Moisture Flow Induced by Thermal Gradients Within Unsaturated Soils[1]

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Introductory Remarks by the Chairman

There can be little doubt that the most complex and least understood area in the field of soil-water relationships is that of the effect of temperature gradients applied to moist soils. One reason for the real, and also the imaginary but no less vexing, difficulties is that soil-water relationships and their dependence on temperature are uniquely individual for each soil system depending not only on the volumes and degrees of dispersion of the solid, liquid and gaseous phases, but also on the character and extent of the physico-chemical interactions at the phase boundaries and their temperature susceptibilities. Obviously, here is not a single effect, but an entire science that has areas of greater or lesser complexity depending on soil composition and condition; it is the science of soil thermodynamics in its widest sense. Before this science can be properly organized, a great deal of dependable experimental work must be done on well defined systems. Professor Hutcheon is presenting the results of an excellent and carefully executed experimental investigation on three soils of different texture under conditions of phase composition that favor moisture transmission in the vapor phase. Even under these conditions, the observed coefficients of vapor diffusion were from six to eight times greater than those calculated from known relationships for isothermal conditions. Grateful acknowledgment is given to Professor Hutcheon for his fine experimental contribution in one important area of the total problem.

●OBSERVATIONS and investigations of the influence of temperature gradients, and variations in temperature, on the retention and movement of water in the soil have been recorded periodically since the beginning of the century. One of the earliest reports was made by King (19) who noted evidence of diurnal fluctuations in the rate of discharge of water from tile drains, and in the level of ground waters in shallow wells. Similar observations have been made for very moist soil conditions by Roseau (39).

In the course of field experiments, Lebedeff (21) and Edlefsen and Bodman (7) noted substantial upward movements of water in unsaturated soils during the winter months, under frost free conditions. They attributed the movement to the influence of thermal conditions on the surface tension and vapor pressure of water.

Moore (25, 26) observed a considerable change in the rate of vertical capillary flow in soil columns under constant moisture-tension gradients when the columns were subjected to a change in ambient temperature conditions. Qualitative observations of the influence of temperature changes on moisture movement have also been made by Hilgeman (16), Haise and Kelley (11) and Pavlovski (27).

One of the earliest laboratory studies of thermal influences on moisture flow was conducted by Bouyoucos (3). He found a marked transfer of water from warm to cold regions of soil specimens. He attempted to segregate liquid and vapor flow characteristics by means of screen gaps and concluded that thermal effects were largely related to flow in the liquid phase.

Smith (41) considered that the effects of temperature on the surface tension of water were not sufficient to cause any appreciable transfer of moisture. However, in later

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experiments (42) he considered that moisture movement under the influence of a thermal gradient was the result of a combined cyclical process of vapor condensation and local capillary flow.

MacLean and Gwatkin (22) and Jones and Kohnke (18) concluded that the thermal migration of moisture occurred largely as a result of vapor pressure gradients induced by the unequal distribution of temperature.

Winterkorn (48) proposes that there is a flow of moisture, in the film phase, along the internal surface of the porous system due to a change in water affinity with change in temperature. He states, "The physical explanation of the phenomena is that the exchangeable cations possess a greater activity (or are more dissociated) at the cold than at the warm side; they cannot move to the warm side because they are held by negative charges of the mineral surfaces. The only way to decrease the concentration potential is by movement of water from the warm to the cold side."

The distribution of moisture under the influence of a thermal gradient has also been studied by Gurr, Marshall and Hutton (10), Rollins, Spangler and Kirkham (38), and by Taylor and Cavazza (44). It is of interest to note that by different techniques these authors have arrived independently at similar conclusions. Gurr, Marshall and Hutton evaluated the magnitude of liquid and vapor flow by measuring changes in the distribution of a small amount of sodium chloride dissolved in the moisture added to the soil. Any movement of the chloride ion was assumed to be due to moisture flow in the liquid phase.

Rollins, Spangler and Kirkham constructed an apparatus in which water vapors, which condensed at the cold plate, were returned to the warm plate by means of an external capillary tube. They compared the distribution of moisture in systems where the external circuit was both open and closed.

Taylor and Cavazza compared the thermal distribution of moisture in continuous and segmented soil columns with similar initial moisture contents. The segmented columns were prepared in five sections isolated by narrow air gaps.

The general conclusions of the above mentioned investigations may be summarized as follows: When a column of soil is subjected to a temperature gradient, the flow of moisture from warm to cool regions occurs largely in the vapor phase. The condensation of excess vapors in the cooler regions results in a flow of moisture, in the liquid phase, from cold to warm regions once a favorable pressure gradient within the liquid has been established. When the soil is sufficiently moist to permit active liquid flow, a state of equilibrium cannot be reached and a continuous circulation of water takes place within the enclosed column.

Croney and Coleman (5) have presented a theoretical analysis of the influence of temperature on both the relative and absolute vapor pressures of soil water, and on the internal pressures of the liquid, under various conditions of soil moisture. Similar calculations have been proposed by Edlefsen and Anderson (8), who also recognize the need for a somewhat different treatment of very dry soil conditions as compared to relatively moist soils.

This discussion is intended to give a critical appraisal of existing theoretical and experimental data relating to the behavior of unsaturated soil-moisture systems under the influence of a linear temperature gradient. Qualitative and quantitative data will be presented on the nature and magnitude of thermally induced moisture flow within the soil. All studies were conducted under laboratory conditions.

Previous investigators have employed relatively short soil columns subjected to temperature gradients ranging from 1.5 to 3 C/cm. In the present study soil columns 30 cm long were enclosed in split lucite tubes with an internal diameter of 10 cm, and a wall thickness of 0.6 cm. Various hot and cold face temperatures were used within the range from -4 to 25 C with temperature gradients ranging from 0.5 to 0.8 C/cm.

The long soil columns and low gradients of temperature were intended to provide a more sensitive evaluation of the relationship between liquid and vapor flow at various initial soil moisture contents, and between various segments of any particular column.

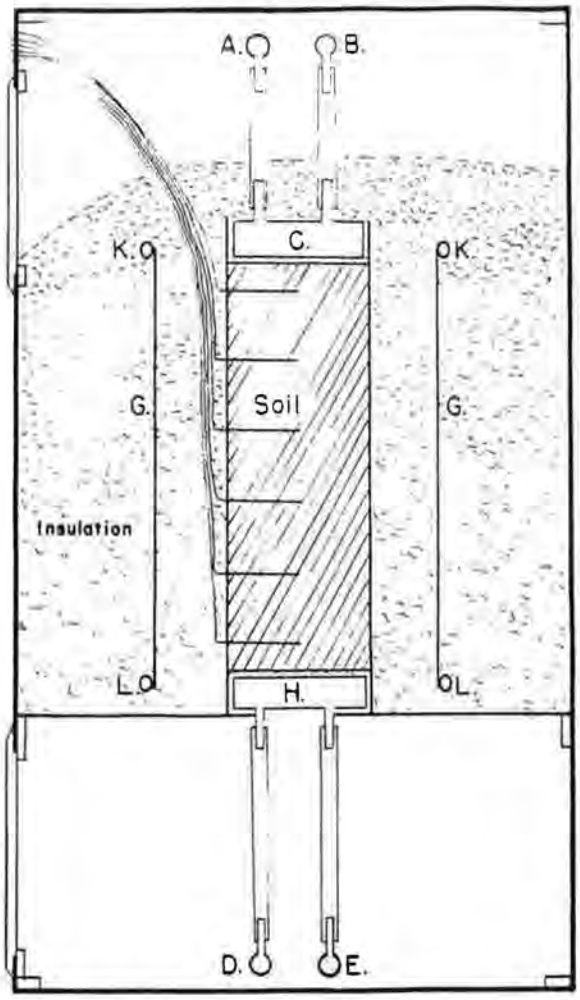

Figure 1. A vertical transverse section of the thermal apparatus showing one soil column in position.

METHODS AND MATERIALS

The necessary bulk of soil, previously conditioned to the required initial moisture content, was poured in a continuous stream into the taped lucite tube which was agitated on a vibrator at 140 vibrations per minute during the filling operation. The soil column was then compacted from each end to a standard length of 30 cm and an apparent density of approximately 1.3 gm per cu cm. The hollow brass circulation plates were placed in position, and the whole unit was sealed with Scotch electrical tape. One hundred grams of Ottawa sand were spread uniformly across the soil surface, before seating the brass plates, to provide a uniform and standard thermal contact.

The details of construction of the thermal unit, with a prepared soil column in position, are illustrated in the vertical transverse section shown in Figure 1. The prepared soil column was positioned in a compartment inside a metal box G. The copper tubes of the brass hot and cold plates H and C were connected in parallel to the circulating hot and cold liquid systems DE and AB respectively. The whole column was then packed tightly around the sides, and over the top, with rock wool insulation. The metal box G, open both top and bottom, was constructed of 16 gauge galvanized iron. The copper tubes K and L were brazed onto the respective upper and lower perimeters of the box, and were also connected in parallel to the hot and cold circulation systems. The metal box was therefore subjected to the same temperature gradient as the soil column. In this way the ambient temperature of each segment of the soil column approximated the desired temperature within the segment when a stable gradient of temperature was attained.

