Atlantic Richfield Hanford Company
Richland, Washington 99352

ARH-1888

**SOIL MOISTURE STUDIES BASED
ON WELLS AT 32-49 COORDINATES**

By

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January 12, 1971

**PREPARED FOR THE U.S. ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION UNDER CONTRACT E (45-1) 2130**

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54-6000-085 (8-75)

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INTRODUCTION

Additional attention must be given soon to the plans for the long-term management of radioactive wastes. This problem becomes increasingly important with the growth of the nuclear power industry. The National Academy of Science - National Research Council Committee on Geologic Aspects of Radioactive Waste Disposal has noticed this and has commented:

"In view of the clear prospect for ever-growing production of atomic energy and therefore the probability of increasing output of radioactive wastes, the Committee believes that safe disposal procedures should be established now rather than at later stages of power development."

In considering the problem, the Committee stated further:

"In the last analysis, it is the property of mobility of hazardous radionuclides in any fluid medium that baffles all who are concerned with safety of disposals."

Two of a number of unusual geological features of the Hanford site are of great significance in providing possible solutions to this problem. One of these important features is the low soil moisture on the arid Hanford site that is believed to limit water movement in the Hanford soils to vapor transport from the water table to the surface. The other important feature is the huge reservoir of basic silicates, in the form of basalt, that extends to a depth

of more than 10,000 feet below the surface. Either or both of these two features provide a means of perpetual containment of radioactive waste, in one case above and in the other case below the water table.

All methods considered feasible for long-term storage of radioactive wastes are based on the concept of preventing radioactive material from dispersal in natural water supplies, i.e., groundwater, water courses and the oceans. This is true because if such dispersal should occur at any point, the process is in practice irreversible and it is, for practical purposes, impossible to regain control of the radioactive substances dissolved or suspended in the water. Because of the basic criterion of maintaining a separation between radioactive wastes and natural water supplies, Erichsen proposes that radioactive materials be stored in arid areas.⁽¹⁾

If this concept is correct, one question that follows is how arid must the climate be for storage of radionuclides? One criterion is that the climate should be sufficiently arid to prevent percolation of water from the surface of the ground to the water table so as to avoid any possible leaching of radioactive materials from the vadose zone above the water table.

In climates that have significant annual rainfall, hydrologists observe a percolation of water from the surface to the water table below. But in arid areas with

(1) L. Von Erichsen, "Storage of Radioactive Waste in Arid Areas", Atomkernenergie, 4, 112-115, 1959.

water tables deep below the surface and in the absence of the use of irrigation water, there must be a limiting value for annual rainfall below which water does not percolate to the water table. In such areas with rainfall below this limit (particularly in deserts), the small rainfall normally is seasonal and usually occurs during the cooler part of the year. This precipitation falls upon a soil that has been desiccated for several feet during the previous summer. Below the limiting value of rainfall, the annual precipitation moves downward slowly because of the low effective permeability of dry soil. As a result, the rainfall penetrates only a few feet and then is drawn back upward by capillarity as well as vapor transport as the heat of the following summer again desiccates the soil. Also during the autumn and early winter, the sinusoidal temperature changes in the soil act as a thermal pump which moves water upward toward the surface.

A limited study has been started to measure the soil-moisture relationships at the Hanford site. Some of the tests have been conducted or are in progress using soil samples from a site located at the 32-49 Hanford Coordinates. These are discussed briefly in the following section.

A. Original Studies on Well 32-49 A

The coordinates 32-49 give the location of four wells, A, B, C, and D southeast of the 200 East Area and within about 50 feet of each other (see Figure 1) that are being used in the study of soil-moisture relationships. Well 32-49 A was Number 2 in a series of 12 wells drilled in the sandy plateau southeast of the

200 East Area in June 1969. This well was not drilled to the water table but only to 250 foot depth where coarse gravel and cobble stones were encountered. The neutron well log, shown in Figure 2, indicates this well to be one with a low and quite uniform moisture content of about 1.5 to 2.0 weight percent water. Table 1 gives gravimetric moisture content of field sample and moisture tension values as a function of moisture contents. Field moisture contents listed in Table 1 in the range of 1.0 to 1.4 weight percent are suspected of being incorrect and low because of some improper closure of the containers at the time of sampling. For this reason it was necessary to calibrate the neutron well log and check moisture content values. Figure 3 shows the calibration curve for neutron log values. There is some scatter of data in Figure 3 because no correction was possible for porosity to permit relating volume percent to weight percent water.

