DANIEL B. STEPHENS & ASSOCIATES, INC.
ENVIRONMENTAL SCIENTISTS AND ENGINEERS

April 21, 1993

0375-3065-93

Dr. Larry Maassen
Environmental Restoration Program Office
Mail Stop M992
Los Alamos National Laboratory
Los Alamos, NM 87545

Dear Larry:

Daniel B. Stephens & Associates, on behalf of the LANL Review Panel, is pleased to submit the final report entitled "Hydrogeologic Review for the Environmental Restoration Program at Los Alamos National Laboratory, Los Alamos, New Mexico." Most of the reviewers' comments have been addressed in the text of the report. Responses to all the comments have been summarized in the attached table "Response to Comments".

I have enjoyed the opportunity to work with you and the LANL staff on this project.

Sincerely,

DANIEL B. STEPHENS & ASSOCIATES, INC.

Daniel B. Stephens

Daniel B. Stephens, PhD, CPH
President

Enclosure

cc(w/enc): Peter Kearl
Roger Lee

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HYDROGEOLOGIC REVIEW FOR THE ENVIRONMENTAL RESTORATION PROGRAM AT LOS ALAMOS NATIONAL LABORATORY

Prepared by:

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Prepared for:

Los Alamos National Laboratories
Los Alamos, NM

April 21, 1993

"HYDROGEOLOGIC REVIEW FOR THE ER PROGRAM AT LANL"

RESPONSE TO COMMENTS

Reviewer: Jamie Gardner

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
1	2, 2, 5	M	Reference should be Smith et al. (1970)	A	
2	3, 3, 2	M	Formal stratigraphic names of formations must be used, as follows: Bandelier Tuff, Puye Formation, and Basalts of the Cerros del Rio	A	
3	4, 3, 7	M	Change "as much as" to "at least" several centimeters	A	
4	4, 3, 13	C	Roots found at 58 feet at TA-49 (Wier and Purtymun, 1962)	C	Roots found to 40 feet at TA-49 (Wier and Purtymun, 1962, p. 150)
5	5, 1, 2	M	Delete "dense"	A	
6	5, 3, -	C	Size distribution on crushed sample is meaningless! Should this be stated?	A	Paragraph deleted
7	8, 1, 2	M	Change "sediments" to "deposits"	A	
8	8, 3, 1-7	M	Structural, geochemical, and hydrologic data all indicate Valles caldera (note lowercase "c"). Can't recharge the "main aquifer." So are we left with recharge in the canyons only? Fact is, we don't know where recharge is from ... state this.	A	The authors' review of regional hydrogeology and recharge sources is constrained to existing literature in this section. The authors agree with this comment, and to the extent that this view is supported in the literature, the reviewer's comment is incorporated (see Section 2.2.3.2, ¶ 1).

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
9	7, 2, 2	C	Why are "alluvial aquifers" treated separately from "perched" ones? I realize this is entrenched in the Lab's literature, but aren't "alluvial" aquifers perched???	A	The authors did not intend to convey that alluvial aquifers were not perched, only that as stream-connected aquifers, they behave differently than deeper perched aquifers located in deposits beneath the alluvium. The paragraph is revised to reflect this.
10	8, 3, -	M	Although the term "main aquifer" is entrenched, I think it is appropriate for this review to question its use and definition. The term is misleading and simplistic in that it implies a huge, homogeneous underground reservoir from which pristine municipal water supply comes. The situation is clearly more complex. Scant reliable fluid geochemistry implies that there are multiple aquifers that constitute the "main aquifer." Why is Los Alamos well field under artesian conditions and the others aren't? etc., etc.	R	The term "main aquifer" does not necessarily imply a single homogeneous aquifer. Further, it is not feasible to identify or define multiple aquifers based on the degree of geochemical variability observed in the main aquifer beneath LANL. The main aquifer, as it refers to regional ground water beneath LANL, is located in the heterogeneous sediments of the Puye and Tesuque Formations and probably consists of numerous aquifer zones of varying permeability and geochemistry. These zones may or may not exist as multiple aquifers separated by impermeable boundaries. It is not practical or feasible to attempt to monitor the main aquifer on such a scale that individual aquifer zones are characterized. The focus of site characterization should be on monitoring impact to the main aquifer, i.e., on the upper zone of the main aquifer. See additions to Section 2.2.3.2, ¶ 1 (p. 8), and Section 2.3, ¶ 5 (p. 13)

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
11	9, 3, 1	M	To the best of my knowledge, there are no data just west of the Pajarito fault system, i.e., "beneath the Sierra de los Valles."	A	Purtymun (1984) observes a steepening of the gradient at the west end of LANL based on water levels in TW-4 and H-19, and extrapolates this gradient to the Sierra de los Valles. There are insufficient data to adequately characterize the regional water table gradient at or west of the Pajarito fault zone.
12	10, 1-2, -	M	Sudden reference to "OU-1071" and "operable unit" is confusing and not particularly relevant. Delete and reword.	A	Sentence deleted.
13a	10, 2, 9	M	Delete "member"	A	
13b	10, 3, 5	M	Delete "member"	A	
14	10, 3, 3-13	M	Refer to review comment #10 of this review. Here is evidence that there may be multiple aquifers that constitute the "main aquifer." Why should springs reflect distinct chemistries after such long residence times in the "main aquifer"? (Why are residence-in-reservoir times not discussed in this review?) In a critical review, these issues need to be discussed!	C	See response to Comment 10.
15a	11 (Fig. 1)	M	Change Totatvi Formation to Totavi Lentil	A	
15b	11 (Fig. 1)	M	Change Cerros del Rio to Basalts of the Cerros del Rio	A	
15c	11 (Fig. 1)	M	Change Bandelier Ignimbrite to Bandelier Tuff	A	
15d	11 (Fig. 1)	M	Change Puye Fm to Puye Formation	A	

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
16	13, 1, 3	M	Change Chino Mesa to Cerros del Rio	A	
17	27, 1, 5	M	"perched alluvium"??	A	Changed "perched alluvium" to "perched alluvial aquifers."
18	34, 2, 4-5	M	How should the wells be sampled? Pumping? In situ?	C	Clarifying language is added to reflect that samples should be taken "in the upper portion of the main aquifer and at depth." A specific sampling protocol is outside the scope of this report.
19	34, 3, 4-5	M	How should the wells be sampled? Pumping? In situ?	C	See response to Comment 18.
20	37, 4, 1	O	I don't understand "validity of work reported and current" ...	C	No change.
21	61, 2, 3	O	Point #2: Does this make sense??	C	Yes, point number 2 is correct as stated. However, it can be restated, "reports that hydraulic heads in wells increase with increasing depth."
22	General	O	I would prefer to see the critical review of the state of knowledge come first with the background discussion following ... this report is mainly for folks pretty familiar with the setting (i.e., with appropriate warnings to the reader, switch Section 2 with Sections 3, 4, 5, and so on).	C	A reorganization of the report has not been undertaken. The purpose of Sections 2.1 and 2.2 is to fulfill the request that we review existing literature. The discussion in Section 2.3 is intended to present and discuss problems with some of the technical views presented in the existing literature.

Reviewer: Bruce Gallaher

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
1	6, 3, 7	O	Include Mortandad Canyon data from Stoker et al. (1991)	A	Language added to p. 6, ¶ 3, ℓ. 7: Saturated hydraulic conductivity tests conducted on core samples of Bandelier Tuff from Mortandad Canyon yielded conductivities ranging from 0.13 to 22 ft/d ($4.7x10^{-5}$ to $7.8x10^{-3}$) cm/s). Unsaturated hydraulic conductivities were approximated from the saturated conductivities using one of the nonlinear, closed-form equations, and indicated values ranging from about $2.8x10^{-7}$ to 2.8 ft/d ($1x10^{-10}$ to $1x10^{-3}$ cm/s) at 39% to 56% volumetric water content (Stoker et al., 1991).
2	9, 3, 5	M	Doesn't contribute to understanding of regional situation; delete entire sentence.	A	Sentence deleted.
3	10, 2, 8	M	Provide reference cite to Waresback and Turbeville (1990)	A	Citation added: Waresback, D. B. and B. N. Turbeville, March 1990. "Evolution of a Plio-Pleistocene volcanogenic-alluvial fan: The Puye Formation, Jemez Mountains, New Mexico." (Waresback and Turbeville, 1990)
4	12, 1, 11	M	The model was principally based on two factors: a hydraulic gradient that rises westerly toward the Jemez Mountains and an abundant potential supply of water for recharge in the Jemez.	A	Sentence changed to read: "This conceptual model is primarily based on two factors: a hydraulic gradient that rises steeply to the west towards the Jemez Mountains, and the large ground-water storage capacity of the Valles caldera." See additional changes to Section 2.3, ¶ 1.

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
5	13, 2, 12	M	Please indicate reference where this assumption is used or relied on for security.	C	The sentence is restated: "However, without additional data for support, the assumption that continuous confining beds may exist in the Totavi Lentil or the Santa Fe Group should not be relied upon in evaluations of contaminant migration potential."
6	15, 1, 1	O	Should this read as recharge into sediments lapped onto the Sangres? Generally, there is very little water available in the granites of the Sangres.	A	Sentence reworded: "Water in the aquifer to the east is recharged by precipitation originating in the Sangre de Cristo mountains."
7	15, 2, 4	M	Please provide any specific examples of reporting errors so they can be corrected and a determination made how the reporting error occurred.	C	Examples are given in the individual reviewer comments, Section 6.3, along with assessments of the causes and recommendations for corrective action.
8	15, 2, 9	O	Should "Appendix 5" read "Section 5"?	A	This should read "Section 6.3."
9	20, 4, 1	O	Not quite sure what this means. Do you mean to update the conceptual model, rather than existing reports.	A	Sentence reworded: "The database for existing reports should be updated..."

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
10	20, 5, 4	M	There is considerable data on as least gross proportions of particulate movement, e.g., suspended vs. dissolved concentrations. What does "not addressed" mean?	C	The sentence is reworded to: "Fate and transport of contaminants in solution or sorbed on sediments in surface water has not been adequately studied." This comment refers to Penrose's work that showed colloidal transport of plutonium. It was not clear whether surface sediment transport of plutonium and the subsequent infiltration or colloidal transport through the ground water was responsible for the observed plutonium concentration.
11	21, 3, 1	O	You should keep in perspective how much of radioactive inventory in canyon bottoms is tied to colloids vs. sediment bound.	A	The sentence is reworded: "Although recent work by LANL in the canyon indicates that the colloidal fraction represents less than 1 percent of the total contaminant inventory (Stoker et al., 1991), the issue of transport of colloidally bound radionuclides needs to be resolved."
12	23, 4, 8	M	Please provide reference cite for Stonestrum and Rubin (1989).	C	This was/is provided on p. 71.
13	27, 1, 2	O	Please provide studies.	A	Travis and Nuttal, 1984.
14	35, 2, 4	M	Missing units for 0.75 pore velocity.	R	There is no unit for 0.75. It is a gas saturation which is expressed as a percentage. Pore velocities are presented in the last sentence in this paragraph.
15	39, 6, 2	M	Please provide specific references to methods.		
16	52. 2. 9	M	Provide reference cite to Purtymun et al. (1974).	C	This was/is provided on p. 71.

No.	Location (p, ¶, ℓ)	Reviewer's Comments/Suggestions (Mandatory, Optional, Comment)		Preparer's Proposed Revision/Resolution (Accept, Reject, Comment)	
17	55, 3, 6	M	Unclear as it reads. Should hydraulic be changed to chemical?	A	Sentence corrected to read: "... inorganic chemical analyses of water must be checked for ion balance."
18	59, 3, 3	M	The tuff is not in contact with the main aquifer. The fractures may accelerate transport to deeper formations, but not directly into the aquifer.	A	Sentence corrected to read: "... fractures may accelerate fluid transport from perched alluvial aquifers to deeper formations."
19	66, 3, 3	M	What data or interpretation is being referred to?	A	This comment refers to data presented in Penrose et al., 1990, 0174, which indicate that movement of colloidally bound plutonium and americium in the subsurface environment is much greater than can be predicted based on sorption characteristics.
20	66, 4, 2	M	W believe it's more likely to be the formation and/or gravel pack materials.		Sentence restated: "... radionuclides may be sorbing to newly disturbed tuff surfaces and non-native filter pack material, especially in the newer well installations."
21	71, 1, 1	M	Change G.S. McLin to S.G. McLin.		
22	71, 6, -	M	Should Spring be changed to Springer?		

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1. INTRODUCTION

This report presents the conclusions of a blue ribbon panel's review of hydrogeologic data needs for the Environmental Restoration (ER) Program at Los Alamos National Laboratory (LANL). The panel consisted of Daniel B. Stephens, assisted by Peggy Johnson, of Daniel B. Stephens & Associates in Albuquerque, New Mexico; Peter Kearl from Oak Ridge National Laboratory in Grand Junction, Colorado; and Roger W. Lee from the U.S. Geological Survey in Austin, Texas. The panel's review goals were to assess the available hydrogeologic data and identify additional data needs for the Environmental Restoration Program. Emphasis was placed on defining a technical approach that would provide the necessary information to complete the ER Program goal within the regulatory time frame, minimize duplication of efforts between characterization studies at the various operable units, and obtain the necessary geotechnical data in a cost effective manner.

A draft of this report was submitted to ER staff by the review panel on August 15, 1991. The panel received review comments on this draft from LANL technical staff in early 1993. Responses to many of the reviewers' comments have been incorporated into this final report. The data, conclusions, and recommendations contained in this final report essentially reflect the status of information available in August 1991 when the draft report was prepared. Accordingly, some of the recommendations for data collection which appear in this report may have been implemented in the interim, and some of the conclusions may require modification in light of new data that have not been available to the panel.

Section 2 includes a summary of existing hydrogeologic conditions. Section 3 presents six general recommendations of the panel. Section 4 discusses specific studies necessary to fill data gaps in the ER Program. Specific questions presented by the ER Program are addressed in Section 5 and individual reviewer comments are given in Section 6.

2. SUMMARY OF HYDROGEOLOGIC CONDITIONS

This section presents an overview of hydrogeologic conditions in the Los Alamos area. This summary is based mostly upon a preliminary review of available data.

The surface and subsurface geology and ground-water resources of the Pajarito Plateau have been the focus of extensive study over the last 30 years (Ross et al., 1961; Theis and Conover 1962, 0219; Conover et al., 1963; Griggs, 1964; Spiegel and Baldwin, 1964; Cushman 1965, 0042; Purtymun 1966, 0187; Bailey et al., 1969, 0019; Purtymun and Cooper 1969, 0197; Smith et al., 1970; Purtymun and Johansen 1974, 0199; Purtymun 1975, 0194; Purtymun et al. 1980, 0208; Purtymun et al. 1984, 0210; and Dransfield and Gardner, 1985). The Pajarito Plateau, a gently dipping plateau on the eastern side of the Jemez Mountains, is composed of volcanic ash flow and ash fall deposits of the Bandelier Tuff. The plateau has been eroded into deep, east-southeast-trending canyons separated by finger-like mesas. The area of interest for the review panel includes the Pajarito Plateau from the eastern wall of the Valles caldera east to the Rio Grande and from Guaje Canyon on the north to Frijoles Canyon on the south.

The canyon-mesa topography and the volcanic ash deposits of the Bandelier Tuff are key features of the Pajarito Plateau and are important in controlling the hydrogeology. The hydrology of the plateau involves complex interactions between surface runoff in the canyons, infiltration into soil/tuff on the mesas, evapotranspiration, and canyon-bottom recharge to perched alluvial and bedrock ground-water systems. The Bandelier Tuff and upper Puye Formation form a vadose zone up to 1100 ft (335 m) thick under the mesa tops. The main aquifer beneath the plateau is isolated from perched waters by a thick sequence of unsaturated tuff and sediments (Purtymun and Stoker 1987, 0204; Devaurs and Purtymun 1985, 0049).