The hot and cold liquids, conditioned to the desired temperatures, were circulated through the respective systems at the rate of 40 to 60 gallons per hour by means of vertical immersion pumps. The rate of flow of the liquids to each of the thermal units, and to the tubes of the metal box, was regulated to provide an equal distribution at all times.

The thermocouple installations were inserted horizontally to the center of the column at predetermined positions as shown in Figure 1. Potentials were read to give a precision of ± 0.05 C.

There were minor variations in temperature at similar depths within columns subjected to the same hot and cold plate conditions at the same time. However, within any particular column studied, the observed gradient of temperature across any six centimeter segment never deviated more than 12 percent from the average gradient for the column as a whole. Some of this deviation could have been due to inaccuracies in positioning the thermocouples which were inserted after the column was prepared. Soil columns, prepared and stored at room temperatures, reached a stable distribution of temperature throughout the column within 24 to 36 hours after they were subjected to a gradient temperature. Under the conditions of temperature applied in the study a stable distribution of moisture was attained within 30 to 40 days.

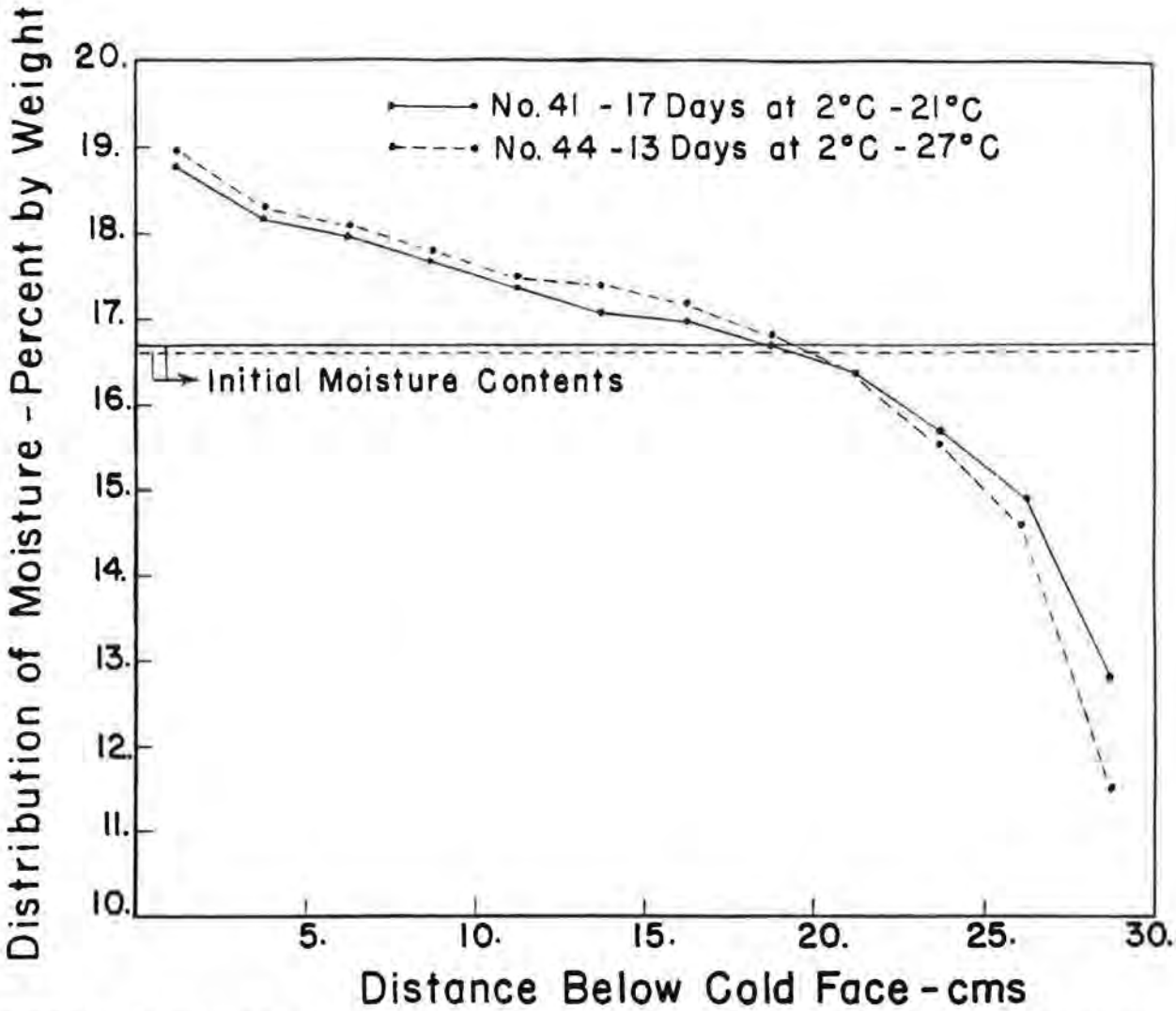

Figure 2. Moisture distribution in columns of clay loam soil subjected to a temperature gradient of 2 to 21 C and 2 to 27 C for 17 days and 13 days, respectively.

Figure 2 illustrates the reproducibility of data under the conditions imposed in the thermal apparatus. After the data for column 41 were analysed, column 44 was prepared to the same initial moisture content and was exposed to a different temperature gradient for a time calculated to give the same degree of moisture movement as occurred in column 41.

The mechanical composition and some moisture characteristics are shown in Table 1 for the three soils studied. All samples were taken from cultivated horizons and had approximately the same organic matter content (3.5 percent). The hygroscopic coefficient is defined here as the moisture content (expressed as percent of oven dry weight) of the soil in equilibrium with an atmosphere of 45 percent relative humidity at 20 C. The permanent wilting percentage, which normally denotes the lowest practical limit of available moisture for plant growth, was determined in the pressure membrane apparatus (36) and is equivalent to the 18 atmosphere percentage. The 3/10 atmosphere percentage was determined on the pressure plate apparatus (36).

TABLE 1

MECHANICAL COMPOSITION AND SOME MOISTURE CHARACTERISTICS OF THE SOILS

Texture	Clay Loam	Very Fine Sandy Loam	Loamy Fine Sand
Percent Sand (2 - 0.05 mm)	40.2	53.5	86.4
Percent Silt (0.05 - 0.002 mm)	28.7	33.4	5.3
Percent Clay (finer 0.002 mm)	31.1	13.1	8.3
Hygroscopic Coefficient	3.4	1.8	1.3
Permanent Wilting Percentage	12.6	7.1	4.5
3/10 Atmosphere Percentage	28.7	15.5	10.8

PRESENTATION AND DISCUSSION OF RESULTS

The moisture distribution under the influence of a thermal gradient, imposed with hot and cold plate temperatures of 10 and 25 C, respectively, was investigated for six columns of clay loam with an initial uniform distribution of moisture ranging from 9.1 to 26.3 percent, for five columns of very fine sandy loam ranging from 4.8 to 15.8 percent initial moisture, and for four columns of loamy fine sand ranging from 5.0 to 13.1 percent in initial moisture content. The distribution of moisture within the various columns of each soil, after a condition of zero net flow was attained, is illustrated in Figures 3A, B, and C for the clay loam, very fine sandy loam and loamy fine sand, respectively.

In all cases illustrated there was a net transfer of moisture from warm to cold regions of the column, which was induced by the imposed thermal conditions. At initial moisture contents below the permanent wilting percentage, the net movement of moisture was very small. As the initial moisture content was increased, there was a gradual increase in the net transfer of moisture towards the cold plate, until a condition of maximum moisture gradient was attained in the case of the columns having initially uniform moisture contents of 16.0, 7.6 and 5.0 percent in the clay loam, very fine sandy loam and loamy fine sand, respectively. These moisture contents are approximately 50 to 60 percent of the moisture content characterized by the 3/10 atmosphere percentage for these soils. As the initial moisture content was increased to higher values, there was a gradual decline in the net transfer of moisture and very little net transfer occurs at moisture contents characterized by soil moisture tensions in the vicinity of 3/10 of an atmosphere. The general relationships between initial moisture content and the net transfer of water, under the influence of a thermal gradient, are similar to those obtained for a loam soil by Gurr, Marshall and Hutton (10). Similar observations were also made by MacLean and Gwatkin (22), who also noted that the net movement of moisture was markedly influenced by the bulk density of the soil column under any particular conditions of initial moisture content.

An analysis of the relationships between soil temperature and the relative and absolute vapor pressures of soil water, together with a consideration of the physical state of the water, will provide an explanation for the characteristic moisture distributions produced by a thermal gradient imposed on a closed soil column. Table 2 shows the moisture content of the clay loam soil characteristic of various soil moisture tension conditions on the drying curve at 20 C. The vapor pressure data and relative humidities were calculated from a modification of the thermodynamic relationships proposed by Bodman and Edlefsen (2) and Edlefsen and Anderson (8) which express soil-moisture potential as a function of relative humidity.

