# TRITIUM MIGRATION AT THE GASBUGGY SITE: EVALUATION OF POSSIBLE HYDROLOGIC PATHWAYS

*Prepared by*

Jenny Chapman, Todd Mihevc, and Brad Lyles

*Submitted to*

Nevada Operations Office
U.S. Department of Energy

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# TRITIUM MIGRATION AT THE GASBUGGY SITE:
## Evaluation of Possible Hydrologic Pathways

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U.S. Department of Energy
Las Vegas, Nevada

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# ABSTRACT

An underground nuclear test named Gasbuggy was conducted in northwestern New Mexico in 1967. Subsequent groundwater monitoring in an overlying aquifer by the U.S. Environmental Protection Agency revealed increasing levels of tritium in monitoring well EPNG 10-36, located 132 m from the test, suggesting migration of contaminants from the nuclear cavity. There are three basic scenarios that could explain the occurrence of tritium in well 10-36: 1) introduction of tritium into the well from the land surface, 2) migration of tritium through the Ojo Alamo Formation, and 3) migration through the Pictured Cliffs Formation. The two subsurface transport scenarios were evaluated with a travel time analysis. In one, transport occurs to the Ojo Alamo sandstone either up the emplacement hole or through fractures created by the blast, and then laterally through the aquifer to the monitoring well. In the other, lateral transport occurs through fractures in the underlying Pictured Cliffs detonation horizon and then migrates up the monitoring well through plugged casing connecting the two formations. The travel time analysis indicates that the hydraulic conductivity measured in the Ojo Alamo Formation is too low for lateral transport to account for the observed arrival of tritium at the monitoring well. This suggests transport either through fractures intersecting the Ojo Alamo close to well EPNG 10-36, or through fractures in the Pictured Cliffs and up through the bottom plug in the well. The transport scenarios were investigated using hydrologic logging techniques and sampling at the monitoring well, with the fieldwork conducted after the removal of a string of 0.05-m-diameter tubing that had previously provided the only monitoring access. No vertical movement of water was detected with a thermal flowmeter through the bottom cement plug and the water chemistry is consistent with the known characteristics of the Ojo Alamo, suggesting no leakage from the Pictured Cliffs through the bottom plug in the well. Though relatively fresh formation water was present across from the perforations in the Ojo Alamo as the well recovered from the tubing removal, the water did not contain measurable tritium in either May 1994 or May 1995. The previously measured tritium was highly variable from one sample to the next and did not display typical breakthrough behavior for a migrating contaminant. Thus, the earlier monitoring samples may not have been representative of Ojo Alamo Formation water through time, because sampling was restricted inside the 0.05-m tubing. The tritium previously sampled from the tubing may have been dispersed to non-detectable concentrations when the tubing was pulled prior to DRI's sampling. Though no tritium was detected in water samples consistent with the Ojo Alamo Formation, low levels of tritium were found higher in the borehole in a zone of chemically and isotopically distinct water. This lower salinity water has an evaporative isotopic signature, suggesting exposure in a surface pond. The tritium content could be related to gas flaring operations during Gasbuggy production testing, with the water introduced to the well through leakage or injection.

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## INTRODUCTION

A nuclear detonation occurred on December 10, 1967 in northwestern New Mexico, for the purpose of testing the effectiveness of such explosives for fracturing tight gas reservoirs to enhance production. This test, named Gasbuggy, was followed by production testing and pressure monitoring through 1976, and site cleanup activities that concluded in 1978. Since that time, groundwater has been monitored in the Gasbuggy area by the U.S. Environmental Protection Agency (EPA) as part of the Long-Term Hydrologic Monitoring Program. A pre-existing gas production well, EPNG 10-36, located 132 m from the test hole, was sealed with sand and cement prior to the nuclear test with the intention that it would be reopened after the test to determine the effectiveness of the experiment. Drilling problems precluded reopening the well to its pretest total depth; however, the well was recompleted for the purpose of hydrologic monitoring, and added to the monitoring program. In 1984, tritium activities well above background began appearing in 10-36 (Figure 1). Though these activities were substantially below the drinking water standard for tritium (20,000 pCi/l), they indicated a possibility of migration from the cavity and warranted further study. This report presents an analysis of the potential migration pathways and the results of a logging and sampling program designed to investigate the Gasbuggy site. It follows the sequence of work performed: background information is presented first, then a conceptual description of possible contaminant release scenarios, followed by a travel-time analysis of those scenarios and, finally, results from the field investigation.
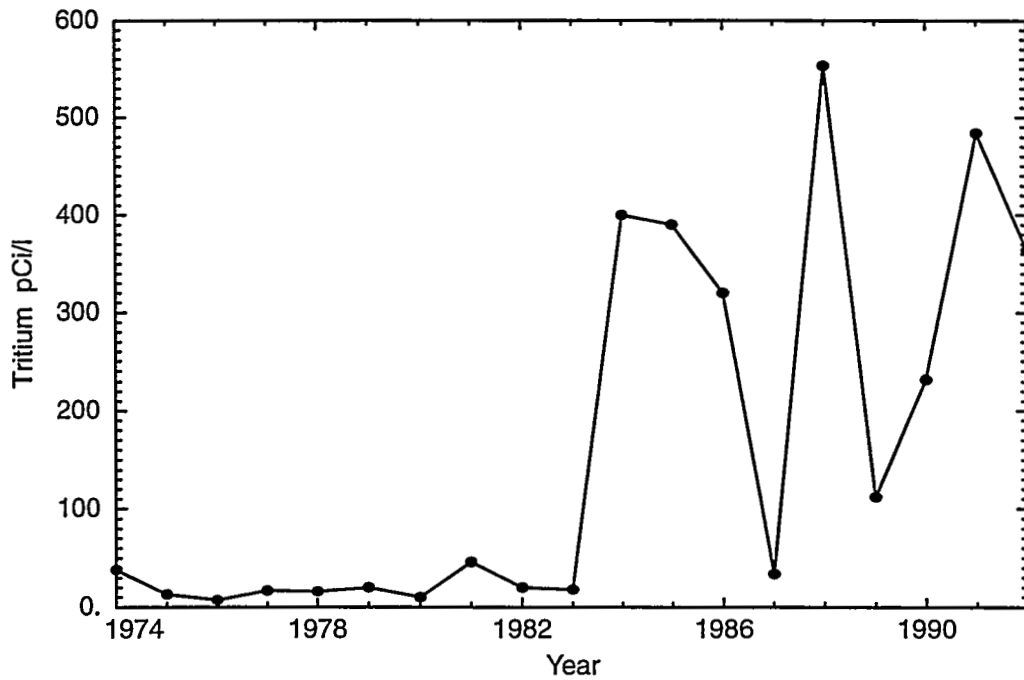


Figure 1.   Tritium concentration for Well EPNG 10-36. Data are from the U.S. EPA Long-Term Hydrologic Monitoring Program (U.S. EPA, 1992).

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# BACKGROUND INFORMATION

The Gasbuggy site is in the San Juan basin, a large structural basin containing about 3,660 m of sedimentary rocks. Groundwater flow from the site is believed to be to the west-northwest to discharge points along the San Juan River about 40 km away (Mercer, 1970) (Figure 2). At the site, hydraulic head values decrease with depth, indicating a potential for downward flow (Sokol, 1970). The gas producing horizon fractured by the shot is the Pictured Cliffs Formation, a tight sandstone between about 1,189 and 1,280 m below ground surface at the Gasbuggy site (Figure 3). The aquifer where the tritium has been detected is the Ojo Alamo Sandstone, located between about 1,057 and 1,110 m below ground surface. The two sandstones are separated by over 60 m of shale and siltstone.
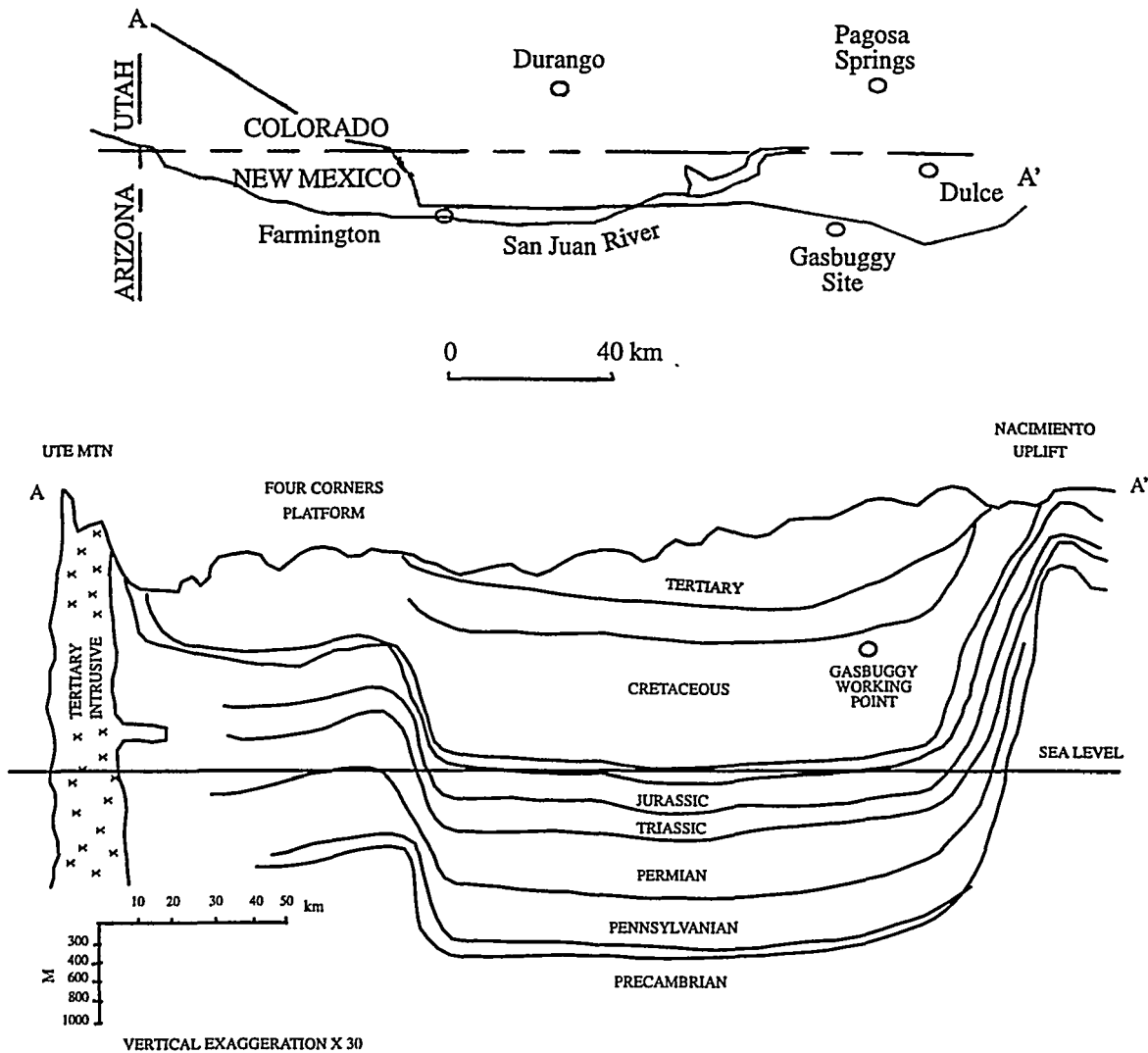


Figure 2. The upper portion of the figure shows the location of the Gasbuggy site in northwestern New Mexico and the location of the cross section shown in the lower portion. The cross section was modified by Sokol (1970) from that presented by Peterson *et al.* (1965).

