1980's 3/1/85

Incomplete

TA-54

ATTACHMENT 1

A Reasonable Worst-Case Water Balance for LANL Hazardous Waste Disposal Areas, With Emphasis on TA-54

The water balance for LANL's hazardous waste disposal areas submitted to EID by LANL on November 1, 1984, did not adequately estimate the potential for infiltration at those areas. Since this submittal was LANL's second attempt at a water balance, the EID drew up the following water balance.

1. Precipitation

The EID is aware of four precipitation stations relevant to LANL hazardous waste disposal areas. The data we currently have available from these stations is shown on page two.

These records show that winters at White Rock - and, presumably, at TA-54, which is only two miles away - are significantly drier than at Los Alamos or TA-59/TA-3. Since the non-summer months are the ones most likely to experience precipitation in excess of evapotranspiration (ET) requirements, applying precipitation data from TA-59/3 or from Los Alamos to TA-54 will tend to overestimate both annual precipitation at TA-54 and the proportion of that precipitation that may be available for infiltration.

For the Los Alamos station, a LANL employee has estimated the frequencies of occurence of annual precipitation totals that equal or exceed given values (Lane, 1981). These are:

RETURN PERIOD	ANNUAL PRECIPITATION IN INCHES
2 years	17.99 (i.e., 17.99 is the median annual precipitation)
5	24.06
10	25.79
25	27.93
50	29.03
100	30.24

To round out this picture, it is desirable to gain some idea of past rainfall from the interpretation of local tree-ring data. In one careful recent study, the authors found no reason to discard their initial premise that the quantity of annual precipitation for the Santa Fe area has remained roughly the same for the last 1000 years (Rose, Dean, and Robinson, 1981). Their work showed that excursions in 10-year averages of annual precipitation at Arroyo Hondo have not exceeded about three inches in the 1000-year record they examined.

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Precipitation Data Relevant to a Water Balance at LANL Disposal Areas

Location	Average Precipitation by Month in Inches												Annual Total
	J	F	M	A	M	J	J	A	S	O	N	D	
White Rock	0.25	0.24	0.24	0.32	1.20	1.50	2.29	3.68	1.73	1.02	0.39	0.67	13.50
(9 years of record here; elevation circa 6700')													
TA-59/TA-3	0.82	0.67	1.14	0.82	1.16	1.10	3.20	3.86	1.73	1.47	0.99	0.97	17.93
(33 years combined record; elevation circa 7400')													
Los Alamos	0.84	0.70	1.01	1.01	1.25	1.33	3.29	3.69	2.01	1.61	0.70	0.93	18.37
(60 years of record; elevation 7410')													
TA-54													(13.45)
(5 years of record; annual total based on 75% of TA-59/3, as per Appendix II, p. 41; elevation circa 6700')													

(Data from Appendix II, Gabin and Lesperance, and

LANL's water balance cites an article which apparently throws a dark cloud on all of dendroclimatalogy, but we have not yet been able to access this article. Only note that, if rising CO_2 levels in the air are a competent cause of decreased tree ring response to moisture, even on semi-arid sites low in other plant nutrients, the effect will be to bias dendro-climatologists toward over-estimating past rainfall. LANL's water balance analyzes possible infiltration from a synthetic rainfall year composed of each of the highest monthly precipitation totals recorded at TA-59/3. This gives an annual total of 57.47 inches, almost twice the estimated 100-year annual precipitation. This figure is roughly equal to the average annual precipitation in Vancouver, B.C.; it is not clear that such a precipitation year could ever occur at Los Alamos without the climatic conditions that may have prevailed here in the Pleistocene. Hence, EID believes LANL's precipitation scenarios to be overly conservative.

A recent LANL study (Abeele, Wheeler, and Burton, 1981) used methods which were not explicit to study Los Alamos tree rings. In the period examined (which apparently extended at least back to 1523), the maximum annual precipitation indicated by the tree ring data was roughly 40 inches, in 1597.

A more reasonable approach than that of the LANL water balance might be to analyze the water balance under a suite of reasonable worst-case assumptions. If significant infiltration could occur under any of these regimes, one must determine both the robustness of this result and where this infiltrated water would be likely to go. The synthetic precipitation regimes that will be examined for TA-54 are shown on page 4.

For LANL disposal areas at roughly the elevation of TA-59/3, the first scenario on page 4 represents typical, rather than worst-case, conditions. The remaining sections of this report will focus on TA-54; generalizations to wetter areas are left to the reader. Note that the second and third synthetic records shown on page 4 slightly exceed the 100-year annual rainfall at Los Alamos.

2. Runoff

The LANL water balance estimates runoff at a flat 20% of incident precipitation, ostensibly based on an SCS Curve Number of 82. There are at least four reasons why this approach will overestimate runoff:

a. Precipitation is assumed to occur as rainfall only. The months of greatest interest experience significant snowfall; snow is less likely to produce runoff than rain.

b. To apply the SCS method, the frequency spectrum of individual storm magnitudes must be known in detail. Appendix II assumes storms deposit an average of roughly 1.25" of rain per storm; this is far too great.

c. What is locally runoff may become infiltration elsewhere, e.g. by running down a ramp into an active pit.

"Worst-Case" Precipitation Scenarios for TA-54

Scenario	Precipitation by Month												Annual Total
	J	F	M	A	M	J	J	A	S	O	N	D	
1. Wet decade at TA-54; data shown is the average recorded for Los Alamos.	0.84	0.70	1.01	1.01	1.25	1.33	3.29	3.69	2.01	1.61	0.70	0.93	18.37
2. Wet single year at TA-54; data shown are monthly autumn maxima from TA-59/3; balance of year is average TA-59/3 data.	0.82	0.67	1.14	0.82	1.16	1.10	3.20	3.86	4.55	6.77	6.60	2.85	33.54
3. Wet single year at TA-54; data shown are monthly spring maxima from TA-59/3; balance of year is average TA-59/3 data.	2.81	1.87	4.11	3.23	3.50	3.40	3.20	3.86	1.73	1.47	0.99	0.97	31.14

d. Moist (neither wet nor dry) antecedent moisture conditions are assumed in the LANL water balance. Most storms will occur with dry antecedent conditions.

A reasonable worst case analysis would assume that the precipitation of greatest interest (that is, precipitation with the greatest potential for infiltration) falls either as slow-melting snow or as individual storms of less than 0.5" in magnitude. These conditions will produce little or no runoff from TA-54, and no abstraction for runoff will be made in the water balances to follow.

3. Interception and Depression Storage

To the extent that evapotranspiration (ET) figures are computed from data for crops or natural vegetation that receive water from rain, snow, or artifical sprinkling, these ET figures already include interception losses. While in forested areas or other situations involving a high leaf area index, or in situations involving roofs, interception is important, it is not likely to be very important at TA-54 due to the sparse plant cover. The potential interception from a 2" grass lawn has been estimated to be only 0.01" (Lull and Sopper, 1969); other estimates and references can be found in Dunne and Leopold (1978). In the following analyses, an interception of zero will be assumed.

In order for depression storage to be significant in preventing infiltration, impervious depressions must be present. These conditions are not, to our knowledge, present at TA-54 to any significant extent.

4. Evapotranspiration

Discussions of evapotranspiration (ET) are often lent an unnecessarily abstract quality by the use of the "potential" ET (PET) concept. PET cannot be measured either directly or indirectly; nevertheless several traditional formulae exist to predict what it would be if it could be measured. What can be measured is the actual ET of a site, and this has unfortunately not been measured at any of the LANL disposal areas.