Figure 4 was plotted making the best interpretation possible of the data in Table 1 and Figures 2 and 3. A trend with percent silt (obtained from Table 2) is indicated by the arcing of values as shown in Figure 4. This is quite apparent at depths from 95 to 135 feet. Arcing shown in Figure 4 at this depth indicates that a single stratified zone may exist between 95 to 120 foot depths. As shown in Figure 4, the greatest negative potential of -29 bars occurs in this zone at 90 foot depth in soil with a silt plus clay content of 12.1 percent. The potential rises (approaches zero) continuously and the silt content drops continuously as the depth increases to 120 feet. Here the negative

water potential has risen to -12 bars and the content of silt and clay has dropped to 3.4 percent. Sharp layering apparently occurs in the next 15 feet of depth. At 125 foot depth the percent silt has risen to 6.6 percent and the water potential has dropped to -31 bars. But at 130 foot depth, only 5 feet below, the silt has dropped to 1.9 percent and the water potential has risen to -6 bars. Five feet further down at 135 foot depth the silt and clay content jump back to 11.3 percent and the water potential moves to -35 bars. Thus the influence of particle size (expressed by percent silt plus clay) on water potential as determined in the laboratory, is quite obvious. However, this influence is believed to disappear to a large extent with in situ measurements. The reason for the disappearance is considered to be the influence of overburden.

The samples tested for water potential in the laboratory are not exposed to the overburden pressure that exists on an in situ sample tested say at 90 feet. The weight of the overburden present in situ measurements tends to collapse some of the pores in the soil. This influence is greater for the silt and clay which have more fine pores than sand and gravel and which are more easily compressed. If the water potential measurements were made in situ, the force of the overburden weight would close some of the smaller capillaries raising the water potential. This influence would move the points in Figure 4 to the left with the greater influence on the layers with the greater percent of silt. This will tend to diminish or remove the arcing of values associated with laboratory measurements. All values will

TABLE 1
MOISTURE CONTENT - MOISTURE TENSION RELATIONSHIP
FOR
WELL 2A (32-49 A)

Mean Depth (ft)	Field Moisture Content (%)	Moisture Content		
		15 Atm	1.5 Atm	0.33 Atm
5	2.6	2.0	2.7	3.4
10	2.3	2.9	3.6	4.3
15	3.1	3.4	3.9	4.2
20	3.0	3.8	5.5	8.3
25	2.7	4.4	5.6	8.0
30	2.0	3.2	3.8	5.1
35	1.0	1.8	3.3	5.6
40	1.0	1.5	3.1	3.2
45	1.0	1.4	3.4	5.6
50	1.7	2.4	4.1	7.3
55	1.0	1.6	3.1	5.3
60	2.0	2.4	5.0	9.0
65	1.4	1.7	3.8	6.4
70	1.3	1.5	2.9	5.1
75	1.8	2.3	5.2	10.4
80	1.2	1.7	2.7	4.3
85	1.4	2.0	4.2	8.0
90	1.1	1.4	2.3	3.6
95	1.0	2.2	4.4	8.1
100	1.8	2.2	3.6	4.9
105	1.4	1.7	3.0	6.6
110	1.8	1.6	2.6	4.1
115	2.8	2.6	4.4	8.3
120	1.3	1.8	2.5	4.0
125	1.1	1.4	2.6	4.7
130	1.3	1.3	2.8	3.0
135	1.2	1.6	3.7	4.3
140	1.3	1.9	3.9	6.5
145	1.1	1.5	2.9	5.0
150	1.0	1.3	2.1	3.7
155	1.7	1.2	3.4	6.4
160	1.3	1.7	4.5	6.0
165	1.2	1.4	2.5	4.5
170	1.3	2.9	3.3	3.7
175	2.0	2.5	3.3	6.2
180	1.4	1.8	3.7	6.1
185	1.4	1.8	3.7	6.1
190	1.5	2.0	2.7	3.9
195	2.1	1.8	2.8	5.0
200	1.3	1.6	2.6	4.3
205	2.2	1.7	4.6	8.6
210	3.2	3.0	7.3	11.2
215	2.0	2.4	4.9	8.5
220	4.3	5.9	5.6	8.3
225	2.0	2.4	4.3	6.3
230	2.3	2.4	3.8	5.8
235	2.9	3.2	7.5	14.0
240	1.6	1.8	2.6	3.7
245	1.7	1.8	3.0	3.9
250	2.1	2.2	3.7	5.9

move to the left toward zero water potential. The values on the dashed line of Figure 4 marked "Lower Limit" represent the coarser sandy layers and would be expected to shift the least. Table 2 also lists the pH of soil paste at various depths and shows the alkaline nature of the soil with pH values from 8.00 to 9.00.

B. Tritium Assays of Soil Samples from
Wells at 32-49 Coordinates

The initial measurements on soil samples from well Number 2A (32-49 A) indicated that the underground soil at this site is slightly stratified and is a silty sand to a depth of about 250 feet with a low moisture content in the range of about 2 weight percent. This site was selected for further study of soil moisture relationships and a second well Number 32-49 B was sunk at this site in October 1969. Figure 1 shows the location of wells 2A, 2B, 2C, and 2D located at the coordinates 32-49. Well Number 2A (32-49 A) was the original well located 37 feet from the center line of the dirt road running north-northeast to the paved east-west road running past the 200 East Area.

