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ANNUAL REPORT FOR 1967
TO THE
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OF
BIOLOGY AND MEDICINE
VOLUME II: PHYSICAL SCIENCES
PART 4. EARTH SCIENCES**

OCTOBER 1968

**AEC RESEARCH &
DEVELOPMENT REPORT**

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ANNUAL REPORT FOR 1967
to the
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VOLUME II: PHYSICAL SCIENCES
Part 4: Earth Sciences

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These reports are drawn principally from personnel of the Earth Sciences Section of the Environmental and Radiological Sciences Department. Contributions and co-authors from other organizations as well as occasional related activities not sponsored by the Division of Biology and Medicine may also be included. Such facts are acknowledged by footnotes.

PACIFIC NORTHWEST LABORATORY
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Part 4: Earth Sciences

LANDSLIDES IN THE PASCO BASIN, THEIR CAUSES AND SIGNIFICANCE

R. E. Brown

INTRODUCTION

Landslides traditionally are considered to be "triggered" by earthquakes owing to the occurrence of spectacular slides during major earthquakes. Recent work, however, emphasizes the importance of moisture in inducing sliding even with major earthquakes. The slides then are but permissive evidence of quakes and the earthquake history of a region cannot be deduced solely from the number of slides. Specific reasons for sliding must be determined where possible by careful study rather than by merely assuming a cause for which other evidence is lacking.

DISCUSSION

Landslides in the Pasco Basin commonly occur on the steep, north-facing slopes of the asymmetrical anticlines. Faults, postulated along some of those steep faces, partly because of the presence of slides, thus lead to the conclusion that earthquakes may have occurred because they are common denominators of both features.

Detailed geologic mapping compared with earlier work disclosed that existing faults are secondary features of limited extent and small offset.⁽¹⁾ Some areas previously considered as slides turned out to be areas of overlap of *en echelon* anticlines where the so-called slide was a tilted plateau-like area of locally sharp and complex folding, irregular erosion and only local sliding.

Glacial Lake Missoula floodwaters, 10,000 to 20,000 years ago, evidently initiated the large Corfu slide on the Saddle Mountains by repeated impact against and erosion of the steep north face of the Saddle Mountains.⁽²⁾ The presence of Lake Missoula at the lower end of the Drumheller Channels, a major scabland channel, is confirmatory. Rapid changes in water levels from at least three floods⁽³⁾ down the Drumheller Channels provided a positive mechanism for slides, whereas only the 1918 Corfu earthquake has been recorded in the area in the last 100 years. Maintenance records of the Chicago, Milwaukee, St. Paul and Pacific Railroad show no evidence

of significant problems resulting from many years of railroad travel across the slide area. Recent irrigation activities, however, are clearly causing abundant sliding in clay-rich Ringold Formation sediments in the general area, without earthquake activity.

Comparison of bonafide slides with the Corfu slide shows numerous similarities: 1) similar positions on the steep, north-facing slopes of the anticlinal ridges, well exposed to the erosive action of the floods, 2) evidence of floodwaters well above the initial toes of the slides, 3) comparable soil development and topographic form of the slide surfaces that indicate an appreciable age. Contrasts in soil development and topographic form that are clearly related to the effects of irrigation and spring changes in river levels, are evident between Corfu and recent slides in the Columbia Basin Irrigation Project and between Corfu and the White Bluffs.

Geologic studies on the Project Arid Lands Ecology (ALE) Reserve are expected to provide further information on the causes and times of sliding. Study of sediment and contained spores and pollen, artifacts and fossils and their relationships to two volcanic ash beds of known origin and age should identify climatic changes related to the Altithermal period, their timing and possible magnitudes and effects.

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INDICATED LOW RATES OF TECTONIC DEFORMATION AND THE LOW SEISMIC ACTIVITY IN THE PASCO BASIN

R. E. Brown

INTRODUCTION

Seismic activity can be only indirectly related to the observed rates of tectonic deformation because earthquakes can and do occur in areas previously not tectonically

active. Earthquakes can originate at depths that preclude surface indications of tectonic deformation, including faulting. Moreover, rates of deformation are averages and integrations of many values and events over long time periods. Nevertheless,

low rates of tectonic deformation, particularly if repeatedly indicated over long time spans, well may be a key to low seismic activity.

DISCUSSION

Samples of coal from depths of 2100 to 4800 ft in the Rattlesnake No. 1 well contained spores and pollen that suggest a late Oligocene age for the included basalt flows⁽¹⁾ rather than the Miocene age preferred by some workers. The rate of emplacement of the basalts in the Pasco Basin, then, is probably nearly linear, from Eocene time perhaps 60,000,000 years ago to early Pliocene time about 10,000,000 years ago. Accumulation of more than 10,000 ft of stratigraphic section and to depths more than 10,000 ft below sea level beneath Hanford indicates steady, slow and continuous sagging of the Pasco Basin at rates averaging between 1 ft per 3000 and 5000 years. Today, the Elephant Mountain flow, the youngest and slightly less than 10,000,000 years old, lies 200 ft below sea level beneath Hanford, but higher than 3000 ft above sea level in the crest of the Rattlesnake Hills. Thus, the average rate of deformation following its emplacement is 1 ft per 3000 years. The rate is probably maximum because the Rattlesnake Hills are the highest in the area but arose only following the emission of that flow.

The basalt deformation also is indicated by the prehistoric courses of what became the Columbia River.⁽²⁾ Sedimentary beds between basalt flows

indicate that the stream periodically flowed through central Washington between the Pasco Basin center and the Yakima area, but not farther east. Its westward displacement from the Basin center was caused by the emission of basalt flows to the south, southeast and possibly east. As they advanced, they forced the river westward. Further basining returned the river to its more easterly courses.

The Ringold Formation records continued slow and progressive sagging of the Basin from probably early Pliocene time to about the beginning of Pleistocene time. Deformation of that formation is progressively less upward,⁽³⁾ indicating simultaneous deposition and deformation, but without discernible angular unconformities of more than very local extent, which could suggest more sudden events.

Deformation evidently continued to Recent times as indicated by low-angle dips in very fine-grained sands and silts of the glaciofluvial sediments. The youngest Touchet beds of those sediments are about 10,000 years old as determined by relationships to the 11,000 to 12,000 year old Glacier Peak ash, now identified at numerous sites on the Project ALE Reserve and elsewhere. The magnitude of the dips, parallelism to the underlying basalt, and local divergence from dip directions expected from the direction of currents depositing them suggest tilting since deposition.^(4,5)

Work at Wallula Gap has shown the virtual, if not complete, absence of

faults hypothesized by others. Because the Gap lies at a long-term structural low, which localized the Columbia River there, and where significant fault offset did not occur, the average rate of uplift should be markedly lower than in the Rattlesnake Hills. Based again upon uplift of the Elephant Mountain flow, the rate is about 1 ft per 17,500 years. The rates are slightly greater if the Horse Heaven Hills at Wallula Gap began to rise appreciably later, rather than slower, than elsewhere. The suggested very low rate, in turn, does not appear to support faulting of the magnitude that has been proposed at Wallula Gap.

Anticipated studies on Project ALE Reserve should add considerable knowledge as to rates and time of deformation because of the presence of volcanic ash beds of known ages at key sites adjacent to the high anticlinal ridges of Yakima Ridge and Rattlesnake Hills.

Evidence uniformly suggests low rates of tectonic deformation, lower by one or more orders of magnitude than those rates observed in California on faults with which earthquakes are associated. Coupled with a lack of surface faults of meaningful displacement and a lack of landslides that logically can be attributed only to earthquakes, the

sum total of evidence suggests a minimal past significant seismic history. This is in keeping with the low incidence of recorded earthquakes compared to that in the Puget Sound area, the Rocky Mountains, and even the Okanogan Highlands.

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GEOPHYSICAL EVALUATION OF A THICK BASALT SEQUENCE
IN SOUTHCENTRAL WASHINGTON*

J. R. Raymond

A deep stratigraphic test well - Rattlesnake Hills Number One - was drilled for the Standard Oil Company of California during 1957 and 1958. The 10,655 ft deep well is located in Section 15, Township 11N, Range 24E in Benton County, State of Washington. The objective of the drilling was to penetrate the thick Columbia River basalt and interbed series near the Columbia Basin center and near the axis of a major anticlinal ridge (Rattlesnake Hills). Knowledge of rock types and structure underlying the basalt would be expected to determine the feasibility of further petroleum exploration, but the basalt was not penetrated at the completed well depth. Since the basalt series itself was of secondary interest, only cursory studies and examinations of the rocks were made: ditch sample visual examination, standard "E" log, dipmeter log, gamma and neutron logs, and some vertical and side-hole coring. Reopening of the well has allowed a much more thorough study of all aspects of the rocks in this deep and significant section.

Reopening of the Rattlesnake Hills Well (Figure 1) provided access again to one of the world's thickest basalt sections and an opportunity for detailed study of the section by use of down-hole geophysical methods. The principal purpose of the investigation was to measure the geological and hydrological characteristics of the basalt section that are pertinent to radioactive waste storage considerations. A secondary but very valuable benefit was the opportunity to determine some of the physical properties of the lower basalt sequence that is not exposed for visual examination or penetrated to this depth at any other location.