Observation of low moisture levels in the tuff at TA-54, and the apparent invariance of this low level with depth beyond a certain depth, lend credence to the idea that infiltration is small at TA-54 (e.g., Abrahams, Weir, and Purtymun, date unknown). Since runoff is not large either, except perhaps in summer thunderstorm events, a close upper bound for the average annual actual ET is simply the precipitation that falls on the site.

In a wet year, transpiration by plants, as well as evaporation from bare soil and snow, will increase above this average value. Winter transpiration alone will not increase very much, however, and will hardly increase at all if only winter-dormant species are involved. Summer transpiration will also increase in a wet year, but not indefinitely and not to the extent that would be possible in denser vegetation communities. The upshot is that while ET will be greater in wet years, there is no guarantee that it will increase sufficiently to prevent infiltration. The

incontrovertible evidence that infiltration does occasionally occur is discussed in a later section.

The Blaney-Criddle method for computing the consumptive use of an irrigated perennial crop will be used to predict the maximum ET that could be experienced in a given month (i.e., the PET). This empirical formula uses day length and mean air temperature to calculate PET. The version of this formula used here (Soil Conservation Service, 1970, cited in Dunne and Leopold, 1978) is more recent, and significantly different, than that used in Appendix II (Cruff and Thompson, 1967). The table below gives the PET for mature alfalfa (a highly water-intensive crop) grown in Los Alamos. That is, these values purport to predict consumptive water use by freely-irrigated alfalfa in Los Alamos.

Month	k	PET
J	0.63	0.39 in.
F	0.73	0.49 in.
M	0.86	0.91 in.
A	0.99	1.89 in.
M	1.08	3.68 in.
J	1.13	5.84 in.
J	1.11	6.53 in.
A	1.06	5.42 in.
S	0.99	3.63 in.
O	0.91	1.99 in.
N	0.78	0.70 in.
D	0.64	0.42 in.
Annual Total:		31.86 in.

Here PET = $0.3937(0.142T_a + 1.095)(T_a + 17.8)kd$ when T_a 3^oC, and PET = $0.3937(T_a + 17.8)kd$ when T_a 3^oC. Here PET is in inches, k is the crop coefficient for alfalfa shown above, and d is a day length variable (Dunn and Leopold, 1978).

The potential ET for bare crushed tuff backfill, or with a cover of sparse grass and widely spaced trees, will be less than the PET for alfalfa shown above. Note that the annual PET computed for TA-54 in LANL's water balance was 41.89", using an earlier version of the Blaney-Criddle formula. This is unreasonably high.

Regional actual ET values have been measured for vegetation types that may approximate in some cases, and bracket, in other cases, the LANL situation. The following actual ETs show, in a broad way, that ETs for forested land tend to be greater than those for brush or grass and are in every case less than that for the alfalfa discussed above (cases cited in Rich and Thompson, 1974):

Cover Type	Location	Season	ET for Season
grassland	CO	June-Sept.	9.5 inches
grassland	UT	May-Nov.	10.0
brush	UT	May-Nov.	13.9
pine	AZ	May-Oct.	23.6
aspen	CO	June-Sept.	18.8

The following annual values for ET have been obtained in three instrumented watersheds south of Flagstaff on the Mogollon Rim. These watersheds lie in elevations between 5000' and 8000' and have soils derived from basalt and volcanic cinders which range from clay to clay

loams and which restrict infiltration. Actual ET figures were obtained by subtracting streamflow from precipitation, and so contain interception, snow sublimation, and any ground water recharge (this last is believed to be very small) (Baker, 1982).

	Dominant Vegetation Type		
	Utah Juniper (lower elevation)	Alligator Juniper (medium elevation)	Ponderosa Pine (highest elevation)
Annual Precip.	18.03 in.	20.71 in.	25.50 in.
Annual ET	16.97	15.94	19.94
Basal area per acre	60 ft^2	20 ft^2	125 ft^2

These watersheds are located at approximately the latitude and elevation of Los Alamos and receive annual precipitation, on the average, that is at least that received at LANL's disposal areas. Although the basal areas shown do not define dense forests, these ET values include whatever brush and herbaceous species that may be present in the understory, and the transpiratory ability of these associations is probably at least that present at TA-54.

At LANL, deep-rooting plants (including all trees) are prevented from growing on backfilled areas at Area G, and at any other areas where hazardous materials (such as tritium) may be drawn to the surface by transpiration. Trees will certainly send roots preferentially into disposal pits, both because it is mechanically easier to grow there and because increased infiltration in those areas may create a more favorable moisture environment for plant growth. Studies cited in a LANL report (Rogers, 1977) document tritium uptake by plants at Area G.

It follows that the Arizona watersheds provide a reasonable high estimate of actual ET for LANL disposal areas. ET at TA-54 could not reasonably be expected to be greater than 20" except in the wettest years, and on the average would be somewhat less than the 16-17" experienced in the juniper-dominated watersheds. It is reassuring that these numbers are at least in the same range as the incident precipitation at LANL.

Unfortunately, the only way to a priori distribute, without actual measurement, these annual estimates of ET among the 12 months of the year is to refer to the estimates of PET we have made above. Assuming these estimates are good ones, and assuming we are happy with a 12-interval discretization of the year's hydrology, we must then translate PET into actual ET.

If the soil is thoroughly penetrated by roots, and if the plants involved are actively transpiring, ET will proceed at the PET rate until the soil moisture tension reaches some threshold level, after which it will fall off according to some (unknown) relationship. The ratio of ET/PET when

moisture is limiting has been investigated by many researchers, with conflicting results that apparently depend on factors unique to the particular experiments. Reviews of this work along with the results of experiments in New Mexico can be found in the bibliography (Sammis, et.al., 1979; Gregory and Hanson, 1976; Al-Khafaf, et.al., 1979; Spurr and Barnes, 1973; Dunne and Leopold, 1978).

In the dormant season, when ET is of most interest to us (and of least interest to the agricultural researchers), ET/PET apparently falls off more quickly than when roots are active. According to one review, soil evaporation falls off to an "insignificant value" after 0.2 to 0.4 inches of water has evaporated, due to the formation of a dry soil mulch at the surface (Dunne and Leopold, 1973).

It follows from the above discussion that it is crucial to know the species, active seasons, rooting depths, and cover densities of vegetation both now and in the future at LANL's disposal areas, if we are to understand the present and future water balance at those areas. Even though the native vegetation appears to have been capable of establishing an ET regime that has led to a constant and low moisture content in the tuff at depth, the treeless shallow-rooted vegetation that has been described as present at TA-54 now may not either be able to extract water as efficiently, or for as many months of the year, as the original vegetation.

In the present rough-and-ready analysis, vegetative dormancy (and the "dry-soil-mulch" effect) are not considered beyond the extent they may already be incorporated into the Blaney-Criddle formula. The present analysis may, therefore, overestimate winter ET and underestimate winter infiltation, to some extent.

Actual ET for the ith month is computed as follows:

$$ET = (PET/AWC)(SM_{i-1} + SM_i)/2$$

where: PET is potential evapotranspiration in inches
AWC is the available water capacity of the soil in inches
SM_{i-1} is the soil moisture at the end of the previous month in inches, and
SM_i is the soil moisture at the end of the current month in inches.

SM_i is, in turn,

$$SM_i = SM_i' \text{ if } 0 \leq SM_i' \leq AWC, \text{ and}$$
$$= AWC \text{ if } SM_i' > AWC$$

where $SM_i' = SM_{i-1} + P - ET$.

Eliminating ET gives $SM_i' = [SM_{i-1} (1 - PET/2AWC) + P] / (1 + PET/2AWC)$.

