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MOISTURE MOVEMENT IN SOILS
ON THE HANFORD RESERVATION

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I. INTRODUCTION

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, viz., surface water, groundwater, and oceans. This is fundamental 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

The possible migration of radionuclides stored in the soils of the vadose zone is of primary importance at the Hanford Reservation. Liquid waste of low and intermediate levels ($<5 \times 10^{-5}$ $\mu\text{Ci/ml}$ and 5×10^{-5} - $100 \mu\text{Ci/ml}$) have been allocated to swamps, cribs, dry wells, and trenches. For immobilization, all of these procedures rely on the absorption of radionuclides within a few feet of the soil surface, and/or the lack of liquid percolation to the water table to prevent dispersion to natural water supplies.

The following program is proposed to study the phenomena of soil moisture movement at the Hanford Reservation and to determine locally if there is a net transfer of water

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

from the water table to the surface, as postulated, rather than from the surface to the water table. The program is necessary to define more completely the potential hazards and problems of radionuclides stored in the subsoil, and to examine the possibility of long-term storage of selected nuclear waste at the Hanford Reservation.

II. SUMMARY

Water from precipitation does not percolate to the water table in arid areas as it does in humid areas. In arid and semiarid regions, there exists a critical value, P_c , for the annual precipitation below which percolation to deep water tables is absent. Values of critical precipitation need to be determined for selected sites of the Hanford Reservation for safety evaluations of crib sites and burial grounds for long-term storage. Critical precipitation values are not well known at present, are influenced by Bowen's ratio, (the ratio of heat transferred by evapotranspiration to the heat transferred by conduction and convection), and are difficult to evaluate. Methods being studied are as follows: (1) the thermodynamic method based on water potential and thermocouple psychrometers; (2) the tracer method using atmospheric tritium; (3) the annual water balance based on the annual heat balance; (4) the field lysimeter using thermocouple psychrometers; (5) the influence of soil breathing as a result of changes in barometric pressure; and (6) the influence of soil stratification.

Progress to date has involved the installation of thermocouple psychrometers from the surface to the water table 310 feet below. These instruments are in the process of equilibration. Isothermal methods of analyzing water potential must be extended to include nonisothermal conditions which are

dominant at the Hanford Reservation. Tracer techniques using tritium analyses of soil samples have successfully demonstrated that archaic water exists in virgin soil at the Hanford Reservation from a depth of approximately 7 meters to the water table, indicating that percolation has been limited to lesser depths. The annual heat balance indicates that quantities of water many times greater than the annual average precipitation of 16 centimeters can be evaporated from the soils at the Hanford Reservation during a normal summer. This indicates that the critical precipitation (P_c) value may be greater than 30 to 50 centimeters of water. More precise values of the Bowen's ratio for the Hanford Reservation are required to refine this computation. The field lysimeter is perhaps the most direct method of determining the critical precipitation values for the Hanford Reservation but as yet has not been used.

III. DISCUSSION

In climates that have significant annual precipitation, scientist observe a downward percolation of water to the water table. However, in nonirrigated arid and semi-arid regions with deep water tables, there is a limiting value of annual precipitation below which water percolation to the water table ceases. In such regions, the precipitation normally is seasonal and usually occurs during the cooler part of the year. This precipitation falls upon soils that have been desiccated to depths of several meters during the previous summer. If the annual precipitation is less than the limiting value, the annual precipitation will percolate downward slowly because of the low effective permeabilities of the dry soils. As a result, the precipitation percolates downward a few meters and then returns to the surface by capillarity and

vapor transport as the heat of the following summer again desiccates the soil. During the autumn and early winter, the sinusoidal temperature changes in the soil act as a thermal pump which also moves water toward the surface. In addition, barometric cycling removes moisture as low humidity air is forced into the soils during high pressure periods and high humidity air escapes from the soil during low pressure periods.

In the arid to semiarid climate of the Hanford Reservation the average annual precipitation is well below the critical precipitation, P_c , for local recharge to the water table. Water infiltration resulting from precipitation appears to be restricted to the upper 5 to 10 meters of the vadose zone and water vapor appears to be transported from the water table to the surface. A limited program to study soil moisture relationships has been initiated to determine the rate and direction of moisture movement in the soils of the Hanford Reservation.

A. Incident Precipitation in
Arid and Semiarid Regions

The most significant question with respect to waste management in arid to semiarid regions is, how arid must the climate be for safe long-term burial of radionuclide contaminated wastes in controlled areas? One criterion is that the climate should be sufficiently arid to prevent percolation of incident precipitation to the water table so as to avoid any possible leaching of radioactive materials from the vadose zone above. Favorable conditions for the management of radionuclides exists at sites where the annual precipitation is less than the critical value, P_c , for local recharge of the groundwater system.