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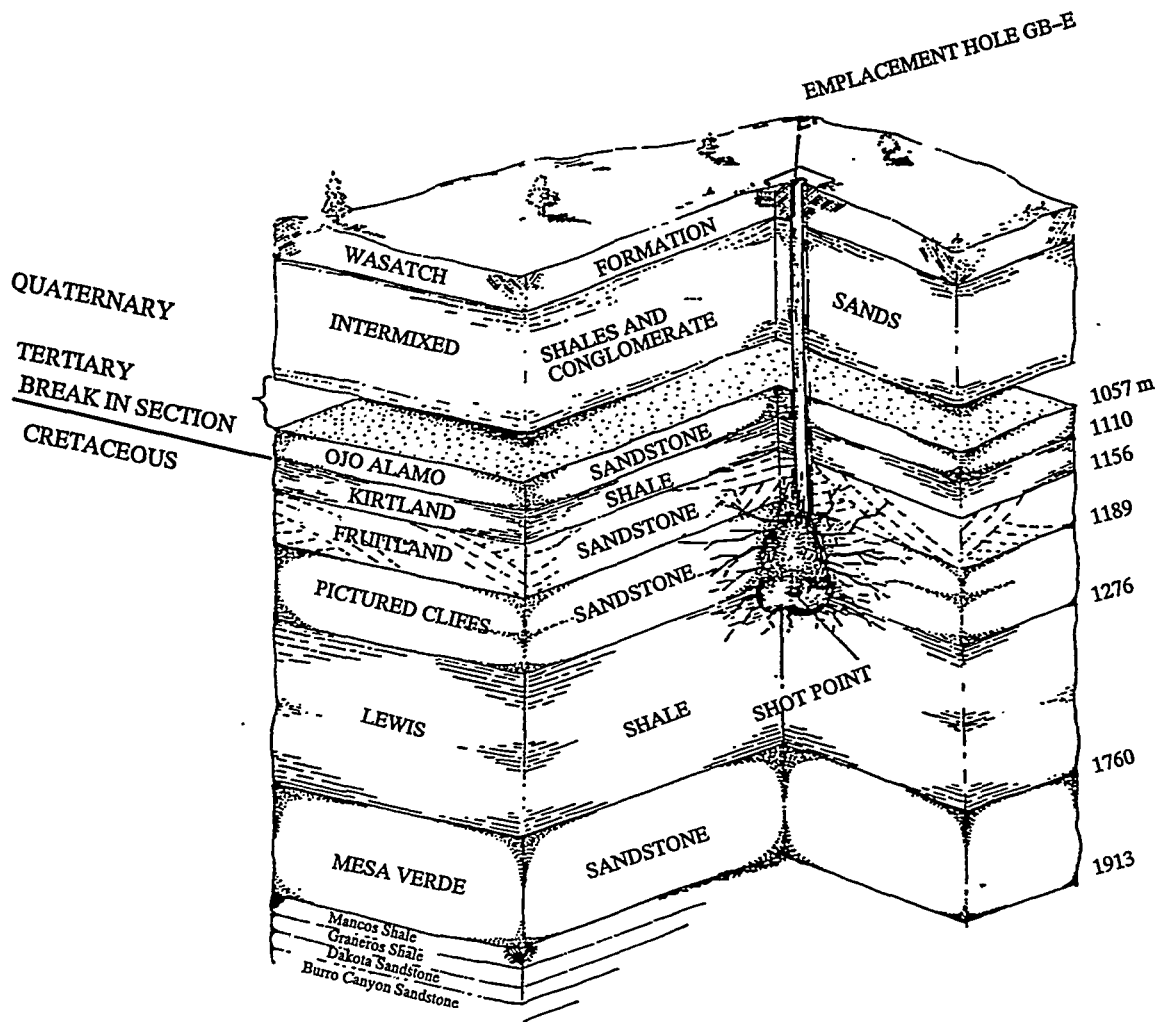
Figure 3. Generalized geologic cross section at the Gasbuggy emplacement hole. From U.S. DOE (1986).

Four holes were drilled as part of the Gasbuggy project (Figure 4). Hole GB-1 was the first exploratory hole, from which many cores were collected during drilling. These cores provide numerous porosity and permeability measurements in both the Ojo Alamo and Pictured Cliffs Formations. Hole GB-2 was a second exploratory borehole. Hole GB-3 was drilled after the detonation, with the purpose of determining the effect of the blast on the underground environment, including the Ojo Alamo. Single-hole hydraulic tests were performed in each of the three holes. Hole GB-E/GB-ER was the emplacement and reentry hole (this somewhat unusual configuration, drilling the reentry hole through the cement plug in the event hole, was performed to save costs by speeding drilling, eliminating a need to set casing, etc.). All of these holes have been plugged to the surface with cement and are therefore unavailable for additional measurements.

The monitoring well, EPNG 10-36 (formerly known as Well 29-4 No.10 and hereafter referred to as 10-36), was originally a gas production well, producing from the Pictured Cliffs Formation.
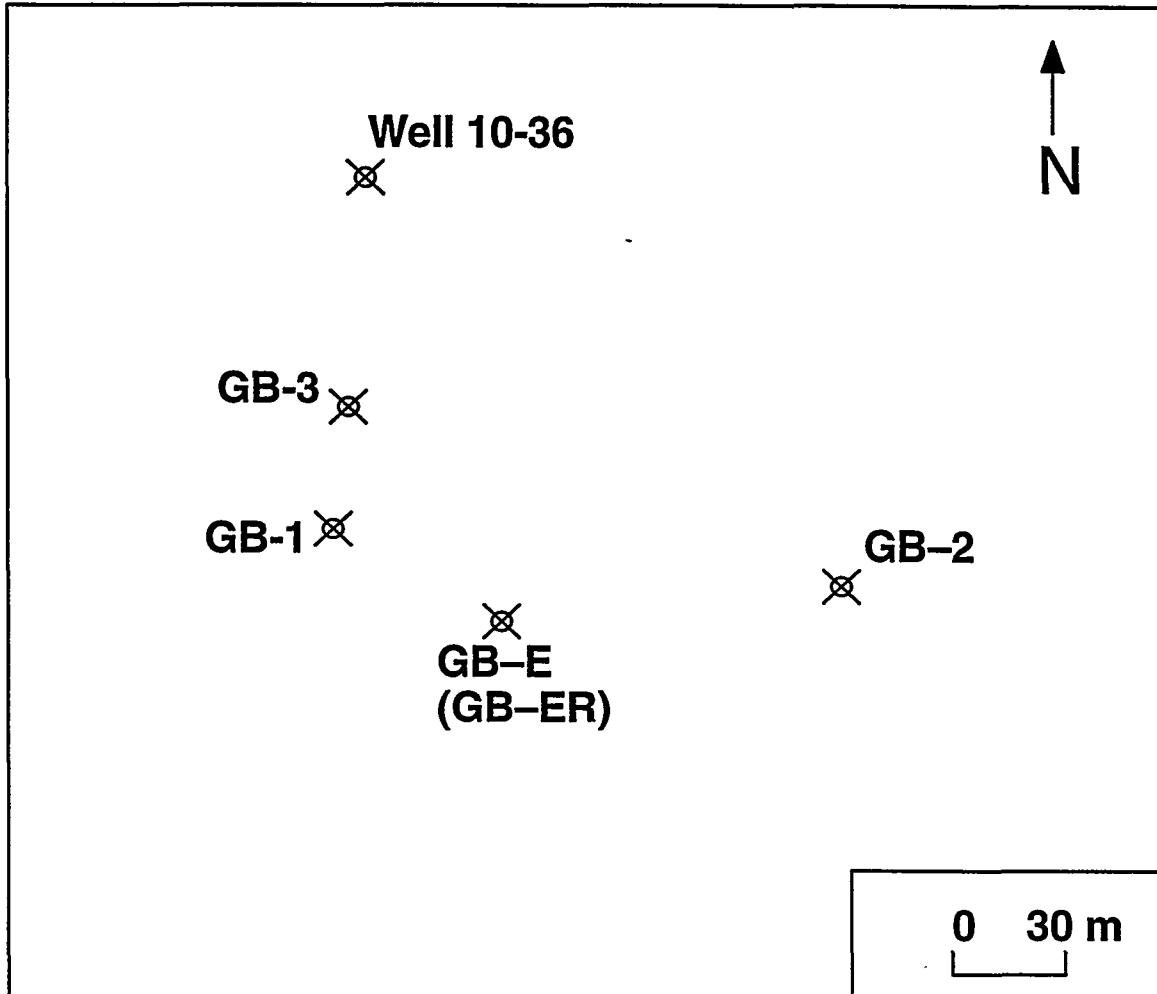
Figure 4.  Locations of the boreholes drilled for the Gasbuggy Project and Well 10-36. The distance from GB-ER (the emplacement and reentry hole) to Well 10-36 is 433 ft.

enhance production, hydraulic fracturing was performed at 10-36 at an unknown time in the past. The well had reportedly been producing for about ten years prior to the Gasbuggy test. The original plans had called for postshot production testing at 10-36, so the perforated portion of the well opposite the Pictured Cliffs was filled with sand, then the remainder of the well was plugged with cement prior to the nuclear test. Postshot drilling to clean out the cement encountered damaged casing near the bottom of the Ojo Alamo that prevented penetration to the Pictured Cliffs. The well was then completed in the Ojo Alamo by shot perforating the 0.14-m casing, and left for groundwater monitoring.

The Gasbuggy nuclear test was conducted in well GB-E at a depth of 1292 m below ground surface. The detonation occurred in the Lewis Shale Formation (Figure 3), but the test was designed

to fracture the Pictured Cliffs gas reservoir directly overlying the Lewis Shale. The Ojo Alamo Sandstone is separated from the Pictured Cliffs by the Fruitland Sandstone and Kirtland Shale. The chimney created by the nuclear explosion (a rubble zone of increased porosity caused by fractures and collapse of overlying material into the void left by the test) was estimated to extend about 102 m above the detonation point (Korver and Rawson, 1968), which should be close to the top of the Pictured Cliffs Formation. Gas-production testing took place through the re-entry well, GB-ER, drilled through the plugged well GB-E.

## Important Observations during Gasbuggy Activities

There are a number of observations scattered throughout reports of Gasbuggy activities that are pertinent to the issue of contaminant transport at the Gasbuggy site. These observations are listed here for clarity and are discussed in the context of transport hypotheses in later sections.

- Tritium was released to the atmosphere during gas-flaring operations and resulted in locally high tritium concentrations in soil water (Eberline Instrument Corp., 1979) and presumably any surface impoundments.

- There is no record of any downhole disposal of fluids into well 10-36.

- A pressure connection between GB-1 and well 10-36 in the Pictured Cliffs was noted during testing in GB-1 prior to the Gasbuggy event.

- Water collected from the Ojo Alamo during reentry drilling of GB-ER contained tritium at twice background concentrations.

- Concentrations of tritium in cavity gas and water could not account for all the tritium produced by the shot.

- There was inflow of water from the Ojo Alamo to the cavity during production testing. Both Korver and Rawson (1968) and Power and Bowman (1970) refer to sealing and stemming difficulties in GB-E, both pre- and post-shot, and attribute the water inflow to those poor seals. No clear details are given on the nature of the problems, though the use of thick sections of sand plugs, rather than continuous cement stemming, was noted as a contributing factor.

- A pressure connection between the cavity and the Ojo Alamo at Well 10-36 was recorded during production testing of GB-ER.

## CONTAMINANT TRANSPORT SCENARIOS

There are three basic scenarios that could explain the occurrence of tritium in well 10-36 (Figure 5): 1) introduction of tritium into the well from the land surface, 2) migration of tritium through the Ojo Alamo, and 3) migration through the Pictured Cliffs. All three scenarios are described below.