This is the linear assumption of Thornthwaite applied to discrete monthly intervals, i.e., ET/PET when soil moisture is limiting is proportional to the difference between soil moisture level and field capacity. Other

assumptions could be used, but the main conclusions that will be reached are, we believe, robust with respect to the functional form of the ET/soil moisture relationship.

5. Soil Moisture Storage

In the interest of time, the approach used in Appendix II to model moisture storage in the soil is provisionally applied here. Note that the discharge and storage of soil moisture is assumed to take place evenly throughout the soil profile in this approach, and soil and tuff beneath the average rooting depth is assumed to not contribute to ET. It almost certainly does contribute to ET, as will be discussed later.

In the water balances below, the value for available water capacity (AWC) given in Appendix II of 4.96 inches (for crushed tuff) is used. By comparison Appendix II uses an AWC value of 5.43 for undisturbed soil.

6. Water Balances

The water balance which obtains from Scenario 1 precipitation is shown as Case 1 in the following table and graphically on page 12. The soil moisture cycle represented by case 1 is quickly reached from a variety of initial conditions, as shown in Cases 3 and 4, and perturbations, such as a very wet month as shown in Case 2, quickly die out. Under Scenario 1, April arrives with the soil just reaching field capacity, and no infiltration ever occurs; actual ET is equivalent to precipitation.* Recall that this represents a fairly wet year at TA-54, and represents a typical year at the Los Alamos weather station (or at TA-59/3, which has a similar elevation and precipitation record).

If a single wet month occurs in the fall, or if the soil should enter the fall nearly saturated due to unusually heavy rains in September, infiltration will occur in every subsequent month until April. As can be seen in Case 2, the total amounts of infiltration can be significant under these assumptions.

Scenarios 2 and 3 result in very large amounts of infiltration in several months, giving up to 7 months of infiltration in the case of Scenario 2. These scenarios, which have long return periods (>>100 years at TA-54) will not be discussed further.

At TA-54, winters (and April) are significantly drier than at Los Alamos, on the average. Nevertheless, it is hard to see why infiltration would not occasionally occur there, as it does at Los Alamos, during periods of wet weather. Unlike at the Los Alamos station, however, PET exceeds rainfall in every month except December, and the propect of several months of infiltration occurring after a wet fall month does not seem to be very likely, unless those following months are also unusually wet.

*Actually, in a soil at field capacity, slow drainage does in fact occur. Note that we have essentially assumed, in the above, that a dense crop of mature alfalfa is ready, all the time, to transpire moisture at TA-54. In

LANL Water Balance: Case 1: Steady-State

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precip.	0.84	0.70	1.01	1.01	1.25	1.33	3.29	3.69	2.01	1.61	0.70	0.93
PET	0.39	0.49	0.91	1.89	3.68	5.84	6.53	5.42	3.63	1.99	0.70	0.41
Soil Moisture	4.61	4.84	4.95	4.22	2.85	1.52	2.30	3.06	2.89	3.27	3.49	4.11
ET	0.34	0.47	0.90	1.75	2.62	2.57	2.51	2.93	2.17	1.23	0.48	0.31
Potential Infiltration	0	0	0	0	0	0	0	0	0	0	0	0

Case 2: Very Wet November

Precip.	0.84	0.70	1.01	1.01	1.25	1.33	3.29	3.69	2.01	1.61	6.60	0.93
PET	0.39	0.49	0.91	1.89	3.68	5.84	6.53	5.42	3.63	1.99	0.70	0.41
Soil Moisture	4.96	4.96	4.96	4.22	2.85	1.52	2.30	3.06	2.89	3.27	4.96	4.96
ET	0.39	0.49	0.91	1.75	2.62	2.57	2.51	2.93	2.17	1.23	0.58	0.41
Potential Infiltration	0.45	0.21	0.10	0	0	0	0	0	0	0	4.33	0.52

LANL Water Balance: Case 3: Beginning from the wilting point in May

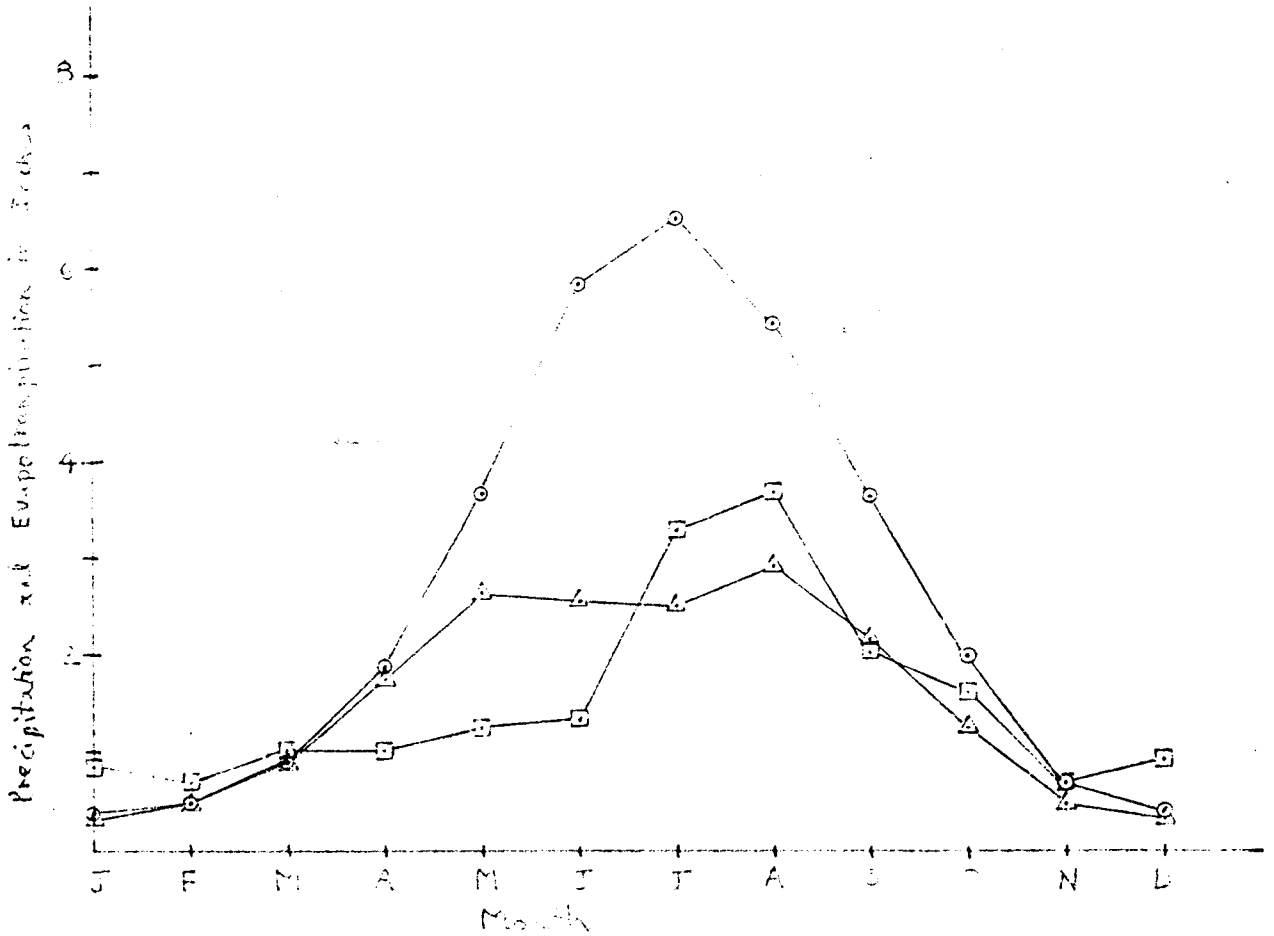
	Jan	Feb	Mar	Arp	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precip.	0.84	0.70	1.01	1.01	1.25	1.33	3.29	3.69	2.01	1.61	0.70	0.93
PET	0.39	0.49	0.91	1.89	3.68	5.84	6.53	5.42	3.63	1.99	0.70	0.41
Soil Moisture	4.60	4.83	4.94	4.21	0*	0.84	2.16	3.02	2.87	3.25	3.48	4.10
ET	0.34	0.23	0.90	1.74		0.49	1.97	2.83	2.16	1.23	0.47	0.31
Potential Infiltration	0	0	0	0	0	0	0	0	0	0	0	0

