headwaters include two nuclear surface cratering events, Palanquin and Cabriolet (Fig. 1). Both tests deposited a significant amount of radioactivity at the surface and both are located at the upper end of a watershed drained by an ephemeral channel that falls within 310 m of the location of Well PM-3 (Fig. 1).

In October 2014, a panel of subject-matter experts was convened that included geologists, hydrogeologists, radiochemist, numerical modelers, and a representative from the Nevada Division of Environmental Protection to evaluate the data from Well PM-3, consider alternative sources of tritium, and recommend a course of action to further characterize the source of tritium. All of the aforementioned hypotheses were considered. Advective transport of radionuclides from Handley was considered the likeliest scenario. Recent reinterpretation of the hydraulic gradient [3] coupled with potential anisotropy imparted by the preferred orientation of fractures and faults in the area resulted in Well PM-3 being considered downgradient of the Handley nuclear test. The Belted Range aquifer was encountered in Well PM-3 and is thought to provide a continuous flow path from the Handley chimney to Well PM-3, although a complication exists with this conceptual model. The Belted Range aquifer intersects Well PM-3 at a depth of approximately 900 m bgs, whereas the highest tritium activities detected in the well occur at a depth of 511 m in a confining unit. The measured vertical gradients at Well PM-3 are such that groundwater should be flowing downward rather than upward in the vicinity of the well. Two other potential underground tests were discussed as possible sources. These tests were Delamar and Purse, although their positions relative to regional hydraulic gradients make them less suitable as potential sources of the tritium found in Well PM-3 (Fig. 1).

The infiltration of surface water either locally around the wellhead or through a nearby ephemeral channel was also discussed. Localized infiltration and leakage down the well annulus was considered possible, especially if fluid stored in the sump was used as the infiltration source. The flaw with that conceptual model is that insufficient tritium has been associated with localized water sources to account for what has been observed within well. This is also true for the water lost in Well PM-3 during recompletion activities. Surface water transport of tritium from the nuclear cratering experiments Palanquin or Cabriolet coupled with localized infiltration through the ephemeral wash located 310 m north of Well PM-3 was also considered. This was determined to be unlikely because a radiation survey conducted in 1994 revealed that gamma emitters associated with the Palanquin and Cabriolet cratering events had not been redistributed due to surface water runoff

(Fig. 1 [19]), although tritium (which would have been undetected by the survey) may have been redistributed because of its greater mobility.

The committee was requested to evaluate potential characterization activities in light of what was known about tritium at Well PM-3, the various hypotheses that had been presented to explain its presence, and the uncertainties associated with those explanations. Potential characterization activities included continued monitoring at Well PM-3, expanded monitoring to include chlorofluorocarbons and noble gases as an indicator of recently recharged water at the site, drilling a single characterization well upgradient of Well PM-3, drilling multiple characterization wells upgradient of Well PM-3, conducting geophysical surveys across the ephemeral wash coupled with coring to look for elevated activity of soil-water tritium, monitoring surface emissions of noble gases that have radiogenic precursors to track potential plumes at the water table, and conducting detailed gamma ray surveys of the ephemeral wash to look for more recent transport. The committee unanimously supported continuous monitoring at Well PM-3. Opinions varied as to the other characterization options. Some on the committee thought that a phased approach was optimal, with additional characterization activities conducted only if tritium activities rapidly increased at Well PM-3. Others thought multiple wells might need to be drilled to definitively characterize the source of the plume. Some thought a single well would suffice, however, several challenges associated with siting a single well were identified. Siting a well too close to Handley would optimize the chance of encountering the plume, but would be less informative regarding tritium transport seven kilometers downgradient at Well PM-3. Siting a well too far from Handley would increase the probability of missing the plume, especially for transport in fractured rock. The general opinion of the committee was that advective transport from Handley was the likeliest candidate, so characterization activities directed at that conceptual model were preferred. The Nevada Division of Environmental Protection member of the committee supported the single-well characterization strategy. This was an important factor that DOE considered while determining the ultimate path forward.