Several approaches to the study of water movement in the vadose zone are required to provide a better understanding of the complex relationships involved.

1. The thermodynamics of moisture movement needs to consider temperature gradients. This will enable a more accurate interpretation of field data and the development of a nonisothermal soil moisture model for the soils of the Hanford Reservation.
2. Tritium tracer studies serve to determine limits of atmospheric tritium percolation into the soil, as a function of annual precipitation.
3. An annual heat budget needs to be developed to define the net flow direction of water in the vadose zone. The heat balance gives the value of the critical precipitation, P_c , but is sensitive to small errors in temperature.
4. A large field lysimeter is proposed for verifying the critical precipitation, P_c , determined by the heat balance.
5. Pressure transducers at various depths in the soil will be used in the study of soil breathing effects and to permit inclusion of water transport associated with breathing in the heat balance computations.
6. The spatial variation of soil texture in the soil moisture model requires investigation to determine the interrelated influence of vapor pressure,

surface tension, temperature, potential, particle size, stratification, and osmotic effects.

B. Water Potential as a Means of Determining the Direction of Water Transport

Thermocouple psychrometer sensors have been installed to the water table to enable the determination of water potential as a function of depth, Figure 1. The second law of thermodynamics implies that water will migrate from a region of high potential to a region of low potential. Therefore, the gradient of potential as a function of depth establishes the direction of water transport in the soil.

The conventional isothermal soil moisture model suggests a net downward movement of liquid water and water vapor. With the nonisothermal model and a temperature gradient positive upwards, the movement of water is upward. Thus, it becomes necessary to examine the influence of temperature in soil moisture models to determine the net movement.

The relationships between water potential, soil moisture content, soil temperature, and the physical characteristics of the soils need to be examined in more detail.

The Atlantic Richfield Hanford Company (ARHCO) isothermal equation relates the soil saturation (weight percent water) to the water potential and includes soil characteristics for specific soils as follows:

$$w = \frac{a}{(-\psi)^b} + c \quad (1)$$

SOIL WATER, %BY WEIGHT & WATER POTENTIALS AS A FUNCTION OF SOIL DEPTHS - MAY 5, 1970

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where: w = weight percent water on dry basis measured by oven drying at 105 °C;

ψ = water tension (or potential) measured in negative bars;

a = a constant characteristic of the soil and approximately equal to the intercept of w - c at ψ of -1 bar;

b = a constant characteristic of the soil and approximately equal to the slope of the curve between ψ of -.1 and -1.0 bars; and,

c = a constant characteristic of the soil and approximately equal to the value of w obtained by extrapolation of the curve to -5000 bars.

Figure 2 is a graphical representation of the ARHCO equation.

The introduction of temperature requires a third dimension and the use of a surface rather than a straight line, to describe the soil moisture relationships.

An alternate procedure for studying temperature effects is the application of thermodynamics to include entropy and enthalpy.

Items that need further study include:

1. nonisothermal ARHCO equation,
2. entropy and enthalpy of soil moisture,
3. nonisothermal soil moisture model, and
4. physical significance of constants in ARHCO equation.

ARHCO ISOTHERMAL IMPROVED EQUATION

(3 CONSTANTS)

C. Infiltration of Fallout Tritium

During drilling of wells, samples of soils have been collected for tritium assay. These data provided a classic example of vertical distribution of tritium in virgin areas of the vadose zone beneath the Hanford Reservation. A plot of these data for the top 100 feet of depth is shown in Figure 3.

The intersection of the curve of T.U. values for infiltrated water with the natural value of about 4.5 T.U. as indicated in Figure 3, gives the maximum depth of percolation, D_p . In order to have percolation to the water table, water must infiltrate to some critical depth, D_c , where reverse transport to the soil surface ceases. The annual precipitation, P , and depth of percolation, D_p , are related to the critical constants P_c and D_c by,

$$\frac{P}{P_c} = f\left(\frac{D_p}{D_c}\right)$$

Continued study of the depth of percolation at the Hanford Reservation will require:

1. six new wells,
2. portable meteorological station, and
3. tritium analyses.