The osmotic pressure of the soil solution is generally considered to be negligible in the case of well drained, non-saline soils at moisture contents within the range between the permanent wilting percentage and the 3/10 atmosphere percentage (37). The internal pressure of the soil water will therefore be due entirely to capillary forces. Under these conditions the following relationship was assumed to be valid for the soils and soil moisture conditions studied:

$$h = -\frac{RT}{Mg} \ln \frac{p}{p_s} \quad \text{where;}$$

h = soil moisture tension as gm cm/gm
R = gas constant
T = absolute temperature
M = molecular weight of water
g = gravitational constant
p = vapor pressure of soil water
p_s = vapor pressure of free, pure water
p/p_s = relative humidity

The relative humidities and vapor pressures characteristic of soil moisture tensions at and above 18 atmospheres

TABLE 2

MOISTURE RELEASE DATA FOR CLAY LOAM SOIL AT 20 C

Moisture Tension (atm)	Percent Moisture	Vapor Pressure Soil Water at 20 C (mm Hg)	Calculated Relative Humidity at 20 C (percent)
0.1	35.4	17.534	99.992
0.3	28.7	17.533	99.978
0.5	25.8	17.528	99.962
1.0	23.4	17.522	99.925
3.0	19.6	17.495	99.780
8.0	16.6	17.430	99.400
15.0	14.0	17.339	98.880
18.0	12.8	17.300	98.660
280.0	6.1	14.221	81.100
-	3.4	7.890	45.000

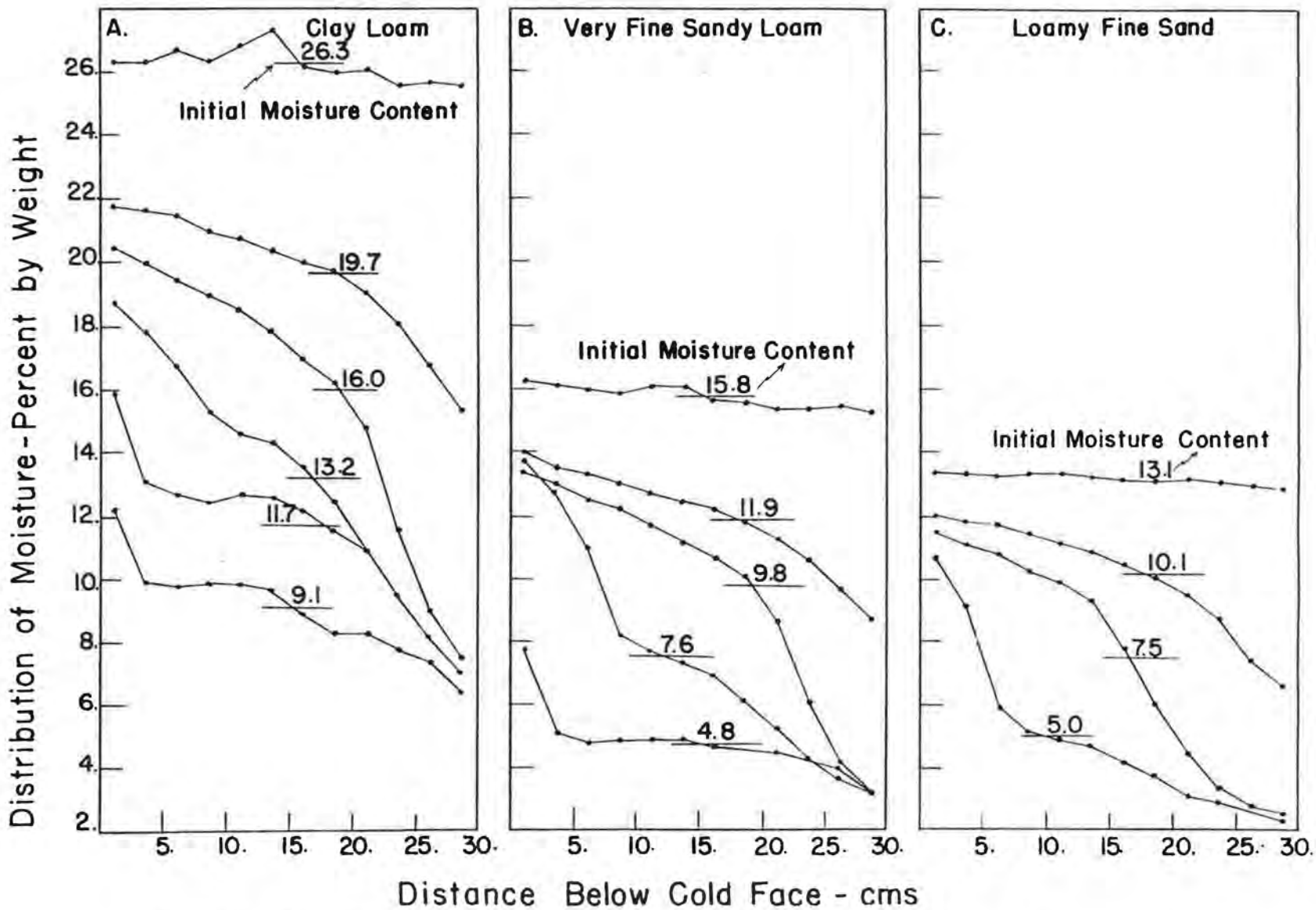

Figure 3. Comparison of moisture distribution at different initial moisture contents within soil columns subjected to a temperature gradient from 10 to 25 C.

were calculated from this relationship. The moisture content characteristic of relative humidities of 81.1 and 45.0 percent respectively were actual determinations obtained by drying the soil samples to equilibrium with a preconditioned atmosphere.

An examination of the data presented in Table 2, and a comparison of the results illustrated in Figure 3 for the various soils, indicate that the behavior of the soil moisture system under the influence of a thermal gradient is closely related to the physical condition of both the soil and the soil moisture. All of these factors must be clearly defined since they will delineate the general relationships which exist between the solid, liquid and vapor phases under any particular thermal state.

It is evident from the data in Table 2 that at soil moisture contents characteristic of relative humidities below 98 percent, the vapor pressure of soil water is a very close function of moisture content. A gain or loss of water will result in a very significant change in vapor pressure. Water will not flow as a liquid (24), and movement will be confined to the vapor phase if unbalanced energy conditions occur within the soil mass. The energy of retention is very great and the free energy of the water molecules is dominated by adsorptive forces. At water contents characteristic of relative humidities below 70 or 80 percent it is likely that the moisture is present as oriented molecular water (1, 8, 13, 23, 40, 45, 47) of various types. The adsorption or desorption of water, as water vapor, will be accompanied by a considerable exchange of heat (5, 9).

At moisture contents above those characterized by 98 percent relative humidity the free energy of the liquid arises from the action of surface forces at the interface boundaries between the solid, liquid and vapor phases (8, 37). This energy condition is commonly described in terms of moisture tension, which is: "A stress equivalent to the surface force action in producing a certain energy status of water" (37, p. 92). Flow of water through the soil takes place under the influence of pressure gradients within the liquid phase, the magnitudes of which are a close function of the relative moisture contents of the soil system. The relationship between moisture content and soil moisture tension is illustrated in Table 2. It will vary considerably depending on the physical nature of the soil system (35).

In the absence of a temperature gradient, movement of water in the vapor phase will be negligible under soil moisture conditions above the permanent wilting percentage. The vapor pressure of soil water will be very close to the saturation vapor pressure over a wide range of soil moisture conditions. Adsorption or condensation of water into the soil will not result in any significant change in vapor pressure. Also, reduction in moisture content as a result of either evaporation or liquid flow, will not produce any real changes in vapor pressures until the soil moisture condition is reduced below that characterized by 98 percent relative humidity. The movement of water within the soil, in the liquid phase, is dependent on both the potential gradient, and on the capillary permeability which is also a variable function of the moisture characteristics (33, 34, 37). This is understandable from the geometry of the system of solids since the liquid is held over the surface of the particles, and in concave form in the pores or wedges between the particles. As the moisture content is decreased, within the range of capillary moisture content, the water will be more strongly influenced by the surface energy of the solids, and in addition, the proportion of total free space within the soil which is occupied with water in the liquid phase will also be decreased. As the soil moisture content approaches the permanent wilting percentage, very large pressure gradients, and therefore large moisture gradients, will be required to produce any appreciable flow in the liquid phase.

It is evident from the preceeding discussions that the influence of an unequal distribution of temperature will likely vary, depending on the physical condition of the soil, and of the soil moisture. At initial moisture contents well below the permanent wilting percentage, a temperature gradient will likely produce a marked gradient of vapor pressure from warm to cold regions of the soil, but will have no influence on liquid flow since the major portion of the soil water is in the absorbed and oriented molecular state. The required shift of water, as water vapor, to produce a state of uniform vapor pressures throughout the soil mass, will be relatively small since the rate of change of vapor pressure is a very significant function of changes in the moisture characteristic. This is confirmed in Figure 3 by the equilibrium moisture distributions for the

clay loam and very fine sandy loam columns at initial moisture contents of 9.1 and 4.8 percent respectively, when exposed to a temperature gradient from 10 to 25 C.