Case 4: Beginning with soil at field capacity in January

Precip	0.84	0.70	1.01	1.01	1.25	1.33	3.29	3.69	2.01	1.61	0.70	0.93
PET	0.39	0.49	0.91	1.89	3.68	5.84	6.53	5.42	3.63	1.99	0.70	0.41
Soil Moisture	4.96	4.96	4.96	4.22	2.85	0.84	2.16	3.02	2.87	3.25	3.48	4.10
ET	0.39	0.49	0.91	1.75	2.62	0.49	1.97	2.83	2.16	1.23	0.47	0.31
Potential Infiltration	0.45	0.21	0.10	0	0	0	0	0	0	0	0	0

*initial month

Potential Evapotranspiration, Computed Average Actual Transpiration, and Precipitation at Los Alamos, NM



⊙ potential ET (Blaney-Criddle alfalfa). See text for assumptions.

△ average actual ET under Los Alamos precipitation (Scenario 1). See text for assumptions.

⊡ average Los Alamos precipitation.

the case of bare or nearly-bare soil, actual ET values will be lower, and infilitration higher, than the figures given.

7. Evidence of Infiltration

The average relative humidity at Los Alamos is circa 40% (DOE, 1979). The soil moisture tension which will equilibrate with this humidity is more than 1000 bars (for pure water) (Hillel, 1980). The circa 4% wetness found in the tuff in some investigations (Abrahams, Weir, and Purtymun, date unknown) is, presumably, much greater than the wetness which would produce 1000 bars of tension. (Unfortunately, moisture tensions do not appear to have been measured in the field at LANL to date). This high wetness must either be a "fossil" wetness remaining from past climates (presumably > 1000 years ago; see section 1) or a quasi-equilbrium established in the present infiltration, percolation, and ET regime. Even the 1% wetness reported for tuff at depth (30-80 meters) at TA-49 (Abeele, Wheeler, and Burton, 1981) appears to result in a suction that is less than the wilting point (see the calculated moisture characteristic curve in this same publication).

One of the papers cited above (Abrahams, Weir, and Purtymun, date unknown) measured little infiltration below ten feet with most infiltration not sinking below a depth of six feet. Unfortunately, these results cannot be applied directly to TA-54 because: 1) the degree of welding in the tuff may not be the same; 2) the clayey layer which was so effective in preventing infiltration may not be continuous at the experimental site, let alone at TA-54, where soil cover is not continuous; and 3) disposal pits have no developed clay layer to impede infiltration. Note that if moisture tension is constant with depth, a net downward water flux is occurring, assuming the osmotic tension is constant with depth. Therefore the constant soil-moisture-with-depth curves shown in the above publications are consistent with the existence of net infiltration. Soil moisture tensions would have to increase roughly 3 bars every 100 ft to counteract the effect of gravity.

Measurements at a neutron probe hole in backfilled material in Area G (location unknown to us) showed a total of 9.44 inches of infiltration in 1978 and 1979, due at least in part to an extemely wet November in 1978. Prompt infiltration to 25 meters was also observed at Area C (Abeele, Wheeler, and Burton, 1981). It is unfortunate that LANL has not installed (to our knowledge) a set of comparable long-term soil moisture holes that would allow construction of a wetness spectrum from the "high"-infiltration areas at LANL's western boundary to the low-infiltration areas on its eastern boundary.

One detailed LANL report (Rogers, 1977) shows photographic evidence of wet patches alternating with dry patches in tuff following a large storm event. In addition, water was observed to issue into an open disposal pit from the soil/tuff interface during this storm event, and to run out from open joints into the pit. These processes will presumably occur with or without crushed tuff backfill and suggest that flow patterns in the tuff will focus in excavated (higher permeability) areas, as would be predicted theoretically.

GM:egr

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ATTACHMENT 2

Unsaturated Zone Characteristics

Introductory Remarks

The following six tasks are suggested by the Technical and Enforcement Section (TES) to be required of LANL by EID to support LANL's groundwater monitoring waivers under sections 206.C.1. and 206.D.1. of the New Mexico Hazardous Waste Management Regulations (HWMR-2). In each case, the methods to be used have been specified to as great a degree of detail as possible and prudent. It is possible that new information and better techniques may come to light during the course of LANL's multi-year compliance schedule. If this occurs, the methods below should be modified to embrace improvements in "the state of the art." LANL should be allowed, then, to suggest modifications to these methods for cause, and it will be up to EID to evaluate any proposed changes and to decide if they meet the requirements of the compliance order. Conversely, any changes suggested by EID once the order is delivered may be freely accepted or rejected by LANL.

LANL's submittals under these tasks should be in the form of coherent and publishable reports. Where ancillary work not specifically mentioned by EID would normally be needed to create such coherent reports, LANL must do this work. Examples of this are proper calibration of instruments, prevention of cross-hole contamination, the thoughtful use of elementary statistics to characterize data sets, etc.

Kent Bostick, Kevin Lambert, and Karl Souder provided valuable advice in the preparation of this attachment.

1. Determination of In Situ Permeability

Highlights

LANL must determine the in situ permeability of the tuff in at least 6 horizons in at least 5 holes (at least thirty tests in all); each hole must be 125' deep. Holes must be at or near Areas L and G. Acceptable field methods include packer tests with air, vacuum, or water, or constant-head infiltration tests. In order to interpret these tests, the permeability of unjointed tuff must be well-known. General theoretical predictions of anisotropy in k are required, based on properties of the fracture system, which properties must be discovered in these tests and from observations of pit walls.

Details

LANL needs to determine the saturated hydraulic conductivity K_s and the intrinsic permeability k of the tuff. These quantities are related by:

$$k = K_s \mu / \rho g$$

where μ is the dynamic viscosity of the permeating fluid at the relevant temperature,

ρ is the fluid density, and
g is the acceleration due to gravity.

The text that follows will primarily refer to the intrinsic permeability k, unless context dictates otherwise.

Permeability is important to know because:

a. In the minimum technological requirements of RCRA, liner materials are specified in terms of K_s (for example, see Section 202 of the 1984 RCRA amendments).

b. k must be used to analyze advective (i.e. non-diffusive) flow of gases in the tuff.

c. K_s provides a starting point for the determination of unsaturated conductivity $K(\theta)$ (where θ is the volumetric moisture content or "wetness" of the tuff) and is usually a necessary coefficient in the theoretical prediction of $K(\theta)$ (see Hillel, 1980, and Abeele, Wheeler, and Burton, 1981).

K_s for competent tuff alone (without joints) is best used for item c. above. Although this quantity has already been more or less determined, the samples used to determine K_s for unjointed tuff were taken from all over the laboratory property (rather than just from TA-54) and may not be representative of the tuff at TA-54, let alone representative of each of the several horizons at TA-54 (Abraham, 1963). Therefore, the EID requires that LANL supplement the Abrahams data on unjointed tuff permeability by conducting new laboratory experiments, unless data of comparable quality and applicability (to $K(\theta)$ and in situ K_s determination) is already available to LANL. These tests should be conducted on samples taken from the same locations and horizons as the samples used for the $K(\theta)$ determinations in item 3. below.