At the drilling of well Number 2B (32-49 B) samples of soil were collected for tritium assay. The results of this assay are listed in Table 3 with the results of an assay of soil from a well at another location, 19-47 B, and results from a well drilled in June 1970 at the 32-49 coordinate location and identified as well Number 2D (32-49 D). Except for the single inconsistency in the assay of the sample for a depth of 175 feet (see footnote Number 1) the data for well

Number 19-47 B (well Number 12 B) may be considered to be a classic example of tritium distribution vertically in virgin areas of the vadose zone of Hanford soils. A plot of these data for the top 90 feet of depth is shown in Figure 5.

The surface value of 1490 ± 50 tritium units (T.U.) for well 19-47 B is influenced by the tritium concentration in the last atmospheric precipitation. This value varies both seasonally and with the altitude at which the precipitation forms and varies from a few hundred T.U. for low altitude showers to several thousand T.U. for some precipitations from the upper altitudes. Figure 5 shows that the tritium concentration decreases logarithmically from the surface to a depth of 15 feet where it has dropped to a value of 17.1 ± 0.9 T.U. If the single exception for the value for the sample from 175 foot depth is excluded, the tritium concentration from a 20 foot depth to the water table including values for both depth limits is shown in Table 4 to be less than 10 T.U. for all measurements and 5.5 T.U. or less for two thirds of the measurements in this zone. These low values are in the range of values associated with archaic water and water isolated from atmospheric contamination for the past 25 or more years; predating atmospheric testing of nuclear weapons.

The tritium assay values for samples from well 32-49 B in general parallel those from well 19-47 B except for a lower tritium assay value at the surface of 236 ± 12 T.U. and for higher values at or near the water table in the range of 20 T.U. The lower value at the surface can be attributed to a lower tritium concentration in the last precipitation prior to sampling.

PARTICLE SIZE ANALYSIS AND pH OF SOIL PASTE
AND 0.01m CaCl₂ FOR WELL NUMBER 2A (32-49 A)

Mean Depth (ft)	Sand (50) (%)	Silt (2-50) (%)	Clay (2.0) (%)	Depth -Feet-	In Paste -Units- ^{pH}	In 0.01 CaCl ₂ -Units-
5	98.5	1.5	0.0	5	8.60	7.85
10	100	0	0.0	10	8.85	8.00
15	94.7	5.3	0.0	15	8.55	7.85
20	80.4	16.9	2.7	20	8.35	7.90
25	87.7	10.8	1.5	25	8.55	7.65
30	93.0	6.6	0.4	30	8.70	7.65
35	89.4	8.9	1.7	35	8.75	7.70
40	94.2	5.2	0.6	40	8.95	7.85
45	86.2	11.4	2.4	45	8.90	7.85
50	75.4	22.1	2.5	50	8.95	7.90
55	92.0	6.1	1.9	55	8.85	7.80
60	71.4	25.2	3.4	60	8.75	7.85
65	86.4	11.7	1.9	65	8.75	7.85
70	90.3	8.3	1.4	70	8.65	7.65
75	83.1	13.0	3.9	75	8.50	7.60
80	93.1	6.1	0.8	80	8.55	7.55
85	81.6	15.6	2.8	85	8.65	7.65
90	98.3	1.7	0.0	90	8.65	7.55
95	87.0	10.6	1.5	95	8.55	7.65
100	90.8	8.1	1.1	100	8.55	7.65
105	92.5	7.0	0.5	105	8.70	7.85
110	92.9	6.5	0.6	110	8.55	7.65
115	94.9	5.0	0.1	115	8.65	7.70
120	96.6	3.4	0.0	120	8.65	7.65
125	93.4	6.6	0.0	125	8.85	7.80
130	98.1	1.9	0.0	130	8.75	7.95
135	88.7	9.0	2.3	135	8.55	7.65
140	90.0	9.1	0.9	140	8.55	7.85
145	92.5	6.7	0.8	145	8.85	7.75
150	95.3	4.7	0.0	150	8.75	7.60
155	89.6	8.8	1.6	155	8.55	7.70
160	86.4	10.6	3.0	160	8.00	8.00
165	94.3	3.2	1.5	165	8.70	7.70
170	89.6	8.6	1.8	170	8.75	7.65
175	92.4	6.1	1.5	175	8.65	7.85
180	86.4	10.8	2.8	180	8.70	7.75
				185	8.45	7.80
190	93.6	5.9	0.5	190	8.65	7.95
195	91.0	7.6	1.4	195	8.70	7.95
200	93.5	5.8	0.7	200	8.75	7.75
205	86.3	10.7	3.0	205	8.75	7.90
210	63.5	31.9	4.6	210	8.95	7.95
215	82.1	14.5	3.4	215	8.90	7.75
220	90.1	9.6	0.3	221	8.90	7.90
225	84.6	12.6	2.8	225	8.90	7.85
230	91.4	8.2	0.4	230	9.00	7.85
235	64.9	31.6	3.5	235	8.80	8.05
240	96.8	3.2	0.0	240	8.95	7.95
245	94.6	5.1	0.3			
250	87.5	11.0	1.5			