## A Surface Origin for the Tritium in 10-36

The ultimate source of tritium in this scenario is the Gasbuggy test, but the tritium is first brought to the land surface during drillback and testing of the re-entry well. As stated above, no

EPNG 10-36 ← 132 meters → GB–ER
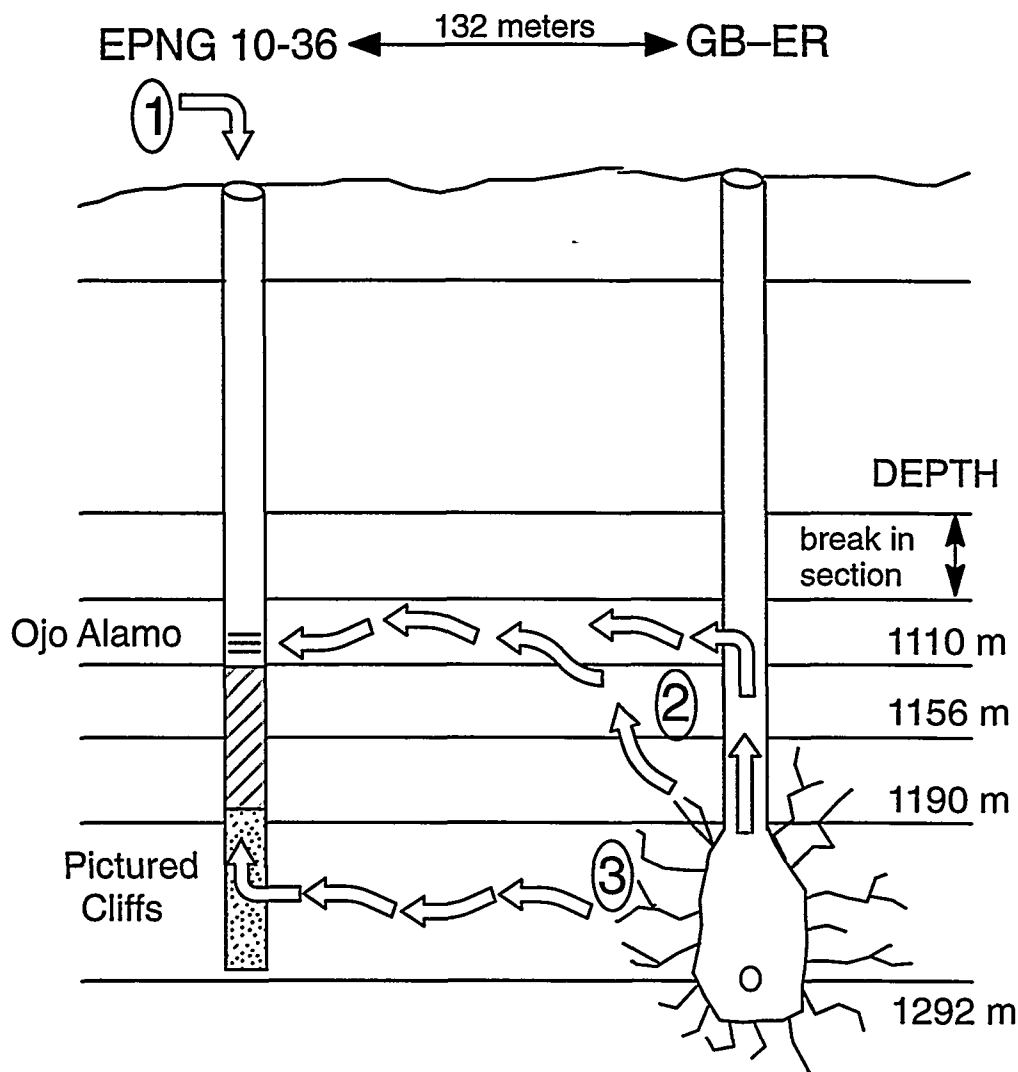
Figure 5. The three basic scenarios for the transport of tritium into the monitoring well, EPNG 10-36. In case 1, tritium is injected or otherwise enters the well from the surface. In the second scenario, transport occurs through the Ojo Alamo Formation after migration up the GB-ER borehole or through a fracture connecting the cavity and the Ojo Alamo. In the third scenario, transport occurs through fractures in the Pictured Cliffs Formation, then up the 10-36 borehole.

records have been found of intentional downhole disposal of fluids into well 10-36, so the mechanism by which the tritium could enter the top of the well can only be speculated. There are a number of possibilities, including unauthorized and/or unrecorded disposal down the well bore, and leakage into the well of water accumulated in the below-grade cellar. Though tritium was not detected until 1984, it should be noted that contamination could have been present in the upper part of the water column prior to that time and would have been undetected because EPA routinely collects its sample at the bottom of the well and, until 1994, was restricted to sampling inside a string of production tubing that was only perforated at the level of the Ojo Alamo. The combined effects of diffusion and mechanical mixing by the bailer during annual sampling could cause changes in the water column through time.

### Transport Through the Ojo Alamo

The second possible contaminant migration scenario is that involving transport through the Ojo Alamo Formation. In this basic scenario, tritium from the nuclear test reaches the Ojo Alamo either through fractures caused by the detonation, or through the GB-ER borehole, and then migrates to 10-36 by lateral flow through the Ojo Alamo (Figure 5).

A fundamental problem with postulating a release from the Gasbuggy cavity to the Ojo Alamo Formation is that pressures measured in the Pictured Cliffs are apparently lower than those measured in the Ojo Alamo (Rawson and Korver, 1967; Power and Bowman, 1970). This means that if connected, water should be flowing downward from the Ojo Alamo into the cavity rather than vice versa. There are three ways of accounting for migration of tritium from the Pictured Cliffs to the Ojo Alamo: 1) prompt injection of tritium at the time of the explosion, 2) tritium migration in the vapor phase, and 3) the possibility that pressure measurements in the Pictured Cliffs are not representative of downhole conditions and that the pre-shot estimate indicating a potential for upward flow is actually correct.

The above-background tritium concentrations in the Ojo Alamo detected during reentry drilling are evidence that some migration occurred immediately after the shot at GB-ER ("prompt injection"). The source of the radioactivity was believed to be leakage of radioactive gas along the explosive arming and firing cable (Korver and Rawson, 1968). However, there was no direct injection of radioactivity to the Ojo Alamo at Well 10-36. The monitoring results show a 16- to 17-year lag from the time of the event to the detection of tritium. This requires some form of migration in addition to any prompt injection.

Rather than being driven into the Ojo Alamo by the force of the blast, tritium may have migrated to the Ojo Alamo in the vapor phase, sometime after the shot. The inflow of water from the Ojo Alamo to the cavity caused problems with gas production testing in GB-ER (Power and Bowman, 1970). Rawson and Korver (1967) note that "...if water can flow into the chimney from the Ojo Alamo, gas from the chimney will likely migrate into the Ojo Alamo, perhaps in significant quantities." Some of this gas, at least at early times, would be tritiated water vapor.

Both prompt injection and vapor phase migration would be less serious as contaminant transport sources because they would be short-term phenomena that would limit the amount of radioactivity released to the Ojo Alamo. However, given the difficulties of accurate downhole pressure measurements, it is possible that the head measurements for the two units are unreliable and that migration could occur from the cavity to the Ojo Alamo along fractures or through boreholes. Though the observed leakage of water from the Ojo Alamo into the cavity tends to support higher head in the Ojo Alamo than the Pictured Cliffs, the cavity at the time of those observations was under stressed conditions, first due to the void created by the nuclear test, and later due to production testing.

The connection between the cavity and the Ojo Alamo through GB-ER has already been mentioned. Though final roll-up activities at the site included stemming GB-ER with cement to the surface, it is possible that the stemming and sealing problems that initially led to the leakage of water

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into the cavity persisted through the final stemming. The pressure connection between the cavity and the Ojo Alamo at well 10-36, recorded during testing of GB-ER, is also noteworthy. Power and Bowman (1970) show that the hydrostatic level in 10-36 responded to decreases in chimney pressure. Though their late-time data suggest a partial sealing of the leak by mid-April 1969, they note that "It now appears that the leak has been plugged by some obscure process although the permanency of this plug is not assured." Though they assume the connection was through GB-ER, there is no reason that it could not have been through fractures.

**Transport Through the Pictured Cliffs Formation**

The third possible tritium migration scenario is transport through the Pictured Cliffs Formation. The 10-36 well was originally completed as a gas-production well, producing from the Pictured Cliffs. The possibility of communication between 10-36 and the ground zero area to the south (Figure 4) is supported by the good connection between GB-1 and 10-36 in the Pictured Cliffs, noted during pre-shot testing of GB-1. The connection was considered to be due to a combination of natural structural weaknesses and hydraulic fracturing in 10-36 (Rawson and Korver, 1967). Hydrocarbon stains along bedding-plane partings at sandstone-shale contacts in GB-1 core were interpreted as indicating flow from the GB-1 area to 10-36 during the ten years of gas production from 10-36. Pre-shot studies led Rawson and Korver (1967, p. 41) to conclude that there would be "very probable communication between the explosion in GB-E and well 10-36."

Migration from the underlying Pictured Cliffs to the level of the Ojo Alamo within 10-36 would be facilitated by the pre-shot stemming in 10-36, which included sand fill in the bottom 91.4 m, where perforations are open to the Pictured Cliffs. This somewhat unusual stemming was apparently done because the original plan was to clean out 10-36 postshot and test-gas production, so they did not want to clog the perforations with cement. Though there are another almost 91 m of cement between the sand fill and the current bottom of the well at 1,099 m below land surface, it is likely that the test compromised the plug's integrity. This is suggested by the damaged casing at 1,101 m, caused by the nuclear explosion, which prevented postshot penetration to the Pictured Cliffs and led to establishing 10-36 as an Ojo Alamo monitoring well (Atkinson et al., 1969). The hydraulic head relationship between the Ojo Alamo and Pictured Cliffs governs whether flow through damaged 10-36 casing would be from the Pictured Cliffs to the Ojo Alamo, or vice versa. As discussed for the scenario of transport through the Ojo Alamo, the assumption is made here that flow could be upward to the Ojo Alamo.

**TRAVEL TIME ANALYSIS**

To evaluate the two subsurface transport scenarios, a travel time analysis (Andricevic et al., 1994) was performed. To derive the probability density function (pdf) of travel time, given available field information, is one of the most important issues of transport theory in porous media. However, very often limited field data force the solution to be highly approximate. Sometimes the spatial structure of hydraulic conductivity is unknown or can only be estimated from observations of similar geologic formations at different sites. Without information on the spatial structure of the flow field, the travel time analysis follows the simplest case of pure convective transport in a uniform flow field. If, on the other hand, the spatial distribution of the flow field can be estimated using available data,

this information should be considered in the calculation of the travel time distribution. There are insufficient data from the Gasbuggy site to estimate the spatial distribution of the flow field.

One possible attempt to analyze the pdf of travel time is to consider the simple kinematic motion neglecting the velocity spatial variation and the pore-scale dispersion:

$$x(t) = Ut \tag{1}$$

where $x(t)$ denotes the mean displacement in direction of flow, $U$ is a mean velocity, and $t$ denotes time. This assumption implies that the transport process is only governed by the estimated mean velocity in the direction of the compliance surface. In general, the mean velocity is not measured in the field, but rather estimated indirectly using Darcy's law. Darcy's law is usually presented with the relation:

$$U = K_g \frac{J}{n} \tag{2}$$

where $K_g$ is the geometric mean of the hydraulic conductivity, $J$ is the mean hydraulic head gradient, and $n$ is the effective porosity. Since these parameters are estimated from the scarce field data at the Gasbuggy site, they are subject to estimation errors which in turn produce the uncertainty in the mean velocity estimate. A detailed description of this probabilistic approach can be found in Andricevic et al. (1994), describing risk assessment for migration from the Nevada Test Site. The specific scenarios evaluated and the values used for the variables in equation (2) are discussed below.

**Specific Scenarios**

The Ojo Alamo and Pictured Cliffs transport scenarios were evaluated with the travel time approach. In both cases, only the horizontal transport through the formation of interest is considered. Vertical migration, whether through a well or fracture, is considered to be essentially instantaneous. Thus, the Ojo Alamo transport scenario consists of the instantaneous injection of tritium from the Gasbuggy nuclear test to the Ojo Alamo through either the GB-ER borehole or fractures connecting the cavity and the Ojo Alamo. The length of the flowpath for transport through the Ojo Alamo was assumed to be constrained by the distance between GB-ER and 10-36 (0 to 132 m), and was treated as an uncertain variable in this scenario because the cavity and the Ojo Alamo could be connected in any number of ways, ranging from at the GB-ER borehole to fractures very near 10-36 (Figure 5). The spread of this range in possible flowpath lengths about the mean was assumed to be +3 standard deviation, resulting in lower probabilities of very short flowpaths (transport directly to 10-36) and very long flowpaths (transport directly up GB-ER).

The Pictured Cliffs transport scenario consists of migration of tritium from the Gasbuggy cavity to 10-36 through the fractured sandstone adjacent to the cavity (Figure 5). The flowpath length through the Pictured Cliffs was assumed to be the distance between GB-ER and 10-36 (132 m). Vertical transport from the screened interval in the Pictured Cliffs up the 10-36 borehole was assumed instantaneous, consistent with the assumption that the cement plug between the Pictured Cliffs and Ojo Alamo was fractured by the test. This also requires the assumption of higher head in

the Pictured Cliffs Formation relative to the Ojo Alamo, the uncertainty of which was discussed previously.

## Hydraulic Gradient

A gradient for the Ojo Alamo in the immediate site area could not be determined. Though five boreholes intersected the Ojo Alamo at and near the Gasbuggy site, a reliable static water level is only available from 10-36, and no precise ground elevation is available there. Head values in the other holes were all collected during hydrologic testing, when expensive rig time precluded waiting for full recovery (static level was estimated by extrapolating from recovery curves). All indications are that there is little gradient between the closely spaced boreholes and very precise measurements of head would be necessary to accurately determine one. For the purposes of this analysis, a regional gradient is assumed, calculated from the Gasbuggy site to postulated discharge points on the San Juan River by Sokol (1970). There were three estimates: 0.036, 0.047, and 0.044. These lead to a mean = 0.041 and standard deviation = 0.008.