CHARACTERIZATION ACTIVITIES

As part of their decision making process, the DOE considered the recommendations of the committee, evaluated the various potential sources of tritium and the effects on the closure strategy if specific release mechanisms were not investigated, and considered the economic impacts and side benefits generated by implementing each characterization activity. The characterization option determined to maximize both short- and long-term benefits was the single-well option. The DOE authorized UGTA contractors to begin the process of siting, constructing, and testing the well.

The aforementioned committee of subject matter experts reconvened in January 2015 and its ranks were expanded to include a drilling engineer. The goal of the committee was to develop a set of scientific criteria for the well; identify its optimal location, depth, and target hydrostratigraphic units; and establish contingencies for dealing with anomalously high levels of tritium at unanticipated depths within the borehole.

The location of the well was selected (Fig. 1) assuming that Handley was the source of tritium found in Well PM-3 coupled with a detailed analysis of the potentiometric surface and potential transport pathways. The planned depth of the well was 1,250 m to intersect the lowermost potentially contaminated aquifer, the Pre-Belted Range composite unit (PBRCM). The objectives for this well were to determine the deepest contaminated aquifer; the vertical distribution of tritium in the well; the lithology, stratigraphy, and hydraulic characteristics of units intersected by the borehole; and to construct the well in order to monitor the most productive, laterally extensive aquifers that contain tritium.

Surveys to site the road and pad were initiated early in 2015. The surveys had to consider both the steep topography of the area and the presence of two fallout plumes [19] left over from the detonation of Palanquin and Cabriolet (Fig. 1). Archaeological and biological surveys followed to ensure that sensitive biological and cultural resources were not affected by well drilling activities. Road and pad construction were completed in September 2015. The drilling rig was mobilized to the site and drilling commenced on October 9, 2015. Drilling was conducted 24 hours per day, 7 days per week. Additional safety precautions taken during the drilling of this well included on-site radiation technicians in case elevated levels of radionuclides were encountered and on-site emergency medical technicians due to the site being located approximately 70 kms from the nearest medical facilities. Drilling fluids were routinely monitored for tritium to determine if the well had intersected contaminated plumes. Wind speeds were strong enough that work needed to be periodically suspended. Winds also blew spent drilling fluids toward the work areas, necessitating the construction of a wind barrier and modifications to the drilling fluid discharge line to prevent drilling fluid from coming into contact with the workers.

One of the first surprises during the drilling of this well was that the uppermost saturated aquifer was not the Timber Mountain lower vitric-tuff aquifer (TMLVTA) that had been planned for, but the Timber Mountain welded-tuff aquifer (TMWTA), which stratigraphically overlies and is in direct contact with the aforementioned unit (Fig. 4 [20]). Detectable levels of tritium (up to 2,234 Bq/l) were also found in the drilling fluids that circulated past both aquifers. The drilling plan was slightly modified to accommodate monitoring the two aquifers as a combined monitoring point. The borehole was reamed from an original diameter of 47 cm to a new diameter of 66 cm extending from the land surface to a total depth of 765.1 m. This was done to allow for all completions in the deeper portion of the boreholes as planned. Cement was emplaced at the bottom of the reamed portion to seal this contaminated zone from deeper, potentially uncontaminated units. Drilling of the borehole continued to a total depth of 1,384.8 m bgs. The borehole penetrated several additional aquifers and confining units. Tritium was present in most of the units, but the highest activities were encountered in the PBRCM as predicted. The well was completed with the main casing located in the PBRCM and four piezometers accessing the following units: the Belted Range aquifer (BRA), the Calico Hills zeolitic composite unit (CHZCM) at two different depths, and the uppermost piezometer, which monitors the TMWTA and the TMLVTA as previously