TABLE 3

TRITIUM ASSAY VALUES FOR WELLS
19-47 B, 32-49 B and 32-49 D

Well No.	19-47 B (12-B)		32-49 B (2B)		32-49 D (2D)	
Date of Drilling	October 1969		December 1969		June 1970	
	Depth Ft.	Tritium Assay T.U.	Depth Ft.	Tritium Assay T.U.	Depth Ft.	Tritium Assay T.U.
	0	1490 $\pm$ 50	0	236 $\pm$ 12	0	481 $\pm$ 15
	7.5	222 $\pm$ 10				
	11	112 $\pm$ 5			10	142 $\pm$ 7
	15	17.1 $\pm$ 0.9			15	13,000 $\pm$ 1000 ⁽¹⁾
					18	24.9 $\pm$ 1.0
	20	4.9 $\pm$ 0.3	21	5.3 $\pm$ 0.4	20	17.9 $\pm$ 0.9
	30	5.5 $\pm$ 0.3	31	4.0 $\pm$ 0.3	26.5	8.2 $\pm$ 0.5
	40	3.7 $\pm$ 0.3	41	5.5 $\pm$ 0.4	40.5	14.9 $\pm$ 0.9
	60	4.4 $\pm$ 0.3			50	8.9 $\pm$ 0.6
	90	4.5 $\pm$ 0.3	96	6.9 $\pm$ 0.4	85	6.6 $\pm$ 0.4
	135	6.3 $\pm$ 0.4	235	7.4 $\pm$ 0.4	110	7.9 $\pm$ 0.5
	150	9.5 $\pm$ 0.5	285	8.6 $\pm$ 0.5	140	5.5 $\pm$ 0.4
	175	9110 $\pm$ 300 ⁽¹⁾	300	26 $\pm$ 9 (G)	200	11.4 $\pm$ 0.6
	175 Check	20 $\pm$ 6 (G)			230	8.4 $\pm$ 0.5
	195	9.4 $\pm$ 0.5	307	20 (G)	260	12.9 $\pm$ 0.7
	211	4.5 $\pm$ 0.3	309	21 (G)	310	28.7 $\pm$ 1.4 ⁽²⁾
	Argon Flush Gas		Argon Flush Gas		Nitrogen Flush Gas	

(1) These very high values at present are believed to be the result of contamination from the cable of the drill rig or possibly from a clump of contaminated soil from the inside of the drive barrel. A check was made with a second sample (stored in plastic bag) from 175 foot depth from well 19-47 B. A gas count of the second sample gave a tritium assay of only 20 $\pm$ 6 T.U.

(2) Liquid water from water table.

(G) Gas count without electrolytic enrichment of sample.

The tritium value of 21 T.U. (G) given for a liquid water sample from below the water table (309 feet) in well 32-49 B was a gas count without electrolytic enrichment. This analysis made by a gas count only is not as accurate as the analyses made for soil samples from 285 foot depth and above, all of which were enriched prior to counting. The value of 26 ± 9 T.U. at the 300 foot depth indicates that the tritium concentration is greater in the groundwater and directly above the water table for well 32-49 B than for well 19-47 B in which the tritium assay for the groundwater was only 4.5 ± 0.3 T.U. This difference indicates a small but positive contamination of the groundwater at the 32-49 coordinates.

The third major well at these coordinates is 32-49 D and was drilled in June of 1970 one year after 32-49 A and six months after 32-49 B (2B) and as shown in Figure 1 is 55 feet -- 1 1/2 inches southerly from well 32-49 A. Samples of soil again were taken for tritium assay during drilling of the well and the results are listed in the last column of Table 3. In general, the values of the tritium assays are greater by a factor of 5 to 10 T.U. for the samples from well 32-49 B. This may be related to the use of dry nitrogen rather than dry argon as a flush gas used in flushing acetone from the 5 liter pyrex flasks used as sample containers. A high value considered to be a contamination from the drill rig [see footnote (1) to Table 3] was observed for the sample from a depth of 15 feet. The sample from below the water table (310 feet) was a liquid water sample for which gas flushing of acetone wash was

not involved. As a result, the tritium assay of 28.7 ± 1.4 T.U. is considered to be correct and essentially free of error. This value supports the earlier values of 21 and 26 ± 9 T.U. determined by gas counting without enrichment for well 32-49 B.

Perhaps more than any other factor studied the tritium analyses support the concept that surface water in general is not percolating from the surface to the water table. How then do we explain the values below the water table of 28.7 ± 1.4 T.U. from well 32-49 D as compared to the value of 4.5 ± 0.3 for well 17-47 B? A flow pattern exists for the groundwater at the Hanford site. If the stream lines are followed upstream from site 32-49 on the hydrological map, shown in Figure 6, this site is found to have flow lines that pass to the 200 East and 200 West swamps used for discharge of process water. Some contamination of the upstream underground water by the seepage from these swamps can be expected. The upstream stream lines from site 19-47 B lie to the south of the 200 West and 200 East Areas. This is believed to account for the "virgin" value of 4.5 ± 0.3 T.U. determined for groundwater from the 19-47 site.