Three separate operations were involved in the Rattlesnake Hills test well evaluation work: 1) well re-entry, cleanout and fluid conditioning; 2) geophysical logging; and 3) drill-stem testing for hydrologic information.

The Rattlesnake Hills Well No. 1 is located on the southwest flank of the Pasco Basin in southcentral Washington. The Pasco Basin is a present and long-standing structural low near the center of the much larger Columbia Basin geologic and physiographic province; the latter encompasses nearly all of southeastern Washington, parts of northeastern Oregon and western Idaho with an areal extent of about 200,000 square miles. The Columbia Basin province may be characterized as essentially a downsagging basin filled by at least three varieties of tholeiitic basalt. The basalts have been downwarped to a maximum of 200 ft below sea level in the Pasco Basin and covered by subsequent fluvial, lacustrine, eolian, glacial outwash and scabland deposits. The upper surface of the basalt stands from 2000 to 5000 ft above sea level on all parts of its periphery. At the end of the period of extrusion, the basalts in the Columbia Basin must have had the form of a

* Work supported by the USAEC Division of Reactor Development and Technology.

FIGURE 1. General Geology Map of Washington

great planoconvex lens with its upper surface nearly flat, and its bottom surface curved. The thickness of this lens can only be conjectured for nowhere except along the uplifted margins of the basin has erosion bitten deeply enough to expose the floor upon which the first basalt was poured. All available evidence indicates that the basalt thickens rapidly toward the center of the plateau. The Rattlesnake Hills Well bottoms in basalt at a depth of 10,655 ft and is the only well to make a significant penetration below the 3000 to 4000 ft of basalt exposed on the surface.

The objective of the geophysical work was to obtain definitive information on the characteristics of the thick basalt - basalt interbed series.⁽¹⁾ The logging program was selected to provide information on the following parameters: basalt flow and interbed thickness, formation resistivities, spontaneous potential, formation density, formation porosity and permeability, mud invasion and mud cake thickness, hole size variations, nature of the pore fluid (saline or fresh water), side-hole core samples, bore-hole temperature at depth and formation seismic characteristics. Ten different wire-line logging tools were utilized to investigate the well: Dual induction-laterolog-8 (DIL); Microlog; Compensated formation density log (CFD); Sidewall neutron porosity log (SNP); Borehole compensated sonic log (BCS); Sonic amplitude - variable density log; Caliper log; Spontaneous potential

(SP); Temperature log; and Side-wall coring.

All of the log functions except the SP curve show clearly the basalt flows and interflow zones. The basalt is defined by high resistivity, high density, low porosity and low sonic transit time. Conversely, the interflow zones are characterized by low resistivity, low density, high porosity and high sonic transit time. A number of transitional or gradational sections were encountered where log functions were intermediate. Temperature gradients in the well varied from 0.8 to 3.5 °F/100 ft, with an average of about 1.5 °F/ft. In general, the higher gradients existed at greater depths.

Water quality studies and drill-stem tests showed that there is a high degree of formation water isolation between major sections penetrated by the well. The drill-stem tests also indicated that formation water pressure decreases with depth.

Log examination showed 92 identifiable basalt flows and 89 interflow zones. A highly altered and weathered complex zone exists from 4950 to 6800 ft in the well; within this complex zone, flows and interflow zones generally could not be differentiated. The basalt flows average about 68 ft in thickness and the interflow zones average about 22 ft in thickness. Table I shows the number and average thickness of basalt flows and interflow zones per thousand feet of depth increments. Both the basalt flows and interflow zones are thicker immediately below the 5000 to 7000 ft complex. It is

*TABLE I. Depth, Number and Average Thickness
of Basalt Flows and Interflow Zones, Rattlesnake
Hills Test Well*

<u>Zone, ft</u>	<u>Number of Basalt Flows</u>	<u>Average Thickness, ft</u>	<u>Number of Interflow Zones</u>	<u>Average Thickness, ft</u>
1000-2000	14	55.3	15	13.7
2000-3000	11	72.9	10	20
3000-4000	10	75	10	21.8
4000-5000	15	45.7	15	19.7
Complex weathered and altered zone from 5000 to 7000 ft				
7000-8000	7	101.6	7	30.3
8000-9000	7	86.7	7	37.2
9000-10,000	11	52.9	11	25.6

hypothesized that the Columbia River basalt series terminates at the top of the complex zone at a depth of about 5000 ft in the Rattlesnake Hills Well. The deep flows, at least in part (from the vertical core thin-section analyses), are andesites rather than basalts.

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PALYNOLOGY AND ITS PALEOECOLOGICAL APPLICATION IN THE PASCO BASIN*

D. D. Tillson

The record of past plant communities provided by the fossil pollen and spore content of sediments is useful in the study of environmental and climatic changes. A reflection of major ecological, evolutionary,

geological and archeological events can be found in changes in the pollen stratigraphic record. Although not all sedimentary deposits contain fossil pollen, a given sedimentary deposit is more likely to contain such microfossils than to contain any other type of plant remains. The chemically resistant outer walls of

* Work supported by USAEC Division of Reactor Development and Technology.

pollen and spores make them the most abundant fossils of terrestrial origin.

As with any discipline, certain problems arise in palynology that may limit the usefulness of the method under specific circumstances. The most obvious consideration is the problem of long distance transport of pollen. An example is the pollen of the Southern Hemisphere beech, Nothofagus, which has been found in postglacial-age peat of Tristan da Cunha, a remote island in the South Atlantic, 4500 km east of the nearest beech forests in South America.⁽¹⁾ Such long-distance transport introduces exotic pollen into different climatic and vegetation zones. Experience, however, has shown that in general this foreign pollen does not obscure the local pollen rain, which as a rule drowns out the fraction of pollen brought from greater distances. A second problem is indigenous to areas of extreme relief, where a small but significant amount of pollen from particularly abundant pollen-producers may drift from one vegetation zone into another. Another more subtle source of error in ecological interpretation of pollen counts is contamination by pollen from older deposits. In arid regions, it is often the case that a large portion of postglacial climatic and prehistoric fossil records can be found in banks of sediments exposed in dissected floodplains (arroyos).⁽¹⁾

Notwithstanding these problems, and a few more of lesser significance, the ALE Reserve within the Hanford Project and the Pasco Basin

presents a near unique set of conditions for the application of palynology and the study of paleoecology. The area which essentially covers all of southcentral and southeastern Washington and part of northeastern Oregon is briefly described as a large closed basin that has been slowly subsiding since early Tertiary (50 to 60 million years) up to and possibly including the Recent period. The basin is filled with over 90 successive basaltic lava flows to a depth of greater than 10,000 ft beneath the ALE lands. The last flow to have been extruded caps most of the higher topographic features and is thought to have been poured onto a near-level surface some 2 to 5 million years ago. Interbedded between the lava flows are weathered basalts, tuffs, and some sediments. Since each lava flow represents a discrete period of time, the interbed material, when present, is in essence a confined paleosystem. A study of the pollen and spore distribution within these confined systems provides a basis for the determination of evolutionary rates in geology, climatology, plant physiology, and ecology over extremely long periods.

A recently completed study of pollen assemblages found in coal seams interspersed between some of the basalt flows in the Rattlesnake Hills Well No. 1 on the south edge of the project illustrates the potential for this type of investigation.⁽²⁾ Eight separate samples were collected from coal seams that occur between 2000 and 5000 ft below the surface. Analysis of the pollen assemblages

recovered from all the samples indicates that the area was at that time (late Oligocene, 25 million years ago) very similar to the hardwood deciduous forest of today in the Cumberland Plateau in Tennessee. Several genera described from the Rattlesnake Hills Well samples have genera that survive today only in valleys of Central China. Figure 1 shows photomicrographs of some of the more common genera from those samples.

Overlying the basalt flows is a series of lacustrine and eolian deposits of Pleistocene (less than 1 million years) to Recent age. Within the confines of the ALE Reserve, two layers of ash also occur interbedded with the lacustrine sediments. These ash layers represent discrete occurrences in time, dated by carbon-14 as 6500 years BP and 12,000 years BP, and are the remnants from Crater Lake, Oregon (Mt. Mazama) and Glacier Peak, Washington volcanic eruptions. Additional ash layers (as yet not identified on ALE lands) present in other areas surrounding the Hanford project offer additional possible time entities for paleoecologic studies.

The principle of uniformitarianism assumes that fossil plant species and their living relatives have similar ecological requirements. Belief in this principle that the present is an ecological as well as geological key to the past is strengthened by the observation that the Cenozoic fossil flora assemblages seldom contain dis-

harmonious mixtures of genera. In order, then, to make any assumptions as to the paleoecology, a comparison of pollen rains with the composition of adjacent plant communities is a primary step. This type of comparison is impossible if the modern communities have been obliterated or greatly altered. For this reason, the ALE Reserve becomes even more important since the ecology has been essentially undisturbed. The first of a series of stations was established on the Hanford project specifically to collect airborne pollen and spores. The findings will be used to characterize the present ecosystem before proceeding into the paleosystem.⁽³⁾ Figure 2 shows examples of recent pollen collected at one of these stations on the Hanford project.