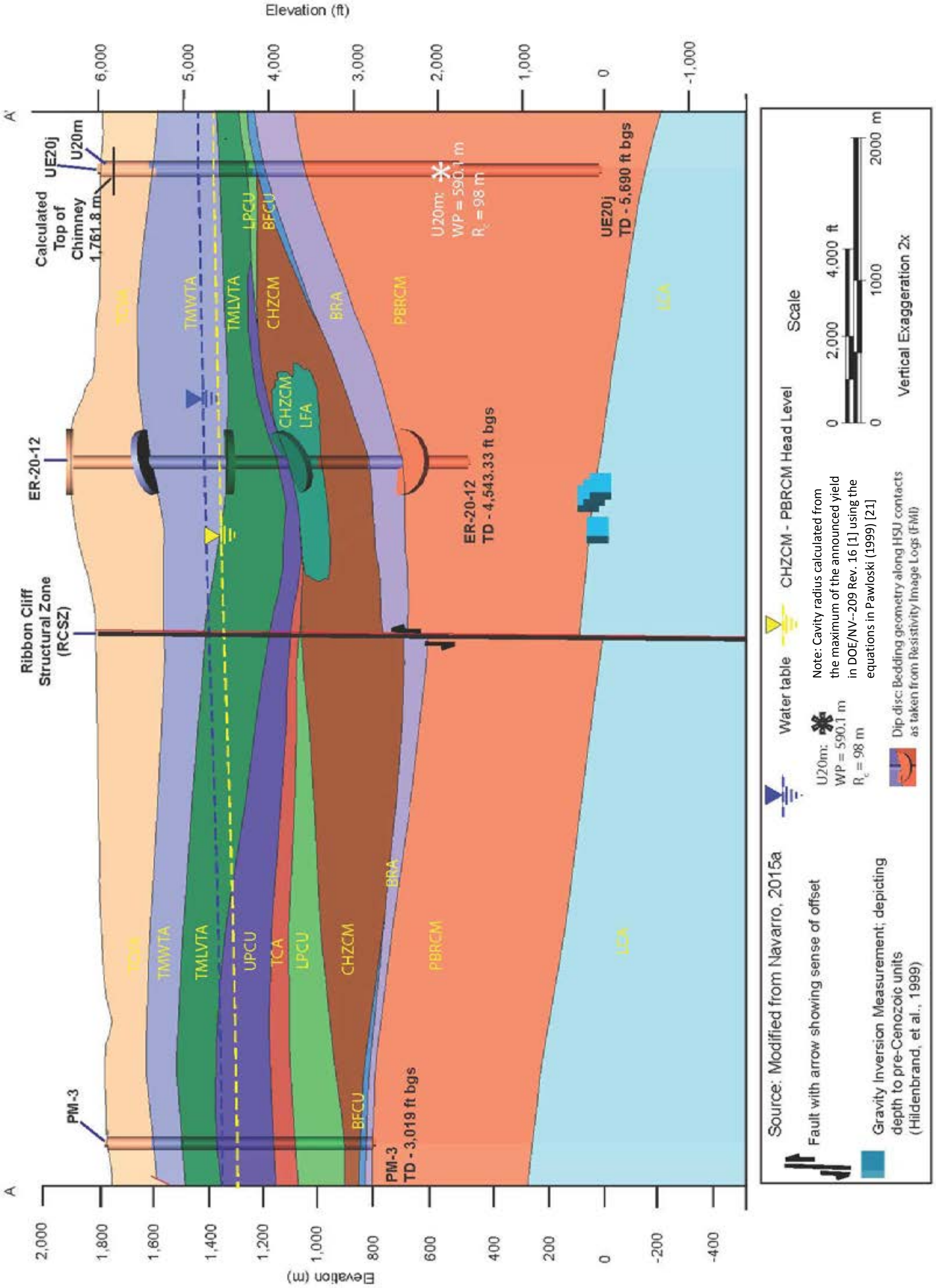

Fig. 4. Hydrogeologic Cross-section from Well PM-3 to Handley *(Thirsty Canyon Volcanic Aquifer [TCVA], Timber Mountain Welded Tuff Aquifer [TMWTA], Timber Mountain Lower Vitric Tuff Aquifer [TMLVTA], Upper Paintbrush Confining Unit [UPCU], Tiva Canyon Aquifer [TCA], Lower Paintbrush Confining Unit [LPCU], Calico Hills Zeolitic Composite Unit Lava Flow Aquifer [CHZCM LFA], Calico Hills Zeolitic Composite Unit [CHCZM], Bullfrog Confining Unit [BFCU], Belted Rang Aquifer [BRA], Pre-Belted Range Composite Unit [PBRCM], Lower Carbonate Aquifer [LCA])*.