2.1 Surface Water Hydrology

Surface water drains across the Pajarito Plateau eastward from the Sierra de los Valles to the Rio Grande and continues south to Cochiti Reservoir through the Rio Grande Valley. Surface water occurs primarily as ephemeral streams in all the major canyons, including (from north to south)

Guaje, Rendija, Barrancas, Bayo, Pueblo/Acid, Los Alamos/DP, Sandia, Mortandad, Pajarito, and Water Canyons (Purtymun 1975, 0194). Springs between 7900 and 8900 ft on the flanks of the Sierra de los Valles supply perennial baseflow to the headwaters of Guaje, Los Alamos, Pajarito, and Water Canyons (Abeele et al. 1981, 0009), but the amount of discharge is not sufficient to maintain perennial surface flow across the plateau. Runoff from heavy summer thunderstorms and spring snowmelt is the sole source of surface water in Guaje, Rendija, Barrancas, and Bayo Canyons. Perennial flow is maintained in sections of Pueblo, Los Alamos, Sandia, and Mortandad Canyons by the release of effluents from industrial waste treatment plants, sewage plants, and cooling water from the power plant (Purtymun 1975, 0194) and may occur up to a mile downstream from points of discharge. Stream loss due to infiltration into underlying alluvium and evapotranspiration typically prevents surface flow in these canyons from discharging across the eastern boundaries of LANL. During periods of excessive storm runoff or snowmelt, surface flow may reach the Rio Grande (Abeele et al. 1981, 0009).

2.2 Ground Water Hydrology

This section presents a detailed discussion of the occurrence and movement of subsurface waters under unsaturated and saturated conditions.

2.2.1 Hydrology of the Vadose Zone

The vadose zone includes up to 1100 ft (335 m) of unsaturated volcanic tuff, sediments and basalts of the Bandelier Tuff, the Puye Formation and the Cerros del Rio Basalts. The hydrology of the vadose zone is discussed in IWP Section 2.6.3, "Geohydrology of Mesa Tops and Vadose Zone." Numerous investigations focusing on hydrologic characterization of the upper 100 ft (30 m) of the Bandelier Tuff have been conducted in the Los Alamos area since the 1950s (e.g., Abrahams et al. 1961, 0015; Weir and Purtymun 1962, 0228; Abrahams 1963, 0011; Purtymun and Koopman 1965, 0201; Purtymun and Kennedy 1971, 0200; Purtymun et al. 1978, 0207; Abeele et al. 1981, 0009; Kearl et al. 1986, 0135; Purtymun et al. 1989, 0214). The remainder of the vadose zone below about 100 ft (30 m) has not been adequately characterized.

The Bandelier Tuff was formed by a series of ash flows and ash falls described as nonwelded, moderately welded, and welded tuffs. The units are gradational both vertically and horizontally. Individual ash flows, or a series of flows that have cooled as a single unit, may show a greater degree of welding near the center than near the upper and lower contacts. Horizontal variation in welding occurs with the greatest degree of welding westward towards the ash source (Purtymun 1975, 0194).

Physical characteristics of the tuff which affect fluid flow result primarily from degree of welding and jointing. The degree of welding, which varies markedly within and between tuff units, influences the nature and variability of hydrologic characteristics. Welding results in increased density, decreased porosity, and decreased hydraulic conductivity (Purtymun and Koopman 1965, 0201). Joints, formed by cooling of the ash flows, typically divide the tuff into irregular blocks. The major joint sets are vertical or near vertical with dips greater than 70°, and joint frequency increases with degree of welding. Joint apertures range from closed to open at least several centimeters. The joints are commonly filled with caliche near the surface, grading downward to clay, and may be open at depths greater than 30 ft (9 m) (Purtymun et al. 1978, 0207; Abeele et al. 1981, 0009). Filled fractures strongly inhibit moisture movement. Open fractures are effective barriers to liquid phase unsaturated flow, but may provide preferential flow paths for vapor transport or rapid water movement of liquid under saturated or near-saturated conditions (Abeele et al. 1981, 0009). Roots have been found in joints to depths of at least 40 ft (12 m) (Wier and Purtymun 1962, 0228; Abeele et al. 1981, 0009) which suggest that joints may be important infiltration pathways.

Natural recharge through the Bandelier Tuff on mesa tops has been considered by previous investigators to be negligible (e.g., Abrahams et al. 1961, 0015; Purtymun 1984, 0196). This conclusion is based on low in situ moisture content, the lack of temporal variations of in situ moisture, the thick vadose zone, the vegetation cover, and annual potential evapotranspiration in excess of precipitation. However, there are no definitive field tests which attempt to quantify natural recharge on mesa tops.

2.2.2 Hydrogeologic Properties and Conditions of the Bandelier Tuff

Many of the early investigations of the hydrogeologic properties of the Bandelier Tuff have been conducted on crushed or disturbed tuff samples; applicability of these values to in-situ tuff is uncertain. Results from laboratory tests on drill cores are expected to be much more representative of in situ conditions, at least at the local scale. Field measurements are usually most representative of in situ conditions; however, very few field test data are available to quantify the important physical properties. The following is a summary of available data on hydrologic properties of tuff at LANL sites.

Total Porosity. Total porosity measurements by Abrahams (1963, 0011) range from 20% to 60% by volume, generally decreasing with increasing degree of welding. Measurements by TerraTek (1985) yielded higher values, from approximately 39 to 74%. Extreme changes in porosity over a short vertical distance have been observed (Abrahams 1963, 0011).

Effective Porosity. Effective porosity refers to the percentage of interconnected pore space and implies some connectivity through the solid medium. In most porous media, effective porosity can be significantly smaller than total porosity, and for a material such as the Bandelier Tuff, the disparity may be much greater. This property plays a significant role when evaluating fluid pore velocities and contaminant travel times, as the pore velocity of ground water increases with decreasing effective porosity. There are no measurements of effective porosity available for any subsurface material at LANL.

Moisture Content. A number of hydraulic properties of the vadose zone vary with changing moisture content. The tuff is typically characterized by a very low volumetric moisture content. Vadose zone characterization studies at TA-54 indicated that typical volumetric moisture contents were 2% to 4%, with localized intervals ranging up to 10% to 28% (IT Corp., 1987). In addition, studies by Abrahams (1963, 0011) showed that moisture content varied between disturbed and undisturbed tuff and, generally, moisture content decreased with depth. Tuff samples taken from just below the surface had volumetric moisture contents ranging from less than 1% in samples from undisturbed areas, to about 26% from disturbed areas. At sites with high near-surface

moisture content may be about 2% to 4%, unsaturated hydraulic conductivity will be much lower than these values. Where the hydraulic gradient is unity, as it commonly is below the root zone, the unsaturated hydraulic conductivity at the field moisture content equals the flux of moisture which could eventually become recharge.

Sorption. The ion exchange capacity of alluvium and tuff allows for significant retention of radionuclides. Polzer and Essington (1984, 0178) report an ion exchange capacity for strontium, cesium, and cobalt of 3.3 μeq/g (0.33 meq/100 g) Christenson and Thomas (1962, 0039) report an ion exchange capacity for plutonium ranges from 0.5 to 3 meq/100 g for the Tshirege member of the Bandelier Tuff. Purtymun and Stoker (1987, 0204) report values of 0.7 to 2.8 meq/100 g. However, actinide sorption may be decreased by complexation with citrates and fluoride which may have been disposed with the radionuclides. Oxidation state also affects sorption. At relatively low pH, plutonium is oxidized to +6 and, although fairly unstable, it is not as exchangeable as Pu^{+4} and Pu^{+3} (Christenson and Thomas 1962, 0039).

2.2.3 Hydrology of the Saturated Zone

Ground water occurs under saturated conditions in three locations beneath the Pajarito Plateau: (1) stream-connected perched alluvial aquifers, (2) perched water in shallow basalts and sediments underlying the alluvium, and (3) the main aquifer of the Pajarito Plateau. Purtymun (1973, 0191; 1975, 0194) indicates that stream-connected alluvial aquifers recharge underlying perched aquifers in Pueblo and Los Alamos Canyons. Although the nature and location of the perching layers are not known, the main aquifer does not appear to be hydrologically connected to the overlying perched zones. The disconnection of the perched alluvial aquifer in Mortandad Canyon was verified in the field by Stoker et al. (1991).

2.2.3.1 Perched Aquifers. Canyons with effluent-fed perennial surface flow -- Pueblo Canyon, Los Alamos Canyon, and Mortandad Canyon -- have alluvial aquifers which are recharged by, and hydrologically connected to, surface stream flows. Liquid waste is also diverted to Water Canyon in a perennial reach. Ground water has been reported in alluvium in Water Canyon, as well as Pajarito and Sandia Canyons (A. Stoker 1991, LANL, personal communication). Surface

water rapidly infiltrates through the permeable alluvium until downward movement is restricted by less permeable deposits of the Tschicoma Formation, the Bandelier Tuff or the Puye Formation, resulting in a shallow zone of saturation perched within the alluvium. These shallow, stream-connected aquifers are typically perennial water bodies which exhibit seasonal water table fluctuations (Purtymun and Kennedy 1971, 0200). As flow occurs down the hydraulic gradient (eastward) in the alluvium, water is lost to evaporation, transpiration, and infiltration into underlying sediments.

Infiltration of alluvial ground water appears to be the main source of recharge for two perched water bodies near the confluence of Pueblo and Los Alamos Canyons and in the midreach of Pueblo Canyon (Purtymun 1973, 0191; Purtymun 1975, 0194; Abeele et al. 1981, 0009). Good reviews of alluvial aquifers by drainage area are included in Purtymun (1975, 0194; 1973, 0191); results of an extensive monitoring study of the alluvial aquifer in Mortandad Canyon are presented in Abrahams et al. (1962), Baltz et al. (1963, 0024), Purtymun (1973, 0191), Purtymun (1974, 0192), Purtymun et al. (1977, 0206), Purtymun et al. (1983, 0209), and Stoker et al. (1991).

2.2.3.2 Main Aquifer. The main aquifer beneath the Pajarito Plateau serves as the municipal water supply for the Los Alamos area and is located primarily within the lower Puye Formation and the Santa Fe Group sediments. Cushman (1965, 0042) suggested three sources of recharge to the main aquifer: infiltration of runoff in canyons, underflow from the Valles caldera through the Tschicoma Formation and infiltration on mesas. However, much hydrologic, structural and geochemical data exist that indicate the caldera may not serve as an appreciable source of recharge for the main aquifer (Conover et al., 1963; Griggs, 1964; Goff, 1991). Furthermore, natural recharge through undisturbed Bandelier Tuff on the mesa tops is believed to be insignificant (Purtymun and Kennedy 1971, 0200), and little or no data exist to support an evaluation of canyon runoff as a recharge source. In general, knowledge concerning recharge mechanisms for the main aquifer is insufficient to adequately evaluate this important water balance component. Water level elevations suggest that ground water flows from the Sierra de los Valles east and east-southeast toward the Rio Grande. The Rio Grande is the principal discharge area for the main aquifer. The 11.5-mile (18.5-km) reach of the Rio Grande between Otowi and the mouth of Frijoles Canyon receives an estimated 4300 to 5500 acre-feet (5.3×10^6

to 6.8×10^{6} m^{3}) of ground water discharge annually from springs and seeps (Purtymun 1984, 0196).

A significant portion of flow in the main aquifer is also discharged by wells and used for the municipal water supply. Three well fields have been developed in the main aquifer; two fields, the Los Alamos Field and the Guaje Field, are located along the eastern and northern margins of the laboratory. The Pajarito Field is located near the east-central part of the laboratory. The Los Alamos Field, located in lower Los Alamos Canyon, consists of five producing wells which have pumped an average 5.54×10^{-1} ft^{3}/yr (1.57×10^{6} m^{3}/yr), or 36% of the total volume pumped from the three fields, during the period 1947 to 1982. The Guaje Field is located in the mid to lower reach of Guaje Canyon and consists of seven wells which have produced 5.72×10^{7} ft^{3}/yr (1.62×10^{6} m^{3}/yr) or 37% of total pumpage, as of 1982 (Purtymun 1984, 0196). The Pajarito Field includes 5 wells, but 3 produce most of the discharge. Production from 1965 to 1982 averaged 8.65×10^{7} ft^{3}/yr (2.45×10^{6} m^{3}/yr), or about 27% of the total pumpage volume. Pumping from the municipal well fields has resulted in an average water-level decline of 1.11 ft/yr (0.34 m/yr) in the Los Alamos Field, 1.71 ft/yr (0.52 m/yr) in the Guaje Field, and 0.098 ft/yr (0.03 m/yr) in Pajarito Field.

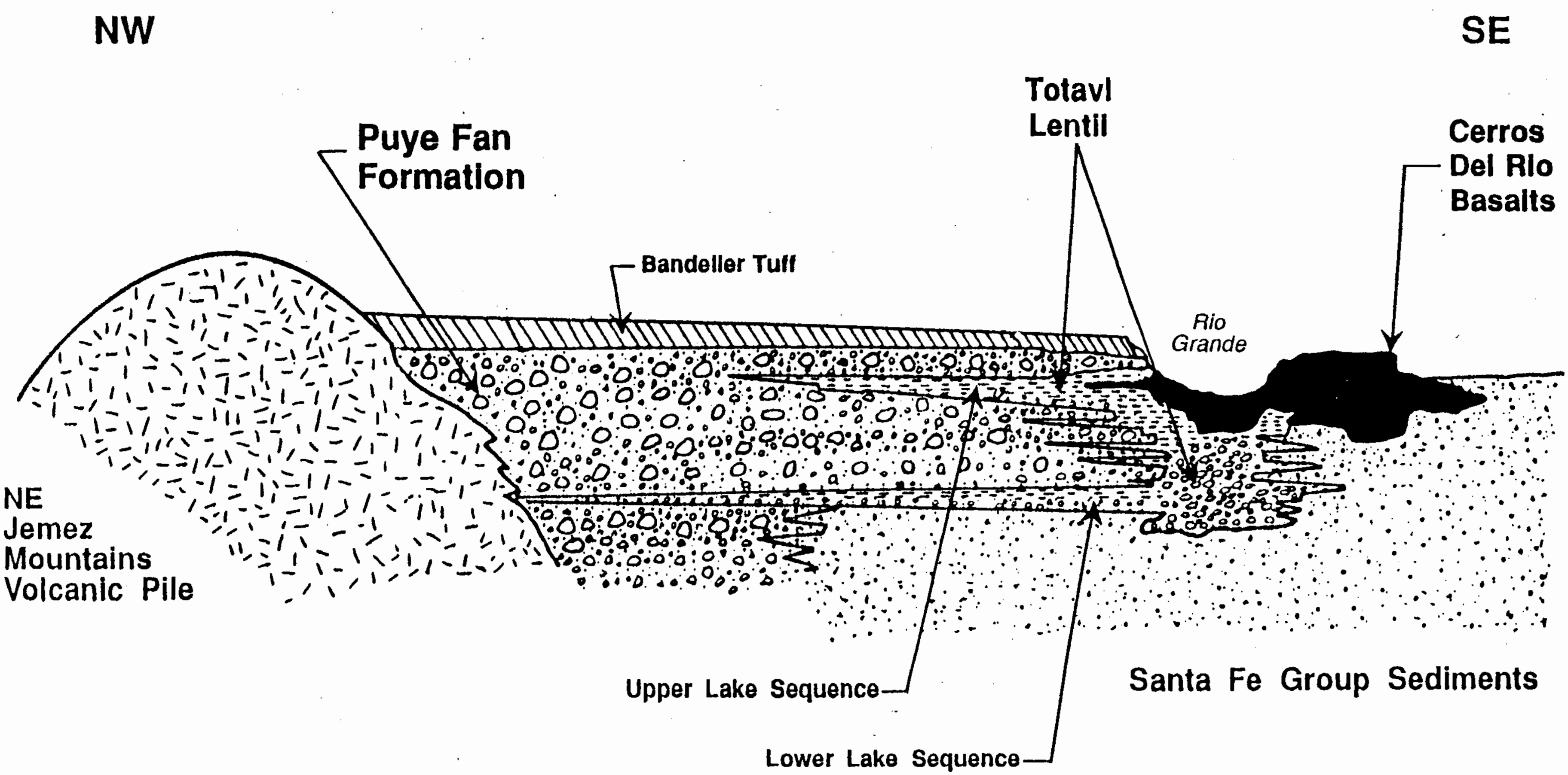
Hydraulic conductivity varies between different hydrostratigraphic units within the main aquifer. Values for the Santa Fe Group sediments in the Los Alamos Field range from 0.40 to 1.24 ft/d (1.4×10^{-4} to 4.4×10^{-4} cm/s). In general, hydraulic conductivities are higher in the upper 1000 ft (305 m) of the Santa Fe Group and decrease to the east toward the Rio Grande. Where Santa Fe Group sediments are interbedded with basalts, as in the Guaje Well Field, and hydraulic conductivities are slightly higher and range from 0.71 to 1.5 ft/d (2.5×10^{-4} to 5.3×10^{-4} cm/s). The Puye Formation in the northern part of the laboratory area (Test Wells 1, 2 and 3) has a hydraulic conductivity of 13 ft/d (4.6×10^{-3} cm/s) (Purtymun 1984, 0196), and near TA-49 in the southern part of the laboratory hydraulic conductivity is about 10.8 ft/d (3.8×10^{-3} cm/s) (Purtymun and Stoker, 1987).