No gradient data are available for the Pictured Cliffs Formation, so for that scenario, the regional gradient of the Ojo Alamo was applied to the Pictured Cliffs.

## Porosity

Porosity measurements were made on 57 core samples of the Ojo Alamo, collected from GB-1 (Rawson and Korver, 1967). The mean of these measurements was 0.128, with a standard deviation of 0.035. It should be noted that the measurements are reported to represent total porosity, as opposed to effective porosity. In the absence of any data on effective porosity, the total values were used. In addition, the measurements represent the vertical distribution of porosity rather than lateral. Despite these problems, the value of porosity is probably the best known parameter in the calculations.

Porosity was also measured on cores from the Pictured Cliffs, with 145 measurements reported (Rawson and Korver, 1967). The mean of these is 0.09, with a standard deviation of 0.033. As with the Ojo Alamo measurements, the reported values are total porosity and are distributed vertically.

## Hydraulic Conductivity

Three field measurements of transmissivity have been made in the Ojo Alamo, in wells GB-1, GB-2, and GB-3. The resulting values range from $4.38 \times 10^4$ cm$^2$/yr to $1.31 \times 10^5$ cm$^2$/yr (Mercer, 1969). Permeability was also measured on 57 cores collected from the Ojo Alamo in GB-1 (Rawson and Korver, 1967), resulting in a large range with a geometric mean of 43 cm/yr. The core permeability data demonstrate the inhomogeneity in the vertical distribution of permeability in the formation, indicating zones of higher permeability, up to 7.6 m thick, interspersed among low permeability horizons (Figure 6). Vertical variations in permeability were also identified during field testing, with the lower part of the formation found to be more transmissive than the upper section (Koopman and Ballance, 1968).

The mean hydraulic conductivity value for the Ojo Alamo that results from the core data (geometric mean of 43 cm/yr) is somewhat higher than that from the field-based data (geometric
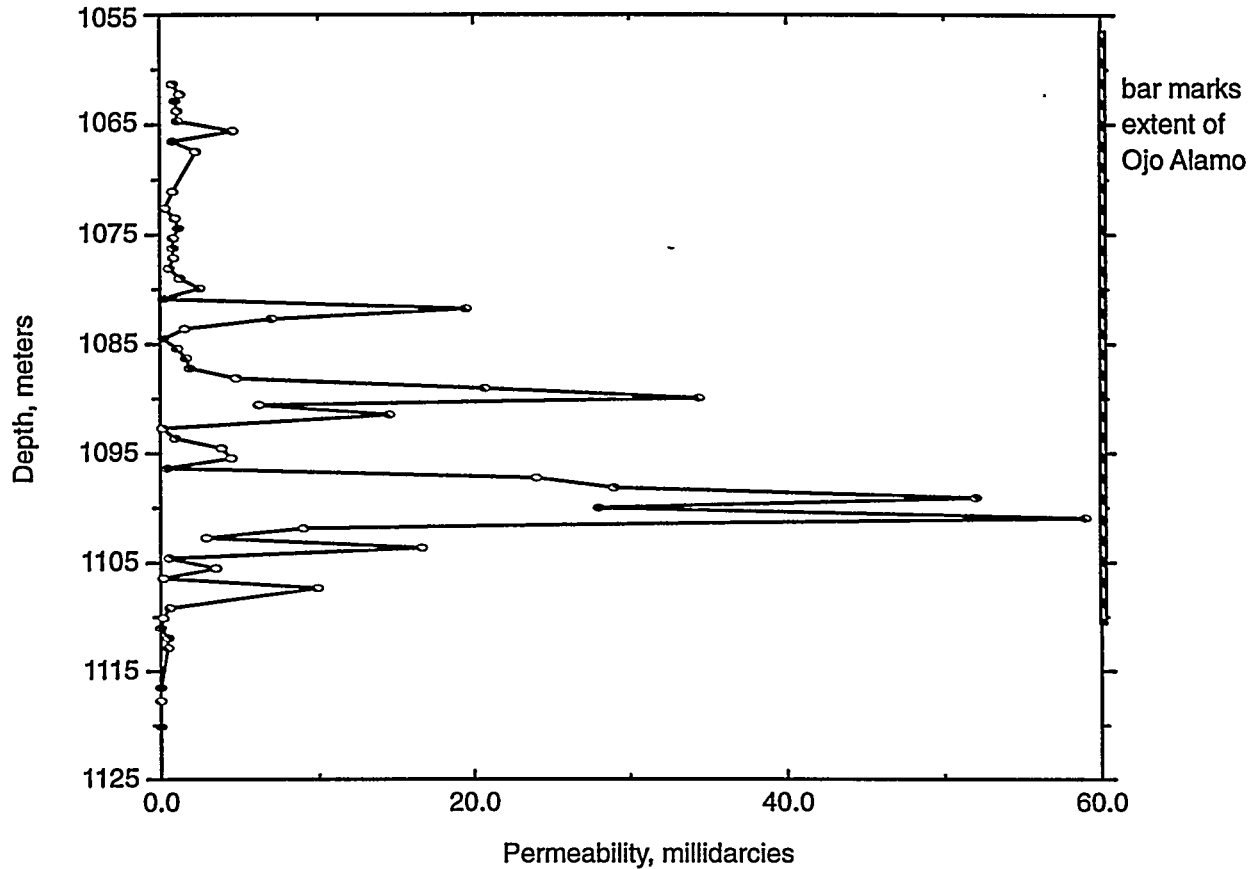
Figure 6.  Vertical distribution of permeability measured in cores from GB-1. Data from Rawson and Korver (1967). Note the limited zones of higher permeability.

mean of 29 cm/yr), a discrepancy which has been attributed to unloading of the cores and/or measurement technique (Rawson and Korver, 1967). The field transmissivity of $1.12 \times 10^5$ cm$^2$/yr was used for the travel time analysis because it was measured in the lower 24 m of the Ojo Alamo, the portion of the formation most likely to be affected by migration from the underlying test. This transmissivity yields a hydraulic conductivity of 47.5 cm/yr, which was used as the mean value in the computations, with the variance estimated from the three field measurements. The mean natural log of the hydraulic conductivity ($\mu_{lnK}$) used is 3.86 cm/yr and $\sigma^2_{lnK}$ is 0.24.

Permeability measurements were also made on 144 cores from the Pictured Cliffs, and give a mean of 3.0 cm/yr with a standard deviation of 4.6. However, those measurements probably represent unfractured values, whereas the scenario considered here involves not only fracturing caused by the nuclear test, but also previous hydraulic fracturing within 10-36 itself. Instead of the core values, the analysis used the published range of fractured-rock hydraulic conductivities ($3.15 \times 10^3$ to $3.15 \times 10^8$ cm/yr, Freeze and Cherry, 1979) to select a mean of $3 \times 10^6$ cm/yr ($\mu_{lnK}$=14.9) and $\sigma^2_{lnK}$ of 2.0. It should be noted that it is assumed that the Pictured Cliffs is saturated with water. The known presence of gas in the formation would serve to reduce both the hydraulic conductivity and effective porosity.

It is assumed that the above parameters are lognormally distributed. The lognormality assumption has been shown to accurately describe the actual variability measured in the field (Hoeksema and Kitanidis, 1985) especially for those parameters which physically cannot assume a negative value (*e.g.*, *K*, *n*).

If all parameters on the right-hand side of (2) are lognormally distributed, then so is *U*, such that the first two moments of the estimated mean velocity are

$$\mu_{lnU} = \mu_{lnK} + \mu_{lnJ} - \mu_{lnn} \tag{3}$$

$$\sigma^2_{lnU} = \sigma^2_{lnK} + \sigma^2_{lnJ} + \sigma^2_{lnn} \tag{4}$$

where $\mu_{lnx}$ and $\sigma^2_{lnx}$ denote a log mean and log variance of any variable $\ln x$, respectively. The above equations give the necessary parameters for the construction of the pdf of the mean velocity estimate which takes the form of the lognormal distribution (Andricevic et al., 1994)

$$p[U] = (\sqrt{2\pi}\,\sigma_{lnU}U)^{-1} \exp\left[ -\frac{(lnU - \mu_{lnU})^2}{2\sigma^2_{lnU}} \right] \tag{5}$$

The mean velocity for the Ojo Alamo that results from the data described above is 15 cm/yr, with a standard deviation of 12. The mean velocity for the Pictured Cliffs scenario is $1.4 \times 10^6$ cm/yr, with a standard deviation of $1.1 \times 10^7$.

## Results of Travel Time Analysis

The data analysis described above for the Ojo Alamo transport scenario results in high probabilities of groundwater velocities in the Ojo Alamo Formation less than 20 cm/yr. The pdf for velocity (Figure 7) has a short upper tail, indicating little likelihood of high enough velocities to cause the observed tritium breakthrough. This is most easily seen on the cumulative distribution function (Figure 8), which for this scenario shows essentially no probability of arrival times to Well 10-36 less than 20 years, as required to cause the tritium observed in the well.

The analysis of the Pictured Cliffs transport scenario results in very rapid travel times to 10-36 (Figure 9). The results make it clear that tritium could have moved from the cavity to 10-36 on the order of weeks after the detonation through fractures in the Pictured Cliffs. Even more rapid travel times would result if a larger gradient were assumed as a result of the detonation. The subsequent delay in breakthrough at the Ojo Alamo would presumably be due to slower transport up the 10-36 borehole through the cement plug than the instantaneous vertical migration assumed here.

The travel time calculations can be interpreted the following way: if the field-measured conductivities accurately represent the hydraulic properties of the Ojo Alamo, then the tritium detected in 10-36 could not have traveled far through the aquifer. This suggests transport through a fracture intersecting the Ojo Alamo close to 10-36, or through the Pictured Cliffs and up the 10-36 borehole. The travel time analysis suggests that transport to 10-36 is more likely to have occurred
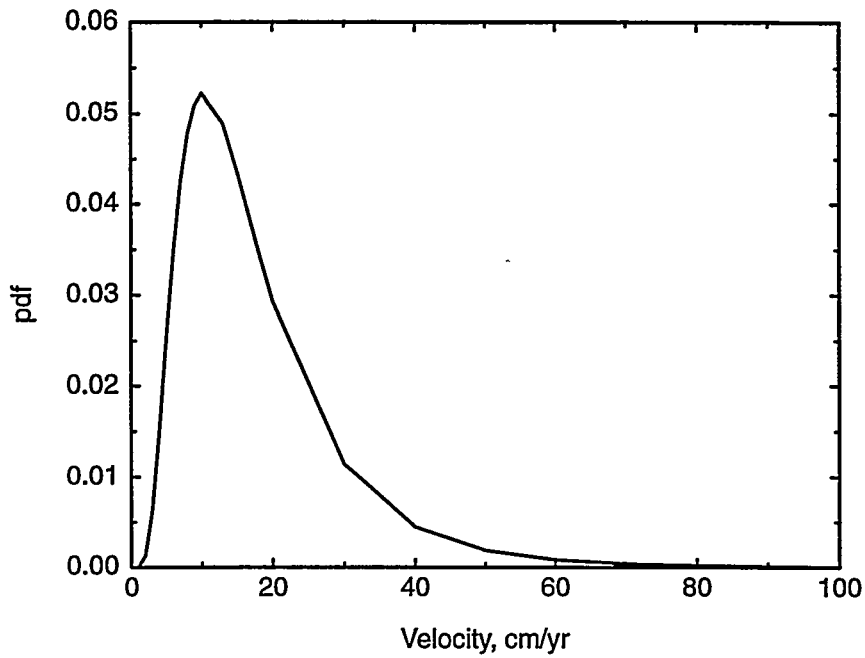
Figure 7. Probability density function for groundwater velocity in the Ojo Alamo Aquifer. There is a high probability of groundwater velocities less than 20 cm/yr.
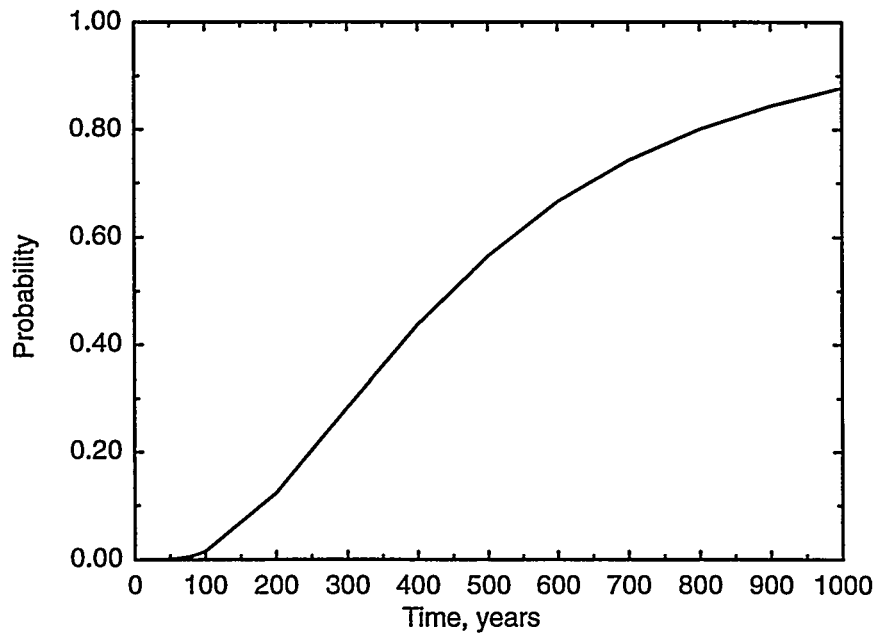


Figure 8. Cumulative distribution function for groundwater travel time in the Ojo Alamo Aquifer to Well 10-36. The travel path length is treated as an uncertain variable because the nature of the connection of GB-ER and the Ojo Alamo is unknown. There is essentially no chance that the appearance of tritium in Well 10-36 17 years after the nuclear test could be due to transport through the Ojo Alamo.