described. All completed zones were individually isolated by a minimum of 33 m or more of intervening cement emplaced within the well annulus. Data collection consisted of mineralogic, petrographic, and chemical analyses of drill cuttings and sidewall cores to determine the lithology and stratigraphy of the borehole. Geophysical logs were run and used to evaluate and refine the lithology, structure, and petrophysical nature of the rocks encountered within the borehole. Water samples were collected to monitor tritium activities both downhole using bailed samples and from samples collected from fluid discharged into the lined sump. Water levels were periodically measured within the well and continually monitored at Well PM-3 within the upper and lower piezometer. Fluid production rates as a function of depth were determined by monitoring the dilution of bromide added to the drilling fluid as a tracer.

Characterization activities continue to be conducted at the site. Water levels are being monitored in the main completion and in the piezometers to help determine the storage coefficient of the units and facilitate processing of earth tide and barometric responses during future aquifer tests. Geochemical sampling is ongoing to facilitate geochemical-based modeling of groundwater flow and acquire discrete depth estimates of radionuclide concentrations within the well.

DISCUSSION

Geologic data collected from Well ER-20-12 reveals that the hydrostratigraphic framework model needs to be revised in the area of this well. The Thirsty Canyon volcanic aquifer (TCVA) and the TMWTA and TMLVTA are thicker and the CHZCM is much thicker than expected. The Crater Flat Group was thought to exist at this location but was not intersected by the borehole. The Upper Paintbrush confining unit (UPCU) is a little thicker than expected (33 m) [20].

The hydraulic data collected during the drilling of Well ER-20-12 showed that the water table was approximately 18 m higher than anticipated. The higher water level and greater thickness of the TCVA, TMWTA, and TMLVTA resulted in the lower portion of the TMWTA being saturated, which was unanticipated at the start of drilling. Discrete water-level information was collected as each piezometer was completed. Water-level information revealed that the hydraulic heads within units below the UPCU were a minimum of 70 m lower than those measured in the TMWTA. This requires that the UPCU and the Lower Paintbrush confining unit (LPCU) work together as a composite confining unit (Fig. 4) in the vicinity of Well ER-20-12 to preserve the observed head differential. Similar head differentials are not observed at Well PM-3 between the UPCU and underlying units (0.6 m head differential), which indicates that the effectiveness of the confining unit is reduced in the region of Well PM-3.

Water production as a function of drilling depth was greatest in the BRA with up to 2,080 l/min produced during drilling of this unit followed by the CHZCM in which 1,140 l/min were produced [20]. Measured tritium activities were highest in the TMLVTA (2,234 Bq/l) followed by another spike in tritium activity deeper in the well within the PBRCM (1,720 Bq/l). Tritium activities in this lower interval may have been diluted by water emanating from the overlying BRA and CHZCM. The presence of tritium at such high activities in both the deep and shallow portions of Well ER-20-12 can only be explained if the tritium originated from the Handley underground nuclear test. None of the other hypotheses can account for the widely varying depths at which tritium occurs and the level of activity associated with it.