Within the range of soil moisture conditions characteristic of moisture tension below the 18 atmosphere percentage, the effects of temperature changes must be considered for both the liquid and vapor phases. Richards and Weaver (35) studied the moisture content of a series of soils of varying texture, at temperatures ranging from 10 to 40 C, in equilibrium with extraction pressures of 0.5 and 15 atmospheres in the pressure membrane apparatus. Their data indicate that the changes in soil moisture tension, induced by a change in temperature conditions, are extremely small. This behavior is also confirmed by a consideration of the calculated changes in moisture tension induced by a change in temperature using equations proposed by both Edlefsen and Anderson (8) and Croney and Coleman (5). Such calculations are based on the assumption that the major changes in the magnitude of the surface forces affecting the energy of the liquid will be due to changes in the surface tension of water. This can be justified at least in very moist, non-saline soils at moisture contents in the vicinity of the 3/10 atmosphere percentage. The following is a modification of the equation proposed by Edlefsen and Anderson:

$$\log H_2 = \frac{T_1}{T_2} \cdot \frac{S_1}{S_2} \cdot \log H_1 \qquad \text{where}$$

T, H and S refer to the absolute temperature, the surface tension of water and the relative humidity expressed as a fraction, respectively.

If a column of clay loam soil, at an initial moisture content of 28.7 percent, and uniform temperature of 20 C, is subjected to a temperature gradient from 10 to 25 C, the relative humidity at the cold face will be reduced to 99.977 percent or will be decreased by 0.001 percent. On the basis of the relationship between moisture content, moisture tension and relative humidity as shown in Table 2 for this soil, an increase of 0.18 percent in moisture content should be sufficient to restore the relative humidity, and therefore the moisture tension, back to the original conditions. Similarly, the slightly decreased moisture tension in the soil at the warm face will be restored to its original value by a comparable small loss of moisture. Similar calculations for other temperature conditions indicate that the pressure gradients induced within the liquid phase as a result of a temperature gradient will not cause any appreciable shift of water, as liquid, from warm to cold regions of the soil under moisture conditions characteristic of those between the 3/10 atmosphere percentage and the permanent wilting percentage. This is confined by the characteristic moisture distribution data shown in Figure 3 for the clay loam, very fine sandy loam and loamy fine sand soils at 26.3, 15.8 and 13.1 percent initial moisture content, respectively.

TABLE 3

APPROXIMATE DISTRIBUTION OF INITIAL VAPOR PRESSURE CONDITIONS WITHIN A COLUMN OF CLAY LOAM SOIL SUBJECTED TO A TEMPERATURE GRADIENT FROM 10 TO 25 C, WITH INITIAL MOISTURE CONTENT ABOVE THE PERMANENT WILTING PERCENTAGE

Distance from Cold Face cm	Temperature C	Initial Vapor Pressure mm Hg	Average Gradient Vapor Pressure mm Hg/cm	Relative Humidity for Zero Vapor Flow
0	10	9.21		100.0
			- - - - - 0.32	
2	11	9.84		97.2
			- - - - - 0.35	
6	13	11.23		82.0
			- - - - - 0.40	
12	16	13.63		67.5
			- - - - - 0.47	
18	19	16.48		55.8
			- - - - - 0.56	
24	22	19.83		46.4
			- - - - - 0.62	
26	23	21.07		43.7
			- - - - - 0.66	
28	24	22.38		41.2
			- - - - - 0.69	
30	25	23.76		38.7

Although a temperature gradient will only produce a very slight instability within the liquid phase under soil moisture conditions above the permanent wilting percentage, it will produce a much greater instability within the vapor phase. Since the vapor pressure of soil water at any soil moisture content above the permanent wilting percentage is very near the saturation vapor pressure, the relationship between temperature and vapor pressure can be considered similar to that for free pure water. Table 3 shows the calculated initial distribution of vapor pressures within a column of clay loam soil having an initial uniform moisture content above the permanent wilting percentage, and exposed to a linear temperature gradient from 10 to 25 C. It is interesting to note that the gradient of vapor pressure is not a linear function of temperature; an unsteady state of vapor diffusion should therefore occur. These factors were overlooked by both MacLean and Gwatkin (22) and Rollins, Spangler and Kirkham (38) in some of their conclusions regarding the transfer of moisture induced by a temperature gradient. The vapor pressure gradient will be markedly changed by either a change in temperature gradient or a change in mean temperature conditions while the same gradient of temperature is maintained across the soil column.

The conditions illustrated in Table 3 will apply initially to any column of clay loam soil having an initial moisture content above the permanent wilting percentage and exposed to a linear temperature gradient from 10 to 25 C. Since vapor pressures will not be changed by condensation of moisture, water vapor should continue to diffuse into, and condense in, the coldest segment of the soil column until the vapor pressure of every warmer segment has been reduced to 9.21 mm of Hg by a net evaporation of water. The characteristic relative humidity at various points within the soil column, if a condition of equilibrium vapor pressure were to be attained, are shown in the last column of Table 3. An approximation of the moisture content of the soil characterized by each of these conditions of relative humidity may be obtained from a study of Table 2. The moisture content in the soil at a distance of 6 cm from the cold face would have to be reduced to approximately 6.1 percent before the vapor pressure was reduced to 9.21 mm Hg. Similarly, at 26 cm below the cold face, the moisture content would have to be reduced by net evaporation to approximately 3.3 percent if a condition of equilibrium vapor pressures were to be attained. If the initial moisture content of the soil column was 16.6 percent, it is obvious that the coldest segment of the column could not possibly retain all of the water which must be evaporated from every other warmer segment before a condition of equilibrium vapor pressure could be attained.

The above considerations will indicate that the major mechanism of water transport, under the influence of a temperature gradient, must be due to water vapor diffusion. In addition, since the changes in moisture tension induced by a change in temperature are very slight, the condensation of diffused water vapors within the coldest regions of the soil will create a moisture gradient, and therefore a pressure gradient within the liquid, from cold to warmer regions in opposition to vapor flow. This latter state can only occur under soil moisture conditions at which some of the water is retained in the soil as liquid. The comparative magnitude of the liquid flow will depend on the rate of diffusion and condensation of vapors within the coldest regions of the column, on the capillary permeability and on the magnitude of the induced pressure gradient within the liquid resulting from the condensation of vapors.

In order to substantiate the deduction that moisture movement from warm to cold regions of the soil will occur principally as water vapor, and to substantiate the existence of opposing liquid and vapor circulation systems, soil columns were prepared to initial moisture contents comparable with those presented in Figure 3, and were subjected to a temperature gradient with freezing conditions within the coldest segments. Frost action should create a pressure gradient within the liquid phase from warm to colder regions and should therefore inhibit any tendency for liquid to flow from cold to warmer regions of the soil columns. In these latter experiments, cold and hot plate temperatures of -4 and 18 C were used. In all columns the soil temperature at a distance of 2.5 cm below the cold face was approximately -1.7 C. The over-all gradients of vapor pressure should have been approximately equal to those induced within similar columns subjected to cold and hot plate temperatures of 10 and 25 C, respectively. The distribution of moisture within paired columns of the clay loam soil having