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Airborne Pollen and Fungus Spores, Miscellaneous Paper 61, Agricultural Experiment Station, Oregon State College, September 1958.

Osmunda Laevigatosporites Ulmus Conifer

FIGURE 1. *Oligocene-Miocene Fossil Pollen and Spores Recovered from Coal Cuttings, Rattlesnake Hills Well No. 1, Benton County, Washington*

Pinus Cedrus Phleum Plantago

320X

*FIGURE 2. Recent Pollen Collected at 200W Area, Hanford Project,
Benton County, Washington*

REGIONAL STRATIGRAPHIC RELATIONSHIP OF THE BASALT FLOWS
BENEATH THE PASCO BASIN AS INFERRED FROM GROSS CHEMICAL VARIATIONS*

D. D. Tillson

INTRODUCTION

A prime requisite in understanding the geologic framework of any area is a knowledge of the regional stratigraphy. This becomes even more desirable in an area such as Hanford where the ability to predict movement of wastes discharged to the ground is in direct proportion to the stratigraphic control available. Numerous wells drilled in the area penetrate only the basalt flows normally seen in surface outcrops. A geophysical evaluation of the basalt sequence in the Rattlesnake Hills Well No. 1 located on the south perimeter of the Hanford Project provided the first real insight into the subsurface stratigraphy below the level of outcrops in eastern Washington.

DISCUSSION

Previous attempts at correlation of basalts have generally been confined to individual basalt flows over a limited areal extent.⁽¹⁻⁴⁾ These correlations assumed that horizontal and/or vertical homogeneity existed in chemical, mineralogical, or physical composition when continuous outcrops were not available for sampling and analysis. Such assumptions were often necessary even though field

evidence from continuous outcrops showed this to be the exception rather than the rule. There were indications, however, that gross chemical homogeneity existed in a group or series of flows related in source, time, environment or in some combination of the three. This gross chemical composition would transcend the composition of any individual flow so that, once a gross regional relation were established, a subdivision into flow by flow units would become much more certain.

Spectrochemical data were available from the original well cuttings taken as random samples at 100-ft intervals in the Rattlesnake Hills Well No. 1. A statistical analysis of the content of eight major metal oxides (SiO_2 , Fe_2O_3 , Al_2O_3 , TiO_2 , MgO , CaO , Na_2O and K_2O) as they occurred singly or in one of 28 possible pair-combinations indicated five major changes in the chemical homogeneity. These changes were represented by statistically significant shifts in the mean ratios over zones of at least 1000 ft (Table I). A visual inspection of the plot of ratio versus well depth indicated that mean ratio shifts occur in the immediate proximity of 1600, 2600, 7700, 8400, and 9500 ft depths. A check of these results from the original cuttings became possible because of fifty sidewall cores taken at the time of reentry. Spectrochemical analyses were made on each sidewall

* Work supported by the USAEC
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TABLE I. Oxide Ratios Determined by Spectrographic Analysis of Ditch Samples, Means of the Ratios over 100 ft Intervals

Ratio	Shift 1	Shift 2	Shift 3a	Shift 3b	Shift 4
K/Na	0.584-0.422	0.422-0.529	0.628-0.434		
K/Ca		0.142-0.239		0.267-0.170	
Na/Ca		0.335-0.452			
K/Si		0.023-0.032			
K/Al		0.086-0.121	0.164-0.105		
K/Fe		0.090-0.132			
Na/Fe	0.174-0.213	0.213-0.249			
Ca/Si		0.162-0.134			
Ca/Al		0.609-0.510			
Ca/Fe		0.638-0.555		0.551-0.641	0.641-0.576
K/Ti		0.547-0.704			
K/Mg	0.301-0.223	0.223-0.384	0.471-0.288		
Ti/Na	1.28 -0.782		0.770-0.643		0.643-0.781
Na/Mg		0.525-0.725		0.738-0.588	0.588-0.678
Ti/Ca	0.376-0.260	0.260-0.335		0.336-0.256	0.256-0.327
Ti/Mg	0.661-0.409	0.409-0.548	0.575-0.416		0.416-0.529
Ti/Si	0.064-0.042		0.045-0.039		0.039-0.045
Ti/Al	0.232-0.158		0.201-0.155		
Ti/Fe	0.222-0.166		0.189-0.166		0.166-0.188
Mg/Si		0.104-0.084		0.081-0.097	0.097-0.085
Mg/Al		0.389-0.318		0.346-0.390	0.390-0.332
Mg/Fe	0.335-0.406	0.406-0.343	0.329-0.402		0.402-0.357
Fe/Si	0.292-0.255				

core and the results analyzed in the same manner as the original cuttings (ditch samples). Four shift-levels in chemical homogeneity were observed in the sidewall core data that coincided with the levels seen in the ditch sample data (Table II). In addition, one level of change suspected from the ditch sample data but not meeting the statistical criterion was found in the core samples. The depths found from the core sample data were 1700, 2700, 4300, 7700, and 8600 ft. The core sampling did not extend deep enough to confirm or deny the existence of the 9500 ft level apparently shown by the ditch samples.

Occurrences of coal seams between 2000 and 5000 ft provided a source of

fossil spores and pollens and a means of relative age dating. The pollen assemblages recovered from these coals described a system in time from early Miocene to late Oligocene (20 to 30 million years ago) and established a time stratigraphic reference on which to base the gross changes observed from the physical and chemical variability.

Studies of the logs of the various geophysical measurements* from the Rattlesnake Hills Well⁽⁵⁾ indicated that four discrete depths exist where changes could be observed visually in

* See J. R. Raymond, "Geophysical Evaluation of a Thick Basalt Sequence in Southcentral Washington," this report, pp. 5-8.

TABLE II. Oxide Ratios Determined by Spectrographic Analysis of Side-Wall Core Samples, Means of the Ratios over 100 ft Intervals

Ratio	Shift 1a	Shift 1b	Shift 2	Shift 3	Shift 4
Ti/Ca	0.425-0.269	0.269-0.307	0.307-0.383	0.383-0.323	
Ti/Mg	0.594-0.418	0.418-0.469	0.469-0.572	0.572-0.307	0.387-0.454
Ti/Si	0.071-0.041			0.044-0.034	
Ti/Al	0.294-0.185		0.195-0.201		
Ti/Fe	0.232-0.178	0.189-0.175	0.175-0.186		
K/Ca		0.149-0.203	0.203-0.326	0.326-0.334	0.334-0.214
Ca/Fe	0.547-0.700	0.670-0.573	0.573-0.495		
K/Mg		0.228-0.307	0.307-0.479	0.479-0.382	
Mg/Fe	0.395-0.462	0.449-0.381		0.337-0.407	0.407-0.342

the log characteristics. These levels are in fair agreement with those described from the chemical variations in the ditch sample and sidewall core data. A list comparing the levels defined by the three methods is given in Table III.

A composite of the three methods indicates that gross physical or chemical changes occur in the proximity of 1600, 2600, 4200, 7700, 8500, and 9500 ft depths. It is proposed that these zones represent either regional changes in the source of the basalt flows, gross regional changes in the conditions under which the flows were extruded, cooled and subsequently weathered or, most likely, a combination of these. A regional stratigraphic section depicting a working hypothesis inferred from these data is shown in Figure 1.

Samples from two additional wells* that have completely penetrated the

TABLE III. Zones of Homogeneous Response

Zones from Ditch Sample Data, ft	Zones from Side-Wall Core Data, ft	Zones from Geophysical Logs Data, ft
0-1650	0-1600	0-1600
1650-2650	1600-2700	1600-2600
	2700-4300	2600-4000
6900-7700	4300-7700	4000-7100
6900-8450	7700-8600	7800-9300
8450-9500	8600	

basalts are presently being analyzed using similar criteria in an effort to establish a regional subsurface stratigraphic picture for Eastern Washington.

* 1. Condon County, Oregon; Standard Oil Company of California, unpublished data.

2. Odessa, Washington; Basalt Explorer No. 1, unpublished data.

FIGURE 1. Regional Stratigraphic Section
Through Rattlesnake Hills Well No. 1

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GAMMA RAY ATTENUATION FOR SOIL WATER CONTENT
MEASUREMENTS USING ^{241}Am

L. G. King

The laboratory measurement of moisture content of soil samples by the attenuation of gamma rays is described with particular reference to the use of ^{241}Am as a source of photons. The ^{241}Am is compared with ^{137}Cs , and some advantages and disadvantages of each are pointed out. The major advantages of ^{241}Am over ^{137}Cs are that less biological shielding is required; the apparatus may be made smaller and lighter; there is greater sensitivity for small soil thicknesses (4.5 to 6 cm). Disadvantages of ^{241}Am are that special preamplification of the 60 keV signal is needed and that it is limited in application to small samples because of the soft gamma rays emitted. Laboratory results are presented showing the comparison of soil water content measured volumetrically with the content determined by attenuation of gamma rays from ^{241}Am . The sample was contained in a small cell where the moisture content was controlled by controlling the capillary pressure. The water was extracted through a saturated porous material and measured in a calibrated horizontal tube. Even with the rather poor agreement of these preliminary results, it is believed that the use of ^{241}Am in a properly designed apparatus will yield good measurements of soil moisture content.