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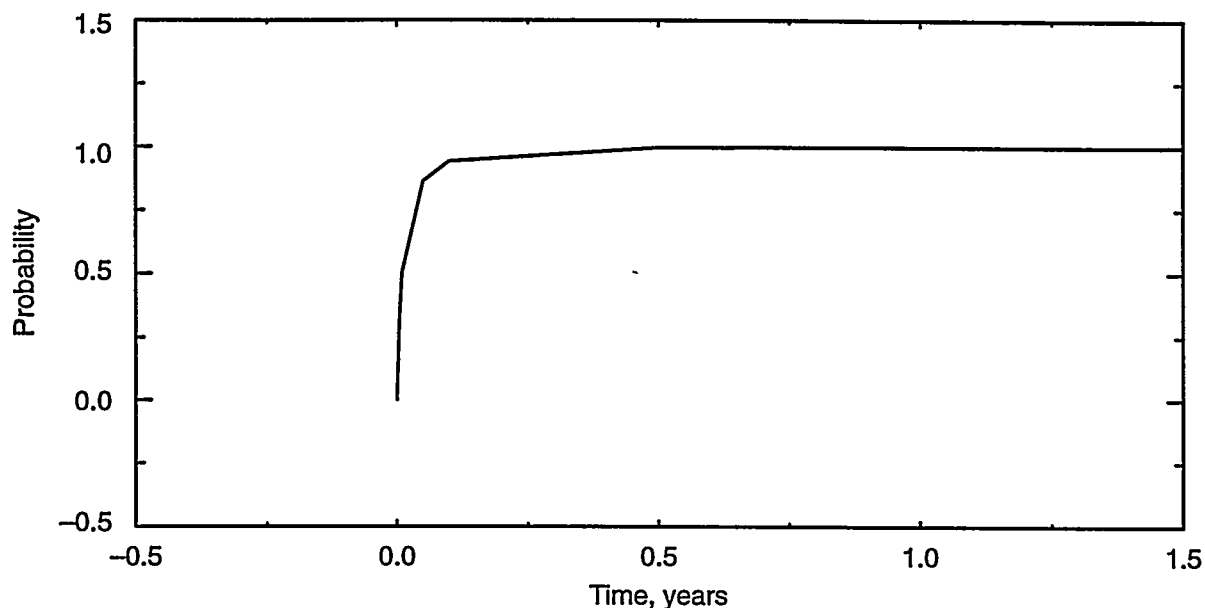
Figure 9. Cumulative distribution function of travel time to 10-36 through a fractured Pictured Cliffs Formation. In this scenario, the travel path length was assumed fixed at the total distance between GB-ER and 10-36, and the regional hydraulic gradient in the Ojo Alamo was assumed to apply to the Pictured Cliffs. Under the assumed conditions, travel is almost certain to occur within a few weeks.

as a result of prompt-injection phenomena. Though Gasbuggy test data support the possibility that material from the cavity could have migrated to the Ojo Alamo, the calculations indicate that they would not travel far through the sandstone before radioactive decay significantly reduces contaminant concentrations. Thus, the travel time analysis suggests that of the two subsurface transport scenarios, the scenario for transport through the Pictured Cliffs is the most likely to account for the observed occurrence of tritium at 10-36.

## FIELD INVESTIGATION OF TRANSPORT SCENARIOS

A detailed hydrologic logging and sampling effort was designed to test the transport hypotheses identified in the travel time analysis. The objectives were to determine if flow is moving up through the cement plug at the bottom of 10-36, and determine a profile of tritium in the water column to reveal where tritium is entering the well. The first field sampling and logging trip was conducted in May 1994, immediately following removal of a string of small-diameter access tubing. A second visit was made in May 1995 to re-evaluate the hydrologic characteristics of the well under equilibrium conditions and further define the tritium distribution in the water column.

### Well Construction

Prior to the Gasbuggy nuclear test, sand was placed in Well 10-36 from the bottom of the well to above the perforated interval at 1,189 m. The remainder of the well was filled with cement. After the test, the cement was drilled out to a depth of 1,099.1 m. Drilling problems precluded recompletion of the well to its original total depth (1,283.2 m). The well was then shot perforated

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from 1,085.4 m to 1,090.3 m and from 1,091.5 m to 1,097.6 m for use as a hydrologic monitoring well. Access tubing (0.05 m) was placed in the well with perforations from 1,093.6 m to 1,099.1 m for use as a sampling port (Figure 10). The access tubing was removed from the well prior to the logging and sampling activities reported here.

## 1994 Field Activities

Field sampling and logging were conducted from May 27 through May 30, 1994. Prior to these activities, on May 22, EPA measured the water level and collected its annual water sample for the LTHMP. On May 23, International Technology Corporation and its contractor removed the 0.05-m tubing from Well 10-36 to allow access for large-diameter logging tools and to facilitate a casing integrity log requested by the U.S. Forest Service.

<u>Water Sampling</u>

Water samples were collected from the following depths: 932.9 m, 1,083.8 m, 1,092.7 m, and 1098.8 m. Samples were collected in order of increasing depth to decrease the potential of cross contamination of the samples through borehole mixing. These sample depths were chosen based on the borehole construction. The 1,083.6 m, 1,092.4 m, and 1,098.5 m depths correspond to points above, between, and below the perforated sections of the borehole. The 932.7 m location was chosen because it is adjacent to the contact between the lower portion of the borehole where the casing is cemented to the annulus and the upper portion that is not, where the space between the borehole and the casing is filled with drilling mud. All of these water samples were malodorous and had black suspended particles that were more prominent the deeper the sample was collected. Two additional water samples were collected at 518.3 m and 640.2 m, based on the results from the chemical log. Although both samples had the bad odor associated with the samples collected deeper in the borehole, the shallower sample was clear in color while the sample from 640.2 m was aqua blue in color. Water samples were analyzed for anions, cations, oxygen and hydrogen stable isotope ratios, and enriched tritium. The results of these analyses are presented in Table 1.

<u>Hydrologic Logging</u>

*Chemical Logging*

Following water sampling, Well 10-36 was logged with the chemical logging tool (Figure 11). The depth to water measured with this tool was 316.6 m. However, prior to the removal of the 0.05-m tubing, EPA measured a depth to water of 286.1 m. The 30.5 m difference can be accounted for by the water that was displaced when the access tubing was in the well (based on a wall thickness of 0.635 cm (1/4") and 813.0 m of wet tubing, the tubing displaced 51.4 m of fluid). When the tubing was removed, the water level dropped to a depth that was proportional to the volume of the tubing. Although the well was recovering (water level rising), it was doing so very slowly. This recovery could be seen in subsequent water level tags that showed the depth to water decreasing with each successive measurement (on May 28 at 15:28, the fluid level was 334.0 m, on May 29 at 15:48 the fluid level was 331.8 m; a one day change of 2.2 m, equal to a rate of 0.15 cm/min). The slow recovery indicates that the formation is not very productive or that the well does not have good
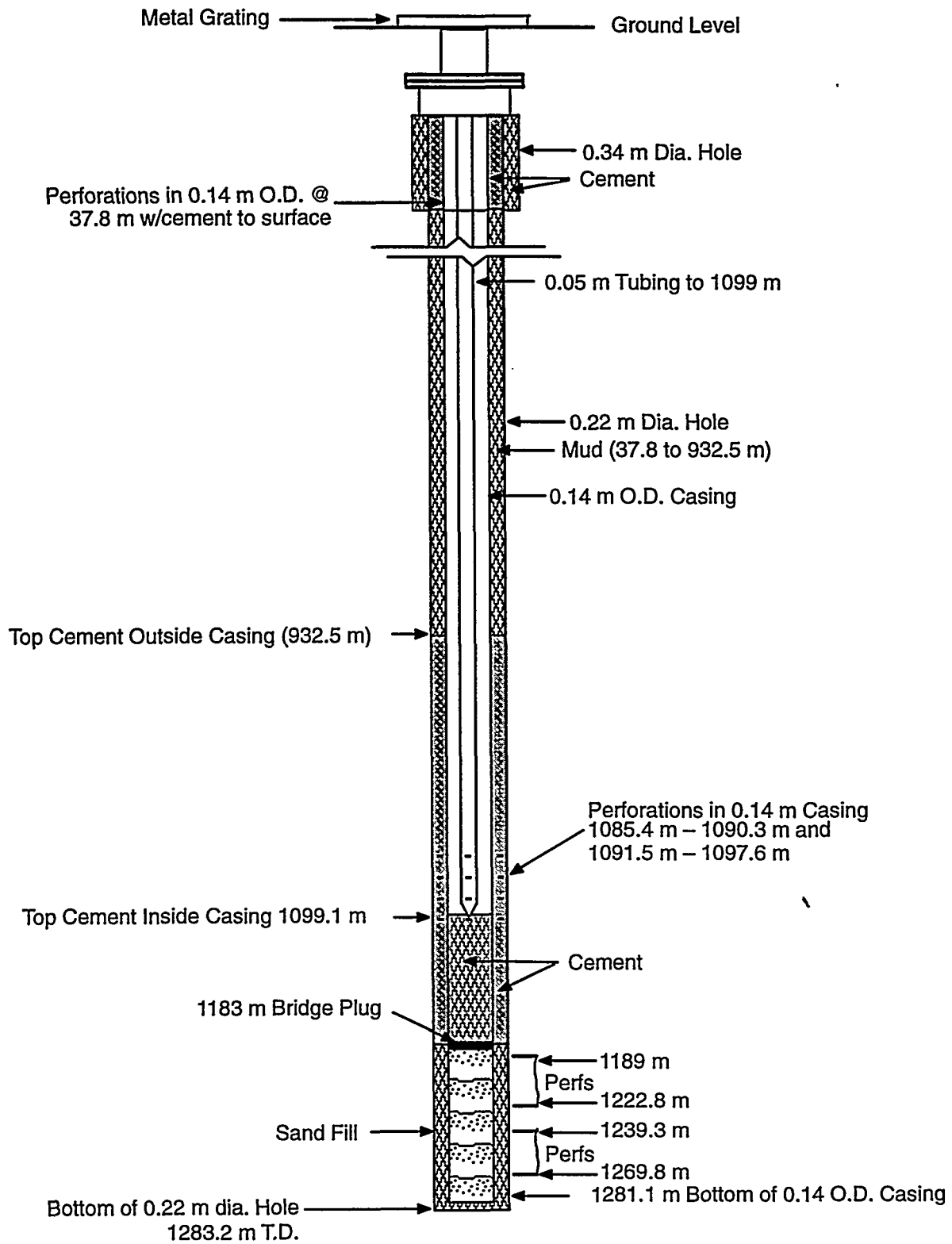
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Figure 10. Status of Well 10-36, from Holmes and Narver (1983) prior to the 1994 field activity. The 0.05-m tubing has been removed from the well.