1969 TRITIUM DISTRIBUTION IN SOIL MOISTURE - WELL 12-B

D. Water and Heat Balance Determination of P_c

Heat balances at the soil surface provides a means of constructing an annual overall water balance,

$$\text{Water Input} - \text{Water Output} = \pm \text{Change in Storage. (2)}$$

On an annual basis for successive years, the change in storage of water in the upper 5 meters of the vadose zone is zero. For the condition,

$$\text{Water Input} \leq \text{Water Output, (3)}$$

there is no percolation below 5 meters. However, for the reverse condition,

$$\text{Water Input} > \text{Water Output, (4)}$$

percolation below 5 meters may occur. Thus, the precipitation that causes the water output to equal the water input is equivalent to P_c the critical precipitation. This is based on the assumption that the upper vadose zone can store the annual water from the time of precipitation to the time of return by evapotranspiration to the atmosphere. The low moisture content of the upper 10 meters of most virgin soils in arid regions and the low annual precipitation at the Hanford Reservation makes this possible. The water balance is based on the climatological heat balance at the soil surface given by Geiger*:

$$S + B + L + V = 0, (5)$$

*Geiger, R., The Climate Near the Ground, Harvard University Press, Cambridge, Mass., 1966.

where:

S = net radiation input equal to solar radiation plus atmospheric radiation minus radiation from earth's surface in $\text{cal cm}^{-2} \text{min}^{-1}$ (Langleys per min.);

B = net flow of heat to or from surface from soil below ("B" is positive at night and negative during the day);

L = convection and conduction of heat from soil to or from air, ("L" is influenced by air velocity); and

V = heat removed by vaporization of water from soil surface, 583 cal g^{-1} at 25°C .

"B" is dependent on the change in temperature of the soil. If a heat balance is made on an annual basis, the temperature of the soil will return at the end of the year to approximately its original value. Therefore, B will reduce to a small value over a yearly basis and can be considered negligible when compared to the large annual totals of S, L, and V. The net annual heat input due to radiation must be equal to the heat removed from the soil by evapotranspiration, conduction, and convection to the air, and the latter sum can be determined by calculating the annual radiation, S:

$$S = -(L + V). \quad (6)$$

The Bowen's ration, L/V is a dimensionless number which compares heat transferred by evapotranspiration, V, with that transferred by conduction and convection, L. The annual average value of L/V represents the ratio of two systems involved in removal of heat and can be used as a parameter to describe local climatological characteristics. Data have been reported on these values for various climates over the world. Knowing the annual

average value of L/V and S , the heat removed by evapotranspiration of water, V , can be calculated and thus the amount of water transported to air can be calculated on an annual basis for use in the water balance.

Table I shows the influence of latitude on the ratio L/V which has a minimum value at the equator.

TABLE I

PREDICTED VALUES OF L/V
ACCORDING TO BUDYKO**
FOR LAND OR SEA

<u>Latitude</u>	<u>0</u>	<u>25°N</u>	<u>30°N</u>	<u>42°N</u>	<u>46°N</u>	<u>50°N</u>	<u>60°N</u>
L	9	20	21	16	15	12	9
V	73	60	59	51	38	30	21
L/V	0.17	0.33	.30	.39	.40	.40	.43

The relationship holds for land or sea provided orographic factors are absent and water is available in the soil for evapotranspiration. If the precipitation is insufficient to provide this water as in arid or semiarid regions, the L/V values may exceed those listed in Table I. In arid regions, the annual value of V decreases because the soil becomes desiccated during the summer. Heat that would appear as evapotranspiration, V , if water were available appears instead

**Budyko, M. I., Atlas Teplovogo Balansa, Leningrad 1955
(s. Ref. H. Flohn, Erdk, 12, 233-237, 1958).

Ibid. The Heat Balance of the Earth's Surface, translated
by N. A. Stepanova, U. S. Department of Commerce,
Washington, D. C.; 1958.

as L and as back radiation. Albrecht*** reports an annual value of about 2.0 for the Gobi Desert (42°N), Table II.

TABLE II

VALUES OF L/V AT SELECTED LAND SITES
ACCORDING TO ALBRECHT***

<u>Site</u>	<u>Djakarta</u>	<u>Ikengung</u>	<u>Potsdam</u>	<u>Irkutsk</u>	<u>Sodankyla</u>
<u>Latitude°</u>	<u>Java</u>	<u>Gobi Desert</u>	<u>Germany</u>	<u>Baykol</u>	<u>Finland</u>
	<u>8°S</u>	<u>42°N</u>	<u>52°N</u>	<u>50°N</u>	<u>67°N</u>
L	8	24	0.	10	0
V	42	12	22	12	10
L/V	.19	2.0	0	.83	0
Rainfall cm/yr	>200	>25	50-80	25-50	25-50

To estimate the value of L/V for the Hanford site, Table I would indicate a value of 0.4 based on latitude alone. But Table II shows that higher values are obtained if the site is arid. Irkutsk, located east of Lake Buykal in Siberia is at 50°N latitude, is semiarid and may be comparable to the Hanford Reservation. It has an annual L/V of 0.83. The continent of Australia has an average annual rainfall of 15 to 18 centimeters almost identical to that at the Hanford Reservation and an L/V of 1.4. However, Australia is much closer to the equator and has a

***Referenced by R. Geiger in The Climate Near the Ground as:
Albrecht, F., "Untersuchungen über den Warmchausalt der
Erdoberfläche in Verschiedenen Klimagebieten," R. F. W. Wiss,
Abh. 8 Nr. 2, 1940.

higher average temperature. The annual value of L/V for the Hanford Reservation is estimated to be between 0.4 and 1.4. Computations were made for annual values of V for the Hanford Reservation based on measured values of S for the years 1958, 1964, 1967, and 1969 and for values of L/V of 1.4, 1.0, 0.6, and 0.4, and are summarized in Table III.