C. Installation of Sensors to the Water Table

Although the tritium assays were important, they were not the prime objective in drilling wells 32-49 B and 32-49 D. The main purpose was the installation of sensors from the water table to the surface to permit measurement of the water potential over the entire depth using thermocouple psychrometers as sensors. The concept here is that the slope the water potential

curve with respect to depth can be used to establish the direction of water migration and using principles of thermodynamics to confirm or deny the absence of percolation of water from the surface to the water table. In using thermocouple psychrometers, a reference temperature is selected and the field measurements are corrected to this temperature.

The temperature at the point of measurement must be known for this purpose and for this reason temperatures values are measured concurrently with the emf of the thermocouple psychrometer. Cables with thermocouple psychrometers and temperature sensors capable of reaching 310 feet to the water table at the 32-49 site were prepared by personnel of Battelle-Northwest Laboratory. The original plan was to lower these cables inside a 6 inch casing at well 32-49 B and then to remove the casing while concurrently returning soil to the casing to bury the instruments. Difficulties were encountered in raising the casing because of the frictional resistance of the dry sandy soil on the outside surface of the casing which had insufficient strength to withstand the tensile force required during removal. The casing failed under tensile load at a depth of about 30 feet. The cables were damaged and were removed for repair. The decision was made to use a stepped casing with incremental diameters decreasing from 12 inches to 10 inches to 8 inches to 6 inches and with increasing lengths as the diameter was reduced. This telescoping of casings permitted removal of individual sections with only about 80 feet of soil in contact with the casing being removed. These stepped casings were used in well 32-49 D and the procedure as described was used successfully to install the sensors throughout the vadose zone. Some

difficulty was experienced in removal of the 8 inch diameter section because of dry flowing sandy soil in the 200 foot depth region. This difficulty was overcome by vacuum removal of a portion of the soil from inside the casing. These operations resulted in some damage to the sensors inactivating psychrometers at 45, 55, 65, and 110 foot depths. Temperature sensors at 40, 45, 50, 65, 70 and 270 foot depths also were inactivated. A total of 57 active psychrometers and 56 active temperature sensors remain with locations as indicated in Table 5.

Personnel of BNWL have made several measurements using these sensors at 32-49 D and have stated that the instruments have not yet reached equilibrium values. None of the data to date on these measurements and no report have yet been made available. A visual presentation of tentative results to date indicated zero water potential at the water table and a negative potential of several bars at a depth of about 50 feet. Although there is some scatter of individual values, they seem to be approaching an essentially linear relationship from a value of 0 bars at a depth of 300 feet to a negative 6 to 8 bars at a depth of 50 feet. In the top 50 feet, the values are still widely scattered.

The interpretation of the emerging values for the vadose zone between 300 to 50 foot depths can vary depending upon the model used as a reference. For a model based on a closed, isothermal, static system in equilibrium, the transport of both liquid water and water vapor is downward. If the model is based on a closed nonisothermal dynamic system, the net transport water is upward. These and other models will be considered in a separate discussion.

TABLE 5

SOIL MOISTURE (PSYCHROMETER) AND TEMPERATURE PROBE
INSTALLATION SOUTHEAST OF 200 EAST AREA AT 32-49 D

Depth (In. or Ft.)	Active Temp. Thermocouple	Active Moisture Psychrometer	Depth (ft.)	Active Temp. Thermocouple	Active Moisture Psychrometer
3"	Yes	Yes	40'	Not Working	Yes
6"	Yes	Yes	45'	Not Working	Not Working
9"	Yes	Yes	50'	Not Working	Yes
1'	Yes	Yes	55'	Yes	Not Working
1 1/2'	Yes	Yes	60'	Yes	Yes
2'	Yes	Yes	65'	Not Working	Not Working
2 1/2'	Yes	Yes	70'	Not Working	Yes
3'	Yes	Yes	80'	Yes	Yes
3 1/2'	Yes	Yes	90'	Yes	Yes
4'	Yes	Yes	100'	Yes	Yes
4 1/2'	Yes	Yes	110'	Yes	Not Working
5'	Yes	Yes	120'	Yes	Yes
5 1/2'	Yes	Yes	130'	Yes	Yes
6'	Yes	Yes	140'	Yes	Yes
7'	Yes	Yes	150'	Yes	Yes
8'	Yes	Yes	160'	Yes	Yes
9'	Yes	Yes	170'	Yes	Yes
10'	Yes	Yes	180'	Yes	Yes
11'	Yes	Yes	190'	Yes	Yes
12'	Yes	Yes	200'	Yes	Yes
13'	Yes	Yes	210'	Yes	Yes
14'	Yes	Yes	220'	Yes	Yes
15'	Yes	Yes	230'	Yes	Yes
17 1/2'	Yes	Yes	240'	Yes	Yes
20'	Yes	Yes	250'	Yes	Yes
22 1/2'	Yes	Yes	260'	Yes	Yes
25'	Yes	Yes	270'	Not Working	Yes
27 1/2'	Yes	Yes	280'	Yes	Yes
30'	Yes	Yes	290'	Yes	Yes
32 1/2'	Yes	Yes	300'	Yes	Yes
35'	Yes	Yes	310'	Yes	Yes

The fourth "well" shown in Figure 1 and identified as 32-49 C (2C) was a hand-augered hole 2 inches in diameter reaching to a depth of 14 feet by 4 inches. Personnel of BNWL placed thermocouple psychrometer and temperature sensors in this hole and returned the soil removed to its original position insofar as possible. This instrumentation will provide a check on the instruments in the 32-49 D location.