# TABLE 1. CHEMICAL AND ISOTOPIC ANALYSES OF GROUNDWATER SAMPLES FROM THE GASBUGGY SITE. All units are mg/l unless noted.

| Well | Depth (m) | Date (dmy) | pH* (S.U.) | EC* (µS/cm) | SiO$_2$ | Ca | Mg | Na | K | Cl | SO$_4$ | HCO$_3$ | CO$_3$ | OH | NO$_3$ | δ$^{18}$O (‰) | δD (‰) | $^3$H (pCi/L) | Total Alkalinity as CaCO$_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EPNG 10-36 | 289.5 | 19-May-95 | 11.7<br>12.2 | 4,351<br>4,060 | 3.8 | 44.7 | <.1 | 482 | 172 | 89.1 | 585 | NA | 49.7 | 186 | <.01 | −2.3 | −34 | 128±9 | NA |
| EPNG 10-36 | 360.0 | 19-May-95 | 11.5<br>12.2 | 4,329<br>4,470 | 4.1 | 46.7 | <.1 | 498 | 164 | 88.4 | 628 | NA | 47.7 | 197 | <.01 | −1.8 | −34 | 107±14 | 670 |
| EPNG 10-36 | 430.1 | 19-May-95 | 12.1<br>12.2 | 4,393<br>4,490 | 4.2 | 49.7 | <.1 | 494 | 164 | 84.8 | 598 | NA | 47.8 | 199 | <.01 | −1.8 | −32 | 138±11 | NA |
| EPNG 10-36 | 487.6 | 21-May-95 | 12.3<br>12.2 | 4,898<br>4,740 | 4.4 | 62.8 | <.1 | 547 | 151 | 82.5 | 740 | NA | 57.2 | 195 | <.01 | −2.0 | −32 | 119±10 | 680 |
| EPNG 10-36 | 518.3 | 30-May-94 | 12.1 | 4,670 | 4.0 | 69.5 | <.1 | 520 | 154.0 | 66.5 | 670 | 0 | 54.7 | 215 | 0.18 | −2.3 | −32 | 121 ± 8 | NA |
| EPNG 10-36 | 579.1 | 21-May-95 | 11.3<br>11.5 | 10,492<br>10,200 | 15.4 | 352 | <.1 | 2,200 | 65.4 | 313 | 5,160 | NA | 34.1 | 49.0 | <.01 | −9.5 | −68 | 14±9 | 220 |
| EPNG 10-36 | 640.2 | 30-May-94 | 11.3 | 10,200 | 18.8 | 382 | <.1 | 2,220 | 56.7 | 261 | 5,520 | 0 | 23.8 | 47.9 | 0.13 | −9.9 | −68 | 12 ± 9 | NA |
| EPNG 10-36 | 932.9 | 27-May-94 | 11.2 | 10,200 | 18.6 | 382 | <.1 | 2,240 | 54.7 | 263 | 5,460 | 0 | 25.1 | 34.2 | 0.13 | −9.8 | −69 | < 10 | NA |
| EPNG 10-36 | 1083.8 | 27-May-94 | 10.1 | 9,760 | 18.5 | 406 | .54 | 2,150 | 67.6 | 266 | 5,390 | 0 | 23.6 | 4.8 | 0.22 | −9.9 | −68 | < 10 | NA |
| EPNG 10-36 | 1083.8 | 20-May-95 | 10.4<br>10.4 | 11,462<br>9,870 | 20.8 | 376 | .1 | 2,160 | 73.4 | 315 | 5,350 | NA | 29.4 | 5.4 | <.01 | −9.7 | −73 | <10 | 74 |
| EPNG 10-36 | 1092.7 | 28-May-94 | 10.3 | 9,760 | 18.3 | 406 | .99 | 2,180 | 69.0 | 263 | 5,380 | 0 | 24.2 | 7.0 | 0.18 | −9.7 | −68 | < 10† | NA |
| EPNG 10-36 | 1092.7 | 20-May-95 | 10.5<br>10.5 | 10,394<br>9,880 | 21.3 | 389 | <.1 | 2,160 | 72.2 | 328 | 5,380 | NA | 40.2 | 2.9 | <.01 | −9.7 | −69 | <10 | NA |
| EPNG 10-36 | 1098.8 | 28-May-94 | 10.2 | 9,830 | 22.7 | 414 | 1.78 | 2,170 | 80.7 | 263 | 5,430 | 0 | 25.4 | 6.0 | 0.13 | −9.9 | −68 | < 10 | NA |
| GB-1[2] | 1071.0 | 23-Feb-67 | 7.7 | 8,210 | 8.0 | 218 | 14 | 2,160 | 14 | 272 | 4,060 | 223 | 0 | 0.0 | 0.0 | NA | NA | NA | NA |
| GB-1[2] | 1098.3 | 26-Feb-67 | 6.9 | 7,450 | 16.0 | 242 | 14 | 1,880 | 12 | 221 | 3,630 | 86 | 0 | 0.0 | 0.0 | NA | NA | NA | NA |
| GB-2[2] | 1056 | 17-Apr-67 | 7.2 | 9,350 | 10 | 251 | 12 | 2,220 | 1.6 | 282 | 4,440 | 306 | 0 | NA | NA | NA | NA | NA | NA |
| GB-2[3] | 1195 | 1-May-67 | NA | NA | NA | NA | NA | NA | NA | 5,320 | 480 | NA | NA | NA | NA | NA | NA | NA | NA |
| Indian E-1[3] | NA | 5-May-67 | NA | NA | NA | NA | NA | NA | NA | 3,700 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Feasel #2[3] | NA | 8-Feb-68 | NA | NA | NA | NA | NA | NA | NA | 12,100 | NA | NA | NA | NA | NA | NA | NA | NA | 3 |
| Bubbling Spring | NA | 21-May-95 | 7.6<br>7.98 | 1,240<br>1,290 | 8.2 | 38.5 | 9.97 | 237 | .98 | 14.2 | 290 | 425 | NA | NA | <.01 | −13.1 | −96 | 45±14 | 325 |

NA = not analyzed or not reported
*Top number is a field measurement taken at the time of collection. Bottom number was measured in the laboratory
†A split from this sample bottle was analyzed by the U.S. EPA and reported to have 11.2 pCi/L ± 4.5 with a minimum detectable amount of 7.1 pCi/L (D. Farmer, pers. comm)
[2]from Mercer (1970)
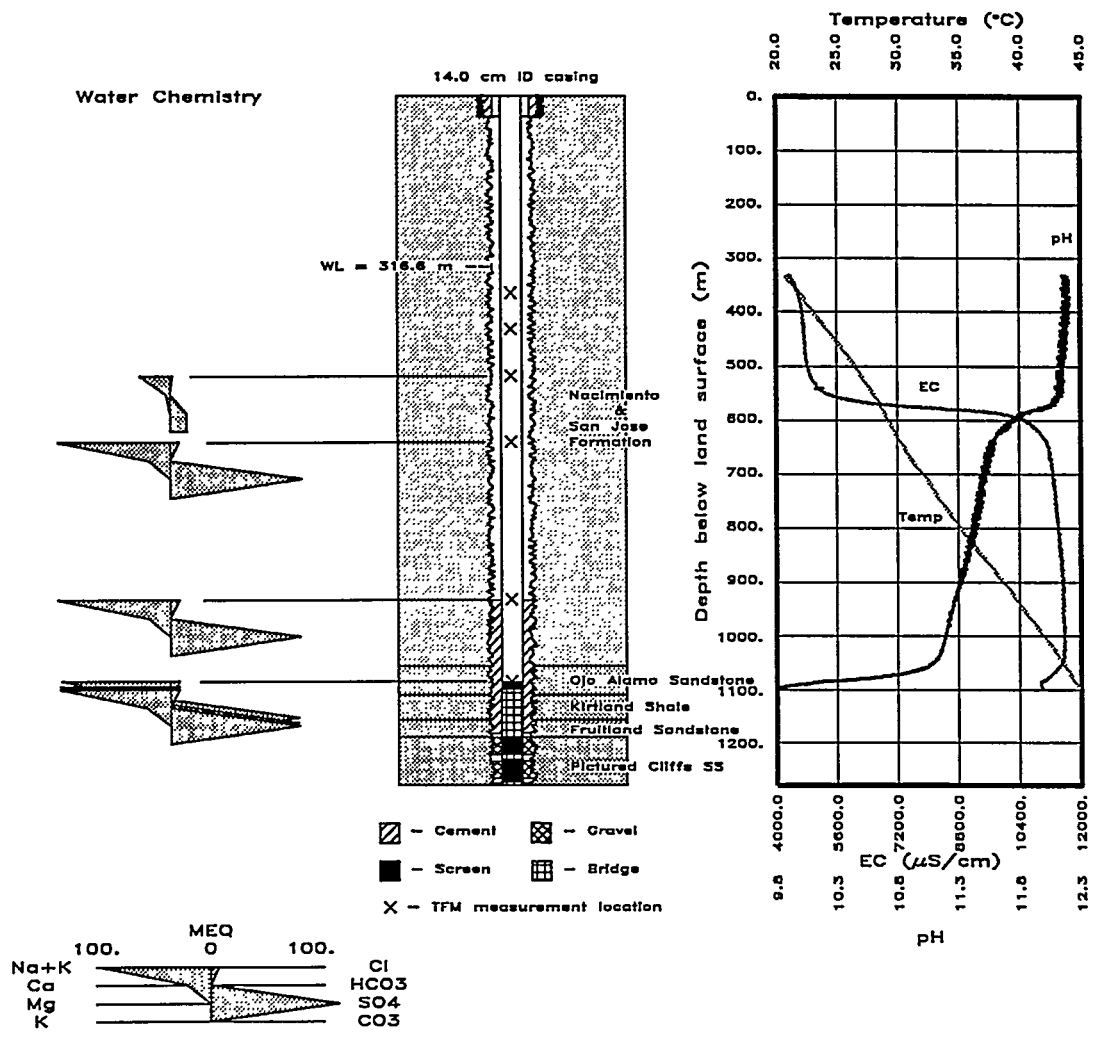[3] Sample from Pictured Cliff Formation, from Power and Bowman (1970)

Figure 11. Chemical log and location of thermal flowmeter measurements in EPNG 10-36, May 29, 1994. Stiff diagrams of chemistry of water samples collected are also shown.

communication with the formation. If the well is recovering only through the screened zone (i.e., if the casing integrity is good), the bottom water samples should be more representative of the formation water.

Temperature: The temperature log follows a relatively straight path along a geothermal gradient of 0.0315 °C/m, although a few minor perturbations do occur. The first of these perturbations occurs from the top of the borehole to a depth of 490 m, where the gradient is slightly steeper than the average geothermal gradient. At this point, the gradient decreases and becomes less than the geothermal gradient to a depth of 685 m. From 685 m to 808 m, the gradient is equal to the geothermal gradient, although the temperature is slightly less than that predicted by the geothermal gradient. The remainder of the borehole can be described as having a gradient slightly greater than the average geothermal gradient.

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Electrical Conductivity: The most notable feature on the conductivity (EC) plot is the sharp increase of conductivity that begins at approximately 525 m. The conductivity at 525 m is 4,900 µS/cm, which rapidly increases to 11,100 µS/cm at 640 m. This substantial increase is indicative of a dramatic change in water chemistry, and the chemical analyses from 518.2 m and 640.1 m confirm these different water chemistries. From 640 m to 1,062 m, the conductivity slowly increases to 11,500 µS/cm but then decreases to 10,900 µS/cm at the bottom of the hole. This decrease in conductivity at the bottom of the borehole is likely the result of fresher formation water entering the borehole as the well was re-equilibrating from the removal of the 0.05-m tubing. This is supported by the fact that the calculated recovery of the well when the chemical logging was conducted was 20.9 m, and the observed break in slope occurred 23.4 m from the top of the screened interval.

pH: In the upper 1000 m of the borehole, the pH responded in a similar but inverse manner as compared to the specific conductance. The pH in the upper part of the borehole was 12.2, which began to rapidly decrease at approximately the same depth the specific conductance increased. At 640 m, the pH had decreased to 11.6 and continued to slowly decrease to 11.1 at 1,062 m. From 1,062 m to the bottom of the borehole, the pH rapidly decreased to 9.8, again indicative of the inflow of fresher formation water. The high pH in this well is likely the result of the water reacting with the cement that was used to plug the well during the test.

*Thermal Flow Logging*

One of the main purposes of the well logging was to determine the source of the elevated tritium in Well 10-36. The thermal flow tool was used to determine vertical movement of water in the borehole. Measurements were made at 365.7, 431.0, 518.1, 640.0, 932.6 and 1,091 m. No vertical movement was detected with the thermal flow tool at all of the zones where measurements were made. Thus, if vertical transport from the cavity to the Ojo Alamo Sandstone through the plugged casing is occurring, it is at a rate below the sensitivity of the flowmeter (0.08 L/min).