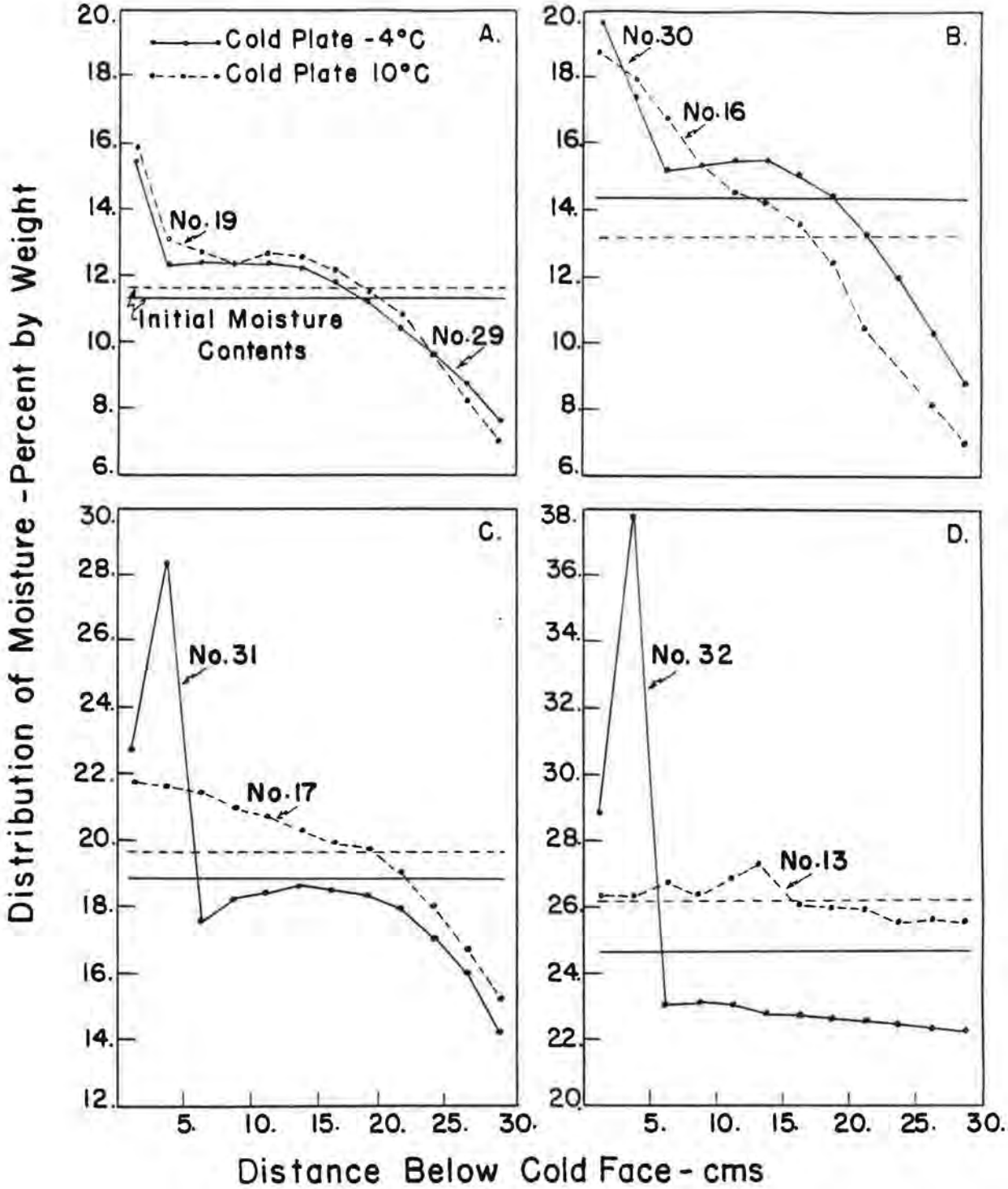

Figure 4. Distribution of moisture within columns of clay loam soil subjected to a temperature gradient from -4 to 18 C for 30 days.

approximately the same initial moisture contents, but subjected to cold and hot plate temperatures of 10 to 25 C and -4 to 18 C, respectively, for 35 days are shown in Figure 4.

In Figure 4A the characteristic distribution of moisture has not been influenced by the frost action at the cold plate although the soil was frozen to a depth of 2 cm below the plate. At this initial moisture content it was not expected that any considerable flow of moisture would occur within the liquid phase. However, the close agreement of the induced moisture distributions within similar periods of time indicates that the over-all vapor pressure conditions must have been similar within the two columns sub-

jected to differing temperature conditions. The initial uniform moisture distribution in both columns was approximately one percent below the permanent wilting percentage.

In Figure 4B the pattern of moisture distribution differs slightly between the two columns in the region from 5 to 20 cm below the cold plate. The frost action has retained all of the condensed vapors within the zone above 4 cm in column No. 30, otherwise the moisture distribution between 5 and 12 cm would have been linear as in the case of the same region of column No. 16. Since there was no appreciable flow of condensed vapors from the coldest segment back into this latter region, the net accumulation of water in column No. 30 between 5 and 20 cm could only have occurred as a result of a small continuous net condensation during an unsteady state of vapor diffusion from warm to cold regions of the column. On this basis the moisture gradient between 6 and 16 cm must have been very small throughout the time of exposure to the temperature gradient. It must be concluded therefore, that the net loss of water from the region between 20 and 30 cm could only have occurred as a result of evaporation and vapor diffusion, under the influence of a vapor pressure gradient induced by the unequal distribution of temperature.

Column No. 17, Figure 4C, was exposed to a temperature gradient from 10 to 25 C for 47 days, and column No. 31 was exposed to a temperature gradient from -4 to 18 C for 32 days. The moisture distribution indicated for column No. 17 is a stable one since a duplicate column exposed to the same temperature conditions for only 30 days had a similar distribution of moisture. In column No. 31 the freezing temperatures near the cold plate have retained all of the condensed vapors as ice, and in addition the frost has induced a small net flow of liquid towards the cold face within the cold half of the column as indicated by the induced moisture gradient, and therefore moisture tension gradient, between 5 and 13 cm. Since the moisture content at the 13 cm depth has not been reduced below initial moisture conditions there cannot have been any transfer of water in the liquid phase from the warm half of the column. This is confirmed by a comparison of conditions at sampling time between column No. 31 and column No. 32, Figure 4D. In this latter column, vapor diffusion conditions must have been similar to those within column 31, but active liquid flow towards the freezing zone has also occurred throughout the column under the influence of the frost induced pressure gradient. Liquid flow was more pronounced in the case of column No. 32 because of the higher capillary permeability, which is a direct function of moisture content. It must be concluded therefore, that if there had been any appreciable flow of water in the liquid phase from the warmest to the coldest regions of column No. 31, the moisture content at the 13 cm depth should have been reduced considerably below initial conditions. The loss of water between 13 and 30 cm must have occurred as a result of vapor diffusion as in the case of column No. 30. It must be assumed that conditions within the column were still unstable at sampling time, and that continued exposure of the column to the temperature gradient would eventually produce a moisture distribution pattern similar to that of column No. 30, with the exception of the freezing zone.

Since columns 17 and 30 were very similar with regard to initial moisture distribution the induced conditions of vapor pressure gradient must have also been approximately the same. A stable distribution of moisture could only have been attained in column 17 if there was a return flow of liquid from cold to warm regions which was equal in magnitude to the vapor diffusion from warm to cold regions in every segment of the column. A similar situation must be responsible for the very small net transfer of water which has occurred within column No. 32. Since the capillary permeability was greater at this mean moisture content, a much smaller pressure gradient (and therefore moisture gradient) will be required to produce a return liquid flow which is equal in magnitude to the vapor diffusion from warm to cold regions of the column.

In the case of column No. 32, Figure 4D, the column was sampled after 32 days of exposure to a temperature gradient from -4 to 18 C. Continued exposure to these conditions should produce a moisture distribution pattern which would pass through the stage indicated by the distribution obtained for column No. 31, and if the freezing zone could contain all of the condensed water vapors, the moisture distribution outside of the freezing zone should eventually resemble that attained within similar regions of column No. 30.

No. 32 at sampling time, as compared to initial conditions, it must be assumed that there has been no appreciable change in the distribution of vapor pressures as a result of moisture movement towards the freezing zone.

If conditions were still dynamic at the stage of moisture distribution indicated in column 32 at sampling time, any further transfer of moisture in the liquid phase from the regions below the 12 cm depth, towards the cold face, would have to take place against a pressure gradient within the liquid phase from cold to warmer regions. The gradient of moisture content from 12 cm towards the 30 cm depth suggests that the liquid should now flow from cold to warmer regions. This condition has likely been induced by the net evaporation within the very warmest segments. Earlier discussions indicated that evaporation of water from the soil would not produce any appreciable change in the vapor pressure of soil water until the moisture content was depleted below the permanent wilting percentage. However, examination of the moisture characteristics and moisture-tension data of Table 2 indicates that differential rates of evaporation could produce a pronounced pressure gradient within the liquid phase without appreciably altering conditions within the vapor phase. It is suggested that, under conditions of unequal temperature distribution within the soil, liquid flow in opposition to vapor flow can be induced by net evaporation within the warmest regions, as well as by net condensation within the coldest regions. The presence of such a circulation system would appear to be characteristic of conditions within the warm half of column No. 31 , Figure 4C, at the time of sampling. The net loss of water within the zone between 13 and 25 cm must have occurred as a result of liquid flow from this region into the net evaporation sink between 25 and 30 cm. The beginnings of such conditions are also indicated in column 32 since the decreased moisture content, and therefore decreased capillary permeability, have begun to restrict the frost induced liquid flow to the colder segments of the column. The over-all net flow of liquid towards the cold