TABLE III

SUMMARY OF ANNUAL HEAT BALANCE COMPUTATIONS OF P_c
FOR HANFORD RESERVATION

<u>L/V = 1.4</u>				
Year	-L+V Langleys	V Langleys	P (Input) Precipitation cm/Yr	P_c (Output) Evaporation cm/Yr
1958	36,700	15,300	22.1	26.2
1964	29,900	12,460	13.7	21.3
1967	23,900	9,960	8.1	17.0
1969	31,500	13,130	16.3	22.6
<u>L/V = 1.0</u>				
1958	36,700	18,400	22.1	31.5
1964	29,900	15,000	13.7	25.7
1967	23,900	12,000	8.1	20.6
1969	31,500	15,800	16.3	27.2
<u>L/V = 0.6</u>				
1958	36,700	23,000	22.1	39.4
1964	29,900	18,700	13.7	32.0
1967	23,900	14,900	8.1	25.7
1969	31,500	19,700	16.3	33.8
<u>L/V = 0.4</u>				
1958	36,700	26,200	22.1	45.0
1964	29,900	21,400	13.7	36.8
1967	23,900	17,100	8.1	29.2
1969	31,500	22,500	16.3	38.6

Although the heat balance appears simple and straightforward initially, the limitation of

accurate applicable data make only approximate balances possible at present. The correlation of reliable L/V values requires further study.

More accurate techniques are required to determine heat losses to the air by convection, conduction, and advection. As an example, a difference of 3 °C in the soil surface temperature can result in approximately 50 percent error in the net radiation input, S.

The following is proposed to determine more reliable values of P_c by the heat balance:

1. determination of net heat flux to atmosphere,
2. determination of L/V ratios, and
3. determination of P_c by heat balance.

E. Field Lysimeter

A large field lysimeter provides a relatively inexpensive means for determining percolation limits.

The proposed lysimeter is closed bottomed and isolates a large sample of soil. It permits controlled observations of soil moisture behavior to a depth of 10 meters. If precipitation exceeds P_c , the soil moisture content will increase towards the bottom of the lysimeter. If water is transported in the reverse direction upward, the soil moisture content will decrease between the percolation depth, D_p , and the bottom of the lysimeter.

Artificial precipitation experiments with lysimeters would be used to study the interrelationships of precipitation, P , percolation depth, D_p , critical percolation depth, D_c , and critical precipitation, P_c .

The following items are proposed to determine percolation depths, P_c , and the interrelationships:

1. installation of an instrumented lysimeter,
2. evaluation of the percolation depth D_p ,
3. computation of heat balance and determination of P_c and
4. evaluation of D_c by artificial precipitation.

F. Soil Breathing

The vadose zone is exposed at the surface to the atmosphere and to changes in the local barometric pressure. As the soil is porous, atmospheric air flows into the soil subsequent to an increase in barometric pressure and out from the soil after the pressure falls. The yearly average absolute humidity of the atmospheric air is less than the yearly average humidity of air from soil pores of the upper vadose zone. The humidity differences result in a loss of soil moisture with the successive exchanges of air masses.

To explore the phenomena further, pressure transducers need to be installed at various depths with simultaneous recording capability. With information on the barometric pressure and its rate of change, flow

rates into or out of the soil may be computed. A material balance may be used to compute the influence of soil breathing on the heat balance.

The following are required:

1. six instrumented wells,
2. evaluation of barometric pressure changes in the vadose zone,
3. determination of air permeabilities and air flow rates in soils, and
4. computation of heat balance corrected for breathing effect.

G. Soil Stratification

Stratification of soils complicates the use of soil moisture models in the vadose zone. Vertical movement of soil water is interrupted by silt interfaces. These layers of finer textured soils have a higher affinity for water than coarser textured soils. This physical contrast can result in horizontal transport of water. A preliminary study is required to determine the relative importance of the numerous pertinent parameters.

Typical recurrent soils observed on the Hanford Reservation require study. The following are required:

1. identification of significant parameters, and
2. influence of parameters on soil moisture models.