The theory is well developed for describing the movement of water

through stable porous media under isothermal conditions. To use the

theory for prediction of water movement, the porous media must be characterized as to the relations between moisture content, capillary conductivity (or permeability), and capillary pressure (or suction); or desirable combinations of these variables. In the interest of rapidity and ease of measurement, a nondestructive method of obtaining the moisture content is desirable. For certain studies, a nondestructive method to determine the moisture content without disrupting the system may be essential. The absorption of gamma rays from a radioactive isotope provides the basis for such a method.

The idea of using the absorption of gamma rays to measure the density or thickness of material or, more specifically, the moisture content of porous media is not new but has existed for many years. Various isotopes have been used or suggested as sources of the gamma rays, including ^{60}Co ,⁽¹⁾ ^{137}Cs ,⁽²⁾ ^{55}Fe , ^{65}Zn , ^{75}Se , ^{109}Cd , ^{170}Tm , and ^{241}Am .⁽³⁾ Probably because of its limited availability to the public until 1962,⁽⁴⁾ ^{241}Am has not yet received wide attention. The most commonly used source for measurement of soil moisture content has been ^{137}Cs . Both isotopes have the desired property of emitting nearly monoenergetic photons in certain ranges of energy. The spectrum of ^{137}Cs shows a major peak at about 662 keV. The intensity of the peak is a factor of 100 greater than that of the valley between the peak and the Compton plateau characteristic of the Compton scattering within the NaI detector crystal.⁽⁵⁾ Such a peak is

well suited for absorption techniques using a pulse height analyzer.

The spectrum of ^{241}Am has a major peak at about 60 keV and on a scintillation detector shows a lower peak at about 26 keV. Actually, the lower peak is a combination of several events including L X-rays, 26.4 keV gamma ray, and the escape peak from the 59.6 keV gamma ray.⁽⁶⁾ Magnusson⁽⁶⁾ states that for the 59.6 keV gamma ray, the full width at the half-height is about 11 keV, and that the ratio of the peak height to the valley on the low energy side is about 100. Where the intensity of the 59.6 keV gamma ray is 0.359, he also reports gamma rays at 26.4, 33.2, 43.5, 99.0, and 103.0 keV with intensities of 0.025, 0.0011, 0.0007, 0.00023, and 0.00019, respectively. The very low intensities (3 orders of magnitude) of the 99 and 103 keV photons relative to the 60 keV energy of interest should not cause any significant error, even when an attempt is made to count the full spectrum. As a further precaution, the use of a thin NaI crystal will reduce the probability of interaction of the higher energy photons with the crystal. However, because of possibilities for interactions at the lower energies, it is recommended that a pulse height analyzer be used with the window set to detect the 60 keV peak.

The less energetic ^{241}Am requires substantially less biological shielding for operator safety than does the ^{137}Cs . Using the mass absorption coefficients⁽⁷⁾ for lead at photon energies of 60 and 662 keV gives the half thickness of lead as about 31

times greater for ^{137}Cs than for ^{241}Am . These differences emphasize one important advantage of ^{241}Am over ^{137}Cs ; that is, the apparatus can be made smaller, lighter, and less costly. The light weight is a distinct advantage when a stationary sample is traversed with a movable source and detector.

The radioactive decay is an important consideration in the selection of a source. Long half life compared to the duration of the measurements means that no corrections are needed to account for decay and that the source need not be replaced frequently. Both ^{137}Cs , with half life of 33 years, and ^{241}Am with 458 years are excellent with regard to radioactive decay.

The choice between ^{241}Am and ^{137}Cs for soil moisture measurement depends upon many factors. Some general comparisons may be made regarding sample size and sensitivity. It has been stated⁽⁸⁾ that for optimum absorption necessary for best precision, the transmitted beam should be between 13 and 37% of the incident beam. These limits may be relaxed somewhat to between 1 and 3 half thicknesses. If the errors are independent of the signal strength of the transmitted beam, the upper value is best; but if the errors are a function of the output signal, the lower value should be used.⁽⁸⁾ Since, however, for water content measurements, we are primarily interested in the differences in overall densities between saturated and dry soils, the effective half thickness for water as it exists in the pores of the soil is an important

value. For the relative values for ^{137}Cs and ^{241}Am , the effective half thickness for similar soil conditions reduces to the inverse ratio of the mass absorption coefficients for water. Thus, for similar soil conditions, the optimum thickness of water in the soil sample is about 2.3 times greater for ^{137}Cs than for ^{241}Am . If we consider the mass absorption coefficients for concrete from Grodstein⁽⁷⁾ to approximate the values for soil, we have $\mu_s = 0.267$ for ^{241}Am , and $\mu_s = 0.077$ for ^{137}Cs . Neglecting the air and sample container, and assuming a porosity of 0.5, a bulk density of 1.32 g/cm^3 , and dry soil gives half thicknesses of about 2 cm for ^{241}Am and 7 cm for ^{137}Cs . For completely saturated soil with the same assumptions, these values are about 1.5 cm for ^{241}Am and 4.8 cm for ^{137}Cs . Thus, if the values of 3 half thicknesses are used, the samples should be about 4.5 to 6 cm thick for ^{241}Am and 14.5 to 21 cm thick for ^{137}Cs . Although these estimates should be used only as rough guides, they do demonstrate that for smaller samples ^{241}Am gives greater sensitivity than ^{137}Cs ; i.e., greater relative change in count rate with change in saturation.

The required source strength also depends upon several factors. One important consideration is to maintain good counting statistics. The standard deviation is a function of the total counts and a measure of the precision of any one count, N , is $N \pm \sqrt{N}$. Thus, it is desirable to balance the geometry of the design with desired counting time and source

strength to give high total counts, N . For any considerations of source strength, the small effective solid angle resulting from proper collimation must be accounted for in its reduction of the point source strength to the beam strength.

Equations for use in measuring moisture content of laboratory soil samples were reported by the author elsewhere.⁽⁹⁾ Their development and limitations were also given and will not be discussed here. For a stable medium (i.e., no shrinking or swelling during removal of water), the resulting equation is

$$\begin{aligned} (S - S_i)/(1 - S_i) \\ = \ln(I_i/I_w)/\ln(I_i/I_1) \end{aligned} \quad (1)$$

where I_i is the count rate when the sample has a saturation of S_i , I_1 is the count rate for complete saturation of the sample, S is the saturation at any other condition with corresponding count rate I_w , and $\ln$ denotes the natural logarithm.

Experiments were set up to compare the saturation of a sample of sand measured volumetrically with the saturation inferred from the absorption of gamma rays from a source of ^{241}Am . The soil sample was contained in a Lucite cylinder of 5.7 cm ID with 6.3 mm wall thickness; the sample was about 3.2 cm high. The water was withdrawn from the sample at both ends through concentric rings of Type M Porvic and measured volumetrically in calibrated horizontal tubes. As the soil desaturated, air was allowed to

enter through rings of fine screen concentric with the Porvic rings on both ends of the sample.

The container was packed with air-dry sand, and the bulk density, porosity, and moisture content were determined by the usual gravimetric methods. The sample was set into the gamma ray apparatus and counted to obtain I_i (Equation 1). Then the sample was placed into a tank of water and completely saturated under vacuum. The tubing system was also filled to the zero readings on the horizontal glass tubes with the water evacuated from the saturating tank. The sample was again placed in the gamma beam and counted while completely saturated to obtain I_1 (Equation 1). The capillary pressure was then increased in small steps to desaturate the sample. After each change of capillary pressure, the system was allowed to come to equilibrium as evidenced by no further movement of the water in the glass tubes. The capillary pressure was recorded together with the volume of water in the glass tubes, and the sample was counted to obtain an I_w value. Hysteresis was prevented by insuring that any change of saturation was produced by an increase of capillary pressure.

Considerable difficulty was experienced in obtaining the desired data and results to be presented at this time are preliminary. Figure 1 shows results for two repeated runs under the same conditions. Since the depth of the sample was 3.2 cm, the capillary pressure head was 3.2 cm greater at the top than at the bottom of the sample. Nowhere on the curve

FIGURE 1. Preliminary Results Comparing Volumetric Measurement of Saturation with Calculation by Equation (1) from Gamma Ray Attenuation

would a straight line of 3.2 cm capillary head cause much error. The sample was counted at the midheight and the volumetric values of saturation--while actually an average over the total sample depth--should correspond very closely with the saturation at midheight. Thus, the volumetric values of saturation are expected to be fairly accurate.

Difficulty with instrument drift when used as a pulse height analyzer prevented data from being collected in this manner. This problem has been traced to the special preamplifier section and has since been corrected. The data shown in Figure 1 for the

gamma ray absorption were obtained by counting the entire spectrum with S calculated from Equation (1). Because of a lack of good collimation, it is expected that these results could be in error. Without sufficient collimation, the radiation received at the crystal could include scattered radiation from outside the desired beam. Such radiation would increase the intensity measured at the detector over that from absorption in the soil and water within the desired beam.