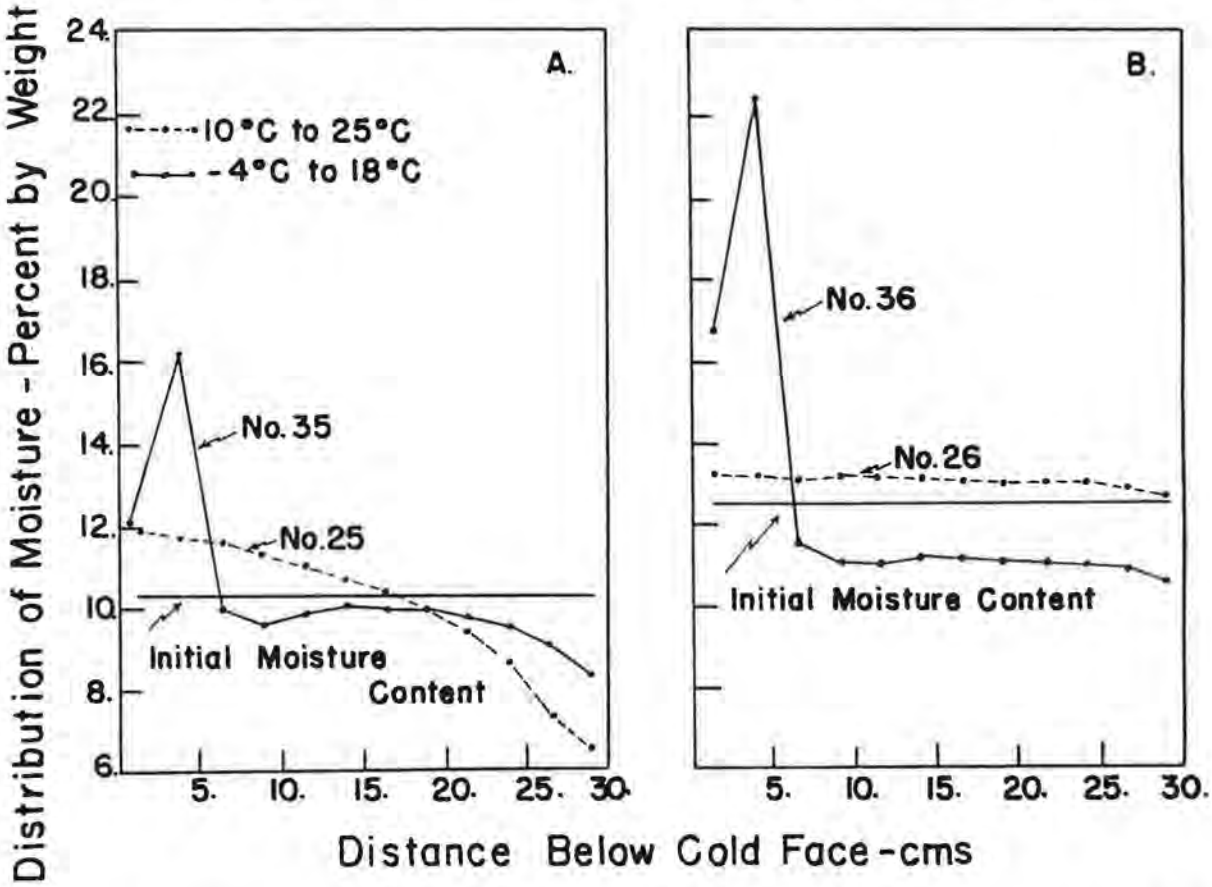

Figure 5. Distribution of moisture within two columns of loamy fine sand subjected to a temperature gradient from -4 to 18 C for 16 days.

face had previously masked the effects of net evaporation at the warm face.

In order to further investigate the influence of net evaporation on the movement of water in the liquid phase, two columns of loamy fine sand were prepared to initial moisture contents of 12.6 and 10.4 percent, respectively, and were subjected to a temperature gradient from -4 to 18 C for 16 days. The net distribution of water, as determined by sampling at this time, is illustrated for these two initial moisture conditions by the data for columns 35 and 36, Figures 5A and B. The moisture distribution data for two other columns prepared to the same initial moisture contents, but which were exposed to a temperature gradient from 10 to 25 C until a condition of zero net transfer of moisture was attained, are also presented for purposes of comparison.

The initial moisture content in column No. 36 was approximately two percent above the 3/10 atmosphere percentage (Table 1). Since the capillary permeability would be relatively high at this moisture content, it is quite likely that, in the early stages of exposure to the temperature gradient, the moisture was flowing in both the liquid and vapor phases from the warmest to the coldest regions; the direction of liquid flow having been reversed in comparison to that of column No. 26 as a result of the frost induced pressure gradient, towards the cold face, within the liquid phase. As the mean moisture content was reduced, and therefore the capillary permeability, the frost-induced liquid flow would be restricted to the colder regions of the column. This is indicated by the comparative depression of moisture content in the region between 7 and 14 cm in column No. 36. When the over-all net flow of liquid towards the cold face had ceased to affect the warm half of the column, the influence of net evaporation on liquid flow became apparent. This is indicated by the slight depression of moisture content in the warmest segment between 27 and 30 cm, which has also initialed a small pressure gradient within the liquid towards the warm face in the region between 20 and 27 cm. At the time of sampling, the moisture content was uniform between 13 and 20 cm in column No. 36. This indicates that, by this time, liquid was no longer flowing from the warm half of the column towards the cold face. At this stage, it must be assumed that there was still an over-all unsteady state diffusion of water vapor from the warmest to the coldest segments, with a small net condensation occurring in every intermediate segment. The net evaporation within the region between 27 and 30 cm has also initialed a flow of liquid into the evaporation sink, as indicated by the small moisture gradient, and therefore moisture tension gradient, from 20 to 27 cm. Within the cold half of the column liquid was flowing along a moisture tension gradient from 13 cm towards the freezing zone.

At the time of sampling in column 36, the mean moisture content between 5 and 30 cm was approaching the initial moisture conditions of column No. 35. The sequence of events that occurred within column No. 35 during the period of exposure to the temperature gradient from -4 to 18 C could be considered to be similar to those which would have occurred if column No. 36 had been exposed to these temperature conditions for a much longer time period. The moisture distribution at the time of sampling as shown in Figure 5A for column No. 35, illustrates very well the beginnings of the pronounced parabolic distribution of moisture which was characteristic of that found in the clay loam column No. 31, Figure 4C.

The decrease in moisture content in the region between 14 and 18 cm in column No. 35 was due to flow in the liquid phase towards both the cold and warm faces. Within the warm half of the column, water had been flowing in the liquid phase along the pressure gradient into the evaporation sink of the warmest segments between 25 and 30 cm. From this latter region the water then diffused as vapor towards the coldest regions of the column, and into the freezing zone. Within the cold half of the column the loss of water has been due entirely to flow within the liquid phase under the influence of the frost induced pressure gradient. Since the temperature gradient conditions were very nearly linear throughout the time of exposure of column No. 35, the foregoing explanation is the only possible mechanism by which the moisture content within the central regions of the column could have been depleted below initial conditions. Previous investigators (10, 38, 44) have postulated that the return circulation of liquid, in opposition to vapor flow, was due entirely to net condensation within the coldest regions of the column, and at the cold plate. However, it is only logical to conclude that, if net con-

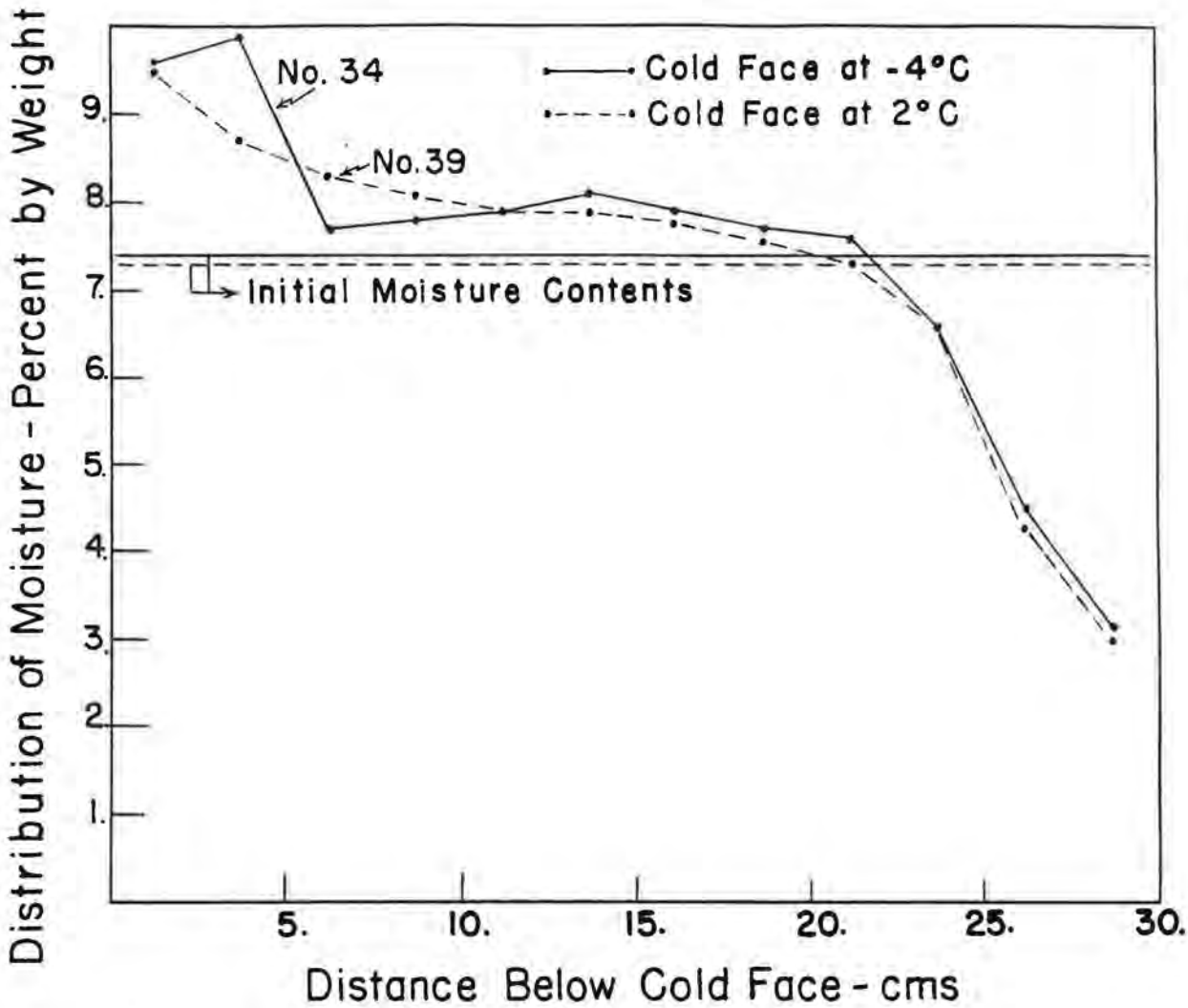

Figure 6. Comparison of moisture distribution within two columns of loamy fine sand subjected to temperature gradients of -4 to 18 C and 2 to 21 C for 16 days.

densation can induce a pressure gradient from cold to warmer regions, net evaporation within the warmest region should also induce a return flow of liquid from adjacent regions into the evaporation sink. The distribution of moisture obtained in soil columns where the cold circulation system was inhibited by frost action would appear to confirm this theory. This latter system will be designated as the warm circulation system; it will not be as active as the cold circulation system since it is associated with a general decrease of water content, and therefore of capillary permeability.