In analyzing the results of the in situ tests described below, the EID requires that the total k obtained be partitioned into the portion of k due to primary porosity (hereafter called "primary k") and the portion due to jointing (hereafter called "secondary k"). Unless the primary k is well-known the secondary k cannot be easily determined. The underlying assumption in this approach is that flow through the joints and flow into the host rock are independent phenomena whose quantities may be superimposed to yield the total flow. The larger the typical joint aperature, the more accurate this will be. While this assumption is, strictly speaking, false, the EID feels that it will provide the basis for a first-order analysis of the field tests, and this is all EID requires in the present context.

One way to obtain primary k from field data, or to check the field data against laboratory-determined primary k, involves analyzing the statistical properties of a large number of permeability tests. If the testing intervals in the holes are small, there will be at least some tests in which the measured k values are just equal to the primary k value, since no fractures will be encountered in some of the tests. In other words, the distribution of measured k values will have a definite lower bound for a given stratigraphic horizon, which is the primary k for that horizon. Once this primary k is determined (either by this method or known a priori by laboratory tests under similar pressures, which is the recommended approach), the secondary k values can be determined by subtraction.

The frequency distributions of total k and secondary k will be skewed, with a few tests exhibiting very high permeabilities. This will make it especially difficult to estimate means from small samples. In order to accurately and inexpensively estimate k from only five tests per horizon, the number, orientation if possible, and character of the joints active in each test must be known and used in the analysis of the data. One way this can be done is described in the following two paragraphs.

Snow (1968) relates joint aperature and spacing to permeability under linear-laminar flow conditions through a parallel set of identical planar joints in impermeable host rock:

$k = \frac{1}{2}Nb^3$, where N is the number of joints per unit distance normal to the joint planes and
b is the joint aperature.

For a cubic system of like fractures (i.e. three mutually orthogonal planar sets as described above), $k = 0.167Nb^3$, and is the same in all directions (i.e. is isotropic). Apparently Snow later generalized this theory to other joint geometries, and for N and b varying from one joint set to another (in a 1969 paper cited in Freeze and Cherry, 1979, p.75).

This theory, or one like it, modified as necessary to account for non-linear laminar and turbulent flow in any very wide aperatures encountered, can be used to theoretically predict secondary k for a given test, if the number, exposure, and aperature of the joints involved in this test are known. Once such a theoretical model for secondary k has been created and verifed using the test data, it may then be used to predict secondary k based on the statistical properties of the joint system as a whole, as determined from analyzing the joints present in all the holes and from existing or concurrent investigations of the joints exposed in pit walls. In this way the accuracy of the estimate of mean secondary k from a small, skewed sample can be improved by the addition of independently-obtained data on the joint system. These methods would not be necessary to determine either total k or secondary k if a larger number of tests were conducted.

One way to conduct these <u>in situ</u> permeability tests is with packers ("lugeon" tests) in which k is determined in each stratigraphic horizon of interest. A total of thirty or more of these tests must be done in at least five 125' deep holes in or near Areas L and G. These tests can and in most cases perhaps should be conducted with air or vacuum, monitoring at least temperature and pressure, and also monitoring flow and relative humidity if appropriate to the method used. If the tests are conducted with air (or vacuum), the holes used may also be used, in some cases, for the other studies described below. Water may of course also be used as the working fluid, in the case of holes which are not close to disposal units. If water is used the effect of entrapped air must be minimized by flooding the formation being tested with carbon dioxide prior to water infiltration, and by using cold water as the infiltrating fluid (Lambert, 1983). Vacuum packer tests (and packer tests using air, by reference) are described in Jakubick (1983,1984).

The values of k obtained by using water <u>versus</u> air may not agree exactly, due to:

1. Water occupying pore spaces in air permeability tests; this should not be a big problem at low wetness and can be corrected for;

2. Air occupying pore spaces in water permeability tests; this can be a big problem but can be minimized by the techniques specified in the previous paragraph;

3. Changes in the porous medium due to hydrolysis of clays, etc.; this should not be a big problem in tuff; and

4. Differences in the velocity distribution of gases vs. liquids in pore spaces, which gives rise to different flow equations or which shows up as apparent differences in k if the same equations are applied to the flow of liquids and gases (see the discussion of the Klinkenberg effect given in Weeks, 1978, and see also Freeze and Cherry, p. 74). This could be a problem in jointed tuff.

5. Inaccuracies in analytically modelling either the air flow (essentially a problem with a single, compressible, fluid phase) or the water flow (a problem involving two fluid phases, i.e. unsaturated flow) or both. Conventional analysis of borehole tests involving water has been shown to give inaccurate results unless unsaturated flow is taken into account (Stephens and Neuman, 1980). Saturated/unsaturated flow analysis for a borehole in a fractured porous system presents a problem which LANL must somehow address in at least a general way if water is used.

These theoretical differences--particularly 2., 4., and 5.--along with many practical considerations, will require LANL to consider carefully whether to use air or water as the permeating fluid in its tests. Ideally, both air and water should be used, with parallel analysis of results and with discussion and reconciliation of the differences encountered with the two fluids. EID does not require this. EID does require LANL to make predictions of permeability to gases if water is used in the tests, and vice versa, since waste mobility involves both liquid and vapor phases.

Permeability will be anisotropic in the field, since jointing in the tuff is strongly anisotropic. General theoretical predictions of the permeability tensor, based on the simple theory of Snow cited above, are required. Note that in Abrahams' data, any primary k anisotropy present is lost in the scatter of the data; LANL may want to double-check this result, although this is not required. A recent review of fracture permeability in general, including the analysis of anisotropy, is that of Gale (1982).

Packer tests are best performed in holes perpendicular to the joint set(s), but vertical holes may be used if the joints encountered in each hole are logged, as noted above, by down-hole and core-analysis methods. Vertical holes will primarily measure horizontal k. If it is practical, optional horizontal holes may be drilled into the side walls of open pits and infiltration or vacuum tests run. These tests will sample a k averaged from vertical k and a component of horizontal k, and would be a valuable adjunct to the data from vertical holes. Inclined holes are another optional possibility.

The pressures to be used in these tests will influence the results obtained, and tests must be run in each horizon of each hole with a pressure or suite of pressures determined after consulting the literature on the subject. The EID does not require sensitivity analysis of the effect of injection pressure on k, although LANL may wish to conduct such analyses. There is some evidence that higher pressures and higher inflow rates will decrease the importance of unsaturated flow (Dan Stephens, pers.

comm.) if water is used, although the pressures selected (using either air or water) must not be large enough to open the formation. The EID has already provided LANL with a bibliography on packer tests obtained from Dr. Priscilla Nelson of the University of Texas.

Because the pressure losses at the packers may be difficult to quantify, LANL may wish to utilize a double packer system. Another possible approach to leakage is to monitor it with downhole pressure transducers outside the packer(s) (Dan Stephens, pers. comm.). There will be differences in the sensitivity of test results to leakage, depending on the type of test performed (e.g. flow vs. pressure transient tests), and LANL should keep this in mind when designing its tests. Apparently the problem of packer leakage is one that is routinely surmounted in current packer test technology.

If holes and tubing are cheap relative to expertise with packers, another method for determining k is to grout off selected horizons in holes, with access tubes in place, and then run what would be essentially packer tests, but without packers. Another method to determine k is to install air pressure sampling ports at selected horizons in the tuff and monitor the response of the tuff to atmospheric barometric changes (Weeks, 1978). This method normally measures only the vertical permeability, but in the case of the exposed sides of Mesita del Buey, horizontal permeability may also be measured to some extent, particularly in holes near the mesa sides. The analysis developed by Weeks applies only to systems with a lower boundary impervious to air, although an assumption of an infinite downward extent in homogeneous material was apparently used by others (see Weeks) to develop analytic solutions to the flow equation in the nuclear chimneys of the Nevada Test Site. The experimental set-up needed to conduct both these tests is identical to an optional pore-gas sampling apparatus described under item 5. below.