**1995 Field Activities**

The May 1994 hydrologic characterization was performed while the well was in a state of disequilibrium. The 0.05-m tubing displaced approximately 30 m of water in the well. With the removal of the tubing the water level dropped 30 m and was slowly refilling at the time of the fieldwork. Because of the slow recovery rate, full recovery to the static water level was estimated to take several months. Of the six samples collected in 1994, only the two uppermost samples, which were furthest from the screened portion of the well, contained tritium concentrations above the detection limit of 10 pCi/L. The tritiated water occurred in a zone of chemically distinct water and in the transition zone between this water and the water below. The upper part of the water column was not one of the original targets but was sampled based on the chemical log; consequently, there was limited vertical resolution in the sampling. Given the transient state of the well in May 1994 and the occurrence of tritium where it was not expected, it was determined that another site visit would be necessary.

The objectives of the 1995 field investigation were to determine the tritium distribution in the upper portion of the well, determine the source of tritium, if possible, and to re-evaluate the

hydrologic characteristics of the well while in a state of equilibrium. The site visit was conducted between May 19 and May 22, 1995. Sampling and logging were performed in a predetermined order to minimize mixing of borehole fluid and sample cross-contamination. The depth to water measurement, taken prior to any sample removal, was 286.7 m, 29.9 m higher than the measurement made by Desert Research Institute (DRI) in 1994. Comparison of this water level with water level measurements made by the EPA prior to the removal of the tubing indicates the well had fully recovered.

Water Sampling

Water samples were collected in the following order at the following depths below land surface: 289.6, 360.0, 430.0, 1083.8, 1092.7, 487.6, and 579.1 m. The first five water samples were collected prior to logging activities in the order of shallow to deep. The last two samples listed, 487.6 and 579.1 m, were collected after the chemical log because they were chosen on the basis of being above and below the chemical transition zone. In addition to the well samples, a spring which was thought to be the water supply for the drilling activities was sampled. Samples were collected for analysis of tritium, stable isotopes of oxygen and hydrogen, and major cations and anions. Field measurements of pH, EC, and alkalinity were performed. Table 1 shows the results of the chemical analyses, as well as the field parameter measurements.

The samples collected at 1,083.8 m and 1,092.7 m were an aqua-blue color. This is in contrast to the samples collected in 1994, where the only aqua-blue-colored sample was collected at 640.2 m. While performing the alkalinity titration, it was observed that the aqua-blue color turned colorless with the addition of acid. The samples that were archived also turned colorless after an undetermined period of time. The unusually high pH values of all the samples are probably due to contamination by cement and results in most of the alkalinity being in the $OH^-$ phase. The somewhat lower pH values of the bottom samples suggest that they are less contaminated.

Hydrologic Logging

*Chemical Logging*

A chemical log was conducted in EPNG 10-36 on May 20 (Figure 12). The parameters measured included temperature, EC, and pH.

Temperature: The temperature log follows a relatively straight path along a geothermal gradient of 0.032°C/m. Although minor perturbations between the temperature log and the geothermal gradient occur, they reflect varying thermal conductivities of the different rock types and are not the result of flowing water in the well. Figure 13 is a plot of the temperature logs from 1994 and 1995. As can be seen, the temperature profiles are virtually identical.

Electrical Conductivity: The EC probe and associated electronics exhibited a great deal of electronic noise while logging EPNG 10-36. Even with the noise, the important features of the log are discernible. The major trends in the log are similar to those observed in 1994 (see Figure 14), although the transition from an EC of 4,750 µS to 11,150 µS occurs higher in the monitoring well than it did in 1994, presumably due to recovery of the static water level through the perforations at the bottom of the well. The 1994 log also shows a sharp decrease in EC at the bottom of the well, which is not present in the 1995 log.
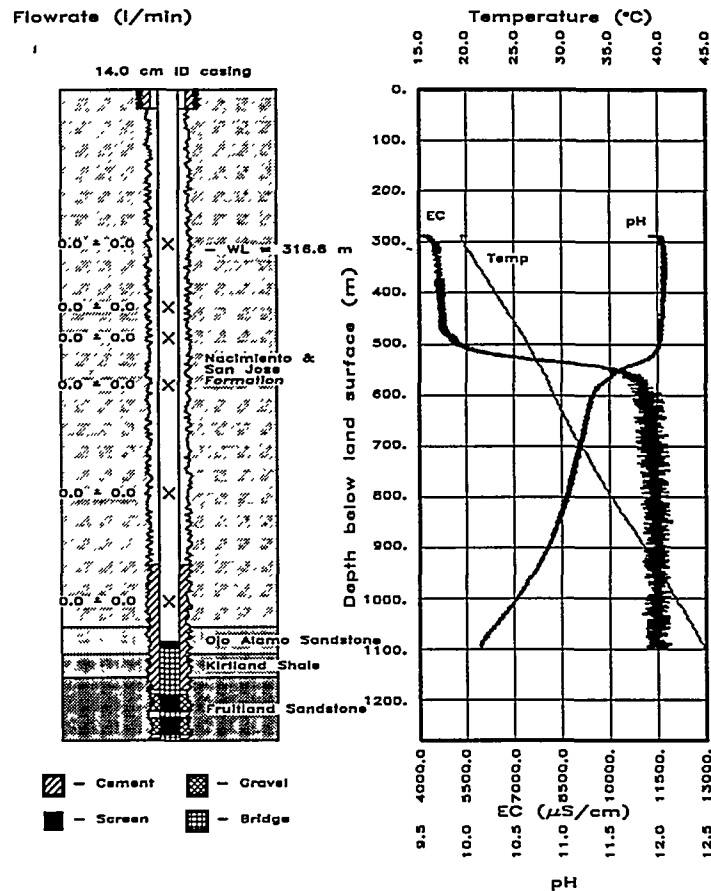
Figure 12. Chemical log and results from the thermal flowmeter survey conducted in EPNG 10-36.

pH: The pH log from 1995 also looks similar to the pH log from 1994, although some differences are noticeable. As with the EC plot, the transition zone for the rapid decrease in pH occurs higher in the monitoring well than it did in 1994. Below 854 m, the trend of the pH log differs from that of the previous year. In 1994, the pH gradually decreases from 11.0 at 854 m to 10.7 at 1,036 m, then rapidly decreases at the bottom of the well. In contrast, the 1995 log shows that the pH decreased from 854 m to the bottom of the well at a faster, but near linear, rate and ended at a higher pH than in the previous year (Figure 15).

*Thermal Flow Logging*

Thermal flowmeter measurements were performed at six discrete depths (Figure 16). The thermal flowmeter was equipped with an inflatable packer and submersible pump to divert borehole fluids through the tool. The flowmeter used in 1995 had higher resolution than the tool used in 1994, 0.03 compared to 0.08 l/min. There was no vertical flow measured within the well that exceeded the detection limit of 0.03 l/min.

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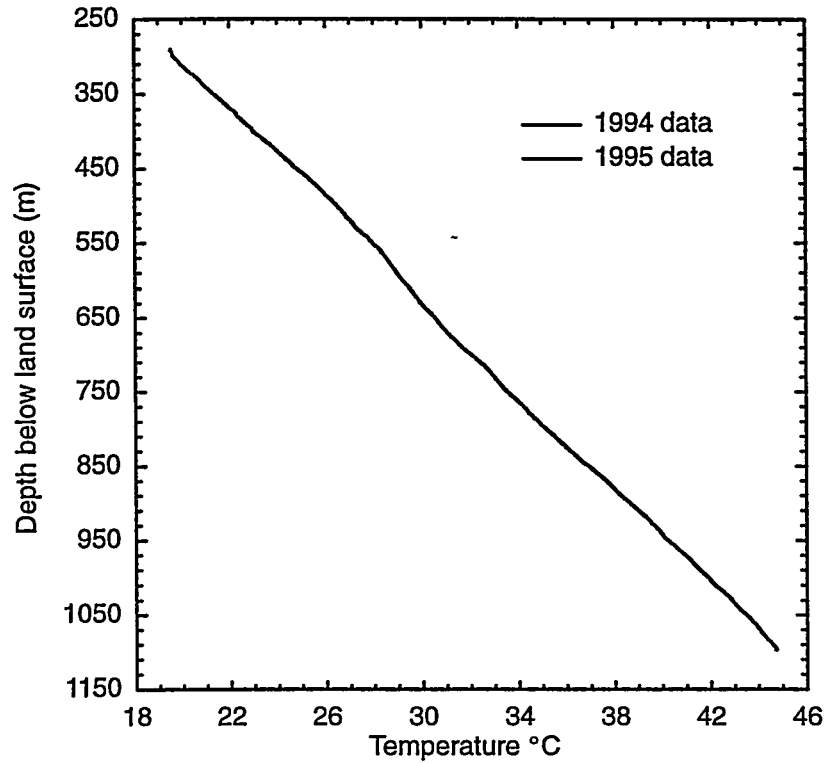
Figure 13. Comparison between temperature logs collected in 1994 and 1995. The two logs are virtually identical and cannot be distinguished at the scale shown.
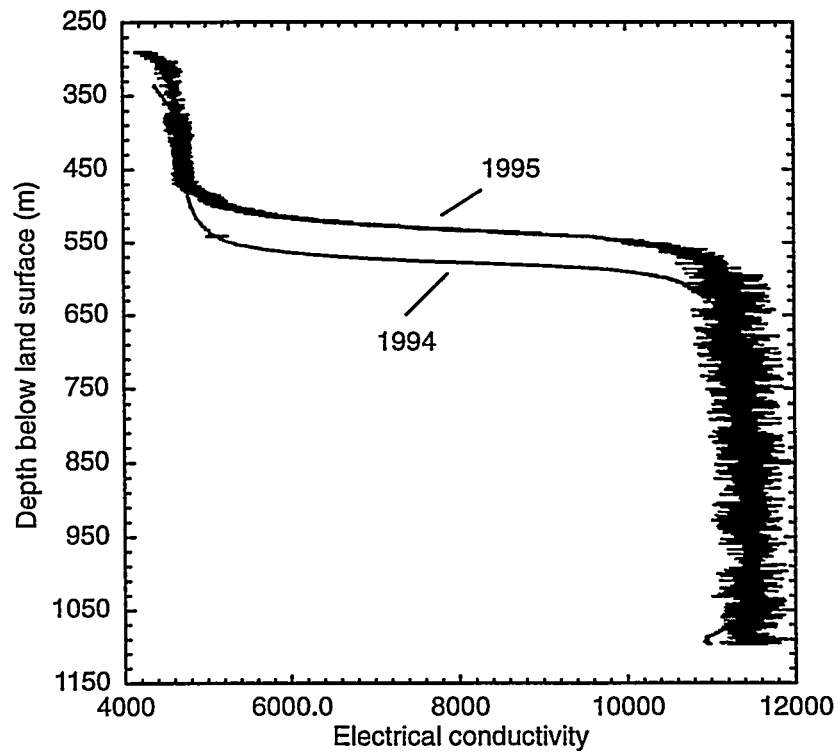