Perturbations in hydraulic head were observed at Well PM-3 in response to the drill bit at Well ER-20-12 penetrating through the bottom of the UPCU. The responses at Well PM-3 were observed in both the upper piezometer, which is completed within the UPCU, and in the lower piezometer, which intersects the Tiva Canyon Aquifer (TCA). The distance between Wells PM-3 and ER-20-12 is approximately five kilometers. The hydraulic responses were of equal magnitude (0.2 m) and timing [20]. This observation requires a strong hydraulic connection between Well ER-20-12 and Well PM-3. Several hydrostratigraphic units may potentially be responsible for transmitting this response. Delineation of the importance of the various hydrostratigraphic units in terms of transmitting the response to the two piezometers at Well PM-3 will require additional work. Similarly, parsing out the roles of the various hydrostratigraphic units in terms of transmitting tritium from Handley to Well ER-20-12 and then to Well PM-3 is a fairly complex problem that requires additional work to answer quantitatively, although the presence of tritium in Well ER-20-12 and the existence of strong hydraulic connections between Well ER-20-12 and Well PM-3 make it very likely that the tritium observed in Well PM-3 was derived from the Handley underground nuclear test.

CONCLUSIONS

Observations of tritium at Well PM-3 were surprising given the location of the well relative to the underground nuclear tests and their respective locations relative to the preconceived potentiometric surface [3]. It was also not forecasted within simulations of groundwater flow and radionuclide transport previously conducted for that area [11]. The process used by the DOE to identify and evaluate potential hypotheses that explain the presence of tritium at Well PM-3 and to identify the appropriate characterization activities to evaluate the preferred hypothesis was exemplary for several reasons.

The principle reasons for the process being exemplary was because it was proactive by design, transparent, and inclusive. Initial detection and confirmation of tritium within Well PM-3 were achieved by relying on routine monitoring programs (RREMP). Evaluations of alternative hypotheses and alternative characterization strategies were conducted using topical committees that are routinely used by the UGTA. Characterization activities were conducted using standard procedures and funded using existing funds within the baseline. Each of these activities, while, routine by nature, are designed to be proactive if anomalous situations occur. They are, in other words, implicitly proactive. The transparency of the process is evident in the timely release of information to the regulatory authority and local citizen advisory board, routine reporting of monitoring results, and presentation of the information at meetings in local communities. Transparency is a key ingredient used by the UGTA to gain public trust and acceptance of the results.

Inclusiveness is demonstrated by the incorporation of employees of the State of Nevada regulatory authority in committees that evaluated the hypotheses and identified the appropriate characterization strategy. Concurrence on the characterization strategy by DOE and NDEP personnel made selecting that strategy a relatively straight forward process.

Secondary reasons for the exemplary nature of the response are severalfold. Workforce safety was a primary concern during characterization activities. This is evident in multiple ways, such as the care taken to site the locations of roads and pads to minimize workforce exposure to fallout from previously conducted nuclear cratering experiments, the multiple stand-downs invoked during drilling because of inclement weather or in response to potentially unsafe working conditions, the on-site presence of radiation technicians to monitor radioactivity in the drilling fluids, and the presence of on-site emergency medical technicians because of the remoteness of the site.

The integration of data collection activities were another exemplary action taken at the site. Hydraulic responses due to drilling operations were identified as a potentiality, planned for, and monitoring systems deployed as a cost-effective way to better understand the hydrogeology of the system based on data collected during routine drilling operations. Leveraging drilling operations as means to gain hydraulic insight saved money and time compared with conducting hydraulic data collection solely during routine well development and testing.

Flexibility in the drilling approach was also exemplary. The well design and drilling program were flexible enough to accommodate the presence of saturated hydrostratigraphic units and significant differences in the stratigraphy encountered during borehole drilling that were unanticipated in the drilling plan.

A final element of the program that is exemplary is the long-term iterative nature of the investigation. The Federal Facility Agreement and Consent Order [22] published the strategy for regulatory closure of areas impacted by contaminant migration of radionuclides from an underground nuclear tests on the NNSS via groundwater transport. An important aspect of that strategy is the long-term iterative evaluation of monitoring results for consistency with model forecasts of contaminant boundaries with the intent of identifying inconsistencies between model forecasts and monitoring data, which would result in refinements to the closure strategy if necessary.

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