Every precaution must be taken that the walls of these holes are not in any way sealed by the drilling process or by any subsequent process prior to permeability testing. If water is used as an infiltrating fluid, it must meet State drinking water standards. When the above tests are completed, these holes must be completely grouted to the surface with cement grout unless they are being actively used in subsequent LANL surveillance. The same is true for any other holes EID requires LANL to drill under this enforcement action.

At our February 13, 1985, meeting with LANL personnel, LANL implicitly agreed in principal that k should be determined <u>in situ</u>, and suggested that constant- or falling-head permeability tests be conducted with water in open boreholes, at various depths. EID agreed that constant-head (but not falling-head) tests are acceptable, subject to all the cautions and requirements applicable to water-based packers tests mentioned above.

At our February 13, 1985 meeting, EID and LANL representatives agreed that measurement of k (along with the vapor diffusivity coefficient, moisture characteristic curves, K(θ), flux, and seepage velocities) for crushed tuff backfill were not important for the 206.C.1. and 206.D.1. groundwater monitoring waivers. Most of this information is appropriate, not for these waivers, but for the informed evaluation of closure plans and for waivers from the minimum technology standards of RCRA. The italicized text below reflects EID's earlier thinking on the subject of k in crushed tuff, and may be useful for these other purposes. More detailed comments on the subject of minimum technology waivers can be found in the concluding section below.

While permeability measurements of crushed tuff backfill in pits have been conducted in the laboratory, the experience of other researchers (Daniels, 1984) indicates that variations in compactive effort of only 10% may lead to 10^2 or even 10^3 ratios in k, and correspondingly wide disparities between laboratory and field permeabilities. Accordingly, LANL needs to conduct in situ permeability tests on crushed tuff backfill, exactly as it is normally employed and compacted in pits and shafts. At least two replicate experiments should be conducted in each of the following settings:

i) Crushed tuff emplaced as per current specifications for pits;
ii) Crushed tuff emplaced as per any previous specifications at Area G, unless this can be predicted by 3.
iii) Tuff compacted to 80% of the effort or density (whichever is relevant) of the specification in 1.
iv) Crushed tuff emplaced as it is emplaced in shafts, if this cannot be shown to lie within the range of compaction defined by 1 and 3.

LANL may propose any of the standard field methods (see Black, et.al., 1965 and Hillel, 1980 for examples) to conduct these experiments.

This concludes Task 1.

The following task, originally No. 2 in EID's list, is shown in italicized text. It was dropped by EID prior to the March 1 EID/LANL meeting for the reasons given below. The text is retained here for background.

Determination of Vapor Phase Diffusivity

The modelling of vapor phase water transport, or of vapor phase solvent transport, for the tuff system cannot proceed without a determination of the vapor phase diffusivity. Both water and solvent diffusion processes are driven by differences in partial pressures of the species involved. In the case of water, differences in tuff wetness alone will probably not induce significant vapor-phase water fluxes, because extremely large differences in tuff wetness equilibrate with nearly equal partial pressures of water in the pore air. Partial pressures of water in the pore air are very sensitive to temperature, on the other hand, and temperature gradient fluctuations in the tuff are capable of "pumping" water vapor up or down to an as-yet-unknown degree.

Diffusion of water due to thermal gradients (and to some extent the diffusion of other gases also, apparently) proceeds at a faster rate in damp porous media than would be expected on the basis of Fick's Law, after correction for porosity and path length. A review of this phenomenon is given in Cass et. al. (1984), and this diffusion "enhancement," as it is called, must be incorporated in LANL's estimate of the basic diffusivity coefficient.

Diffusion coefficients may be determined in the laboratory (see references in Hillel, 1980), in the field (Raney, 1950, cited in Hillel, or Lai, 1976), or from theory (see Cass et. al., 1984 for an update of Hillel's 1980 review). If the statistical properties of the joint system are known, diffusivities calculated from any of these methods can be theoretically resolved to give diffusivity estimates for each principal coordinate direction.

Unless the temperature and moisture content field in the tuff and its variation through time are known in a detailed way, however, these vapor-phase diffusivities cannot be applied to analysis of recharge-discharge relationships in the tuff. In addition, many of the contaminants of concern at LANL cannot be transported by vapor-phase processes. Finally, researchers at the Hanford

Reservation suggested that temperature-induced vapor phase flow is negligibly small compared to unsaturated liquid flow in the upper ten feet of the vadose zone there (Gee and Simmons, 1979). For these three reasons, the EID has dropped its requirement that LANL determine vapor-phase diffusivity.

2. Determination of Moisture Characteristic Curves

Moisture characteristic curves relate matric potential to volumetric moisture content ("wetness" hereafter). These curves are hysteretic; i.e. they depend on the history of the matrix, although Jones et. al. (1982) state that the effects of hysteresis are negligible for many materials below potentials of about -1 bar. These curves can be used to theoretically predict: 1) unsaturated hydraulic conductivity as a function of wetness; 2) the vapor diffusion coefficient for a given permeant; 3) effective porosity as a function of wetness; and therefore 4) seepage velocities under known potential differences. These curves are also necessary to interpret the field monitoring data developed in item 5. below.

Experimental determination of moisture characteristic curves must be conducted for at least 20 samples over a moisture range that embraces all the conditions found at TA-54 (i.e. saturation to circa 3% volumetric wetness) for at least four horizons of undisturbed tuff. These samples must be from depths extending to at least 100' and from at least five sites in or near Areas L and G. Any of the standard laboratory methods (e.g. those described in Hillel, 1980) may be used; more than one method will probably be needed to include the entire moisture range needed (as in Gee and Simmons, 1979). Only drying curves need be determined.

3. Determination of Unsaturated Hydraulic Conductivity and Seepage Velocities

Highlights

A sufficient number of laboratory and theoretical methods must be integrated to give trustworthy predictions of $K(\theta)$ for at least four horizons, representing depths to at least 100'. These samples, at least 20 in number, must be from the same locations as those for Task 2.

Details

Unsaturated hydraulic conductivity $K(\theta)$ (or $K(\psi)$, where ψ is matric potential) needs to be known, within a reasonable uncertainty, for each horizon of undisturbed tuff. $K(\theta)$ is needed to predict water fluxes and seepage velocities in analytical and numerical unsaturated flow models, and is needed to interpret the results of the monitoring required in Task 5. below.

Laboratory methods will be the primary means of determining $K(\theta)$, although the EID requires LANL to also make theoretical predictions of $K(\theta)$ based on moisture characteristic curves and to reconcile these with experiment. A sufficient number of approaches to $K(\theta)$ must be taken by LANL to give trustworthy predictions. At least twenty samples, taken from the same locations and horizons as in 2., must be used in these tests. Only drying curves need be run.

The table below summarizes EID's references on $K(\theta)$ determination. This table does not pretend to be summary of recent research titles on this subject but will be useful as an entry into the abundant literature.