Purtymun (1984, 0196) states that the regional ground water gradient beneath the Sierra de los Valles and the western Pajarito Plateau is about 0.023 within interfingered units of the Tschicoma

and Puye Formations. As ground water moves eastward into the more permeable sediments of the Puye Formation beneath the central plateau where LANL is located, the gradient decreases to 0.011 to 0.015. Along the eastern edge of the plateau the gradient increases to 0.015 to 0.019 (Purtymun 1984, 0196).

Depth to the main aquifer ranges from approximately 1100 ft (335 m) at the western margin of the operable unit to about 250 ft (75 m) at the SWMUs in lower Los Alamos and Guaje Canyons to the east. Ground water flow rates are estimated to range from about 20 to 345 ft/yr ($6x10^{-3}$ to 10^{-1} km/yr) across the plateau. The main aquifer is apparently unconfined beneath the western and central portions of the plateau. Along the eastern margin of the plateau near the Los Alamos Field, the aquifer is under artesian conditions (Theis and Conover 1962, 0219). Cushman (1965, 0042) noted that the artesian conditions are probably caused by upward-moving ground water in the discharge zone near the Rio Grande. However, recent geologic interpretations by Waresback and Turbeville (1990) identify two laterally extensive, low-permeability lacustrine sequences in the Totavi Lentil . These low permeability deposits may act as confining layers for the main aquifer beneath the eastern margin of the plateau (Figure 1).

Water quality in the main aquifer is excellent for domestic purposes. The chemical characteristics of water in the main aquifer depend on lithology of the aquifer, depth of the well, and local variation in aquifer conditions. Purtymun et al. (1980, 0208) have divided ground water from the main aquifer into groups based on the chemical quality of water discharging from springs in various hydrostratigraphic units. Water from the Totavi Lentil is a calcium and bicarbonate water with average sulfate and chloride concentrations of about 4 mg/l and concentrations of dissolved solids ranging from 112 to 210 mg/l. Water from the coarse-grained sediments of the upper Santa Fe Group is a sodium and bicarbonate water with average sulfate and chloride concentrations of about 3 mg/l and concentrations of dissolved solids ranging from 154 to 262 mg/l. The fine-grained sediments of the Santa Fe Group also produce a sodium and bicarbonate water but with a higher sulfate concentration of about 10 mg/l, a chloride concentration of about 3 mg/l and concentrations of dissolved solids ranging from 194 to 236 mg/l. Calcium and sodium bicarbonate waters are typical of ground water in the Los Alamos and Santa Fe areas, and reflect



Schematic Cross Section of the Pajarito Plateau
(Waresback and Turbeville, 1990)

Figure 1

the degree of Ca-Na exchange that occurs as ground water flows through sediments of varying permeability.

Isotopic data have recently been collected from the main aquifer in the Los Alamos area, including tritium and ^{14}C in waters from 12 springs and five wells (Goff 1991, LANL, written communication; Stoker 1993, LANL, written communication). Results indicate that tritium concentrations range from less than detectable to about 7 pCi/l, and estimated ^{14}C ages vary from approximately 1,000 years to more than 30,000 years. The combination of detectable tritium and ^{14}C ages greater than 1,000 years suggests that mixing is occurring between "old" ground water and recent recharge.

2.3 Discussion

Much of the literature (e.g., Purtymun 1966, 0187; Purtymun and Cooper 1969, 0197; Purtymun and Johansen 1974, 0199; Purtymun 1975, 0194; Purtymun et al. 1980, 0208; and Purtymun et al. 1984, 0210) commonly relied upon in Laboratory environmental reports presents a simple conceptual hydrogeologic model for the regional ground-water system which proposes that water in the main aquifer moves from a recharge area in the Valles caldera eastward to a discharge area at the Rio Grande. This conceptual model proposes that minor recharge may occur in the deep canyons containing perennial streams, but that little or no recharge is added to the main aquifer from intermittent streams in the canyons, and that no recharge can infiltrate to the main aquifer through the Bandelier Tuff from mesa tops. The current model thus proposes that virtually all recharge to the regional aquifer system flows through the Tschicoma Formation which bounds the water-bearing sediments of the Santa Fe Group on the west. This conceptual model is primarily based on two factors: a hydraulic gradient that rises steeply to the west towards the Jemez Mountains, and the large ground-water storage capacity of the Valles caldera. However, no subsurface data exist west of the Pajarito fault zone on which to base an evaluation of either the water table gradient or the transmissivity of the Tschicoma Formation. The steepening of the gradient in this area is based on two data points (Test Well TW-4 and Test Hole H-19) located east of the Pajarito fault zone which are extrapolated to the west based on the assumption that the water table will rise toward the caldera. The gradient could also be steepening to the west

in response to a recharge area located along the Pajarito fault zone or along the perennial streams in the heads of the canyons.

Other investigators working in the 1960s (e.g., Conover et al., 1963; Griggs, 1964; Spiegel and Baldwin, 1964; and Cushman 1965, 0042) proposed hydrologic models for the caldera and/or the Pajarito Plateau which are not consistent with the conceptual model described above and heavily relied upon by Laboratory environmental efforts. Conover et al. (1963) and Griggs (1964) present data which support the concept that ground-water discharges from the caldera to the southwest not the east, and that the Tschicoma Formation is completely impermeable to ground-water flow. Griggs (1964), Spiegel and Baldwin (1964), and Cushman (1965, 0042) all propose that the major recharge component for the regional aquifer is from precipitation and runoff infiltrating through canyon-bottoms on the plateau and from streamflow moving eastward across the Sierra de los Valles/plateau boundary. No surface water studies have addressed mesa-top runoff or canyon-bottom recharge.

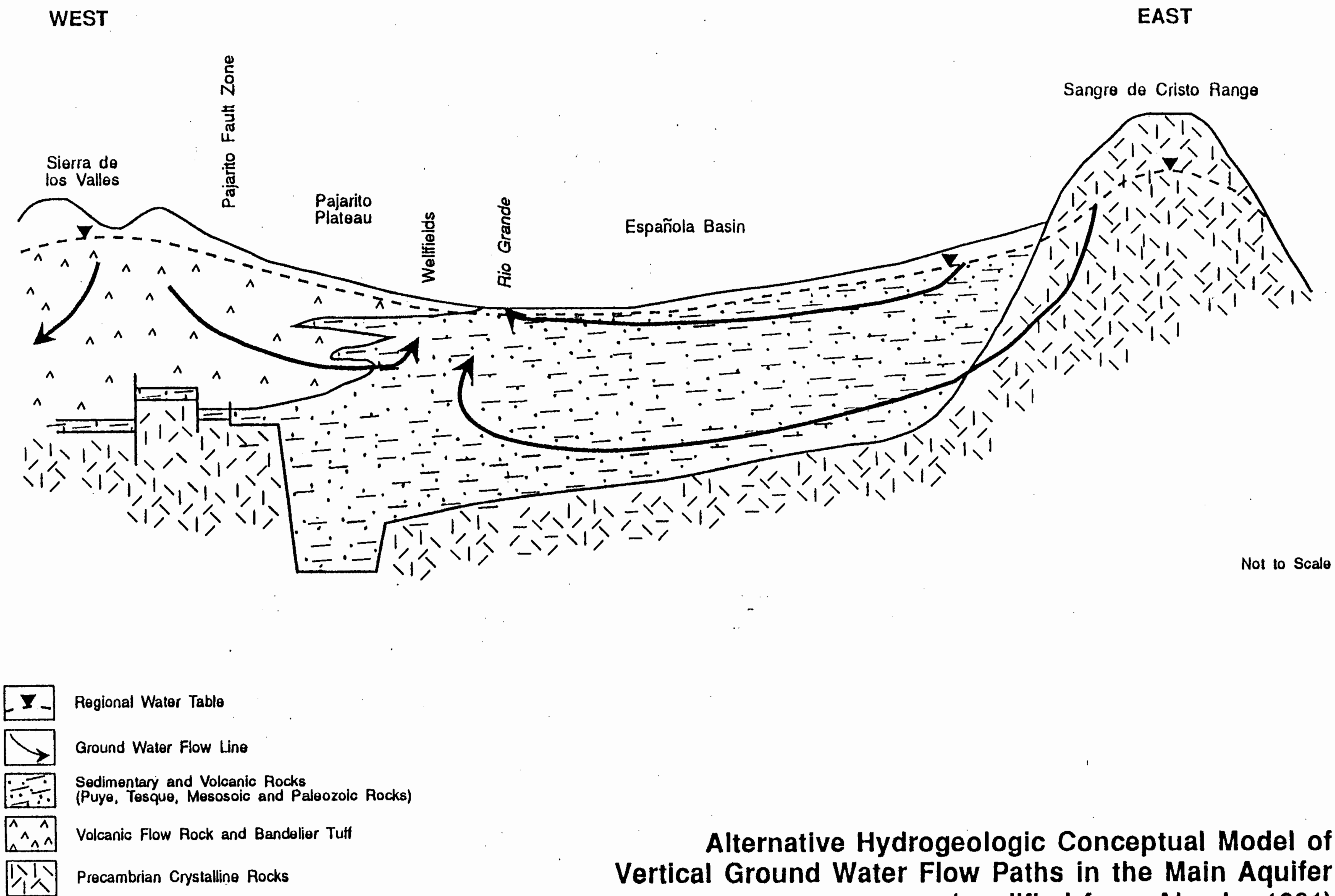
It is generally accepted that stream loss recharges perched alluvial aquifers that exist in many of the canyons on the plateau. Deeper perched aquifers are also known to occur at depths up to 200 ft (61 m) in the Puye Formation and Cerros del Rio Basalts beneath Pueblo and Los Alamos Canyons. The vertical and lateral extent of the perched aquifers, the nature and extent of perching units, and the potential for migration of perched water to the main aquifer have not been addressed by investigators to date.

It is also generally accepted that the Rio Grande is the discharge area for the main aquifers which occur in the Santa Fe Group sediments both west and east of the river (Spiegel and Baldwin, 1964; Cushman 1965, 0042; Purtymun et al. 1980, 0208; Purtymun 1984, 0196); however, the nature of the flow domain and gradient conditions near the river are not well understood. Artesian conditions occur in the Los Alamos well field in lower Los Alamos Canyon, but no continuous, well-defined confining layer has been identified. Cushman (1965, 0042) recognized that water in the aquifer in the vicinity of these wells and the Rio Grande has a strong upward flow component, probably due in part to proximity to the natural discharge area. The assumption that the main aquifer in the vicinity of the Los Alamos Well Field occurs under confining conditions is

speculative. In some areas, the lacustrine deposits of the Totavi Lentil may serve as confining beds for ground water in the relatively permeable portions of the Puye Formation. Clays in the Santa Fe Group are more likely candidates for confining beds in other areas. However, without additional data for support, the assumption that continuous confining beds may exist in the Totavi Lentil or the Santa Fe Group should not be relied upon in evaluations of contaminant migration potential.

A better understanding of the flow domain of the regional aquifer is necessary in order to evaluate contaminant migration and the potential for impact of the main aquifer. The conceptual hydrogeologic model for the regional flow system presented above is overly simplistic and not supported by all data. Although regional hydrologic data are scant, to the extent that data exist, they are more consistent with a complex flow system with multiple components of recharge including infiltration from the surface of the plateau along the Pajarito fault zone as well as other fault or brecciated zones, and infiltration along canyon bottoms. Isotopic data collected by Goff (1991) show tritium concentrations ranging from 0.02 to 5.47 tritium units in regional ground water from 12 springs in White Rock Canyon and five production wells in the main aquifer. Additionally, ^{14}C data show ground-water carbonate ages of approximately 1,000 to 30,000 years. The occurrence of detectable tritium together with very old ground-water carbonate ^{14}C ages suggests that regional ground water with a very long residence time is mixing with a significant component of recent (less than 35 years) recharge. Additional isotopic studies focusing on variation of aquifer residence times with depth will be necessary in order to adequately characterize the contribution of recent recharge to the aquifer water balance.

An alternative conceptual model, illustrated in Figure 2, is proposed for the regional aquifer system. The alternative model proposes a significant recharge component on the plateau, through canyon bottoms and major fault zones. Flow through the Tschicoma Formation from the Valles caldera is likely; however, it may not be the major recharge source. The main flow direction is eastward, but the flow domain proposed for the discharge area differs from the current model. It is possible that water discharging in springs and seeps along the Rio Grande, and that water occurring in certain wells in the lower Los Alamos Well Field, has a source contribution from the regional aquifer east of the Rio Grande. Water in the aquifer to the east is recharged by



Alternative Hydrogeologic Conceptual Model of Vertical Ground Water Flow Paths in the Main Aquifer (modified from Abeele, 1981)

Figure 2

precipitation originating in the Sangre de Cristo Mountains. The general movement of ground water is westward and northwestward, with discharge to the Rio Grande in a similar pattern as the Pajarito aquifer; however, the ground-water basin on the east is much larger (338 mi^2 versus 252 mi^2, Spiegel and Baldwin, 1963), and flow near the Rio Grande is impeded by low permeability units of the Cerros del Rio volcanic field. The strong upward flow component observed west of the Rio Grande in the Los Alamos Well Field is consistent with upwelling of flow from the east towards its discharge area. This proposed flow domain is also consistent with arsenic and uranium data from Los Alamos Wells 1b and 6, the Buckman wells east of the Rio Grande and spring 3b in White Rock Canyon, and ^{18}O data from White Rock Canyon springs which suggests than the water was recharged at an altitude higher than the Sierra de los Valles (Goff, 1991).

Chemical data from existing reports for all of the occurrences of water in the vicinity of LANL are adequate for most environmental assessments, with limited use in comparing to water quality guidelines. As a geochemical data set, the body of analyses reported is greatly lacking. Inadequate quality assurance practices and reporting, questionable collection methods, many data reporting errors, and incomplete analytical schedules of parameters limit the data use. As is, these data cannot be effectively used for geochemical interpretation of rock-water interactions. A program should be developed to correct present errors where possible, and establish proper approaches for future chemical data collections. More specific examples are given in the individual reviewer comments in Section 6.3, along with assessments of the causes and recommendations for corrective action.