The data of Gurr, Marshall, and Hutton (10) also indicate that a warm circulation system, induced by the net evaporation within the warmest segments of the column, was functioning during the early stages of redistribution of moisture within soil columns exposed to a temperature gradient. The existence of two maxima and two minima of chloride concentration as illustrated in Figure 2 of their published data can only be explained by this mechanism. If these columns had been examined at the end of two or three days, instead of five days, the depletion of chloride within the region between 5 and 7 cm would have been more pronounced, at least in those columns which had an initial moisture content above 7.9 percent. This explanation would also account for the apparent flow of water in the liquid phase at very low moisture contents.

In order to minimize any discrepancies which might be attributed to the wide differences in temperature conditions in the previous comparisons between comparable soil columns exposed to temperature conditions of 10 to 25 C and -4 to 18 C, some further studies were conducted. Soil columns of similar initial moisture contents were exposed

to temperature conditions of -4 to 18 C and 2 to 21 C for 16 days. Figure 6 shows the comparative distribution of moisture at the end of 16 days exposure to the respective temperature gradients within two columns of loamy fine sand. Column No. 34, which was subjected to freezing temperatures within the coldest segments, had an initial uniform moisture content of 7.4 percent. The initial moisture content of column No. 39, which was exposed to cold plate temperatures just above freezing, was 7.3 percent. These moisture distributions may also be compared to the loamy fine sand column of Figure 3C which had an initial moisture content of 7.5 percent, and which was exposed to cold and hot plate temperatures of 10 and 25 C, respectively, for 44 days. This latter column had reached a stable distribution of moisture before sampling time. The data for column 39 therefore represents an intermediate stage in the sequence of redistribution of moisture under non-freezing conditions, since continued exposure to the temperature gradient produced a moisture distribution very similar to that shown for the comparable column in Figure 3C.

The very close relationship of the induced moisture distributions within the warm halves of columns 34 and 39 indicates that the operating mechanisms of water transport must have been identical. The small net accumulation of moisture in the regions between 10 and 20 cm in both columns could only have occurred as a result of condensation of diffusing water vapors, during an unsteady state diffusion. The distribution of moisture, and therefore of pressure gradients within the liquid phase, eliminates the possibility that there has been any transfer of water in the liquid phase from the warmest to the coolest regions. The existence of independent cold and warm circulation systems is also confirmed by a comparison of moisture distribution between the two columns in the regions from the cold plate to 10 cm and from 15 to 30 cm, respectively. It must be assumed that, at the time of sampling, water must have been flowing in the liquid phase within column No. 39 from the cold plate to a depth of 10 cm. This flow was inhibited in column 34 due to the freezing conditions which retained all of the condensed vapors as ice. Within the warm half of both columns, water must also have been flowing in the liquid phase from within the region between 15 and 23 cm into the net evaporation sink between 23 and 30 cm.

If column No. 39 had been exposed to the temperature gradient for a longer period of time, the net evaporation sink would have extended above the 23 cm zone, and eventually the cold and warm circulation systems would have merged to give a continuous flow of liquid from the cold face back to the evaporation sink. It must be assumed that these conditions are established within the stable system at the time of sampling of the loamy fine sand column of Figure 3C which had an initial uniform moisture distribution of 7.5 percent. Within all the segments above the 18 cm depth in this column, it is assumed that liquid and vapor flow were equal in magnitude and opposite in direction.

The comparisons discussed in the preceding sections would appear to confirm the fact that moisture transfer from warm to cooler regions within the soil, when a condition of unequal temperature exists, would appear to take place largely within the vapor phase. Either net condensation, or net evaporation, may induce a flow of liquid in the opposite direction to the vapor flow. The relationship between moisture content and capillary permeability will determine the magnitude of the induced moisture gradient, and therefore moisture tension gradient, which must be created before any appreciable flow in the liquid phase will occur.

The existence of a warm circulation system was indicated earlier by Preston (32). Cold circulation systems have been described in other types of porous materials by other workers (17, 20).

THE CHARACTER AND MAGNITUDE OF VAPOR DIFFUSION

Very little experimental data are available for the prediction of the magnitude of vapor diffusion within the soil. Penman and Schofield (28) applied Penman's equation (29, 30) to the calculation of the magnitude of vapor diffusion through the soil when an unequal condition of temperature exists. They indicated that it was of very little consequence. More recent evidence however indicates that such calculations may be considerably in error (10, 38, 44). It is of interest therefore to examine the apparent

coefficients of vapor diffusion, and the nature of the diffusion process, within some of the soil columns in which the flow of moisture from warm to cold regions was known to have occurred within the vapor phase.

In a number of instances, such as columns 34 and 39, Figure 6, the columns were sampled after a relatively short exposure to the temperature gradients, and well before a condition of zero net flow had been attained. It was quite evident, as was pointed out in the case of column No. 39, that the moisture accumulation within intermediate segments must have occurred as a result of condensation accompanying an unsteady state diffusion of water vapor. The data from a number of such columns were selected for a study of the apparent coefficients of vapor diffusion. The segment of each column which was still at the initial moisture content, at the time of sampling, was chosen as the one across which vapor diffusion rates were calculated. The data were all selected from columns in which it was well established that the liquid flow from the cold face had not affected the moisture status of any segment of the warm half of the column. The total of accumulated moisture within regions colder than the segment selected for analysis, should then represent the total of diffused vapors which had passed through the segment.

The coefficients of vapor diffusion were calculated by the equation for steady state, undirectional flow of vapor (29), where a linear gradient of concentration exists between vapor concentrations $\overline{C_1}$ and C_2 at a distance dX apart. Therefore:

$$\frac{dQ}{dt} = D\,A\,\frac{dc}{dX}$$

Q/A = total vapor diffused in time t, through a unit of cross-sectional area, expressed as gm per sq cm;
D = coefficient of vapor diffusion as sq cm per sec;
c = volume concentration of vapor as gm per cu cm; and
X = distance across segment, normal to the concentration gradient.

The vapor concentration gradients were calculated on the assumption that the soil moisture vapor pressures were approximately equal to the vapor pressure of free pure water at the respective temperatures. All columns studied had an initial moisture content well above the permanent wilting percentage. Even though the vapor pressures are slightly in error as a result of this assumption the calculated gradients of vapor concentration should not be affected to the same degree. It should also be noted that all evidence indicates that the vapor diffusion was an unsteady state condition. However,

TABLE 4

COEFFICIENTS OF VAPOR DIFFUSION, UNDER VARIOUS CONDITIONS, FOR THE SEGMENT OF EACH COLUMN WHICH REMAINED AT THE INITIAL MOISTURE CONTENT DURING EXPOSURE TO A TEMPERATURE GRADIENT

Texture	LFS	LFS	LFS	VSL	VSL	VSL
Air-filled pore space, percent	39.8	40.4	39.6	37.3	37.7	38.2
Mean temperature of segment, C	13.5	17.3	11.5	13.4	17.4	10.7
Average temperature gradient in column, 9C/cm	0.65	0.79	0.67	0.63	0.81	0.53
Moisture content, percent	7.3	6.3	7.4	7.8	7.5	13.4
Total diffusion, gm/cm^2	0.26	0.32	0.26	0.26	0.27	0.22
Coefficient of diffusion, cm^2/sec	0.41	0.34	0.42	0.39	0.33	0.40
Cold and hot plate temperature, C	2 + 21	2 + 27	-4 + 18	2 + 21	2 + 27	1 + 16

the coefficients calculated from the steady state equation should still represent conditions across that plane segment of the column at which the vapor concentration gradient was equal to the one used for the calculations shown in Table 4.

The calculated coefficients of vapor diffusion, together with other data characterizing the temperature and air-filled pore space conditions, are shown for six columns of very fine sandy loam and loamy fine sand in Table 4. The six columns had approximately the same percent air-filled pore space, and were exposed to temperature gradients of from 2 to 21 C, 2 to 27 C, and -4 to 18 C. There is remarkably close agreement between all columns in which the mean temperature conditions were similar, the coefficients varying from 0.39 to 0.42 sq cm per sec. The two columns exposed to the higher temperature gradient from 2 to 27 C showed a marked decrease in the magnitude of the coefficient of diffusion.