Methods to Determine Unsaturated Hydraulic Conductivity

1. General overviews
   Klute, 1972
   Hillel, 1980
   Wilson, 1982

2. Theoretical methods not cited in Hillel
   Elzeftawy and Mansell, 1975
   van Genuchten, 1980
   Campbell, 1974
   Mualem and Dagan, 1978
   Bresler, Russo, and Miller, 1978

3. Laboratory methods not cited in Hillel
   Alemi, Nielsen, and Biggar, 1976
   Dirksen, 1979
   Perroux, Raats, and Smiles, 1982
   Ehlers, 1976
   Mualem and Klute, 1984
   Daniel, 1982
   Scotter and Clothier, 1983

4. Field methods not cited in Hillel[1]
   Libardi, et. al., 1980
   Dane and Hruska, 1983
   Jones and Gee, 1984

5. Previous work at LANL (on crushed tuff)[2]
   Abeele, Wheeler, and Burton, 1981
   Daniel, 1982

Notes
1. EID does not require field methods for K(Θ) determination because they do not appear, at first glance, to be practical for application at depth in solid tuff.
2. EID does not require K(Θ) determination for crushed tuff in the present context of groundwater monitoring waivers; this information is for reference only.

As laboratory data are being integrated with theoretical predictions, estimates of the effective porosity at each Θ must be made, and representative seepage velocities under the range of observed conditions calculated. These seepage velocities may be confirmed by tracer experiments if LANL chooses (for an example of this kind of work see Lewis and Stephens, 1985). EID does not require tracer experiments to meet the 206.C.1. or 206.D.1. waiver standards.

4. Analysis of Infiltration and Redistribution in the Tuff

Highlights

One 100' neutron access hole, one 40' matric potential nest, and one 100' matric potential nest must be present at each of two sites, one at Area L and one between filled pits at Area G. Using whatever tools are necessary, LANL must determine the

vertical flux, the water potential, and the moisture content as functions of depth and time at these sites.

Details

In order to accomplish these objectives--which to a large extent integrate all the previous tasks-- these two sites should be instrumented with capabilities to monitor matric potential, moisture content, and (optionally) salinity and temperature, with depth and time. If salinity and/or temperature monitoring are needed for the matric potential sensors LANL chooses, LANL must monitor for the needed quantity(ies) also.

EID anticipates that LANL will use neutron access holes to monitor changes in tuff wetness. If so, the effects of casing materials, uneven hole diameter, and non-water neutron-moderating and neutron-capturing substances in the tuff (e.g., lithium) need to be taken into account. It is EID's understanding that LANL has developed techniques that control or correct for the first two of these effects, and these techniques must be implemented and documented in LANL submittals.

Review of the literature (Griswold and Daniels, 1984; Morrison, 1983; Wilson's 1980, 1981, 1982, and 1983 papers; and Jones et. al. 1982) and conversations with individuals experienced in vadose zone monitoring (both within and outside of EID) suggests that soil moisture blocks and tensiometers, perhaps along with thermocouple psychrometers and heat dissipation sensors, are practical matric potential sensors in the TA-54 environment. The matric potential sensors should be arranged in a vertical nest next to the neutron access holes, but outside the measurement sphere of the neutron probe. The EID does not require that LANL install any particular type of matric potential sensor. LANL must select the best available methods to determine the water potential, the moisture content, and the vertical water flux as functions of depth and time.

Each of the two sites must have one 40' deep and one 100' deep matric potential nest, along with one 100' deep neutron logging hole. Neutron logs and matric potential measurements must be taken at least fortnightly during the period from October 1 to April 30, and at least monthly during the balance of the year. In addition to this schedule, daily logging must be done after two major autumn storms for a period of one week after each storm. LANL must use its best judgement as to what storms to consider "major;" this will depend primarily on the size of the storm and the antecedent soil moisture conditions.

Matric potential measurement horizons shall include the following:

In the 40' deep holes: at 1', 2', 3', 5', 7', 10', 15', 20', 30', and 40' deep.
In the 100' deep holes: at 2', 5', 10', 15', 35', 50', 65', 80', and 100' deep.

Neutron logs shall be taken at 2', 3', 4', 5', 6', 7', 10', and subsequently at 5' intervals to the bottom of the 100' neutron logging hole.

Jones et. al. (1982), after a careful review of the instrumentation available to measure matric potential, concluded that only tensiometers provided sufficient accuracy to determine water fluxes. The theoretical moisture content curve for solid tuff presented by Abeele, Wheeler, and Burton (1981) suggests that the lower limit for successful tensiometry will occur at about 10% moisture content by volume in the tuff. The key to successful tensiometry at low water potentials seems to be

the maintenance of an intimate link between the tensiometer cup and the surrounding matrix, and this can apparently be accomplished by installation of the tensiometer in a slurry of silt-sized material. Accordingly, the EID is biased toward a monitoring scheme involving tensiometers installed at the following depths:

In the two 40' holes: at 1', 2', 3', 5', 7', and, unless shown to be impractical, 10'
In the two 100' holes: at 2', 5', and, unless shown to be impractical, 10'.

At these depths and at all the other depths, a secondary type of matric potential sensor should also be installed. The selection, calibration, installation, maintenance, and use of, as well as analysis of data from, all these instruments shall be done in a careful way to ensure that the overall goals of this task are met. Redundancy of sensors may be necessary to achieve useful results, and LANL should determine the precision, accuracy, and reliability of the sensors during the calibration phase to determine the degree of redundancy, if any, required. Whether tensiometers are or are not used at the depths shown above, LANL needs to be sure that its instrumentation is adequate in every way to meet the goals of this section.

An apparatus like that described above can in theory be used to determine $K(\theta)$ in situ, at least relatively near the surface at possibly at depth as well, by controlled drainage experiments (see Hillel, 1980, p. 213). These experiments have been done by saturating a portion of the instrumented column (plus a wide buffer area) with water and then covering the surface and measuring redistribution of the added moisture in the column. Application of this method to deep holes in Bandelier Tuff is probably unwieldy or impossible, but LANL may supplement its laboratory and theoretical $K(\theta)$ determinations in this way or by any other in situ method if it chooses to do so.

LANL may feel that its past and present network of neutron moisture-logging holes is sufficient to track the redistribution of meteoric water. While these studies are useful they fail to provide a picture of the distribution of moisture potential, since moisture potential is a very sensitive (and hysteretic) function of tuff moisture content. It is soil moisture potential, not moisture content, that determines flow direction. Workers at Hanford have questioned the isolated use of neutron data to determine water fluxes in a semiarid environment (Enfield, Hsieh, and Warrick, 1973).

The description of this task differs quantitatively from that previously discussed with LANL representatives by the deletion of two neutron access holes and the suggested addition of nine matric potential sensors, specifically tensiometers. The Technical and Enforcement Section feels that this change will significantly improve the data obtained.

The present requirements involve three fewer sites than the TES's original recommendations. While it would be of interest to monitor infiltration and redistribution in backfilled pits, the EID no longer requires this monitoring in the present context. A third site (in Pajarito Canyon) was originally requested by EID, but this requirement has been provisionally dropped pending the submittal of work on moisture redistribution in Mortandad Canyon (see item 5. below). A fourth site originally requested by EID but subsequently dropped was at TA-59 or TA-3, where the robustness of the TA-54 findings could be examined in a slightly wetter climatic regime.

Note that the required work stops short of providing the data base needed for the verification of a complete model for unsaturated flow at LANL's disposal areas. LANL may wish to supplement the required program in order to accomplish this (optional) objective; the principal missing data could be generated by repeating the work described above in crushed tuff backfill.

5. Investigate the Movement of Hazardous Constituents

A total of at least 6 core holes should be drilled in Areas L and G (at least 4 in Area L and at least 2 in Area G). The Area L holes should be located as follows:

1. one outside the fenced area to the west of Area L, to serve as a background hole (80' deep);
2. one as close as possible to Pit B, and between Pit B and Pit C if possible (40' deep or 20' past the last detected contamination, whichever is greater);
3. one as close as possible to Shaft 17 (100' deep or 20' past the last detected contamination, whichever is greater);
4. one as close as possible to Shaft 4 (100' deep or 20' past the last detected contamination, whichever is greater).