3. GENERAL RECOMMENDATIONS

Based on a review of the available geotechnical literature for the site and the region, and discussions with LANL scientists and staff, the panel has the following six general recommendations:

- Select a time frame for predicting environmental impacts;
- Develop a site-wide hydrological and chemical data base that meets specific QA objectives;
- Implement a LANL communication plan;
- Develop conceptual models;
- Conduct investigations employing numerical modeling of vapor transport, unsaturated transport, and regional ground-water flow;
- Conduct specific geotechnical studies.

3.1 Select a Time Frame

It is not clear to the panel what the time frame is for assessing potential impacts of past waste disposal practices. Understanding the regulatory time requirements for predicting the extent of contaminant migration has direct implications on data requirements and recommendations presented in this report. Discussions with the appropriate regulators to agree upon a time frame should be held as soon as possible.

3.2 Develop a Site-wide Data Base

A review of the site hydrogeologic and geochemical data has shown that site information is contained in numerous technical reports, surveillance reports, unpublished data, and personal files. These scattered data have impacted the panel's review and will affect background data searches for future site characterizations. Incorporating this data into a comprehensive data base has several advantages. The data will be at a single location for easy access. Data can be reviewed and a quality assurance program implemented. Data collected during future site

investigations can be incorporated to continually update the data base. Using this data base, information from different sites can be correlated, regional data can be compared with site specific data, and data can be documented for regulatory quality assurance.

3.3 Implement a Laboratory Communication Plan

Several groups within the Laboratory are conducting work related to the ER Program. Other groups are working on site projects that have gathered information useful to the program. There are also LANL scientists working on volcanic tuffs at the Nevada Test Site. It is clear from recent meetings that researchers are not fully aware of activities that relate to their own investigations. To overcome this problem, the panel recommends symposia or scheduled meetings where all interested investigators can present their recent work. This approach will allow an exchange of information and reduce duplication of effort. Increased communication will be essential to developing ER documents which present a consistent hydrogeologic framework for facilitating regulatory review.

3.4 Develop Conceptual Models

Due to the complex nature of the region's hydrogeology, several interpretations of the processes controlling contaminant migration have been presented. The panel recommends that three separate conceptual models be developed for flow and transport processes at the site, to include: vapor transport (diffusion/density-driven) for the mesa tops, variably saturated flow for the valley bottoms below perched zones, and a regional ground-water flow conceptual model. Different versions of each conceptual model should be developed to test the significance of the transport processes. For instance, recharge and liquid transport in porous and fractured media should also be included as alternative mesa-top conceptual models. Several conceptual models have been proposed for regional ground-water flow; for example, previous work at LANL suggests that ground-water recharge to the regional aquifer occurs at the Valles caldera and discharge occurs at the Rio Grande. Another conceptual model states that recharge occurs along the Pajarito Fault Zone. One panelist believes that recharge originating on the eastern side of the Rio Grande may contribute to discharge on the western side of the river and account for the strong upwards

ground-water flow observed in that area. Developing alternative conceptual models will help to validate or invalidate the controlling transport processes.

3.5 Conduct Numerical Modeling

With the available data, the panel recommends that investigations applying numerical modeling of the controlling transport processes at the site be initiated as soon as possible. The numerical modeling should follow the conceptual models (i.e., vapor transport, variably saturated flow, regional ground water flow).

An important component of the numerical modeling is a sensitivity analysis program. The importance of individual transport parameters can be assessed and the results used to determine the amount of effort necessary to further define the controlling transport parameters.

Several excellent studies have been conducted by LANL scientists that provide data necessary to verify the numerical models. At TA-54, data has been collected from vapor wells for several years as part of a monitoring program for organic vapors. This data provides an excellent opportunity to verify a diffusion/density-driven vapor transport model. At TA-50, controlled experiments were conducted to study infiltration into tuff. At Mortandad Canyon, a recent study has provided a quality set of data regarding tritium migration in tuff beneath the alluvial aquifer. This "accidental" tracer test provides the data to verify a variably saturated transport model. In addition, the test involving infiltration and monitoring of large volumes of water and radionuclides at TA-21 also provides information to verify an unsaturated transport model. The numerical model studies are also highly relevant to validating codes for long-term performance assessments.

4. SPECIFIC GEOTECHNICAL INVESTIGATIONS

This section discusses specific studies necessary to fill data gaps identified by the panel. These studies are intended to measure or assess hydrogeologic processes or parameters for an individual operable unit and ideally will provide data transferrable to characterization studies at other operable units. In addition, the panel is aware that some of these studies are already planned and only wants to reinforce their importance.

4.1 Isotopic Ground-Water Studies

One of the first steps in characterizing regional ground-water flow is conducting a sampling program of existing wells, springs, or seeps to measure and assess the ground-water ages. This survey will help to better understand the recharge and discharge areas, the relationship of perched zones with the main aquifer, and ground-water flow rates. In addition, results from an age dating program can identify and guide further ground-water characterization programs. Improved parameter lists of chemical samples and environmental isotopes will provide a more complete set of geochemical data for this and other purposes of interpretation. The isotope sampling should include ^{14}C, ^{13}C, ^{34}S, ^{3}H, as well as ^{18}O and ^{2}H.

4.2 Installation of a Ground-Water Monitoring Network

Several wells at the LANL facility are used to monitor ground water. These wells, however, were designed for other purposes such as water supply. The panel recommends that a series of monitoring wells be installed up and downgradient of the Laboratory to assess regional hydrogeologic and hydrogeochemical properties. At least two upgradient wells, one on each side of the Pajarito Fault Zone, are recommended to assess background water quality and recharge areas. Based on the assumption that valleys tend to concentrate recharge on the Pajarito Plateau, at least several downgradient wells should be located in the canyons near the Laboratory's eastern boundary.

The installation and construction of the monitoring wells should ensure that the appropriate hydrogeologic and geochemical data are collected. Coring for lithologic and pore-water geochemical analyses, permeability testing, and installation of discrete sampling points for fluid (air and water) pressure, and chemistry measurements are important components of the monitoring wells.

A goal of the regional monitoring network is to sufficiently describe the regional aquifer so that data can be extrapolated to the individual operating units. This approach will minimize the need to install monitoring wells at the individual operating units and thereby result in sufficient hydrogeologic data at a significant cost savings.

4.3 Hydrogeologic Assessment

The hydrogeology of the Los Alamos areas has been studied by numerous investigators. The data base for existing reports should be updated based upon a comprehensive re-evaluation of existing data and new information which may be collected as a result of our recommendations or other ER activities.

The basic hydrogeologic data needs include gaging discharge of all perennial streams and the principal ephemeral streams. This is important data to quantify the stream infiltration component of the water balance and to evaluate the transient water level fluctuations in shallow and deep ground water. Fate and transport of contaminants in solution or sorbed on sediments in surface water has not been adequately studied.

Basic field mapping is recommended to document all springs and seeps which may discharge to canyon bottoms and escarpments. The documentation should include geologic features, discharge rates, vegetation, and water chemistry sampling. Field mapping should also focus on delineating fracture systems which may be zones of recharge, especially in canyon bottoms where there are alluvial aquifers and areas on mesa tops where runoff or ponded water may occur locally in channels or depressions. Field mapping and drilling should also identify the horizontal and vertical extent of perched aquifers reported in Pueblo, Los Alamos, Sandia,

Pajarito, and Water Canyons. Field tests should determine the ground-water discharge rate, flow direction, and mean velocity in all perched alluvial and perched bedrock aquifers which occur in watersheds of the operating units.

A regional scale water budget of the hydrogeologic system should be completed based on new and existing data. The water balance should identify all sources of recharge, discharge, and storage within the perched alluvial, perched bedrock and main aquifers.

4.4 Assess Colloidal Transport

The role of colloids in the transport of immobile radionuclides such as plutonium should be examined. Work by Penrose et al. (1990, 0174) suggests that colloids have played a significant role in the transport of plutonium and americium in the perched alluvial aquifer in Mortandad Canyon. Although recent work by LANL in the canyon indicates that the colloidal fraction represents less than 1 percent of the total contaminant inventory (Stoker et al., 1991), the issue of transport of colloidally bound radionuclides needs to be resolved.

A ground-water sampling program that specifically targets colloids in ground water is a possible option. Samples could be taken using a colloidal borescope to determine the concentration and chemistry of the colloids. The colloidal borescope is a downhole camera capable of viewing colloidal-size particles. When used during the sampling, the borescope ensures that representative particles are sampled. The importance of colloidal transport in the vadose zone should also be investigated.

4.5 Mobility Analyses

Many of the radionuclides are generally recognized as highly immobile, due to sorption mechanisms. Nevertheless, some of these radionuclides occur at much greater depths in the field than expected. It is possible that the radionuclides are mobilized by other chemicals. Investigations on the importance of sorption and complexation in field transport are recommended.

Organic chemicals are also subject to sorption, especially in the presence of organic matter in the porous media. The attenuation capacity of organic chemicals moving through representative alluvium and uncrushed tuff should be quantified.

4.6 Dispersion

Transport through alluvium and tuff is influenced by the dispersive characteristics of the porous and fractured media (e.g., Springer and Fuentes, 1987). Dispersivity should be quantified, at least initially, by laboratory experiments in undisturbed, representative media under both saturated and unsaturated conditions. Methods to extrapolate the laboratory measurements to the field scale should be developed.

4.7 Vadose Zone Characterization

Hydraulic properties of the vadose zone have been characterized in TA-54 and Mortandad Canyon. The data sets should be carefully compared. Differences may be attributable to spatial variability in geology, or testing methodology. From a cost perspective, it would be highly advantageous to establish that there is little variability in the hydraulic properties so that such information can be extrapolated with reasonable confidence to operating units where little or no data exist.

If the analysis shows significant differences in data sets, we recommend developing a program to understand the source of variability. This program could include collecting shallow core samples along transects, determining hydraulic properties in the laboratory, and conducting a geostatistical analysis. Spatial variability within and between tuff units could also be evaluated on outcrops or shallow excavations with field permeameters. To address whether variability is due to testing bias, different testing methods should be applied to the same samples.

Much of the vadose zone characterization data collected to date is within approximately the upper 200 ft (61 m) of land surface. These data are derived from laboratory analyses of core samples. If model validation efforts endorsed earlier in our report (Section 3.5) lead to unreasonable results,

part of the explanation may be that the existing hydraulic properties used in the model are not representative of field behavior. To address this issue, a comparison of laboratory results and standard, near-surface, in situ methods is recommended for determining vapor and liquid transport coefficients.

For many remedial designs, the most important process driving the design decision will be recharge. Field programs are strongly encouraged to quantify recharge at representative sites.

In developing sampling plans, the ER program staff should recognize that there are no field methods to determine in situ unsaturated hydraulic properties at depths below about 3 m. Methods of deep vadose zone characterization in boreholes using water or air injection only yield values of hydraulic conductivity at saturation, or permeability to air at field moisture content, respectively. Air permeameters are considered attractive because no water is introduced to the formation to mobilize liquid contaminants. We recommend, however, a careful review of mathematical developments for air permeameters to assess the significance of the gas slip phenomenon (e.g., Stonestrum and Rubin, 1989) and the relationship between air and water permeability. Development of practical in situ techniques for deep vadose zone characterization should be encouraged.

Neutron probes and other vadose zone monitoring devices require careful calibration, especially when attempting to compare measured spatial distributions of moisture. The effects of monitor well materials, borehole geometry, and formation chemistry should be considered.

4.8 Make Unpublished Data Available

As previously discussed in the communication recommendation, work being conducted by various groups at LANL needs to be disseminated. In addition, previous work that has an impact on the ER program should be made available.

In 1986, Bendix Field Engineering conducted an investigation of TA-54 (Kearl et al. 1986, 0135). As part of this investigation, soil-gas sampling ports were installed at various locations and depths

across the site. Additional sampling ports were installed by LANL the following year. It is our understanding that LANL has been actively collecting chemical data from these soil-gas sampling ports for a number of years. Apparently, this data has yet to be published. It is important that this data be evaluated to determine the extent of migration of organic waste at the site. These data could provide the needed input for modeling studies and potential remediation designs. In addition, new insights regarding vapor migration in tuff may be obtained that could be useful to other sites at the Laboratory. Other reports of useful data include, for example, water inflow to a vadose zone boring (Test Hole 2-M) at TA-49, dispersivity experiments, and fracture mapping of outcrops.

There remain several unresolved issues regarding water movement in the canyon bottoms beneath saturated alluvium. The first step in understanding flow is to determine the water balance for the system. Transpiration losses due to vegetation is the central issue. Considerable controversy exists regarding the contribution of ponderosa pines to transpiration losses. The depth to water combined with the shallow root structure of the trees suggests that only near-surface soil water is utilized for growth. Transpiration losses from the deeper ground-water system would be negligible. Conversely, previous studies of plant uptake of tritium indicate that substantial quantities of tritium are present in ponderosa pines. These unpublished data need to be re-examined to determine the location of the trees sampled in relation to available surface water contaminated with tritium.

5. SUMMARY OF COMMENTS ON ISSUES IDENTIFIED BY THE ER PROGRAM

The following is a brief summary of the panel's comments on issues identified by the ER staff. Detailed comments by each reviewer are provided in Section 6.

ISSUE 1. Do we have enough hydrogeological data at LANL to defensibly answer pertinent hydrogeological questions related to the ER site cleanups (e.g., stabilization in place)?

There is considerable uncertainty in several aspects of hydrogeology which needs to be addressed. However, at a few sites such as Mortandad Canyon and TA-54, sufficient hydrogeological data may already be available to support some ER program decisions. Primary areas of concern include the importance of vapor and liquid transport on mesa tops, characterization of perched aquifers, and radionuclide uptake by vegetation.

ISSUE 2. Is there adequate flow and transport data to defend calculation of the subsurface pathway?

Data may be sufficient only at sites that have been characterized, such as TA-54 and Mortandad Canyon. Even at these sites there is uncertainty in the spatial extent of contamination, hydraulic properties, and transport processes such as colloidal mechanisms. Moreover, the quality of the existing water chemistry data base which could be used to evaluate pathways is considered deficient in several aspects (Section 2.3).

ISSUE 3. Do we know enough about the role of fractures?

The panel is somewhat divided on this question. On one hand, some geologic evidence suggests that fractures lack connectivity over great depths and fractures may provide capillary barriers to unsaturated flow. On the other, roots and weathering patterns suggest that some fractures on mesa tops may be preferential paths for infiltration. Our primary concern for liquid flow in fractures is in canyon bottoms where fractures in bedrock may intersect perched alluvial aquifers. There are few field data on the role of fractures, but there is also very little one can do to

adequately and quantitatively characterize variably saturated fracture flow and transport coefficients. At small site scales, the role of fractures as transport pathways and their connections to regional pathways will likely have to be addressed for each site individually.

ISSUE 4. Can we defensibly model LANL hydrogeology using a porous continuum model?

Much of the experimental and environmental monitoring data suggests that a porous media flow model would be appropriate. However, porous media models should be used to predict observed behavior in order to validate the models and to confirm the validity of the porous media approach.

ISSUE 5. Are we sufficiently certain of ground-water flow direction regionally that we can know ground-water flow direction at a specific OU? Additionally, is there any reason to believe that there are local ground-water gradients?

Generally sufficient data exist to establish that regional flow is to the east. Local effects undoubtedly occur near the well fields, and it is possible that small perturbations may occur in the main aquifer beneath perched aquifers or other potential recharge areas. Additional information is required to monitor horizontal and vertical pathways and to confirm sources of recharge. Mapping details of drawdown and "zones of capture" around the well fields would add to the knowledge base.

ISSUE 6. Can we defensibly state there is no connection between any perched zones and the main aquifer?

Existing data are insufficient to state that no perched water percolates to the main aquifer. In fact, recent work at Mortandad Canyon shows that vertical transport has occurred in the Bandelier Tuff to at least 150 ft (46 m) beneath the perched alluvial aquifer. Little is known of vapor phase transport in these areas.