The count rate as used for Figure 1 was too low for good counting statistics (40,000 to 60,000 counts/3 min). This can be significantly increased by

increasing the slit sizes at the source and detector crystal. To confine the beam, good collimation should be used with the increased beam size. The lead shielding the crystal was too thin (about 2 mm) and too close to the crystal (about 1 cm) thus allowing a good chance for back-scattered radiation from a substantially larger volume.

Even with the poor agreement of these preliminary results, it is believed that the use of ^{241}Am in a properly designed apparatus will yield good measurements of soil moisture content. It is expected to correct the faults of the present experimental apparatus and refine the method.

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INVESTIGATION OF ELECTRICAL RESISTIVITY METHODS FOR DETERMINING THE IN-PLACE MOISTURE CONTENT OF RELATIVELY DEEP SOIL ZONES

D. E. Peterson

Solid earth geophysical studies of the Hanford Reservation, including seismic, gravitational, magnetic and electrical techniques, have been carried out with varying degrees of

success over the past 20 years. As an example, electrical resistivity logs obtained from uncased water wells have provided useful information on the characteristics of soils

and rocks. In contrast, the results of an electrical resistivity survey in 1948, using a horizontal electrode array, were considered unsatisfactory because of the low conductivity of the relatively dry Hanford soils.

In 1967, investigations were undertaken to find a rapid and accurate method for defining the wetted pattern in relatively deep (up to several hundred feet) soil zones beneath liquid waste disposal sites. Such information was desired to determine the extent of lateral waste spread due to stratigraphic effects and capillary forces. The present method of obtaining this information is through test hole drilling, which is both time consuming and expensive. Because of a significant contrast in resistivities between the relatively dry soils under natural conditions and the moistened soils, it appeared that horizontal resistivity traverses could be a means of delineating the wetted zones.

Both electric resistivity logs and horizontal resistivity data are obtained by applying current to the ground through two electrodes. The potential difference is usually measured between two other electrodes in line with the current electrodes. In the case of horizontal arrays, the electrodes are generally copper-plated steel stakes which are driven into the ground. The resistivity (actually, the apparent resistivity) along each traverse of this study was obtained using the apparatus and electrode spacings illustrated schematically in Figure 1 where C_1 and C_2 are current electrodes, P_1 and P_2 are potential electrodes, a = electrode spacing, E is dc power supply, A is a milliammeter, V is a potentiometer.

The apparatus provides commutated direct current to the electrodes in order to avoid the polarization problems often associated with using

FIGURE 1. Circuit for Measuring Ground Resistance

direct current. A battery is used as the source of current which is supplied to the ground through a commutator which reverses the direction of flow at each half-revolution; concurrently a second commutator on the same shaft reverses the connections to the potentiometer. In this way, the current and the voltage remain in phase with each other and are measured by dc methods.

The apparent resistivity was calculated from the formula

$$\rho = 2\pi a \frac{\Delta E}{I}$$

where

ρ = apparent resistivity in ohm-meters,

a = electrode spacing in meters,

ΔE = voltage between P_1 and P_2 ,

I = input current.

The apparent resistivity represents the effective resistivity between the potential electrodes and to a depth approximately equal to the electrode spacings.

The results of a traverse centered at a selected disposal site are illustrated in Figure 2. The apparent resistivity is plotted as a function of electrode spacing.

FIGURE 2. Apparent Resistivity Versus Electrode Spacing

The effects of both near-surface moisture and increasing soil moisture near the water table are indicated by lower resistivities for electrode spacings of less than 10 m and for spacings greater than 70 m, respectively.

This and other traverses indicated, as expected, that the method will discriminate between moist and relatively dry soils. However, the re-

solution limitation brought about by large electrode spacings when greater depth of penetration was required made it difficult to satisfy the objective of delineating capillary fronts at increased depths. Consequently, resistivity traverses have limited utility as a practical substitute for the contemporary drilling programs at Hanford.

COMPARISON OF THE TRADITIONAL AND ENERGY DISSIPATION METHODS FOR PERMEABILITY DETERMINATION

D. B. Cearlock

INTRODUCTION

The ability to accurately predict changes in groundwater flow systems, such as flow paths, travel times, infiltration rates and groundwater potentials resulting from changes in waste management practices or other environmental conditions, requires an accurate knowledge of the permeability distribution. The traditional method used in determining the permeability distribution of a flow system has been to measure the permeability at several locations using pumping tests, or other similar methods, followed by extrapolating the permeability to other locations through geological relationships. However, this method has proved less than satisfactory when the number of permeability measurements available is small and the extrapolation dis-

tances are large. The development of economical methods for accurately determining permeability distribution has received considerable emphasis. From this work has come the theoretical basis of the energy dissipation method for the economical measurement of permeability in heterogeneous systems^(1,2) and several computer programs which are the analytical tools necessary for use of the energy dissipation method.⁽³⁻⁵⁾ This method involves measuring the distribution of ground water potential for the existing saturated ground water flow system, after which the tabular potential data are reduced to equation form by orthonormal regression and blending techniques. The STREAM computer program analyzes the potential function to determine how energy is dissipated in the flow system. With this information and a

minimum number of permeability measurements, the program accurately deduces the permeability distribution for the entire flow system.

DISCUSSION

Both methods were used to determine the permeability distribution over a portion of the Hanford groundwater flow system. The permeability distribution determined by the traditional method was based upon pumping tests, well logs and other pertinent geological data. The permeability distribution determined by the energy dissipation method was based upon groundwater potentials and pumping tests. A comparison of the two resultant permeability distributions showed them to be quite dissimilar. Verification tests were performed to determine which distribution most represented the field situation.

The procedure for verifying the permeability distribution involves setting up the boundary conditions for the flow system being analyzed and then solving for the potential distribution using the calculated permeability as input to the solution model. The agreement between the calculated and the measured potential distributions is an indicator of the validity of the permeability distribution. However, for the verification test to insure uniqueness, the measured permeabilities must be true, i.e., the verification test does not check the accuracy of the measured permeabilities used in generating the permeability distribution.

The verification of the permeability distribution determined by the energy dissipation method is shown in Figure 1. The dashed contours in the figure are the computed potentials and the solid contours are the measured potentials. Good agreement was obtained near the river with gradually increasing differences noted near the left part of the figure. The differences are very likely due to the interaction with the poor permeability distribution used in the region near 200 East Area where the energy dissipation method was not used because of inadequacies found in the original blending methods.

A comparison of the actual potential with the potential calculated using the permeability distribution (determined by the traditional methods) is shown in Figure 2. The dashed contours are the computed potentials and the solid contours are the measured potentials. Ten to thirty-foot differences occur over much of the region between the two distributions and the general patterns of the distributions are grossly different. A comparison of Figures 1 and 2 indicates that the energy dissipation method is considerably more accurate than the traditional method in determining permeability distributions.

The results reported here have provided a comparison between two methods for determining permeability distributions in groundwater flow systems. Comparisons of the calculated potentials, using the permeabilities determined by the two

Neg 0672186-5

FIGURE 1. Comparison of the Original Potential Distribution and the Potential Calculated from the Permeability Distribution Obtained by the Energy Dissipation Method

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FIGURE 2. Comparison of the Original Potential Distribution and the Potential Calculated Using the Best Geological Observations Including Pumping Tests, Well Bore Data and Stratigraphic Surveys

methods, with the measured potentials pointed out the accuracy of the energy dissipation method in determining permeability distributions.

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IMPROVED GENORO DATA FITTING ROUTINE FOR APPLICATION IN HYDROLOGICAL ANALYSIS

A. E. Reisenauer

An improved double precision version of the GENORO computer code permits the determination of a fitting function for a given set of data points, the evaluation of that function, or the evaluation of any function of the proper form on a grid or at random points. The data points may be any N arbitrary points in a D -dimensional space. Several functional types are available.

The energy dissipation method for the analysis of ground water flow systems* is dependent on the reduction of data, having irregular tabular intervals, to functional forms. These data include potentials in three space variables, boundaries, and boundary permeabilities. Reduc-

tion of the data to function form is accomplished by the generalized orthogonal regression program, GENORO.

An improved version of GENORO, now in use, is a modification of the original program.⁽¹⁾ The theoretical basis for the modified program is the same as the original and will not be discussed here.^(2,3)

Since energy dissipation methods are highly sensitive to the function

* D. B. Cearlock. "Comparison of the Traditional and Energy Dissipation Methods for Permeability Determination," this report, pp. 25-29.

formed by the fitting routine, it became necessary to reduce the round-off error normal to the manipulation of large matrices. To accomplish this, the program was converted to double precision. As further protection against round-off and overflow error, caused by raising large numbers to powers, the ability to scale the dependent and independent variables was added.

Several different functional forms are available in the different versions of this program: the power series, log e polynomial, harmonic polynomials, Chebyshev polynomials, and sine and cosine. The most useful form in the fitting of hydrologic and geographic data appears to be the power series.

In addition to fitting, the program can evaluate the function at

specified random points or across a uniform matrix.