D. Soil-Moisture Models

1. Closed, Static, Isothermal Model in Equilibrium

Figure 7 shows a diagram indicating a column of vapor and air above a surface of open water. The column is considered to have unit cross-sectional area and to extend to an unlimited height above the water making a closed system. The temperature can be selected but is considered constant over the height of the column making the model isothermal. The following relationships known as Laplace's law of atmospheric pressure when derived for air was given by Edlefsen and Anderson⁽²⁾

By the ideal gas law for air

$$\begin{aligned}pv &= RT \\ \text{or } p &= \rho RT \\ \text{and } \rho &= \frac{p}{RT}\end{aligned}\tag{1}$$

Consider Figure 7 and note that the pressure at point A exceeds that at point B by the weight of the column of air and vapor in section dz. This

(2) Edlefsen, N. W. and Anderson, A. B. C. "Thermodynamics of Soil Moisture", Hilgardia, 15 page 129, 1943.

weight is equal to $\rho g dz$. The pressure change from A to B is $-dp$. Equating these two quantities gives Equation (2)

$$-dp = \rho g dz \quad (2)$$

Substitution of Equation (1) eliminates ρ and gives

$$\frac{-dp}{p} = \frac{g}{RT} dz \quad (3)$$

Equation (3) may be integrated from the water surface where $z = 0$ and $p = p_0$ to height A at z distance above to give Equation (4)

$$\ln \frac{p}{p_0} = \frac{-g}{RT} z \quad (4)$$

Taking the antilog gives Equation (5) known as Laplace's law of atmospheric pressure.

$$p = p_0 e^{\frac{-gz}{RT}} \quad (5)$$

Equation (4) holds for both air and water vapor insofar as vapor at low humidity obeys the ideal gas law. The value of π_0 is the vapor pressure at the temperature of the water and the isothermal system. The mol fraction of water vapor in the air is considered to be the same at points A, B and C. Therefore, the absolute humidities will be the same at three points. By Dalton's law the partial pressures of individual components in a mixed gas are proportional to the mol fraction. Therefore, the water vapor pressure at point A

will be reduced in proportion to the reduction of total pressure, that is, proportional to p/p_o .

Thus $p/p_o = \pi/\pi_o$ which gives Equation (6)

$$\ln \frac{\pi}{\pi_o} = \ln \frac{p}{p_o} = \frac{-g}{RT} z$$

or rearranging gives:

$$z = \frac{-RT}{g} \ln \frac{\pi}{\pi_o} \quad (6)$$

Equation (6) is identical to the definition of water potential as measured by the water vapor pressure at isothermal conditions. Thus, the "potential" of water vapor at height z above a reference plane under isothermal static conditions is equal to $-z$ in height of water or $-\rho z$ in units of pressure.

The potential of liquid water in a vertical column also is equal to $-\rho z$ in units of pressure and for the isothermal static condition the potential of liquid water and water vapor are identical. The rather lengthy derivation above is given for purpose of record and to derive the potential for isothermal water vapor independently from the potential of liquid water at the same temperature. The relationships can be reached more quickly if the influence of height is treated concurrently on both liquid water and water vapor. For this purpose consider a tall, vertical, capillary-tube filled with water with the bottom of the tube submerged below a free surface of water in a pan. The system is isothermal and enclosed by a tall bell jar as shown in Figure 8. Water fills the capillary over the height " z ". The water in the

pan is at T_0 temperature, p_0 total pressure, and has a vapor pressure of π_0 . As the system is isothermal the temperature T at the top of the capillary is equal to T_0 at the bottom. The total pressure at the surface of the water is p_0 . The vapor pressure π_0 at the bottom of the bell jar over the open surface of water is determined from the steam tables (or an equivalent source) as a function of the temperature.

The "tension" or water potential on the column of liquid water is $-z$ in units of height of water. Therefore, the water below the meniscus at the top of the capillary is under a tension of $-z$ or $= p_0 - z$. Vapor leaving the surface of the upper meniscus of water is in equilibrium with water at $p_0 - z$ pressure. If p_0 is atmospheric, we can say that the tension on both the liquid water and the water vapor is $-z$ at the top of the capillary for the condition of static isothermal equilibrium in a closed system. Thus by deduction, we arrive at Equation (6) more easily.

2. The Nonisothermal Dynamic Model

Hydrologists have found isothermal models of water systems to be convenient. Usually little error is involved in neglecting the normally minor influence of temperature on the flow properties of water. Isothermal conditions often are assumed for the two-phase flow condition in the vadose zone without introduction of significant errors. For the isothermal approximation to be essentially valid the water content of the soil should be greater

than the "residual" saturation (field capacity in agronomical terminology). If the moisture content is in the range that lies between the residual value and the flooded (100 percent saturation) value, water flows over the individual particles of soil in laminar-flow relationships or equivalent which can be used for water transport computations.