ISSUE 7. Do we know enough about gas exchange between the subsurface and atmosphere as a potential contaminant transport pathway?

Gas exchange has been observed near open shafts and boreholes. Density driven gas phase transport of chlorinated solvents, for example, may also be important, but has not been documented in the field at LANL. The importance of gas transport and the characterization of gas transport pathways requires additional study.

ISSUE 8. Do we know enough that modeling as a homogeneous, steady state system adequately defines the system? Alternatively, do we know enough to model as a non-homogeneous, transient system?

Except for scoping calculations, field observations and model studies show that some degree of heterogeneity will need to be incorporated into the conceptual models of flow and transport in the vadose zone, in the perched aquifers, and in the main aquifer. Transient effects will need to be considered to simulate transport at least within perched alluvial aquifers, and in pumping scenarios for the main aquifer.

ISSUE 9. To meet ER cleanup objectives, is there sufficient LANL and/or literature information on retardation factors?

Available data are scarce, and details of experimental procedures need to be published. A model study using existing sorption data underestimated observed radionuclide transport. Available data do not appear to be sufficient to defend ER objectives.

6. INDIVIDUAL PANEL MEMBER'S COMMENTS

6.1 Daniel B. Stephens (Daniel B. Stephens & Associates, Inc., Albuquerque, NM)

ISSUE 1. Do we have enough hydrogeological data at LANL to defensibly answer pertinent hydrogeological questions related to the ER site clean ups (e.g., stabilization in-place)?

There are many sites for which existing hydrogeologic data may be adequate to design and implement corrective measures. These sites include ones where either detailed site-specific studies previously have been conducted (e.g., parts of Mortandad Canyon), or where the impacted soil at the SWMU will be excavated to background conditions and no long-term predictions of post-closure performance are necessary. Examples of the latter SWMUs potentially could include some of the domestic septic tanks and firing ranges.

For those sites where corrective measures include in-place stabilization (e.g., capping, vitrification), performance assessments to support the designs may require additional hydrogeologic information. It is likely that mathematical modeling of flow and transport will be required for the vadose zone and the main aquifer. The subsurface flow paths from the source to the receptor will be influenced by spatial variability in hydraulic properties and the type and spatial distribution of the waste source (e.g., proximity to mesa or canyon, point or diffuse source, head of liquid at source). The travel time along the vadose zone flow path will depend mostly on the recharge flux through the soil and cover materials and the retardation factors.

It does not appear that site specific data are available on natural recharge rates in either the mesas or canyon bottoms. There have been numerous estimates of recharge, but these vary widely and in most cases are not based on field measurements. Depending upon local site conditions, natural recharge could occur by either porous or fracture flow, or both. Fracture flow will be very important where perched aquifers overlie deeply fractured tuff and where ponded rainfall or snow melt occur on bedrock with open, deep, connected fractures or joints. The

corrective measure should be designed so that significant, rapid fracture flow does not occur. Maps of fractures and joints are not available at most ER sites.

The fracture pathways are also relevant to vapor transport of tritium and volatile compounds. The rates of vapor advection in the vadose zone are controlled mostly by the barometric pressure fluctuations on the mesa tops and canyon walls, and the rock permeability to air, especially of the fractures. There are no field data available to assess the importance of natural vapor transport in the porous and fractured media, but some field information and general observations suggest this pathway may be important. For example, a number of well casings in the Los Alamos area are reported to transmit significant volumes of air between the vadose zone and atmosphere and, in fact, we visited one of these wells in Mortandad Canyon (TW-8). Purtymun et al. (1974) measured air transfers at test holes DT-10 and Alpha, and they noted that "though the phenomenon (of air transfer in wells and unsaturated media) is well known, little effort has been made to determine volumes, rates, and pressures at which the air transfer takes place." In the canyons, Abeele et al. (1981, 0009) identified stable thermal stratification as an inhibitor of vertical mixing of tritiated water vapor. However, they also noted that strong cross-canyon winds or unstable atmospheric conditions could cause mixing and transport of tritium vapor from canyon bottom to mesa top. Not only is this vertical transfer a potential source of tritium input to the land surface at ER sites, it is possible that air pressure variations along the canyon walls may also influence the exchange of gas between the canyon walls and vadose zone beneath ER sites, especially via interconnected fractures and joints which are highly permeable to air. This type of contaminant transport, although probably very minor, has not been evaluated, but could have significance to the corrective measures designs and short-term monitoring at remediated sites. A very preliminary assessment of gas-pressure gradients in the vadose zone was conducted at TA-54 for about two months in 1985 (BFEC, 1985); however, little definitive results were obtained at that time.

Tritium transport was investigated near shafts at Area G, TA-54, as reported by Rogers (1977, 0216). Field drilling and sampling showed tritium migration after 4 years about 40 ft (12 m) vertically beneath a shaft and about 105 ft (32 m) west of the shaft. The horizontal path was along a contact between ash flow units where pumice and reworked tuff were relatively abundant.

Owing to the relatively low moisture content (0.1 to 6.4% by volume), it was believed that tritium transport occurred mostly by water vapor diffusion; however, no studies were done to confirm the relative importance of vapor and liquid transport. Maps illustrating the shape of the tritium plume suggest that some liquid transport due to gravitational and capillary forces may have occurred.

The hydrogeological characteristics of the perched aquifers are not well known. It is the local perched aquifers in alluvium and shallow bedrock which appear to be the first aquifer beneath the site. Basic hydrogeologic data on the areal and vertical extent of the perched aquifer is available only in Mortandad Canyon (Stoker et al., 1991). Perched aquifers occur in other canyons, as described previously in Section 2 and as discussed by Devaurs and Purtymun (1985, 0049); however, we know little about their source of water, geometry, water level fluctuations, nature of perching layer, hydraulic conductivity, effective porosity, hydraulic gradient, leakage to underlying units, evaporation losses, and uptake of perched water by vegetation. There is insufficient hydrogeologic data currently available on the perched aquifers to make defensible quantitative assessments of risk for this subsurface flow pathway. This transport pathway can be rather rapid. For example, in the perched alluvial aquifer at Mortandad Canyon, Purtymun (1974, 0192) reported tritium moving at a rate of about 20 m/d in a sandy zone of the perched aquifer. Perched aquifers also discharge, at least in part, to springs in the lower portions of Pueblo and Los Alamos canyons, where potential contaminants could reach receptors. Because this transport pathway is relatively rapid and close to the potential sources, characterization of hydrogeological properties of perched aquifers will be very relevant to ER remedial designs at many SWMUs.

The source of water in the three well fields which tap the main aquifer is important to the ER program if long-term performance assessments of individual operating units are required. For example, if nearly all pumped ground water is derived from recharge on the Pajarito Plateau, then potential contaminants from the operating units will not be mixed and diluted to any significant extent with other water. Potential sources of mixing outside the plateau include ground water from east of the Rio Grande, ground water from the Valles caldera, and stream flow depletion from the Rio Grande.

A proper formulation of a hydrogeologic conceptual model is even more important if one must consider the collective impact to ground water from all the operating units. Runoff or seepage from the different operating units within a drainage basin probably is blended in the canyon bottoms. The deep ground-water flow paths beneath some of the different operating units probably converge at the well fields or discharge to the Rio Grande. In some instances, there may be lateral pathways across OU boundaries of vapor or liquid transport in the vadose zone. Consequently, the performance assessment of one operating unit alone may not predict adverse impacts, whereas the sum of impacts from all the operating units will undoubtedly be much more problematic. The ER group is to be commended for designating the canyon bottoms as a single operating unit. However, it must be realized that not all subsurface pathways from mesa top waste sites will lead to canyon bottoms.

The importance of hydrogeologic information to the ER program is critically dependent upon the time scale of interest. For time scales typical of landfill closure requirements of about 30 years, travel distances are short, consequently, we would be most interested in the shallow vadose zone and perched aquifers. On the other hand, if travel times of 1000 or 10,000 years are of interest, then the hydrogeologic characterization of the deep vadose zone and main aquifer are much more important. There should be a clear policy statement from the ER program, regulatory guideline, or DOE order regarding the time of interest for the various waste types (radionuclides, volatiles, inorganics). Without resolution of the time domain issue, we do not know what spatial data are needed and one cannot properly design a remedial action program.

ISSUE 2. Is there adequate flow and transport data to defend calculation of the subsurface pathway?

There is adequate data to characterize flow at only a few operating units where rather detailed field investigations have been conducted (e.g., TA-54 and Mortandad Canyon). In general, the existing subsurface investigations are limited to the upper 100 to 200 ft (30 to 60 m) of the vadose zone. The assessment of available data as adequate is based on the assumption that there is no deeper path through the vadose zone. If deep pathways exist, then deeper site characterization of hydrogeologic conditions would be required.

There is potentially a significant cost savings in hydrogeologic data acquisition that could be realized if it can be established that hydrogeologic conditions at well characterized sites are similar to those at sites where much less data are available. At first glance, it appears that there is a substantial uniformity in hydrogeologic properties within major geologic units. However, geostatistical analyses have not been conducted to confirm this. Available data in scattered publications appear to be insufficient for such analysis of spatial correlations; nevertheless, all available hydrogeologic data should be compiled in a single document in a convenient form for this and other purposes, such as modeling. Visual inspection of fractures in outcrops and limited quantitative analysis suggests that fracture characteristics on mesas are quite variable laterally within geologic units, probably due in large part to variability in welding of tuff (Ken Wohletz 1991, LANL, personal communication). If degree of welding varies laterally, there could be significant variability in important hydrogeologic properties as well. It may be feasible to develop a correlation between relatively easy to characterize index properties such as degree of welding and more difficult to quantify hydrogeologic or hydrogeochemical characteristics.

An issue related to defense of the adequacy of the available data is its quality. It appears that the existing hydrogeologic data (e.g., water level elevation, well logs, aquifer tests, hydraulic properties, well discharge, spring flows) have not been compiled onto a single data base and evaluated through a comprehensive QA/QC audit. For example, wellhead casing elevations must be determined by a first order survey, wells must be tied to a common grid coordinate system, and inorganic chemical analyses of water must be checked for ion balance. There also may be inconsistencies in existing data sets (e.g., Mortandad Canyon and TA-54) that may be attributed to differences in analytical methods. Sources of bias must be evaluated and eliminated where practical with respect to the ER program data needs.

Some transport data apparently are not sufficient to defend calculation of the subsurface pathway. These include field dispersivity and sorption characteristics for radionuclides and organics on representative geologic units which may exhibit variable degrees of saturation. It is also likely that some of the organic compounds may be abiotically or biologically transformed by processes whose decay coefficients ("half-lives") have yet to be quantified at LANL. These transport data play secondary roles to hydrologic data (e.g., hydraulic conductivity fields) in predicting the flow

pathways. The transport data are, however, very important in predicting travel times and breakthrough concentrations along the pathways. Dr. Robert Rundberg with INC-11 at LANL has indicated to the panel that dispersivity data are in fact available for LANL materials; however, there is no published information to date.

The role of colloidal transport is also highly relevant to performance assessments. Most recently, attention has been focused mostly on colloid transport in surface water. However, colloidal transport should be considered at least for transport in the perched aquifers. A model study by Travis and Nutall (1984) showed colloidal transport best accounted for movement of plutonium through about 100 ft (30 m) of tuff on the mesa at TA-21.

ISSUE 3. Do we know enough about the role of fractures?

Fractures play an important role in rapidly transmitting ponded liquids and vapor, and in some cases slowing or preventing transmission of partially saturated liquid phases. Ponded conditions can create positive pressures which allow liquid from runoff, perched aquifers, or impoundments, for example, to rapidly infiltrate fractures. Field observations of staining and weathering, at least along some fractures, suggests some preferred pathways occur even on mesa tops.

Detailed studies of water movement in fractures beneath a mesa have been conducted in pits excavated at TA-54, as summarized by Rogers (1977, 0216). Photographs taken after rains clearly illustrate preferential flow in some joints and fractures, even below caliche zones. Fractures were as much as 10 cm wide. Mineralogical studies indicate that there are three zones of alteration within fracture-filling: an upper calcite-filled zone, intermediate mixed caliche-montmorillonite zone, and a lower montmorillonite zone. This zonation was interpreted as reflecting standing water in fractures, some of which were plugged at depth. Excavations also revealed numerous roots which followed zones of moisture along fractures and joints, both horizontally and vertically to depths of at least 20 ft (6 m). Preferential flow of water in fractures on mesa tops is important to the ER Program, especially where a "no action" alternative for remediation is recommended, where vapor phase transport is important, or where failure of engineered capping materials is hypothesized. Without extensive site characterization, we do not

know how to predict which fractures conduct water or the area of the land surface which feeds the fractures. If liquid transport in fractures is to be predicted, we need to make rapid progress to develop methods to measure unsaturated hydraulic properties and transport coefficients in fractures, especially in the field.

From existing drilling data (e.g., TA-54) and field inspection of selected outcrops, fracture connectivity appears to be limited by the vertical extent of the particular cooling unit; however, in other areas, such as near the Pajarito, Guaje, Water Canyon, and Los Alamos fault zones, fractures and joints may be more likely to penetrate across the cooling units and formations. The most important area of concern to the ER program seems to be where fracture or fault zones pass beneath perched aquifers in the canyon bottoms.

Travis and Nutall (1984) simulated, using TRACER 3D, radionuclide transport in a porous media beneath impoundments at DP West, TA-21, and inferred that colloidal transport processes best explained the distribution of radionuclides to depths of about 100 ft (30 m). On the other hand, Christenson and Thomas (1962, 0039) thought fractures were important conduits for radionuclide transport at this site. Later work by Nyhan et al. (1985, 0168) showed that radionuclide concentrations were rather uniform with depth and few fractures were encountered during drilling, which led them to conclude that porous media flow dominated transport. Two field investigations near TA-50 of infiltration by Abrahams et al. (1963, 0012) and Purtymun et al. (1989, 0214) apparently showed that porous media flow and spatial variability would account for observed behavior.

Fractures may be more important to the transport of volatile hydrocarbons (e.g., dense chlorinated solvents) and tritium in water vapor. Field data or scoping calculations are necessary to assess the importance of fractures on vapor phase transport. There are no data available at this time, at least none known to this author, to evaluate whether, or under what conditions, vapor transport is more important in fractures than in the porous matrix of representative geologic units at LANL. It may be possible to use existing tritium data in tuff surrounding shafts at Area G, TA-54 (Abeele and Nyhan 1987, 0008), in model studies to address this issue.

Where fractures may be important to remedial design evaluations, we must recognize that reliable methods are not yet available to quantitatively assess the rate of flow and transport of liquid in an unsaturated fracture or fracture system. Because the ER program is concerned with remediation of existing conditions, rather than predicting historic behavior, fractures are much less important to quantify for the purpose of predicting leaching of contaminants from soil in the vadose zone, especially where sites have stable engineered covers.

ISSUE 4. Can we defensibly model LANL hydrogeology using a porous continuum model?

This issue is comprised of two subordinate issues:

(1) Is the physical system behaving as an equivalent porous media?
(2) Can a model predict, defensibly, flow and transport?

The first sub-issue is mostly addressed in the previous response to Issue 3. At most ER sites, especially on mesa tops, the assumption of dominantly porous media transport through thick vadose zone is probably reasonable, based on infiltration experiments. One does have to recognize that on mesas where there have been impoundments or ponded conditions, fractures may have played an important role in initially distributing contaminants at least through the shallow subsurface. Excavations on mesa tops at Area G, TA-54, suggest natural infiltration of precipitation occurs in fractures (Rogers 1977, 0216).

The second sub-issue pertains to the question of model validation, that is, the demonstration that the model can use available hydrologic properties to match observed field conditions. For multi-dimensional, unsaturated flow and transport, I am aware of no models which have been validated, although there has been some very good progress recently using data from unconsolidated alluvium at the Jornada site near Las Cruces, New Mexico. Controlled vadose zone field experiments in bedrock would provide a much needed data base to validate numerical codes such as TRACER 3D.