It should also be noted here that coefficients were calculated for the clay loam columns No. 41 and 44, Figure 2. The calculated coefficient of vapor diffusion for conditions within column No. 41 was 0.36 sq cm per sec. Using this calculated coefficient, it was estimated that if column No. 44, which was prepared to the same initial moisture content, was exposed to a temperature gradient from 2 to 27 C for 13 days it should give approximately the same distribution of moisture. This calculation was based on conditions at the 20 cm plane within the column. It can be seen from the distributions of moisture that the total of diffused vapors was very similar to that of column 41. The calculated coefficient of vapor diffusion for column No. 44 was 0.34 sq cm per sec.

The coefficients calculated for the clay loam columns differed quite widely from those calculated for the loamy fine sand and very fine sandy loam columns under similar temperature conditions. They were approximately 20 percent lower. It has been suggested by other workers that vapor diffusion characteristics within granular structured soils may cause deviations from the observed vapor diffusion coefficients for single grain soils.

The calculated coefficients of vapor diffusion, based on conditions at the 20 cm segment, for columns 34 and 39, Figure 6, were 0.42 and 0.41 sq cm per sec, respectively. On the assumption that liquid flow had not appreciably affected conditions at the 11 cm plane, and that the total of accumulated moisture between 11 cm and 20 cm was due to unsteady state condensation, coefficients of vapor diffusion were also calculated for temperature conditions at the 11 cm plane. The total diffused vapors were calculated from the moisture accumulations between the cold plate and the 11 cm depth. These coefficients agreed very closely with those calculated at the 20 cm plane and were 0.43 and 0.41 sq cm per sec, respectively.

The accumulated moisture between the 11 cm and 20 cm planes of columns 34 and 39 was considered to be due to the fact that the vapor concentration gradient was not a linear function of temperature. Accordingly, coefficients of vapor diffusion were calculated from the unsteady state diffusion equation:

$$\frac{dQ}{dt} = D\ A\ \ d^2c/dX^2\ dX$$

where Q in this case was calculated from the total of accumulated vapors between 11 and 20 cm. It was then assumed that all of these accumulated vapors had condensed within a small segment across which d^2c/dX^2 was equal to the rate of change of the vapor concentration gradient as expressed by the difference between the gradients calculated for the 21 cm and 11 cm planes, respectively. The calculated coefficients using this latter equation, and based on conditions within columns 34 and 39, were 0.44 and 0.42 sq cm per sec, respectively. This would appear to confirm the fact that the major movement of water from warm to cold regions of soil columns exposed to a gradient of temperature does occur within the vapor phase, and that where the temperature gradient conditions are nearly linear, the diffusion of vapors is an unsteady state condition which produces a small net condensation within every intermediate segment of the column between the evaporation sink and the net condensation sink near the cold plate.

The observed coefficients of vapor diffusion for all the columns studied were from six to eight times greater than those calculated from the relationship proposed by

Penman (29, 30); D/Do = 0.66S, where Do is the coefficient of vapor diffusion in air at the appropriate temperature, S is the fraction of air-filled pore space, and 0.66 is a constant which corrects for the increased length of the diffusion path resulting from the tortuous nature of the pore space.

It should be noted that Penman's relationship for calculating diffusion of gases and vapors through the soil was derived from experimental conditions where gases and vapors were used which had no appreciable thermal reactions with the solids, or liquids, of the soil system. In addition, the experimental conditions imposed a linear gradient of gas, or vapor, pressure throughout the system. In the case of water vapor diffusion through the soil it is only under very special circumstances that there will be a linear gradient of vapor pressure; and under all moisture conditions an appreciable exchange of heat will accompany the evaporation, condensation or adsorption of vapors. The total exchange of heat involved in these processes will be due to (a) the latent heat released or absorbed during condensation or evaporation of vapors, which will always be present, and its magnitude will be directly related to the quantities of water involved; and (b) the heat of wetting arising from the interactions between the water and either the surfaces of the solid or the surfaces of the liquid in the capillary pores.

Henry (14, 15) has analysed the conditions of both heat and vapor transfer through porous media in which there is a coupled diffusion resulting from the interactions between the porous media and the diffusing vapors. His conclusions may be summarized as follows: the observed diffusion coefficients, where coupled diffusion occurs, are always such that one is greater and the other less than they would be if they occurred independently. The faster diffusion rate, which may be either for heat or for moisture, may be many times the "isothermal diffusion constant" for moisture or the "constant vapor concentration, diffusion coefficient" for heat, whichever is the smaller. This may explain the deviations between the observed coefficients of water vapor diffusion in these experiments and those calculated for the same conditions from Penman's relationship. This may also explain the reasons for the marked depression of the observed vapor diffusion coefficients, as shown in Table 4, for the columns subjected to hot and cold plate temperatures of 2 and 27 C, respectively. Under these latter temperature conditions the unsteady state condensation would be markedly increased as compared to that which occurred within the columns subjected to temperature gradients from either 2 to 21 C, or -4 to 18 C. There is need for a good deal of further study and analysis of the characteristics of the diffusion of water vapors through soil, and other porous media, in relation to both temperature and moisture conditions.

SUMMARY

Qualitative and quantitative data have been presented to illustrate the character and magnitude of thermally induced moisture flow within unsaturated soils, with particular reference to soil moisture conditions characteristic of moisture tensions in excess of 0.1 atmospheres.

The comparative data obtained from the exposure of relatively large soil columns to temperature gradients which were calculated to give similar conditions of vapor pressure distribution, but which produced both freezing and non-freezing conditions adjacent to the cold plate, would indicate the following conclusions with regard to the character and magnitude of thermally induced moisture flow within the soil:

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2. If soil moisture conditions are below the permanent wilting percentage, small changes in moisture content will produce a large change in the vapor pressure of soil water. An equilibrium of vapor pressure conditions can be attained by a relatively small net diffusion of water vapor from warm to cold regions of the soil.
3. When soil moisture contents are above those characteristic of the permanent wilting percentage, the induced conditions of vapor pressure gradient will be such as

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3. When soil moisture contents are above those characteristic of the permanent wilting percentage, the induced conditions of vapor pressure gradient will be such as

to create an unsteady state diffusion of water vapor from warm to cold regions, and since the soil-water vapor pressures are very close to the saturation vapor pressures at similar temperatures, the condensation of vapors will produce no change in vapor pressure conditions; and the evaporation of water will only affect the vapor pressure conditions if the soil moisture content is reduced below the permanent wilting percentage within the evaporation zone. In the initial stages of vapor flow, there will be a net evaporation within the warmest segments, and a maximum of condensation within the coldest segments due to the presence of the cold plate. Every intermediate region will show a small net condensation of water vapor due to the unsteady state diffusion; the magnitude of the latter condensation will be greatest within the warmest parts of the soil adjacent to the net evaporation sink. The magnitude of the unsteady state condensation will also be closely related to both temperature gradient and mean temperature.

4. Since the temperature-induced gradients of pressure within the liquid phase will be extremely small, the net condensation and net evaporation will induce a pressure gradient within the liquid phase and will create a flow of liquid in opposition to the vapor diffusion within both the warmest and coldest regions. These systems have been designated as the warm and cold circulation systems, respectively, and under certain conditions they may operate independently within the respective regions of the soil. In the absence of a cold plate, or any other feature which might initiate a zone of net condensation, a considerable readjustment of moisture distribution could occur, within relatively moist soils, under the influence of a net evaporation or warm circulation system. A zone of net evaporation will always be present within any soil at initial moisture conditions above the permanent wilting percentage, and within which an unequal distribution of temperature is characteristic.

5. Under soil moisture conditions in the vicinity of, and slightly above the permanent wilting percentage, a large gradient of pressure within the liquid phase will be required to initiate liquid flow from cool to warmer regions, since the capillary permeability will be very low. A condition of maximum moisture gradient will therefore be attained.

At soil moisture conditions approaching those characteristic of the 3/10 atmosphere percentage, the capillary permeability will be relatively much greater, and the magnitude of the vapor diffusion will be somewhat reduced due to the decreased content of air-filled pore space as compared to moisture conditions near the permanent wilting percentage. The cold and warm circulation systems will merge, and a continuous flow of liquid will occur from the coldest to the warmest regions, in opposition to vapor flow, under the influence of a relatively small pressure gradient within the liquid, and therefore with a relatively small gradient of moisture between the warmest and coldest regions. A state of equilibrium vapor pressure cannot be attained and a continuous circulation of soil moisture will take place with liquid and vapor flow being equal in magnitude, but opposite in direction, within every segment.

6. The conditions described above will be responsible for the parabolic relationship observed between net moisture movement under the influence of a thermal gradient and the mean moisture content of the soil.

7. For moisture conditions above the permanent wilting percentage, the observed coefficients of vapor diffusion were from six to eight times greater than those calculated from known relationships for isothermal conditions. The magnitude of the observed coefficient appears to be affected by temperature, gradient of temperature, and the structural nature of the soil.

8. Frost-induced pressure gradients within the liquid phase will not cause any appreciable flow of water when soil moisture conditions are drier than those characteristic of moisture tensions in the vicinity of one atmosphere.

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