As the saturation is decreased below the residual value (field capacity), the error introduced by considering the vadose zone isothermal increases rapidly. Equation (6) is correct for the static isothermal condition, can be applied to the vadose zone on the Hanford area in the region of the test site 2D (32-49 D), and the discrepancy resulting from the isothermal approximation can be demonstrated.

As an example, consider a well with a depth of 340 feet from the surface to the water table. This is only about 30 feet deeper than well 2D in which the thermocouple psychrometer and temperature sensors are installed. The water table is used as a reference at 0 bar potential and one atmosphere of pressure. The water potential at the surface is equal to $-gz$ or -10 bars if 34 feet of water is taken as equivalent to 1 bar of pressure.

If the system is closed, isothermal and in static equilibrium the potential on the water vapor will be -10 bars also (because the liquid and vapor are in equilibrium). The obvious conclusion that

follows is that if water is available in the zone at or near the ground surface at a water potential from 0 to -9.99^+ bars, the surface water and its vapor will tend to migrate to water table. However this conclusion is contrary to observations in the field as born out by the tritium studies and to observations of water potentials in the top 12 feet of soil of -1.0 bar. The field conditions are not isothermal, are not a greater closed system and are not in static equilibrium which renders this model invalid.

Temperatures are fairly constant at the water table. South of the 200 East Area (at well 2D) the water at the water table has a temperature of about 20.6°C for the entire year. At a depth of about 15 feet below the ground surface the temperatures average $15.6^{\circ}\text{C} \pm 1.0^{\circ}\text{C}$. Above this depth there is increasing temperature variation with seasonal conditions. These measurements show that a temperature difference of about 5°C occurs over the depth of the well. The direction of the temperature gradient is in the direction of moving both the liquid water and the water vapor upward. The concept of water potential thus is not sufficient to define the system because the concept is based on the isothermal condition in which influence of temperature appears only as a density correction in the ideal gas relationship.

The 340 foot deep well used for an example may be considered to be isothermal at 15.6°C in a closed system and in static equilibrium. Computations given in Table 6 show that for the

isothermal closed system in static equilibrium the vapor pressure at 15.6 °C for saturated air at 1 atmosphere pressure is 0.25621 psi (from steam tables). At a tension of -10 bars this drops to 0.25427 psi. Thus if the 340 foot well had a temperature of 15.6 °C from the top to bottom and was saturated with water vapor at 1 atmosphere total pressure the vapor pressure of water at the water table would be 0.25621 psi. The influence of a "z" of 340 feet on the vapor pressure is to reduce the potential by -10 bars and the vapor pressure by 0.25621 - 0.25427 or 0.00194 psi.

However, the true temperature at the water table is 20.6 °C. The vapor pressure at 20.6 °C as given in the steam tables is 0.35080 psi. If a tension of -10 bars is added, the vapor pressure drops to 0.34818 psi. The true driving force on the water in terms of vapor pressure is the difference between 0.35080 psi at the water table ($T = 20.6\text{ °C}$, $\psi = -0\text{ bars}$) and 0.25427 psi at 340 feet above ($T = 15.6\text{ °C}$, $\psi = -10\text{ bars}$). This difference is 0.09653 psi which gives a factor of: $(0.09653/0.00194) = 49.8$ or about 50.

Thus driving force in terms of vapor pressure difference is about 50 times greater for the influence of the temperature gradient than for the influence of tension. The influence of temperature gradient on vapor transport is upwards whereas that of tension is downward. The net result for dry soil such as at Hanford is that the potential created by the temperature gradient for practical considerations involving

TABLE 6

VAPOR PRESSURE AS A FUNCTION OF TEMPERATURE OR POTENTIAL

(Computations by Emmitt Kraft)

At static, isothermal equilibrium in a closed system the water potential is a function of height above a free standing water surface. For a height of 340 feet above the water table, the water potential ψ is -10 bars. Using Equation (6) shows the effect of height on vapor pressures.

$$\psi = \frac{-RT}{V} \ln \frac{\pi}{\pi_0} \quad (6)$$

Where R is the Gas law constant

T is the absolute temperature

V is specific volume of water

π is vapor pressure at 340 feet

π_0 is saturation vapor pressure at temperature T_0

At the isothermal condition of 20.6 °C (which is the temperature at the water table), π_0 is 0.35080 psi. Equation (6) is solved for π , the vapor pressure at 340 feet above.

$$\psi = -10 \text{ bars} = \left(\frac{1.314 \text{ bars ft}^3}{\# \text{ mol } ^\circ\text{K}} \right) (293.6 \text{ } ^\circ\text{K}) \left(\frac{1\#}{.01605 \text{ ft}^3} \right) \left(\frac{1\# \text{ mol}}{18\#} \right) \left(\ln \frac{\pi}{.35080} \right)$$

$$\pi = 0.34818 \text{ psi @ } 20.6 \text{ } ^\circ\text{C}$$

At the isothermal condition of 15.6 °C (which is the temperature at 15 feet below ground surface), π_0 is 0.25621 psi. Using the same calculation:

$$\pi = 0.25427 \text{ psi @ } 15.6 \text{ } ^\circ\text{C}.$$

transport of water overshadows the influence of tension by a large factor for the conditions given. To explore the importance of temperature gradient in moisture transport in dry soils a short survey of the literature was made and comparisons of the rates of water transport by hydraulic gradient and temperature gradient in dry soil were found.