In the absence of new field experiments in the vadose zone, a good bit of confidence can be achieved in the predictive capabilities of models if the model of choice were tested using previously conducted field experiments (e.g., Abrahams et al. 1961, 0015; Purtymun et al. 1989, 0214).

Within the saturated zones (perched and main aquifers beneath the plateau), fractures are not likely to be important primarily because, except in the basalts, the aquifers are located in poorly consolidated alluvium which is not likely to exhibit open fractures. In tuff, on the other hand, fractures may accelerate fluid transport from perched alluvial aquifers to deeper formations. Detailed model investigations to date have had mixed success in predicting flow and transport within aquifers. However, it is my opinion that regulators will accept, and LANL can defend as state-of-the-art, model predictions of aquifer flow and transport which are based on well characterized hydrogeologic systems. Deficiencies in hydrogeologic data necessary to adequately characterize LANL sites are discussed in other issue sections.

ISSUE 5. Are we sufficiently certain of ground-water flow direction regionally that we can know ground-water flow direction at a specific OU? Additionally, is there any reason to believe there are local ground-water gradients?

The shallowest ground water beneath or adjacent to operating units is most likely perched in alluvium or bedrock. For perched aquifers and aquifers outside of Mortandad Canyon, data are insufficient to quantify the hydraulic gradient and aquifer geometry. Perched, alluvial aquifers are reported in Pueblo, Sandia, Pajarito, Los Alamos, and Water Canyon. Canyon bottom characterization of shallow ground water is recommended in these watershed areas which contain operating units. Local gradients away from the canyon bottom slope could occur where a ridge of shallow ground water develops beneath canyon bottom channels. Zones of increased moisture may occur beneath mesas where there is lateral seepage from the alluvium, based on neutron logging (Steve Reneau 1991, LANL, personal communication). Simple model studies may be applied to estimate the potential of spatially distributed recharge (horizontal line source) to induce local gradients on the regional water table.

A potentially very important issue related to the ER program is the local flow paths between the canyon bottom and formations beneath the mesa. It is proposed that the canyon bottoms be a separate operating unit because they represent the collection point of drainage from the multiple waste sites on mesa tops. This concept is valid for surface drainages which may transport contaminants. However, we have no data to confirm whether seepage beneath the mesas, should it occur, migrates to the canyon bottom. It is more likely that very small amounts of seepage from mesa tops would be diverted away from the channel bottom by lateral flows of moisture from the losing streams and leaky alluvial aquifers. Numerical modeling of variably saturated flow would give us a better understanding of these local pathways and their importance to the ER program.

The data base to establish the regional direction of ground-water flow includes test wells and springs. Within the approximately 40 square mile area comprising the operating units and areas east to the Rio Grande, there are only about nine unpumped wells to measure water level elevations in the main aquifer. Most of these wells are located on the central part of the plateau and penetrate substantial thicknesses of the aquifer. Data are adequate to establish that the regional flow direction is west to east. However, water level data are not adequate to evaluate vertical flow components or to establish sources of recharge. Vertical flow in the main aquifer is potentially important in the ER program to predicting deep pathways of contaminant migration. Nested monitor wells constructed with short screened intervals would be useful in evaluating vertical gradients as well as in monitoring water quality.

It is also my understanding that none of the existing wells are surveyed to a common grid system and wellhead elevations are mostly estimated from topographic maps. To have more confidence in the inferred flow directions, a first-order survey of all wells is recommended.

Figure 2 is an alternative conceptual model of flow in the main aquifer. This conceptual model is derived from multiple sources of information including: existing geologic and hydrologic reports, environmental surveillance data, and recent geochemical data on stable isotopes collected by Frazer Goff (1990). This new conceptual model suggests that ground water west of the Rio Grande is derived from a mix of recharge from sources both east and west of the Rio Grande.

The potential for ground-water flow westward beneath the Rio Grande is attributed to several factors, including (1) the westward dip of stratification within the Santa Fe Group sediments, (2) the barrier to discharge from the east provided by impermeable units of the Cerros del Rio volcanic field, (3) the thickening of the basin fill aquifer west from the Rio Grande, and (4) the greater elevation of the recharge area in the Sangre de Cristo Range compared to the Valles caldera or Pajarito Plateau sources. Primary discharge areas for the deep ground water are upward flow to shallower zones including the Rio Grande, pumpage by wells, and springs. The upward flow components near the Rio Grande are consistent with the following observations:

1. artesian conditions occur in some wells just west of the Rio Grande and in the Buchman field east of the river;
2. reports that total hydraulic head in wells increases with increasing depth (Cushman 1965); and
3. no continuous confining layer has been confirmed by hydrogeologists.

Additionally, an eastern component of ground-water flow is inferred by oxygen and deuterium isotope data from some wells and springs west of the Rio Grande which suggest recharge from an elevation greater than that in the caldera area (Goff 1990).

There are other local flow components that will occur near pumped wells. The well fields have produced a broad water level decline beneath the plateau. However, water level monitoring density is inadequate to assess the local flow conditions surrounding the well fields. Identifying the ground-water capture zones near the well fields is an important element in a wellhead protection program that may be required for the municipal well fields. For some operating units, especially in the canyon bottoms immediately west of the well fields, local flow due to pumping may be important to recognize in long-term performance assessments. Near the well fields and Rio Grande, the ground-water flow field may be depicted most accurately with a three-dimensional perspective.

ISSUE 6. Can we defensibly state there is no connection between any perched zones and the main aquifer?

No. To so state would require one to find that there is either zero permeability, zero hydraulic gradient, or an upward gradient between the perched zones and main aquifer. Alternatively, one could use geochemical methods, vadose zone monitoring, and continuous well hydrograph data to evaluate the potential for interconnection. Potential for connection between perched and main aquifers along improperly sealed well bores and test holes must also be recognized. To my knowledge, there has been no prior investigation with an explicit objective to evaluate the connection between the perched and main aquifer.

Recently available data indicates, however, that ground water in the perched aquifer does move downward. For instance, in Mortandad Canyon, tritium and nitrate occur with tuff beneath the alluvial aquifer (Stoker et al., 1991). The hydraulic head field beneath Mortandad Canyon alluvium seems to be mostly gravity controlled, and laboratory tests on core samples confirm that the tuff is moderately permeable.

While liquid transport is probably the primary pathway of interest, one should also consider the connection between the perched and main aquifers via the air phase. If dense, volatile hydrocarbons (e.g., chlorinated solvents) occur in the perched aquifers, then density driven transport in the gas phase should be considered in the conceptual model.

ISSUE 7. Do we know enough about gas exchange between the subsurface and atmosphere as a potential contaminant transport pathway?

There has been very little work to date on assessing whether gas phase transport of contaminants is occurring to any extent at LANL operating units. Some discussion of gas transport was presented previously in Issue 1. The gaseous transport processes to consider include diffusion, vapor phase advection, and density-driven gas flow.There is sufficient literature and analytical and numerical capability available to conduct scoping calculations to ascertain which of these processes is likely to be significant for LANL site conditions. Abeele and Nyhan

(1987, 0008) have begun such calculations to explain tritium distributions near a shaft at Area G, TA-54. Recent data from Area L, TA-54, suggest that organic vapor plumes have been detected to depths of nearly 200 feet (61 m), but the process can be simulated with a gas diffusion model in porous media (K. Campbell 1991, LANL, personal communication).

Although we have predictive capability to model gaseous phase transport, we lack in three respects: (1) field data to confirm whether gaseous transport is important, (2) field validated codes for gaseous transport in LANL media, and (3) convenient and accurate methods to obtain field-scale gas phase transport coefficients.

ISSUE 8. Do we know enough that modeling as a homogeneous, steady state system adequately defines the system? Alternatively, do we know enough to model as a non-homogeneous transient system?

Perched alluvial aquifers appear to be typical of most alluvial materials and are inherently heterogeneous at a small scale. At the larger scale, there also may be significant and abrupt facies changes in the alluvium, especially orthogonal to the axes of the channels. For example, in Mortandad Canyon the alluvium is comprised principally of a coarse sand layer overlying silt and clay layers. However, there is no quantitative information on the spatial variability in physical properties which control flow and transport. Variability in recharge to the alluvial aquifer due to seasonal snow melt and runoff events imposes temporal fluctuations on water levels, hydraulic gradients, and sources of contaminant influx. Therefore, alluvial aquifers should be modeled as a heterogeneous transient system, especially for predicting performance over time scales less than several years. To predict mean flow and transport over much longer times, or over much larger distances (e.g., miles), the importance of local spatial or temporal variability may be substantially diminished, at least in deterministic models, and the system may be effectively homogeneous and at steady state. Consequently, the performance assessment model efforts to predict mean behavior may be greatly simplified. On the other hand, to incorporate uncertainty of geologic data in predictions using stochastic models for example, spatial correlation structures and statistical moments of hydraulic properties must be determined. The above arguments

indicate that the time and space domain of interest, as well as model approach, must be specified before this question of heterogeneity and transient behavior can be answered fairly.

Beneath mesa tops and canyon bottoms, the vadose zone is poorly characterized, except at a few sites, as discussed previously among other issues. While it appears that the volcanic units have high uniformity and large areal extent, there have been no studies dedicated to confirming this. It is apparent from existing laboratory data that hydraulic properties can vary vertically, and perhaps horizontally, with degree of welding. Therefore, geologic field mapping should continue to delineate the geometry of zones which have similar welding characteristics. Field moisture data beneath Mortandad Canyon clearly show the effects of formational contacts and contrasting unsaturated hydraulic properties between and within formations (Stoker et al., 1991, p. 80). To simulate the observed transport of radionuclides and other chemical constituents, one should view the system as a heterogeneous and variably saturated flow field. We do not know whether there are significant transient effects on solute transport in the vadose zone at Mortandad Canyon because there is no deep soil-chemistry monitoring to establish a time series. The unsaturated hydraulic properties at Mortandad Canyon have only been characterized for relatively small laboratory core samples; future simulation efforts should assess whether field scale characterization of hydraulic properties in the vadose zone is necessary to improve the predictions of observed behavior. However, there are no reliable field methods to obtain in situ unsaturated hydraulic properties at depths below about 3 m at present, although research is progressing in this area and should be encouraged strongly. Vadose zone characterization has only extended to about 200 ft (61 m), so very little is known about heterogeneity and transient effects in the remainder of the vadose zone.

When simulating some types of seepage into dry materials in the vadose zone, one may also need to recognize the anisotropic nature of the porous media. McCord et al. (1991) could not accurately simulate observed bromide tracer movement in a homogeneous sand dune without introducing anisotropy to the model which is dependent on the degree of saturation. It has not been determined whether state-dependent anisotropy is relevant to LANL problems, although Abrahams (1963, 0012) found significant lateral flow components in his field infiltration experiment. The importance of anisotropy could be addressed by numerical simulation -- after

the code (e.g., TRACR-3D) is modified to account for this newly identified process. The net effect of the anisotropy is to cause more lateral moisture and solute movement relative to vertical transport. If state-dependent anisotropy of unsaturated tuff is in fact relevant to the ER program, then research should be initiated to develop field or laboratory methods to quantify it.

The main aquifer is characterized by deep drilling for test holes and water production wells. Some of the wells have been pumped to determine aquifer characteristics by single well test methods. Interference testing using one or more observation wells is a preferred method to obtain reliable, field-scale measurements of aquifer properties. The main aquifer is generally considered to include the Santa Fe Group and, in places where saturated, the Puye Formation. In the west the main aquifer intertongues with the Tschicoma Formation and is underlain by Mesozoic and Paleozoic sedimentary rocks which may have moderate permeability. In the east, it includes basalt and Rio Grande alluvium. The Tschicoma may have thin but permeable breccia zones and/or clastic layers (F. Goff 1991, LANL, personal communication) and the Puye contains a mix of sand, gravel, and cobbles with a lower gravel and sand layer, the Totavi Lentil. Waresback and Turbeville (1990) suggest that extensive lake deposits occur within the Puye fan. Aquifer thickness also varies considerably beneath the plateau. For instance, the Puye portion of the main aquifer ranges from 0 to as much as 725 ft (221 m) (Griggs, 1964). There are no isopach maps of principal units which comprise or intertongue with the main aquifer. Such information is important for accurate simulation. One should also consider that the main aquifer is anisotropic, especially in the Santa Fe Group which consists of thin layers of predominantly sandstone and mudstone. Consequently, the permeability perpendicular to the bedding will be less than the permeability parallel to the bedding. In most aquifer tests, the horizontal permeability is measured. However, the depth to which potential contaminants may mix in the main aquifer will be controlled by the vertical permeability, in addition to the vertical hydraulic gradient components.

ISSUE 9. To meet LANL ER clean-up objectives, is there sufficient LANL and/or literature information on retardation factors?

In reviewing documents for this panel and other LANL projects, I found few references on measurements of retardation factors for undisturbed tuff or other units at LANL. Purtymun and Stoker (1987, 0204) reported ion exchange capacity for plutonium to range from 0.5 to 4.0 meq/100 g. Polzer and Essington (1984, 0178) reported an ion exchange capacity for strontium, cesium, and cobalt of 0.33 meq/100 g. There is, however, a wealth of experience on radionuclide mobility derived from environmental sampling. There is also some literature on retardation factors for radionuclide transport for porous materials in general.

Travis and Nutall (1985) simulated plutonium movement at TA-21 using K_d values of 100 (units unspecified) for plutonium, but their model far underestimated actual radionuclide transport. Likewise, at Mortandad Canyon, there is evidence that very small amounts of $^{239,240}Pu$ and ^{241}Am occur at much greater distances downgradient from the discharge point than expected based on sorption characteristics (Penrose et al. 1990, 0174). The mobility of radionuclides such as ^{239}PU requires further investigation. Processes such as colloidal transport or mobilization by versene (Rogers, 1977, p. 23), by low pH, or by citrate and fluoride complexation may need to be considered.

Sorption can also occur during water quality sampling. The recent Mortandad Canyon report (Stoker et al., 1991, pp. 56-57) suggests that radionuclides may be sorbing to newly disturbed tuff surfaces and non-native filter pack material, especially in the newer well installations. Acquiring representative formation samples in the environmental monitoring program is essential. Additional work is necessary to design and test monitor wells and sampling equipment for radionuclide sorption effects.

Sorption also affects organic chemical transport. Chemicals such as petroleum hydrocarbons and organic solvents adsorp onto organic matter and inorganic substances in the porous media. There are few studies to develop sorption isotherms for organic chemicals. Such studies are encouraged and should include sorption mixtures of organic compounds typical of ER sites.

6.2 Peter M. Kearl (Oak Ridge National Laboratory, Grand Junction, CO)

ISSUE 1. Do we have enough hydrogeological data at LANL to defensibly answer pertinent hydrogeological questions related to the ER site clean ups (e.g., stabilization in-place)?

This is a difficult question to answer because one can never have enough data to satisfy reviewers or regulators. However, to effectively address the overall hydrogeology of the site, the hydrogeologic data requirements should be divided into three categories: unsaturated mesa-top transport, unsaturated valley-bottom transport, and the regional ground-water flow system (including both the perched and main aquifer). Models for each of these individual systems should be developed as part of the overall performance assessment. In many cases, it will not be possible to obtain all of the needed data for these models. Assumptions that are inherent in the modeling process will be necessary. Sensitivity analysis, a critical component of the modeling process, can be used to assess the importance of the measured data and the appropriate assumptions used in the model. Based on the results of the sensitivity analysis, additional data may be necessary for assumptions that have a controlling influence on model results.

There is a great deal of hydrogeologic information available for the mesa-tops at the lab. This data includes moisture contents, unsaturated hydraulic properties, and contaminant distributions. Analysis of this data indicates that for flow on the mesa tops, vapor transport will dominate. Consequently, diffusive and density-driven flow should be investigated further. If contaminants such as tritium are capable of migrating in the vapor phase, then diffusion coefficients in a porous medium such as the tuff should be measured. Density-driven flow is discussed in a following section.