Figure 14. Comparison between EC logs collected in 1994 and 1995.
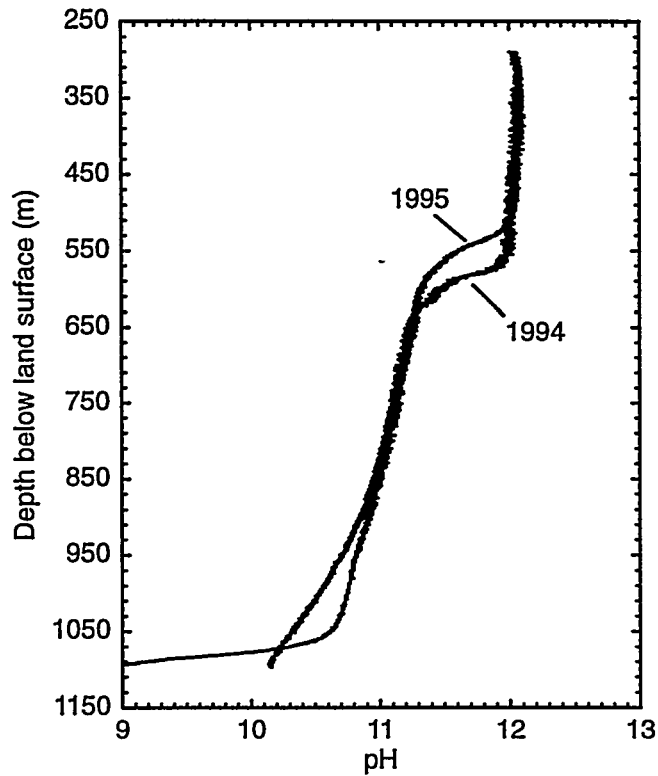
Figure 15. Comparison between pH logs collected in 1994 and 1995
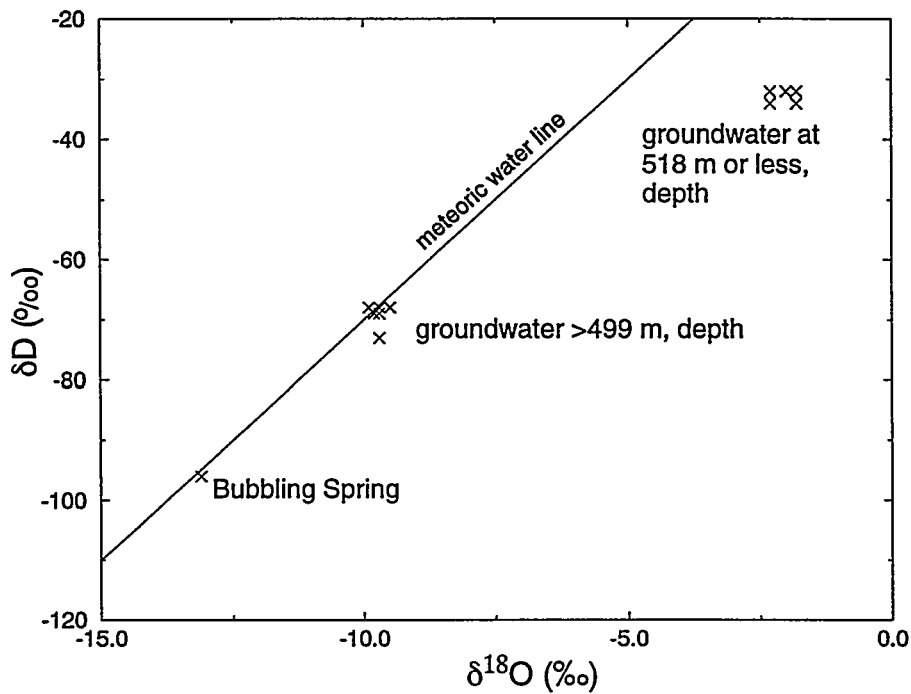


Figure 16. Stable isotopic composition of water samples from well EPNG 10-36 and Bubbling Spring. The more enriched composition of samples from depths of 518 m or less lies on a possible evaporation line trajectory with a slope of 4.8 from the deeper well water. The depleted composition of Bubbling Spring appears unrelated to the well samples.

**Interpretation of Logging, Chemistry, and Radiochemistry Data**

With the well recovering from the removal of the 0.05-m tubing, and given that the only perforations are across from the Ojo Alamo at the bottom of the well, there should have been upward flow occurring at the time of the May 1994 logging. Such flow was below the detection limit (0.08 l/min) of the thermal flowmeter, suggesting a very slow recovery from the tubing removal. Water level measurements made before the removal of the access tubing in 1994 and measurements made by DRI in May 1995 indicate that the well had fully recovered at the time of the 1995 field activity. The comparison plots (Figures 13 and 14) indicate that the fluid in the borehole was displaced upward, which is consistent with fluid entering at the screens, rising upward until static equilibrium was achieved. Thermal flow characteristics indicate that under the equilibrium conditions in 1995, no vertical flow exists in the well.

The water samples can be divided into two groups based on their chemical and isotopic characteristics. All of the samples belong to the Na-SO$_4$ facies, but the samples collected at 488 m, and above, contain lower concentrations of all the ions, with the exception of CO$_3^=$, OH$^-$, and K$^+$, as compared to the samples collected below. The unusually high pH values of all the samples result in most of the alkalinity being in the OH$^-$ phase. In the pH range usually encountered in natural water, OH$^-$ is a minor constituent, but at pH values above 10, it is important. The chemistry of the samples collected close to the perforations does not vary significantly, though the pH is lower than the upper samples, confirming the logging results and suggesting fresher formation water.

The two water zones are also differentiated by their stable isotopic composition (Figure 16). The deeper samples are more depleted in the heavy isotopes of hydrogen and oxygen and plot near the meteoric water line (MWL). Samples collected at 488 m and above show non-equilibrium enrichment in the heavy isotopes, plotting to the right of the MWL, on a line with a slope of 4.8 from the cluster of analyses from deeper in the well. The two samples collected from the transition zone identified in the logs are indeed transitional in their chemistry, but the stable isotopic composition of the sample from 488 m clearly identifies it with the upper zone, while the sample from 579 m belongs with the lower. The tritium analyses coincide with this division, with tritium above 100 pCi/L measured in samples at 488 m and above, non-detectable tritium below 579 m, and tritium very near the detection limit at 579 m.

Comparison of the recent 10-36 sample analyses with published chemical analyses of water (Table 1) from the Ojo Alamo and the Pictured Cliffs formations strongly suggests that the water present in the lower part of well 10-36 originates in the Ojo Alamo. With the exception of the pH and alkalinity, the 1994 and 1995 samples bear a strong resemblance to the samples collected from the Ojo Alamo in well GB-1 as part of the Gasbuggy Project (Mercer, 1970). In contrast, the incomplete Pictured Cliffs analyses reported by Power and Bowman (1970) reveal a chloride rather than sulfate-dominated water in the Pictured Cliffs. This distinction is large, an order of magnitude less sulfate and an order of magnitude more chloride in the Pictured Cliffs, and was used by Power and Bowman (1970) to determine the source of water infilling the Gasbuggy cavity.

The unusual pH and alkalinity difference between earlier Ojo Alamo analyses and the current samples indicate that the water in 10-36 is no longer representative of natural conditions and has been

altered by some process, most likely the cementing of the well prior to the shot. Residual cement has clearly raised the pH, changed the distribution of alkalinity species, and resulted in carbonate precipitation. The water in the upper zone has also been affected by these processes, but has a chemical and isotopic signature suggestive of a water source other than the Ojo Alamo. Records of the source of drilling water for Gasbuggy operations are sketchy, but there is mention that the source of site water was a spring located about five miles from the site (Eberline Instrument Corp., 1979). Bubbling Spring was sampled as the possible source of drilling water, but the water chemistry (Table 1) is unlike either of the water types in Well 10-36. The spring's stable isotopic composition is also significantly depleted in heavy isotopes, as compared to the well water (Figure 16).

The tritium analyses indicate that tritium was not entering the well at the Ojo Alamo perforations at the time of sampling in either May 1994 or May 1995. The lower pH value at the Ojo Alamo perforations suggests that relatively fresh formation water was entering the well in May 1994 in response to removal of the tubing (though at a low rate of flow according to the flowmeter results), yet none of the seven samples collected near the perforations contained measurable tritium (<10 pCi/L).

The water level and logging results, as well as chemical indicators (pH), are consistent with the recent entry of groundwater into the well through the screens at the Ojo Alamo. In neither the 1994 nor 1995 sampling has detectable tritium been found in samples collected from the screened intervals. Indeed, tritium was not detected throughout the lower portion of the water column, distinguished by a groundwater chemistry suggestive of the Ojo Alamo. These results indicate that tritium is not currently entering EPNG 10-36 from the Ojo Alamo. The reported presence of cesium on the bottom of the 0.05-m tubing, detected from a swipe sample taken when the tubing was removed from the well, may reflect prompt injection of a gaseous precursor immediately after the test. If tritium was also transported by the same mechanism, that transport has apparently ceased.

The absence of tritium in the lower portion of the well was surprising based on the EPA monitoring results (Figure 1), though differences between the EPA and DRI results can be expected because the well conditions were radically changed by the removal of the tubing. The 0.05-m tubing may not have been in good contact with formation water, particularly above the perforations, so the tritium detected by EPA inside the tubing may not have been representative of the tritium concentration in the Ojo Alamo through time. The highly variable tritium concentrations from year to year (Figure 1) do not exhibit the breakthrough behavior expected for a plume of contaminant transported by groundwater. The tritium may have had some other source, perhaps higher in the well or from the surface. Once inside the tubing, the tritium may have been effectively trapped there and resampled by EPA year after year. Pulling the tubing prior to DRI's sampling would have dispersed the tritium throughout some length of the well, diluting it below the detection limit.

The source of the water and tritium in the upper part of the borehole remains unknown. The enriched stable isotopic composition suggests water that has been exposed to evaporation, which in turn suggests surface exposure. This is consistent with a temporary surface water pond on site, with the tritium content related to gas flaring activities during production testing after Gasbuggy. Given the well completion and the stratified nature of the water column, it is most likely that the water

present in the upper portion of the well entered either by flowing down from the cellar as a result of the below grade completion, or was injected into the well, perhaps during drilling or testing. In either case, the introduced water remained at the top of the water column due to density differences. Tritium may have been present in the upper portion of the well for many years and would have been undetected due to the limited sampling access through the tubing and/or EPA's practice of collecting the water sample near the bottom of the well. Bubbling Spring can be ruled out as a water source because the chemistry and isotopes are not consistent with the well water, but the spring cannot be confirmed as the primary water supply for the project. The stable isotopes are consistent with the upper water being evaporated from water deeper in the well, but the chemistry of the upper zone cannot be derived by simple evaporative concentration of Ojo Alamo water (e.g., the Cl concentration is higher deeper in the well). The chemical and isotopic character of the upper water zone thus suggests that the tritium located in the upper portion of Well 10-36 has a source other than the Ojo Alamo.

## CONCLUSIONS

Based on the tritium time-series trend observed as part of the LTHMP, tritiated fluid entered the 0.05-m tubing in EPNG 10-36 between the 1983 and 1984 sampling events. The ultimate source of the tritium is likely to be the Gasbuggy underground nuclear test located 132 m away. Three scenarios have been identified that could explain the transport of tritium from the Gasbuggy test to well EPNG 10-36: 1) introduction of tritium into the well from the land surface, 2) migration of tritium through the Ojo Alamo, and 3) migration through the Pictured Cliffs. A travel time analysis using hydraulic data gathered at the time of Project Gasbuggy suggests that the hydraulic conductivity of the Ojo Alamo is too low for transport to 10-36 (scenario 2) over the time frame of interest. This means that transport over the time span covered by the monitoring data requires migration through either a fracture intersecting the Ojo Alamo close to Well 10-36, or through fractures in the Pictured Cliffs and up through the bottom plug in the well (scenario 3).

The logging and sampling program was designed to address the issues raised by the travel time analysis and resolve the source of the tritium. Results from logging and sampling in 1994 and 1995 at Well EPNG 10-36 do not support scenario 3, vertical transport from the Pictured Cliffs through the bottom plug in the well. Flow logging did not detect any vertical movement up through the bottom plug, within the sensitivity of the measurements (0.08 L/min in 1994, 0.03 L/min in 1995). Hydrochemical logging and sample results are also inconsistent with groundwater in the well originating in the Pictured Cliffs. The logging and sampling data in 10-36 are consistent through the lower portion of the well with the known characteristics of groundwater in the Ojo Alamo, with the exception of altered pH and alkalinity conditions presumably caused by cementing operations.

At the time of sampling in 1994 and 1995, no measurable tritium was located at the bottom of the well, adjacent to the Ojo Alamo perforations. The abrupt appearance of tritium in 1984 and disappearance in 1994, with the erratic concentrations measured in between, are inconsistent with breakthrough of a migrating plume of tritium contaminated water in the Ojo Alamo. The restrictive nature of the production tubing through which sampled occurred prior to 1994 and the absence of tritium in the fresh formation water sampled when the tubing was removed, suggest that the

previously measured tritium was limited to that tubing and perhaps related to conditions higher in the well. A zone of water of unknown origin occurs at the top of the well, marked by lower water salinity, an isotopic signature indicative of evaporation, and measurable tritium. These characteristics suggest surface exposure, perhaps in a project-related pond that subsequently entered the well. The combined findings of the travel time calculations and field investigations thus suggest that the first scenario, a surface source, is the best explanation for the tritium currently found in the upper portion of the 10-36 water column. The source of the tritium measured by EPA at the bottom of the old tubing may never be known, but is unlikely to represent transport from the nuclear test to 10-36 through either the Ojo Alamo or Pictured Cliffs.

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