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FUNEVAL, A ROUTINE FOR BLENDING SURFACE FUNCTIONS

D. B. Cearlock and D. R. Friedrichs

INTRODUCTION

The increasing need for accuracy in modeling ground water flow systems, specifically with reference to determining travel paths and travel times of ground waters and contained pollutants, has provided the impetus to develop better fitting methods and techniques for analytically describing ground water potential (head) distributions.^(1,2) One such technique, piecewise fitting, was

made possible through the development of the blended surface concept.

DISCUSSION

The purpose of the FUNEVAL program is the production of blended surfaces that will match in value and in first and second derivatives with surrounding surfaces. Options are available for determining the statistics of fit of the blended surface with respect to the data contained in the

region of definition and for the evaluation of the blended surface on a specified grid. The program is written for the UNIVAC 1108 in FORTRAN V computer language.

In general, the surfaces to be fit have a considerable amount of undulation and it is therefore usually quite difficult, if not impossible, to obtain a single function to accurately represent the entire surface. However, if the surface is divided into small regions, where the undulation within each region is minimal, accurate functional fitting of the smaller surfaces is possible. Since surface representations are usually obtained using approximate fitting methods, it is difficult to guarantee that the surfaces and their subsequent derivatives will match at the regional boundaries. If narrow strips are removed to separate the surfaces being fitted, it is possible to match the surfaces and their derivatives by inserting blended surfaces into the strips and retain the advantage of dividing the surface into small regions. The technique of fitting small, unconnected portions of an undulating surface with mathematical functions and subsequently connecting the fitted portions with blended surfaces is referred to as "piecewise fitting."

Sophisticated computer programs are available for performing functional fitting;⁽³⁾ however, routines are not available for obtaining blended surfaces. The purpose of the FUNEVAL program is to provide a method for forming and evaluating blended surfaces which smoothly connect func-

tionally fitted surfaces together so that the desirable capabilities of piecewise fitting can be utilized.

Prior to the discussion on the application of blended surfaces, it is appropriate to discuss the notation used. Any function of U and V over a region designated " n " will be denoted as ${}_nF(U,V)$. The preceding subscript " n " refers to the region, ${}_nU_0 \leq U \leq {}_nU_m$ and ${}_nV_0 \leq V \leq {}_nV_m$, for which the function is valid. The boundary functions of any region " n " are denoted as ${}_nF(U_0,V)$, which in this case refers to the $U = U_0$ boundary curve of ${}_nF(U,V)$. For the boundary curve ${}_nF(U_0,V)$, it is implied that ${}_nU_0$ is one of the boundary limits of the n^{th} region; i.e., when ${}_nU_0$ is contained within a function such as ${}_nF(U_0,V)$, the presubscript is dropped.

The blended surface concept is based on the principle that the interior of a surface can be represented by its boundary curves.^(4,5) That is, if the four boundary curves of Region 2, (Figure 1): ${}_2F(U_0,V)$, ${}_2F(U_m,V)$, ${}_2F(U,V_0)$ and ${}_2F(U,V_m)$ are known, the surface ${}_2F(U,V)$, defined over the region ${}_2U_0 \leq U \leq {}_2U_m$ and ${}_2V_0 \leq V \leq {}_2V_m$, can be expressed as a linear combination of these four boundary curves.

The primary function of the FUNEVAL computer program is the production of blended surfaces (similar to that shown in Figure 1) that will match in value and in first and second derivatives with the surrounding surfaces. The inputs required for the program to perform this task are the four boundary curves and the

FIGURE 1. Typical Blended Surface

region limits of the surface. The region limits serve a two-fold purpose: they are an index that defines the region over which the surface is valid and they are used as scaling parameters for both the independent and dependent variables of the fitted functions in order to minimize the possibility of overflow problems occurring in the computer when large numbers are raised to high powers.

The four boundary curves are obtained from either polynomial surface fits of adjacent surfaces or from polynomial curve fits of the boundary curves. If the boundary curve is obtained from a surface fit, it is termed a constrained boundary, since the blended function and the derivatives of the blended function must be made to match the surface fit along this boundary. Boundaries obtained

from curve fits are termed unconstrained boundaries because there are no surface functions or derivatives that need be matched across these boundaries.

Since the constrained boundaries are fixed, the unconstrained boundaries must be made to match the constrained boundaries at their intersection, i.e., at the corner points. However, the use of approximate fitting methods makes it impossible to insure that the functions and the first two derivatives of the functions will match at the corner points. Therefore, any mismatching that occurs must be absorbed into the unconstrained boundaries. This implies that if two constrained boundaries are adjacent in a blended surface, the functions and first two derivatives of the functions must

match at the corner points. If they do not match, then one of the two boundaries must be an unconstrained boundary. This is a very important point to be remembered when dividing a surface for piecewise fitting. In most instances, the amount of mismatching that occurs at the corner points can be made negligible; thus, the resulting change in the unconstrained boundaries is within the range of the accuracy of the data being fitted.

As an example of the application of the blended surface, consider the input required to produce the blended surface similar to that shown in Figure 1. Assume that the blended surface joins two surface functions as shown in Figure 2 and that the functions ${}_1F(U,V)$ and ${}_3F(U,V)$ are obtained from surface fits. The

constrained boundaries of ${}_2B(U,V)$ [i.e., ${}_2B(U_0,V)$ and ${}_2B(U_m,V)$] are obtained by evaluating ${}_1F(U,V)$ at $V = {}_1V_m$, and ${}_3F(U,V)$ at $V = {}_3V_0$. The other two boundary curves of ${}_2B(U,V)$ [i.e., ${}_2B(U_0,V)$ and ${}_2B(U_m,V)$] are unconstrained boundaries which are obtained by fitting the portion of the curves $U = U_0$ and $U = U_m$ that connect ${}_1F(U,V)$ and ${}_3F(U,V)$ together. The inputs required by the program are the two surface functions and the two curve functions. The program makes the proper substitutions into the surface functions to obtain the constrained boundary curves and also calculates the first and second partial derivatives that the blended surface will be forced to match. Any mismatching that occurs at the corner points will be absorbed into the unconstrained boundaries. Other

FIGURE 2. Blended Surface Connecting Two Polynomial Surfaces

applications of the blended surface are given in the formal document of the program. (6)

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QUALITATIVE AND QUANTITATIVE EVALUATION OF INFRARED IMAGERY COLLECTED OVER SURFACE WATER

J. R. Eliason, H. P. Foote and G. R. Taylor

INTRODUCTION

Techniques for qualitative and quantitative evaluation of the information obtained from infrared and other sequentially-scanning, remote-sensing systems are needed to fully realize the potential of these systems for scientific studies. The development of recording and display techniques for interpreting data collected by sequentially-scanning, remote-sensing systems appears to be the primary gap in the evaluation phase. The techniques needed must be

capable of processing the large quantity of data collected by scanning systems at or near the collection rate, and displaying the results in a form that is interpretable by scientists and others who will benefit from their use.

The evaluation of most remote-sensor data has been limited by the shades of gray that can be displayed on a cathode-ray tube or recorded on film. Many remote-sensing systems have capabilities of detecting very small differences in radiation which, when displayed or

recorded by conventional techniques, may be lost because of the limited dynamic range of the recording system. These differences or gradients may have significant value to the geologist, hydrologist, ecologist, meteorologist, or other scientist evaluating the data. Several techniques for displaying and evaluating sequentially-scanned, remote-sensor data have been developed by Battelle-Northwest to aid in obtaining quantitative interpretations.

DISCUSSION

Infrared imagery collected by the U.S. Department of Agriculture Forest Service, Northern Forest Fire

Laboratory of Missoula, Montana, for the Hydrogeology Unit of Battelle-Northwest was used for this study. The imagery was collected during daylight hours over the Columbia River adjacent to a nuclear reactor area on the Hanford Project. Primary features in the imagery such as reactor effluent retention basins, Columbia River, riverbank hot springs, island, and effluent discharge points, are identified in Figure 1. The data were collected by magnetic tape recording the output of the detector in the infrared scanner system. These magnetic tape records are the primary data from which the evaluations were made.

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FIGURE 1. Oblique Three-Dimensional Display of an Infrared Image Collected Over the Columbia River Near a Nuclear Reactor Site on the Hanford Project

The infrared imaging system scans an area normal to the aircraft flight path and 60 degrees either side of nadir. The relationship of the scanning system to the ground is illustrated in Figure 2; a typical scanner sweep path and the instantaneous field of view of the scanner are indicated.

A generalized diagram of an infrared imaging system is shown in Figure 3. This system is divided into three basic units: the control and recording unit, radiation conversion unit and the scanning unit.

Most imaging systems produce a film output which is intensity modulated by the detector response

(Figure 4). This output is limited by the dynamic range of the film used and the number of shades of gray which can be resolved. These limitations make quantitative interpretation of radiation intensities quite difficult and the primary application of this display is for general qualitative evaluations. Also, the quality of the intensity modulated, two-dimensional displays developed directly by scanning systems is sometimes difficult to control. Magnetic tape recording of a scanner system detector output permits processing the data under controlled laboratory conditions. This allows the person evaluating the data to

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FIGURE 2. Infrared Imaging Systems Relationship to the Ground

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FIGURE 3. Infrared Imaging System

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FIGURE 4. Intensity Modulated Display

produce an intensity-modulated photograph with maximum resolution.