There remain several unresolved issues regarding water movement in the valley bottoms beneath saturated alluvium. The first step in understanding flow is to determine the water balance for the system. Transpiration losses due to vegetation is the central issue. There is some controversy regarding the role of ponderosa pines in the amount of water used by the trees. The depth to water combined with the shallow root structure of the trees suggests that only near-surface soil

water is utilized for growth. Transpiration losses from the deeper ground water system would be negligible. Conversely, previous studies of plant uptake of tritium indicate that substantial quantities of tritium are present in ponderosa pines. This data are unpublished and need to be re-examined to determine the location of the trees sampled in relation to available surface water contaminated with tritium.

The unsaturated hydrologic characteristics of the tuff also need to be resolved. Moisture characteristic curves (pressure versus saturation) developed by TerraTek show extremely high moisture retention values compared with recent data. This discrepancy needs to be resolved.

One final recommendation regarding the valley hydrogeology is the need for a deeper borehole in Mortandad Canyon. The depth of tritium penetration at this site has not been fully defined. This information is important because the site can be interpreted as a large scale tracer test. Actual flow rate and contaminant transport rates can be calculated using this data. Subsequent impacts on the underlying ground-water system can also be assessed using this additional information.

ISSUE 2. Is there adequate flow and transport data to defend calculation of the subsurface pathway?

This question has been addressed in the answers to the other questions. There are still some items that need to be considered such as a pumping test of the regional aquifer (see regional and local ground-water flow question). However, if modeling is divided into three categories as recommended, there should be sufficient data to conduct flow and transport modeling and perform the necessary sensitivity analysis. This statement assumes that existing data will be incorporated into the modeling data.

This existing data include studies conducted on vapor transport in Technical Area 54 (see gas exchange question) and the uptake of tritium by plants in Mortandad Canyon. The plant uptake study has important implications on the water balance issue for the valley-bottom unsaturated modeling. Specifically, the question of whether ponderosa pine trees that were found to have

elevated tritium levels were adjacent to a surface water course or were they able to obtain ground water from depths of several meters or more needs to be addressed.

The role of colloids in the transport of immobile radionuclides such as plutonium should be examined. Work by Penrose et al. (1990) suggests that colloids have played a significant role in the transport of plutonium in Mortandad Canyon. Recent work by LANL in the canyon indicates that sediment transport may be responsible. This issue needs to be resolved.

A ground water sampling program that specifically targets colloids in the ground water is a possible option. Samples could be taken using the colloidal borescope to determine the concentration and chemistry of the colloids. The colloidal borescope is a downhole camera capable of viewing colloidal-size particles. When used during the sampling, the borescope ensures that representative particles are sampled.

ISSUE 3. Do we know enough about the role of fractures?

Fully understanding the role of fractures in transporting contaminants at the site is difficult if not impossible. A great deal of research has focused on the subject, and presently there is no widely accepted methodology for handling fractures. Experience at the site indicates that fractures may provide preferential pathways but only for short distances. Cooling fractures are the dominant type of fracture at the site. These ring-type fractures tend to be limited to individual flow units. For regional tectonic fractures, nonwelded units would tend to mend these types of fractures. A notable exception would be the large fault zones such as the Pajarito and Water Canyon fault complexes.

Consequently, fractures would influence short distance transport. Fractures may inhibit the movement of liquid water by forming capillary barriers. Moreover, fractures do not provide a continuous interconnected pathway that would enhance contaminant transport. Therefore, a porous continuum model with the appropriate assumption stated is a reasonable approach for modeling unsaturated flow in the system.

ISSUE 4. Can we defensibly model LANL hydrogeology using a porous continuum model?

For the regional ground-water flow system, there are no other viable options. Considering the sedimentary composition of the regional aquifer, a porous continuum model is the best choice. To assess the role of fractures would be difficult if not impossible. The cost of gathering data to characterize the effect and extent of fractures in controlling the flow of ground water would be prohibitive and the data of questionable value. The modeling approach previously recommended (see response to Issue 1) would be a more realistic option for developing defensible models at LANL.

ISSUE 5. Are we sufficiently certain of ground-water flow direction regionally that we can know ground-water flow direction at a specific OU? Additionally, is there any reason to believe there are local ground-water gradients?

Additional work is necessary to provide an adequate understanding of the ground-water flow system at the site. It is important to develop a comprehensive understanding of the regional ground-water flow system and use this understanding to assess local ground-water flow directions. It would be expensive and of little value to characterize the ground-water flow system beneath each individual OU.

Prior to discussing a phased approach to characterizing the ground-water flow system, consideration should be given to conducting a large scale pumping test of the main aquifer. An existing pumping well can be used, but it may be necessary to drill at least one observation well. This test is needed to determine the storativity of the main aquifer. Additional data on aquifer transmissivity would also be useful. Data from the pumping test could be extrapolated to other wells based on comparisons of individual well specific capacities.

Because of the magnitude and cost of characterizing the regional ground-water system, we recommend a phased approach that could be terminated when sufficient data for characterization purposes have been collected. One of the first steps in this phased program would be a sampling program to determine the relative ages of the ground water in the upper portion of the main

aquifer and at depth. Selected wells should be sampled and analyzed for the appropriate isotopes. This data should be compared with regional ground-water flow maps to assess the level of understanding regarding recharge and discharge areas, ground-water flow directions, and interconnection of perched and main aquifer zones. If there is good agreement, it will then be possible to incorporate reasonable assumptions into the ground-water modeling effort. Subsequently, it will not be necessary to continue to collect field data for the ground-water characterization program.

ISSUE 6. Can we defensibly state there is no connection between any perched zones and the main aquifer?

Based on a review of the available geotechnical literature, there is insufficient data to determine the connection between the perched zones and the main aquifer. The perched aquifers have not been clearly delineated. To address this problem, we have recommended that ground-water isotope studies be conducted at the site. These studies would consist of selected sampling of representative wells completed in the perched zones and the main aquifer. Appropriate isotopes would be analyzed to determine the relative ages of the ground water. Additional work would be based on the results of the age dating.

ISSUE 7. Do we know enough about gas exchange between the subsurface and atmosphere as a potential contaminant transport pathway?

Atmospheric pressure fluctuations are not a major influence in the transport of subsurface contamination. Gas flow observed in wells at the site is due to the existence of the wells. As barometric pressure changes relative to the soil atmosphere pressure adjacent the well screen, air flows through the well casing in response to the pressure differential. This flow is rapid because the well provides a pathway that has a permeability approaching infinity. Where a well does not provide this pathway, calculations indicate that the deep subsurface gas flow in response to barometric pressure changes is minimal. Recent discussion with Ed Weeks of the USGS, an expert on air flow in tuffs at the Nevada Test Site, support this conclusion.

A more important transport mechanism that needs to be addressed is the density-driven flow of dense contaminant gases. In particular, dense chlorinated solvents, such as those disposed of in TA-54, have the potential to move significant distances. Falta et al. (1989) calculate the maximum downward gas pore velocities for gas saturations at 0.75 percent in a porous media with an intrinsic permeability of 1×10^{-11} m . Permeability measurements conducted in the Bandelier Tuff are comparable to this value. For chlorinated solvents such as trichloroethylene (TCE) and 1,1,1 trichloroethane (TCA), maximum downward velocities were estimated at 0.63 and 1.08 m/d.

In Area L at TA-54, liquid solvents were disposed of in 20-meter deep shafts drilled into the Bandelier Tuff. After disposal, these liquids migrate into the tuff under capillary forces until residual saturation values are reached. These solvents then begin to evaporate, forming dense, chlorinated-solvent gas plumes. Directly adjacent to the residual liquid solvents, the gas plumes would approach saturated vapor conditions where total gas densities for TCE and 1,1,1 TCA are 1.58 and 1.87 kg/m , respectively. These densities compare with soil air of 1.17 kg/m at 1 atm and 25°C.

In 1986, Bendix Field Engineering conducted an investigation of TA-54 (Kearl et al. 1986, 0135). As part of this investigation, soil-gas sampling ports were installed at various locations and depths across the site. Additional sampling ports were installed by LANL the following year. It is our understanding that LANL has been actively collecting chemical data from these soil-gas sampling ports for a number of years. Apparently, this data has yet to be published. It is important that these data be evaluated to determine the extent of migration of organic waste at the site. These data could provide the needed input for modeling studies and potential remediation designs. In addition, new insights regarding vapor migration in tuff may be obtained that could be useful to other sites at the Laboratory.

6.3 Roger W. Lee (U.S. Geological Survey, Austin, TX)

I have studied the many reports of investigations in the vicinity of Los Alamos National Laboratories and found the work to be thorough and most of the objectives of the studies to have

been met. The group of investigators have done a noteworthy job of data gathering and interpretation to meet environmental concerns and to advance the understanding of hydrologic and geologic phenomena in the region. I have attempted to identify areas where problems or uncertainty exist. It is not my goal to be judgmental, but to point out technical weaknesses in order to improve what has been done as well as to prepare for future work. Technical problems, however, were few, which credits the many investigators of environmental concerns in this region.

In my part of the review of activities to delineate ground-water hydrology and geochemistry of the area below and surrounding the Los Alamos National Laboratories, I will address three specific areas and efforts to delineate geochemistry and contaminant chemistry for those areas. The areas include the

- site specific work for disposal areas C, G, and L,
- unsaturated zone pore fluids and perched water in Canada del Buey, Pajarito Canyon, and Mortandad Canyon, and
- the geochemistry of the main aquifer for this region.

I understand that I should consider validity of work reported and current, and recommend some direction for further work as necessary.

6.3.1 Site Specific Work at Areas G and L

Review of reports dealing with areas C, G, and L, principal disposal sites of TA-54, LANL, was generally favorable to approaches, discussions, and conclusions. Investigations of transport of radionuclides from pits into underlying rocks or overburden revealed significant transport only of tritium from disposal areas in moisture as HTO, or in the vapor phase. Although tritium concentrations were measured, no attempts were made to determine long-term flux. The flux of tritium across the air/soil interface to the atmosphere is significant, and should be studied for changes in tritium concentrations in local precipitation. Complete models of tritium cycling in the

local hydrologic cycle from the sources to atmosphere, soil moisture, surface waters, and ground waters would be of considerable interest.

There appears to be a lack of data on tritium in local rainfall and surface water. There also does not appear to be any chemical data on effluent discharges, rainfall, or surface water. These data would add to the understanding of sources of constituents in ground waters under investigation.

Other man-made radionuclides present in waste areas were shown as static, with no indication of significant movement from disposal areas. Area C indicated some presence of americium, plutonium-238, and plutonium-239 in soil cores. An apparent downward gradient indicates that these resulted from spills at the surface during disposal operations rather than movement from the disposal pit.

Projects have been conducted to identify and determine transport of other contaminants at disposal areas, specifically Areas G and L. Area G has received wastes since 1957, containing low-level radioactive materials, asbestos, beryllium residues, pesticide cans, PCB-contaminated wastes, and solid trash contaminated with suspected or known carcinogens. Many of these contaminants are volatile organic compounds (VOC). Study shows that no metal contaminants are present below 20 ft depth. VOCs, however, are present up to 100 ft depth near disposal pits. VOCs detected were principally 1,1,1 trichloroethane (TCA). Owing to the generally unsaturated conditions in the shallow subsurface, much of the VOC is contained in the vapor phase, and more likely to be transported larger distances by vapor phase processes or gravity (denser vapor than unsaturated zone gases).

Area L has been used since 1964, and contains mostly chemical wastes. Solvents are mostly VOCs such as methyl ethyl ketone, acetone, methylene chloride, and TCE. These are present in pore gases of the unsaturated zone up to 100 ft depth in the area.

Sample handling has been fully appropriate as described, and analytical procedures and detection limits are also fully acceptable for VOCs. Description of 2-pentanone in background core hole LLC 85-13 as cross-contamination in sampling procedures is likely the correct conclusion.

Design, sampling, and descriptions of results of pore gases are fully appropriate, and show clearly that VOCs are moving from the disposal shafts into the unsaturated zone. Further effort should be made to determine the dynamics of transport in order to assess risk to ground-water contamination. Some determination of whether any of the VOCs are being degraded either chemically or biologically should be made as well.

Chemical analyses of pore fluids should be done to determine chemical evolution in the direction of ground-water movement in the unsaturated zone. Methods are available to extract fluids from relatively dry rock, for example, triaxial compression (Yang et al., 1988), which should be utilized in investigations at the Los Alamos sites.

Principal references

1. Hydrogeologic assessment of TA-54, Areas G and L, Los Alamos National Laboratory (Docket No. NMHWA001007).

2. Radiochemical analyses of samples from beneath a solid radioactive waste disposal pit at Los Alamos, New Mexico, LA8422-MS, informal report, 1980.

3. Geohydrology of Bandelier Tuff, LA8962-MS, 1981.

6.3.2 Unsaturated Zone Hydrology and Perched Water Chemistry

None of the investigations of hydrology have adequately measured flow or chemistry of effluent releases and runoff in the canyons. Descriptions of runoff do not indicate whether discharge actually leaves the canyons and reaches a confluence with any other streams or rivers. This information is important as both a transport pathway and part of the hydrologic budget, and also in quantifying source terms for possible contaminants. Further work in these canyons should include surface-water monitoring of discharge and chemistry of effluent.

6.3.2.1 *Canada del Buey.* The work here was not fully satisfactory. The fact that shallow wells in the alluvium did not receive water does not necessarily mean that water does not move through the sediments as a result of infiltration of storm runoff waters or snowmelt. More sophisticated techniques for tracking infiltration should be done to determine the amount of water moving through the alluvium and its route(s). Use of porous cup lysimeters or perhaps more frequent monitoring of wells, especially after storms or during extensive snowmelt, may be more productive.

6.3.2.2 *Pajarito Canyon.* Perched water does exist here. Collection of samples using a brass bailer (Ref. 1) is not typical, but probably acceptable. Collection of radionuclides and VOCs was acceptable. Filtration and acidification of samples for cation analyses should be done in the field. There was no indication of whether pH was measured in the field. Presentation of major cation and anion data as stiff (Ref. 1) diagrams was not well done. There was no indication of units or the center line of zero concentration on the stiff diagrams. Radiochemical data address drinking-water standards, but no discussion of the significance of the reported concentrations, such as 3200 pCi/L of tritium, or other radionuclides was presented. No explanation was given for "negative activities" of some radionuclides. Chemical data reported for major cations and anions contains no discussion of quality assurance, for example, cation-anion balance.

It is also apparent that little attempt has been made to characterize flow or chemistry of runoff in either of these two drainages, except to show that overland flows for the period of record were lost to alluvial sediments before reaching their respective canyon mouths.

6.3.2.3 *Mortandad Canyon.* This canyon is unique in that it has received NPDES wastewater discharge since 1963, which has developed a perennial flow in the stream channel, above perched alluvial water.

Investigation of the hydrology of this canyon (Ref. 2) addressed a multitude of issues relating to possible contaminant transport in this area. Tritium was described as moving with the water molecules, but not acknowledged to undergo isotopic fractionation due to its greater mass. This

should be acknowledged as evaporation and vapor phase movement of the tritium isotope does occur, although analytical sensitivities are insufficient to show the fractionation effects.

An aqueous ionic complex for plutonium is described on p. 29 (Ref. 2) without reference. This needs some elaboration or explanation.