3. Comparison of Water Transport by Temperature and Potential Gradients

W. R. Gardner points out that the capillary pressure is not sufficient to define the thermodynamics of a soil moisture system. The temperature, relative amount of soil water (as given by saturation) and the osmotic influence from dissolved salts also are involved. In the presence of thermal gradients, there is simultaneous movement of water in the liquid and vapor phases. Gardner⁽²⁾ comments that "since vapor pressure is very sensitive to temperature, thermal gradients of the magnitude to be found in soils can lead to large vapor pressure gradients. Much of the difficulty has arisen from the fact that the observed water transport has been much larger than that predicted from the theory of vapor diffusion. . . The water movement in excess of that due to vapor diffusion is attributed to liquid flow due to temperature gradients."

(2) Gardner, W. R. "Soil Water Relations in Arid and Semi-Arid Conditions" in Plant - Water Relationships in Arid and Semi Conditions. Review of Research. UNESCO, Paris, page 37, 1960.

Cary⁽³⁾ measured water flux in soil and compared the transport produced by thermal gradients with that produced by pressure gradients. He also found that "vapor transport through the soil was several times greater than could be predicted by Fick's law" and observed that the relative importance of vapor transport increases as the soil becomes drier.

Cary's experimental values for transport of water, (1) in liquid phase by pressure, (2) in liquid phase by thermal gradients and (3) in vapor phase by thermal gradients are plotted in Figure 9. These data are from samples of Columbia loam soil, a pressure gradient of 5 cm of water/cm and a temperature gradient of 0.8 °C/cm. The data are for water tensions (suctions) of less than -0.5 bars. The comparison was limited to this range because the water transport for liquid water moved by tension dropped to essentially zero when the tension reached -0.46 bars. Below a tension of about -0.15 bars liquid film transport by tension is the controlling mechanism in the soil tested. The data plot as essentially straight lines on log-log paper. The liberty was taken of extrapolation of the data to a tension of -10 bars to obtain an order of magnitude comparison of vapor transport by temperature gradient with liquid film transport by tension in dry soil. At -10 bars the extrapolation of the line for vapor transport rises to a value of about 10 mm/day. The extrapolation of the line for liquid transport by tension intercepts the -10 bars potential at about 10^{-3} mm/day.

(3) Cary, J. W., "Water Flux in Moist Soil: Thermal Versus Suction Gradients," in Soil Science 100, No. 3, Williams and Wilkins Co., page 168, 1965.

Thus for the gradients used in Cary's tests and an extrapolation to -10 bars potential the vapor transport by thermal gradient is about 10,000 times greater than the liquid transport by tension gradient. The approximate depth of well 2A in metric units is 100 meters. Cary's thermal gradient of 5 cm H₂O per cm corresponds to 500 meters/100 meters or about 50 bars for the well depth. Thus Cary's gradients correspond to a factor of about: $\frac{8000}{5} \times \frac{10}{50} = 320$ times greater in favor of the thermal gradient. Correcting the ratio of rates for the 340 foot well conditions by dividing the factor of 10,000 by the factor of 320 gives a factor of about 30 for the ratio of water moved by vapor transport to that moved by tension in the 340 foot well. This has the same order of magnitude as the factor of 50 computed previously based on the ratio of vapor pressure gradients. This may be largely fortuitous because difference in soil characteristics can influence the values. At this writing other data to permit comparisons are not available. Although the use of such comparisons are not satisfactory except for order of magnitude comparisons the extrapolated values support the concept that the temperature gradient and not hydraulic gradient predominates in water transport in dry soils of semi-arid areas such as Hanford.

Fig. 1 LOCATIONS OF WELLS 2-A,B,C,&D AT COORDINATES 32-49 WITH RESPECT TO CENTER LINE OF ROAD

Fig. 2 NEUTRON LOG OF WELL 2-A (32-49A)

Fig. 3 CALIBRATION OF NEUTRON LOG READINGS - 12/11/69

Fig. 4 WATER POTENTIAL vs DEPTH FOR WELL 2-A (32-49) BASED ON BEST INTERPRETATION POSSIBLE OF DATA FROM TABLE 1 AND FIGURE 1

Fig. 5 1969 TRITIUM DISTRIBUTION IN SOIL MOISTURE

Fig. 7 COLUMN OF AIR AND WATER VAPOR IN A GRAVITATIONAL FIELD

Fig. 8 CAPILLARY TUBE WITH WATER IN CLOSED, STATIC, ISOTHERMAL SYSTEM

Fig. 9 EXTRAPOLATION OF CARY'S DATA TO -10 BARS POTENTIAL