The use of magnetic tape records of scanner output allows the interpreter to examine an individual scan line in detail from any point in an image by photographing the waveform of the scan displayed on an oscilloscope. Wave-forms displayed using this technique (Figure 5) were taken from the data displayed in Figure 4 at points A and B, respectively. The vertical deflections recorded, proportional to the detector output, are comparable to film density variations that may be collected with a densitometer by traversing a black and white photograph. A wider dynamic range may be recorded on magnetic tape than can be recorded by photographic techniques. Also, the intensity variations are obtained directly from the primary record; thus, a secondary processing step, as in the densitometer evaluations of film records, is not required.

Wave forms may be used to determine the relative detector output at selected points on an image, and to relate output levels to points at which ground control data were collected for absolute intensity evaluations.

The display shown in Figure 6 was produced by using a technique developed to display specific levels of radiation detected by a scanner. This photograph, a plot of points at one specific radiation-level setting, effectively shows contour points at that radiation level. The appropriate corrections for signal attenuation and scanner sweep-rate

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FIGURE 5. Radiation Profiles Produced by a Single Sweep of an Infrared Scanning System

must be made to quantitatively evaluate imagery with this technique. A number of contours at specific levels may be produced at one time, but using a black and white display system limits the number of levels that can be discriminated because of the signal noise-level and the minimum point size that can be produced. Generally, more than two contour

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FIGURE 6. *Specific Radiation Contour Display*

levels results in confusion, thus most quantitative evaluations have been made using only one level per frame.

An interpreter may desire to know the distribution of radiation intensities within fixed limits or the distribution of a specific temperature range over an area. A technique was developed that allows an image to be segmented into variable level widths rather than specific contours. The upper and lower limits are variable so that levels enhancing the item of interest may be selected. Using black and white displays, it is possible to distinguish several shades of gray or

alternate black and white bands which allows several selected levels to be displayed in one frame, or each level may be displayed separately as in Figure 7.

A new dimension was added to scanner data displays by using the signal intensity not only to modulate the CRT beam but to displace it vertically in an oblique view. Figure 1 is an example of an oblique three-dimensional display. The display enhances variations in radiation intensity by vertically producing an apparent displacement which allows small variations to be resolved. This display technique aids qualitative evaluation by allowing the full

Level 1

Level 2

Level 3

Level 4

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FIGURE 7. Displays of Radiation Levels

dynamic range of the tape recorded data to be displayed without the shades of gray (which can be resolved) limiting the display. The contouring technique described earlier may be used to superimpose quantitative control markers on an oblique display.

The surface produced by the three-dimensional display system may be viewed from any desired angle to enhance the objects of interest. This allows views to be produced having slightly different viewing angles for stereo coverage of the radiation surface. An oblique stereo

pair is shown in Figure 8. Stereo coverage aids the interpreter in qualitative evaluation of the imagery and, by adding contours at selected levels for quantitative control, the interpreter may use stereo coverage to resolve specific contour levels.

Initial evaluation of the color display system has demonstrated its utility for color-coding specific radiation levels and developing false-color imagery. Most display techniques are limited for quantitative studies by the number of gray shades that can be resolved. Therefore, several reprocessing steps are

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FIGURE 8. *Oblique Stereo Pair*

often required to obtain the detail needed to evaluate the data and it is usually necessary to draft composites of several black and white displays for the final quantitative evaluation. The human eye can discriminate many more color hues than gray shades. Thus, there are definite advantages in using several color-coded contour levels (or a continuous color spectrum) to represent the radiation signal range of the tape record. Color display units are available that can produce several distinct colors by properly mixing the color-gun output percentages. The resolution of color display systems is limited in comparison to the resolution of black and white display systems, but the detail obtained with an initial test of a color system using only two color guns demonstrated the potential application.

Initial evaluation of infrared imagery by the techniques described

has shown that data collected by imaging systems can be useful for quantitative as well as qualitative studies. Computer generated displays can be produced at or near the data acquisition rate. Quantitative studies should be limited only by the noise level of the instrument and the optical resolution of the system, provided surface control data are available to make the proper correlations and corrections. Contouring specific radiation levels will allow the interpreter to quantitatively determine radiation gradients and patterns that may not have been obvious in other displays. Qualitative evaluations of imagery using oblique three-dimensional displays and stereo coverage will allow the interpreter to have a better feel for the true intensity relationships in the imagery. The potential of color display systems for color-coding specific radiation levels and

developing false-color imagery has also been demonstrated. These techniques and variations of them should aid scientists and others in realiz-

ing the true potential of imaging systems for large-scale ecological and related research.

ZEOLITE AMMONIUM ION CAPACITY IN MIXED CATION EQUILIBRIUM SYSTEMS

L. L. Ames

INTRODUCTION

Several trials were made of a method for determining zeolite cation equilibrium capacities through their binary selectivities in mixed cation solutions. Ammonium ion selectivities in a solution containing sodium, potassium, calcium, magnesium and ammonium ions were predicted from the binary equilibrium data with good results. The method is useful for predicting the equilibrium capacity for any number and ratio of cations, providing the relevant equilibrium data are available.

As soil studies proceed, it is becoming increasingly clear that single cation soil mineral capacities are of less consequence to cation equilibrium soil mineral capacities in mixed cation systems than is cation selectivity. If the zeolites, or other soil minerals, are to be studied, a coherent theoretical approach to the relationship between the cation on the zeolite and cation ratios in the contacting solution must be predicted. The experimental study of more than two cations at one time becomes very

tedious and the equilibrium results are difficult to present graphically. It was therefore decided to test the assumption that an equilibrium zeolite capacity in a mixed cation environment could be determined from related binary equilibrium data. Results for the easily-analyzable ammonium-mixed cation systems are presented here.

DISCUSSION

The natural clinoptilolite used in this study was from the Hector, California area. The AW 400 and AW 500 are synthetic zeolites produced by the Linde Company and the Zeolon is a product of the Norton Company. The properties of the zeolites are listed in Table I. All of the capacities given in Table I are for the zeolite with the amounts of binder and water indicated. Capacities measured with cations other than ammonium can be substantially different.

Equilibrium studies were accomplished by utilizing a small column technique similar to that reported by Howery and Thomas.⁽¹⁾ One-half gram

TABLE I. Zeolite Properties

Zeolite	SiO ₂ /Al ₂ O ₃	Binder, wt%	H ₂ O at 25 °C, wt%	Structural Type	NH ₄ ⁺ Capacity, meq/g
AW 500	4-5	25	15	Chabazite	1.67
AW 400	6-7	25	12	Erionite	1.88
Zeolon	10	--	12	Mordenite	2.02
Hector Clinoptilolite	8-10	5-20	12	Clinoptilolite	1.81

of 30 to 50 mesh zeolite was placed in a straight sealing tube containing a fritted glass disc. The sealing tubes had been cut off just below the frit to allow placement of the tube and zeolite into a 500 ml Kjeldahl flask for ammonia determination. A solution of known chemical composition was slowly passed through the zeolite column until equilibrium was attained. The contact time and solution volume necessary to reach equilibrium was determined previously by passing several volumes of influent through a group of columns and ascertaining the volume and time elapsed before ammonium ion values on the zeolite remained constant. By obtaining several equilibrium points with constant normality influents of variable cation ratio, an isotherm could be determined for each binary system. The isotherm represents a series of equilibrium points at the same temperature between the equivalent fraction of one of the cations on the zeolite and the equivalent fraction of the same cation in the equilibrium solution.

From the solution and zeolite cation compositions, a selectivity coefficient, K_A^B , was obtained with the following relationship:

$$K_A^B = \frac{(A)_z^{nA} (B_N)^{nB}}{(B)^{nB} (A_N)^{nA}}$$

where (A_N) , (B_N) = normality of cations A and B in the equilibrium solution,

$(A)_z$, $(B)_z$ = equivalent fractions of cations A and B on the zeolite,

nA , nB = the number of cations A and B represented in the chemical equation for the exchange reaction of A and B.

In conjunction with ammonium ion removal, the main competing cations in natural waters normally will be sodium, calcium, magnesium and potassium. The present study, therefore, is concerned

with zeolite ammonium selectivities from the binary systems sodium-ammonium, calcium-ammonium, magnesium-ammonium, and potassium-ammonium.