Numerous data collection and reporting errors were observed in Ref. 2; for example, no HCO_3, pH, conductivity, or NO_3 were reported. Concentration units are mixed with mg/L and µg/L in Table 6.2.1-IV, and not adequately identified. The chemical profile of unsaturated zone liquids and gases would be of significant use (for example, carbon-14 in CO_2) to characterize chemical gradients that should conform with liquid or gaseous circulation patterns. Isotopic data (D and 18-O) would also help characterize water chemistry and deep circulation of fluids. Leachate chemistry reported from the EP-toxicity methods is of some use, but limited due to added dissolution of the tuff matrix and lack of anion analyses. These chemical data do not meet geochemical goals of determining vertical fluid movement, chemical gradients, or even the role of fractures. Tritium activities were low in cores from the base of the Tshirege Member in MCM 5.1 and MCM 5.9. This should be related to physical properties of the core at those intervals in future work. The tritium profile (and C-14 age in CO_2) should be tracked through the entire unsaturated zone down to the main aquifer in several new core holes.

Principal references

1. Hydrogeologic assessment of TA-54, Areas G and L, Los Alamos National Laboratory (Docket No. NMHWA 001007).

2. Extent of Saturation in Mortandad Canyon, Los Alamos National Laboratory -- Environmental Restoration. LA-UR-91-1660, 1991.

6.3.3 Main Aquifer

Chemical data reported for wells and springs are inadequate for determining other than minimum drinking-water standards. Numerous errors such as cation/anion balances, specific conductances, alkalinities (no CO_3 reported when pH exceeds 8.3), were detected in chemical data reported by Purtymun (1984, 0196). In addition, several significant chemical constituents have not been analyzed; for example, boron, dissolved oxygen, aluminum, potassium, and sulfide. No cation/anion balance has been done. Conductivities appear to be in error for much of the data. No indication of pH values were determined in the field. Alkalinities reported as HCO_3 at pH greater than 8.3 should include some CO_3, but have been shown to be zero for analyses of wells and springs. Because carbonic acid is a diprotic acid (H_2CO_3), it can dissociate to $HCO_3(-1)$ and $CO_3(-2)$ over the range of pH of natural waters. Thus, the measurement of alkalinity by titration has two endpoints, at a pH of 8.3 and 4.5. At the former value, CO_3 becomes less than 1% of the total inorganic carbon, and most of the alkalinity is HCO_3 (see Figure 3). For pH greater than 8.3, a substantial amount of CO_3 is present in the solution and a concentration should be reported.

Chemical maps showing distributions of solutes can be prepared and aqueous chemistry can be determined using equilibrium thermodynamic models such as WATEQF, SOLMINEQ, or MINTEQ. However, more complete chemical analyses and field parameters must be better determined. Subsequent investigations should consider adding chemical parameters, stable isotopes C-13, D & O-18, N-15, and S-34, and radioisotope carbon-14 in order to get relative and absolute ages of ground water. If C-14 ages are to be determined in future investigations, then geochemical mass transfer modeling must be done in order to adjust raw age determinations to account for dilution of the carbon-14 at recharge. If chemical mass balance for these ground waters includes precipitation or dissolution of carbonate minerals, some correction is required, as well as measurements of carbon-13 for the various phases present in the system. Accurate assessments of carbon-14 ages can also be used to determine regional ground-water flow rates. For ground water older than about 40,000 years, Cl-36 dating may be more appropriate.

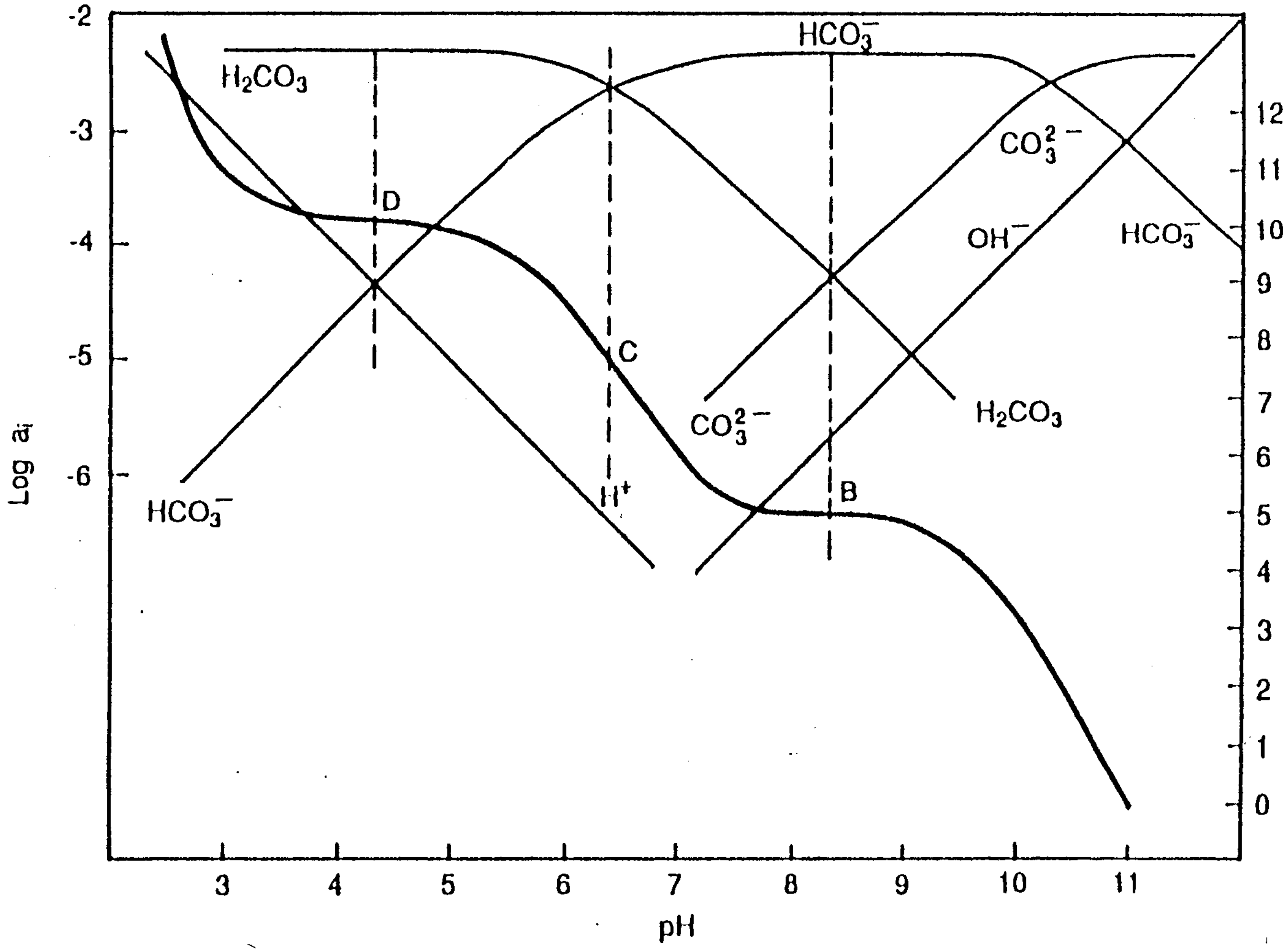


Figure 3. Titration curve (heavy line ABCD) for $5x10^{-3}$m Na_2CO_3, with acid, and Bjerrum plot for $\Sigma CO_2 = 5x10^{-3}$. B is carbonate end point, C is region of strong buffering, and D is bicarbonate end point.

Principle References

1. Hydrogeologic assessment of TA-54, Areas G and L, Los Alamos National Laboratory (Docket No. NMHWA 001007).

2. Hydrologic Characteristics of the Main Aquifer in the Los Alamos area: Development of ground water supplies. UC-11, 1984.

6.3.4 Recommendations to Improve Chemical Data for Database and Geochemical Interpretation

Chemical data collected for various investigations have been adequate for drinking water standards or for environmental regulatory concerns as needed. However, much of the chemical data is incomplete and lacking proper quality control of the reported results. Improvement in data collection, reporting, and documenting methods and handling should be implemented and maintained throughout any project work. Reliable data should be entered into a database with other hydrologic information and perpetually maintained for future investigations.

The first significant use of chemical data will likely be geochemical mass transfer studies along flow paths in the main aquifer, perched aquifers, and the unsaturated zone. Such projects will require both reliable data, and more complete sets of chemical parameters for each site sampled.

Standard procedures for sample collection, field analytical techniques, and review of results should be required and documented for any hydrologic investigation. Procedures are routinely available through EPA and U.S. Geological Survey, Water Resources Division to accomplish these quality assurance objectives. Several aspects of this goal should be considered.

6.3.4.1 Extend parameter lists to be complete. Chemical analyses of water samples should be complete, containing all the parameters of interest required for a geochemical interpretation. A basic analysis should consist of calcium, magnesium, sodium, potassium, iron, manganese (major cations), bicarbonate, carbonate, chloride, sulfate, fluoride (major anions), nitrate,

phosphorous, organic carbon (nutrients), silica, and field parameters of pH, temperature, specific conductance, alkalinity, and dissolved oxygen. In addition, aluminum, lithium, barium, strontium, boron, arsenic, and any other solutes deemed significant for an investigation should be added. This will provide the principle data set for determining quality of the data, and most geochemical interpretative methods.

6.3.4.2 Field methods and analyses. Field methods should be established according to procedures of EPA or USGS, consisting of proper sample treatment (filtration, acidification, preservation, and handling). Field analyses should also follow standard procedures and be adequately documented.

6.3.4.3 Use quality assurance/quality control methods. QA/QC procedures should be employed in any investigation or monitoring such that 10-20% of the samples be duplicates, blanks, spikes, and splits. These will permit assessment of sampling errors and lab errors inherent in the samples as collected and analyzed.

6.3.4.4 Review analyses as received. This important step should be carried out in order to request reruns by the lab or to collect resamples if necessary. Checking of the complete analysis for validity can be done several ways. The cation-anion balance is one of the easiest methods. In water analyses, the dissolved cations and anions should balance according to the equation

$$Z = \frac{\text{sum meq cations} - \text{sum meq anions}}{\text{sum meq cations} + \text{sum meq anions}} * 100 \qquad (1)$$

This assesses gross analytical errors. Standards for analytical data are such that an acceptable analysis is -5% > Z < 5%. For samples containing low concentrations of dissolved solids (< 100 mg/L), 10% may be considered acceptable. Many of the analyses reported in existing literature of the main aquifer and the perched aquifer were in excess of 10%.

The sum of major cations, anions, and nutrients, with a correction for the bicarbonate and carbonate should be nearly equal to the dissolved solids concentration measured in the laboratory, within 5% error. If not, then an analytical error for one or more solutes, an analytical

error for the dissolved solids measurement, or an omission of a significant solute or solutes in the analysis has been made. Further analytical work is required to produce a reliable result.

Dissolved solids and specific conductance should be related by

$$\textit{Dissolved Solids}\ [mg/l] = (0.7\ \textit{to}\ 0.9) * \textit{Specific Conductance}\ [\mu s/cm] \qquad (2)$$

In some of the analyses reported, this criterion was not met. Any interpretation relying on conductivity of the sample would be incorrect. Further, the reviewing analyst should look for anomalously high or low results that appear in the analyses, or that exceed statistical limits based on QA procedures and experience with data from the area. Reruns should be requested or resamples taken to rectify unusual or bad results as appropriate.

6.3.4.5 Data interpretations. Use of certain interpretative methods should follow some technical guidelines for presentation. Stiff diagrams are not interpretable without proper explanations of scales as observed in the IT Corp. document. Other methods of recommended interpretation include distribution maps showing particular chemical constituents or ratios, piper diagrams, statistical methods, regression analyses, graphs, or aqueous geochemical models. If a reliable chemical database were available, these methods could be applied for interpretative use, and will likely be applied in future studies.

6.3.4.6 Documentation. Data collection notes, handling, description of methods or references, and summaries of QA statistics should be made available as a separate publication or in appendices to the body of any reports on the investigation. Reliable chemical data should be handled in a computer database where selection and production of interpretive graphics, statistics, or other procedures may be easily accomplished. Any new chemical data gathered should be reviewed, entered and verified, and the database should be maintained in perpetuity for the area.

6.3.5 Recommendations for Projects at Los Alamos National Laboratories

Based on my assessment of present understanding of hydrology at the Los Alamos National Laboratories, and feedback from fellow panel members and Los Alamos technical staff, I feel that

two major regional-scale projects, and several smaller scale projects should be developed. These projects should serve to organize existing information, determine new data needs, answer many of the questions regarding hazardous materials stored at various sites, and assess the risk of contamination to ground-water supplies. The regional projects should address the hydrogeology and geochemistry of the main aquifer, the perched aquifers and the unsaturated zone. Several smaller projects would address such phenomena as variable-density, two-phase (liquid/vapor) transport in the unsaturated zone, role of colloids in transport, deep tritium circulation at specific sites, sorption of radionuclides, role of fractures in contaminant transport at specific sites, and others.

6.3.5.1 Hydrogeology and geochemistry of the main aquifer. The purpose of this project is to provide a thorough hydrogeologic and geochemical understanding of the main aquifer underlying LANL. The scope of the project would involve organizing existing hydrologic and chemical data into a reliable database, development of a digital model of ground-water flow, presenting chemistry, chemical processes, mapping distributions of solutes in the main aquifer, and producing geochemical mass transfer models of the main aquifer. This integrated approach should provide values for recharge, storage, and discharge of the system,as well as provide hydrogeologic information that will be useful in the assessment of risk of contamination from overlying land use activities. Recharge from deeper geothermal systems can be assessed quantitatively, with better understanding of the source of arsenic, presently thought to originate from deep geothermal waters.

This project would use a complete hydrologic data base, digital simulation of ground-water hydrology, and geochemical mass transfer modeling of chemical processes occurring along ground-water flow paths. New test wells in the main aquifer along with new cores, hydraulic testing, and new, more complete geochemical samples for analyses and interpretation would be added to the extensive information already available. In addition to chemical data, stable and radioisotopes can be used to verify hydrologic and geochemical processes modeled, as well as determining age and flow velocities of ground water.

6.3.5.2 Regional investigation of hydrology and geochemistry of perched aquifers and the unsaturated zone. The purpose of this project is to determine the nature of water movement between the land surface and the main aquifer underlying LANL, as well as the chemistry of pore fluids contained in the unsaturated zone. The scope of such a project would be regional, dealing with the complete hydrologic budget for the area, including flow and chemistry of surface water, effluents, and rainfall.

The project would require collection of cores from land surface on the plateau and in the canyons, down to the main aquifer. Cores would be characterized according to hydraulic properties, water content, and chemistry and isotopic composition of pore fluids. Use of water extraction methods developed at the Yucca Mountain Site by USGS (triaxial compression), or centrifugation can be used for chemistry and isotopic data. In addition, test holes could be thoroughly analyzed for borehole geophysics, hydraulics, vapor phase movement, chemistry, and isotopes, moisture content, and any other tests pertinent to delineation of fluid movement or transport of contaminants across the unsaturated zone or the perched aquifers. Modeling of movement of fluids (water or vapor) through the unsaturated zone could be accomplished for predictive purposes. Knowledge of surface-water hydrology, both the amount of flow and the chemistry, is important for the hydrologic budget of the region and a knowledge of the chemistry of sources of recharge. In some cases, perennial flow in canyons results from effluent discharges, whose chemistry must be known to determine chemical processes occurring in the perched aquifer and in the unsaturated zone. Also, evapotranspiration must be determined to complete the hydrologic budget. Understanding the hydrology of the perched aquifers and the unsaturated zone will allow risk assessment of potential contamination of the main aquifer.

6.3.5.3 Smaller scale projects. Several small scale projects are needed to address site-specific questions or to provide results to assess the potential for contamination of ground water or surface water. The following list of projects are some of the more substantial efforts needed:

a. Modeling of two phase variable density flow in unsaturated tuff.

b. Sorption and role of colloids in transport of heavy radionuclides.

c. Significance of fractures as conduits for transport of organic molecules and radionuclides in the Bandelier tuff.

d. Sources, distribution, transport, and deep circulation of tritium in air, water, and rocks in the vicinity of Los Alamos National Laboratories.

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