The Area G holes should be located near areas of liquid waste disposal. If no such areas exist at Area G, two additional holes must be drilled at Area L at EID-chosen locations.

Core samples from these holes must be quantitatively analyzed at ten foot intervals for the following parameters:

1. Anthropogenic As, Ba, Cd, Cr, Pb, Hg, Se, Ag, Li, Cu, NO_3^-, NH_4, and F.
2. Volatile organics, by gas chromatographic methods (if volatiles are detected in a given sample they must be identified)
3. Any other hazardous wastes, hazardous waste constituents, or characteristics of hazardous waste which LANL feels could conceivably be present in the cores, based on past disposal records.

Inorganic parameters must be added, or may be dropped, to this list in the case of Hole 2. above depending on their presence (in at least one) or absence (from all) of the surficial samples from Pit B now being analyzed by LANL. Proposed sample workup and analysis techniques must be provided to EID, and approved by EID, prior to further sampling under this task.

These holes must be equipped with a permanent pore gas collection system, capable of repeatedly sampling pore gas from the bottom of each hole. Pore gas should be analyzed for volatile organic constituents with gas chromatographic screening and, if necessary, mass spectrometry, on a quarterly basis. An (optional) improvement to this set-up is to monitor pore gas from selected horizons in the tuff.

6. Investigate the Distribution, Quality, and Fate of Perched Water in Side Canyons

The system of six observation wells proposed in LANL's November 1 submittal, along with a detailed summary of the on-going research and data gathered on moisture redistribution in Mortandad Canyon, should adequately describe the perched water in the side canyons. The observation wells should be screened for their entire length (except for the top five feet) and can either be constructed as described in LANL's submittals or with manufactured perforated casing. There is a chance that

the Mortandad Canyon work will be inapplicable to the situation in Pajarito Canyon, in which case EID may specify further work under this task.

These six wells must be sampled, and water level measurements taken, quarterly. Analysis must be done for the suite of constituents listed for analysis under Task 5. above.

Concluding Remarks

It cannot be emphasized enough that the tasks above, while serving to clarify LANL's position vis-a-vis the 206.C.1. and 206.D.1. groundwater monitoring waivers, are by no means the "last word" on the hydrogeology of LANL hazardous wastes. Even when this work is done, many serious unanswered questions will remain. Some--though not all--of these questions can and should be addressed under closure and post-closure plan review, minimum technology standards, and the review of "on-going" releases now required as part of the permitting process.

Unfortunately, the most serious hazards at LANL (described in a previous memo) are specifically exempted from RCRA/HWMR-2 regulation, which is currently the only active regulation at the LANL landfills. It remains a valid approach for EID to regulate these "unregulatable" wastes by regulating the RCRA wastes interred along with them, to the extent this is possible. The hydrogeological issues related to the management of these unregulated wastes have been largely unaddressed in the above six tasks; they can be addressed to at least a small extent in the following three items on EID's regulatory agenda. Needless to say, hydrologeological issues are not the only ones of interest, but they are the only ones discussed here, and are themselves discussed in a cursory manner.

Closure and Post-Closure Plan Review

To begin with, EID's Oct. 26, 1984 letter to LANL outlined certain elements that would be necessary as part of an approvable closure plan. Many of those elements dealt with hydrogeological issues, and many of them have not been addressed in LANL submittals.

The 206.D.2. and 206.D.10.f. standards give EID both very broad, as well as certain very specific, mandates. In our Oct. 1984 letter to LANL, we asserted that our mandate might extend to protecting the public and the environment from any and all biohazards at closed hazardous waste landfills. The TES suggests that this theory be submitted to the Legal Bureau for critique, with a query as to other legal authority EID may have to regulate non-RCRA hazards at a closing RCRA site. Without legal review, EID will not know the appropriate hydrogeological questions to ask.

A review of the standards at 206.D.f.(1)(e) and f.(1)(a) suggests that LANL must, to meet these requirements, perform the deleted tasks above for crushed tuff backfill (including saturated and unsaturated permeability determinations, moisture characteristic curves, and infiltration studies). LANL apparently has already done some of this work (though they never told us; see the new work of Abeele and others cited in Lane and Nyhan, 1984). In addition, LANL should also conduct other experiments of the following general types:

--tracer studies in the lab and in situ
--age dating, if possible, of the water in the tuff

--sorption studies in crushed tuff and in solid tuff

and should be required to institute trench-specific monitoring systems. A comprehensive hydrological model of the mesa should be constructed and verified; much of LANL's work has been directed toward this end already. This model, or an equivilently-achieved analytic approach, should be used as an aid in evaluating proposed cover designs.

Further discussion of the hydrogeological elements of a good closure plan at this combination chemical/low-level radiological/ transuranic waste landfill must wait until another day.

Minimum Technology Standards

A complex set of standards applies to LANL operations, stemming from the old HWMR-2 and its interdigitation with the new RCRA amendments. An example is the 206.D.10.b.(2) waiver standard, which gives to the EID a very strong regulatory mandate for essentially any hydrogeological studies it feels are necessary to establish the complete chemical safety, in perpetuity, of LANL's new landfill units. Since the studies suggested in the six tasks above are not adequate to meet this standard, EID should use this opportunity--should LANL request this waiver--to press for the safeguards that are needed. Other standards can be found in the new amendments; not all of them are located under the tile of "Minimum Technology Standards." An informal memo enumerating these was given to Tony D. in late 1984.

"On-going" Releases

Most of the past disposal areas at LANL are of radiological, rather than chemical, interest. But there are exceptions, and EID can assert its jurisdiction over some of these areas based on statements in official LANL reports that hazardous waste was disposed of at such-and-such a place. More revealing would be to interview or to depose individuals connected (past or present) with the Lab's ongoing researches into its past waste-disposal areas. Some of these areas may be of serious environmental significance.

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SUMMARY OF TASKS AT LOS ALAMOS NATIONAL LABORATORY: CONTINUED

Parameter/Task	Acceptable Method(s)	Frequency/No. of Samples	Location(s)	Reporting Date	Importance
4. infiltration and redistribution of meteoric water into tuff	both tuff moisture content and matric potential must be measured by neutron logging and either moisture blocks and/or psychrometry	at least 4 holes; two 50' deep and two 100' deep; biweekly neutron logging with daily logs after two autumn storms; 10 potential sensors per hole	Two at Area L and two at Area G.	equipment in place and functioning by 3/86	--gives potential gradients in tuff --allows integration of 2. and 3. into overall picture --gives actual infiltration rates and water fluxes
5. core and pore gas analysis	standard methods of soil science for inorganics to be done on cores; GC or GC/MS for VOs both on cores and on gas samples collected in field.	at least 6 holes of varying depths; cores analyzed for inorganic contaminants and VO scan at 10' intervals; pore gas samplers in bottoms of holes (at least 1 per hole); analyze quarterly	4 at Area L out of the 6 previously discussed; 2 at Area G	core analysis by 7/85; pore gas results by 9/85, 12/85, etc.	--direct measurement of movement of wastes in tuff --surveillance prior to closure of impoundment at Area L
6. analysis of perched water	observation wells in side canyons and report summarizing applicability of research in Mortandad Canyon	6 wells bottoming in tuff screened throughout max. saturated thickness; samples and water levels quarterly;	Three in Canada del Buey and three in Pajarito Canyon	Analysis by 7/85, 10/85 etc.	--monitoring of hazardous constituents in perched water --helps quantify thickness, seasonal extent, and fate of perched water in side canyons