Isotherms for the systems sodium-ammonium, calcium-ammonium, magnesium-ammonium, and potassium-ammonium with the zeolites AW 500, AW 400, Zeolon and Hector clinoptilolite at 23 °C are given in Figures 1, 2, 3, 4, and 5, respectively. The experimental equilibrium points are indicated in each case. Several general characteristics of the isotherms may be noted. The first characteristic is that all of

the above zeolites select potassium to ammonium ions and that all are ammonium-selective in systems containing calcium, sodium and magnesium. The univalent-univalent cation isotherms may be used directly to read the fraction of cation on the zeolite if the cation ratio in the solution is known, because the expression for the selectivity coefficient contains no squared terms. The divalent-univalent selectivity coefficients are affected by total cation concentration as well as cation ratio. Consequently, the isotherms for calcium-ammonium and

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FIGURE 1. The 23 °C Isotherm for the Reactions, $(Mg)_z + 2(NH_4)_N = 2(NH_4)_z + (Mg)_N$, $(Na)_z + (NH_4)_N = (NH_4)_z + (Na)_N$, $(Ca)_z + 2(NH_4)_N = 2(NH_4)_z + (Ca)_N$ and $(K)_z + (NH_4)_N = (NH_4)_z + (K)_N$ with AW 500.

(Total solution normality was constant at 0.1 for all systems. The subscripts "z" and "N" refer to equivalent fractions of the cation on the zeolite and cation normality in the equilibrium solution, respectively.)

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FIGURE 2. The 23 °C Isotherm for the Reactions, $(Mg)_z + 2(NH_4)_N = 2(NH_4)_z + (Mg)_N$, $(Na)_z + (NH_4)_N = (NH_4)_z + (Na)_N$, $(Ca)_z + 2(NH_4)_N = 2(NH_4)_z + (Ca)_N$ and $(K)_z + (NH_4)_N = (NH_4)_z + (K)_N$ with AW 400.

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FIGURE 3. The 23 °C Isotherm for the Reactions, $(Mg)_z + 2(NH_4)_N = 2(NH_4)_z + (Mg)_N$, $(Na)_z + (NH_4)_N = (NH_4)_z + (Na)_N$, $(Ca)_z + 2(NH_4)_N = 2(NH_4)_z + (Ca)_N$ and $(K)_z + (NH_4)_N = (NH_4)_z + (K)_N$ with Zeolon.

(Total solution normality was constant at 0.1 for all systems. The subscripts "z" and "N" refer to equivalent fractions of the cation on the zeolite and cation normality in the equilibrium solution, respectively.)

magnesium-ammonium are valid for determination of ammonium ions on the zeolite only if the total system normality happens to be 0.1 as it does in Figures 1, 2, 3, and 4.

There is another way of presenting the equilibrium data that facilitates selectivity comparisons. Selectivity coefficients may be determined at several points on the isotherm and these values plotted versus corresponding ratios of cation normalities in the equilibrium solution. The re-

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FIGURE 4. The 23 °C Isotherm for the Reactions, $(Mg)_z + 2(NH_4)_N = 2(NH_4)_z + (Mg)_N$, $(Na)_z + (NH_4)_N = (NH_4)_z + (Na)_N$, $(Ca)_z + 2(NH_4)_N = 2(NH_4)_z + (Ca)_N$ and $(K)_z + (NH_4)_N = (NH_4)_z + (K)_N$ with Hector clinoptilolite.

sults of such a plot are presented for magnesium-ammonium and calcium-ammonium in Figures 5 and 6, respectively. To facilitate comparison of ammonium ion selectivities at various cation ratios, similar graphs are given for sodium-ammonium and potassium-ammonium in Figures 7 and 8, respectively.

If we assume that the various exchange systems operate essentially independently of each other, and this has shown to be a valid assumption,⁽²⁾

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FIGURE 5. Selectivity Coefficients Versus Concentration Ratios of Magnesium and Ammonium in the Equilibrium Solution at 23 °C for the Reaction, $(Mg)_z + 2(NH_4)_N = 2(NH_4)_z + (Mg)_N$.

$(Mg)_z$, $(NH_4)_z$ = Equivalent Fraction of Magnesium or Ammonium on the Zeolite

$(Mg)_N$, $(NH_4)_N$ = Normality of Magnesium or Ammonium in the Equilibrium Solution

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FIGURE 6. Selectivity Coefficients Versus Concentration Ratios of Calcium and Ammonium in the Equilibrium Solution at 23 °C for the Reaction $(Ca)_z + 2(NH_4)_N = 2(NH_4)_z + (Ca)_N$.

$(Ca)_z$, $(NH_4)_z$ = Equivalent Fraction of Calcium or Ammonium on the Zeolite

$(Ca)_N$, $(NH_4)_N$ = Normality of Calcium or Ammonium in the Equilibrium Solution

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FIGURE 7. Selectivity Coefficients Versus Concentration Ratios of Sodium and Ammonium in the Equilibrium Solution at 23 °C for the Reaction, $(Na)_z + (NH_4)_N = (NH_4)_z + (NH_4)_z + (Na_N)$.

$(Na)_z, (NH_4)_z$ = Equivalent Fraction of Sodium or Ammonium on the Zeolite

$(Na_N), (NH_4)_N$ = Normality of Sodium or Ammonium in the Equilibrium Solution

then the fraction of ammonium ion on the zeolite can be estimated. Activity corrections can be neglected at low concentrations. For example, given the simulated waste containing the cations shown on Table II, the total cations on AW 400 would be defined as $(NH_4)_z + (Na)_z + (Ca)_z + (Mg)_z + (K)_z = 1$, where the subscript "z" refers to the equivalent fraction of cation on the zeolite. Making substitutions in terms of ammonium on the zeolite, and solving the resulting quadratic equation (see Appendix A), the estimated meq/g of ammonium ion on AW 400 is 0.55, while an actual column loading experiment gave an AW 400 ammonium ion loading of 0.47 meq/g.

TABLE II. Simulated Soil Solution

Cations	Concentration, mg/liter	Normality
Na^+	130	5.7×10^{-3}
K^+	15	3.8×10^{-4}
NH_4^+	20	1.2×10^{-3}
Ca^{++}	60	3.0×10^{-3}
Mg^{++}	25	2.1×10^{-3}

In terms of the total AW 400 ammonium ion capacity of 1.88 meq/g, the estimated value and the measured value differ by only 4%. Other estimated and actual ammonium equilibrium capacity values are given in Table III.

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FIGURE 8. Selectivity Coefficients Versus Concentration Ratios of Potassium and Ammonium in the Equilibrium Solution at 23 °C for the Reaction $(K)_z + (NH_4)_N = (NH_4)_z + (K)_N$.

$(K)_z, (NH_4)_z$ = Equivalent Fraction of Potassium or Ammonium on the Zeolite

$(K)_N, (NH_4)_N$ = Normality of Potassium or Ammonium in the Equilibrium Solution

TABLE III. Ammonium Equilibrium Capacity Values

Zeolite	Predicted NH_4^+ , meq/g	Measured NH_4^+ , meq/g
Zeolon	0.63	0.57
AW 400	0.55	0.47
Hector Clinoptilolite	0.51	0.45
AW 500	0.067	0.061

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APPENDIX A

ESTIMATION OF AMMONIUM ION ON AW 400

Given: A solution of the composition of Table II; $(\text{NH}_4)_z = 1 = 1.88$ meq/g AW 400.

$$\text{From Figure 7, } \frac{(\text{Na}_N)}{(\text{NH}_4)_N} = \frac{(0.0057)}{(0.0012)} = 4.75, K_{\text{NH}_4}^{\text{Na}} = 10,$$

$$\text{from Figure 8, } \frac{(\text{K}_N)}{(\text{NH}_4)_N} = \frac{(0.00038)}{(0.0012)} = 0.317, K_{\text{NH}_4}^{\text{K}} = 0.71,$$

$$\text{from Figure 6, } \frac{(\text{Ca}_N)}{(\text{NH}_4)_N^2} = \frac{(0.0030)}{(0.0012)^2} = 2083, K_{\text{NH}_4}^{\text{Ca}} = 430,$$

$$\text{from Figure 5, } \frac{(\text{Mg}_N)}{(\text{NH}_4)_N^2} = \frac{(0.0021)}{(0.0012)^2} = 1458, K_{\text{NH}_4}^{\text{Mg}} = 10300;$$

$$K_{\text{NH}_4}^{\text{Na}} = \frac{(\text{NH}_4)_z (\text{Na}_N)}{(\text{Na})_z (\text{NH}_4)_N}, 10 = 4.75 \frac{(\text{NH}_4)_z}{(\text{Na})_z}, (\text{Na})_z = \frac{(\text{NH}_4)_z}{2.105}$$

$$K_{\text{NH}_4}^{\text{K}} = \frac{(\text{NH}_4)_z (\text{K}_N)}{(\text{K})_z (\text{NH}_4)_N}, 0.71 = 0.317 \frac{(\text{NH}_4)_z}{(\text{K})_z}, (\text{K})_z = \frac{(\text{NH}_4)_z}{2.240}$$

$$K_{\text{NH}_4}^{\text{Ca}} = \frac{(\text{NH}_4)_z^2 (\text{Ca}_N)}{(\text{Ca})_z (\text{NH}_4)_N^2}, 430 = 2083 \frac{(\text{NH}_4)_z^2}{(\text{Ca})_z}, (\text{Ca})_z = \frac{(\text{NH}_4)_z^2}{0.2064}$$

$$K_{\text{NH}_4}^{\text{Mg}} = \frac{(\text{NH}_4)_z^2 (\text{Mg}_N)}{(\text{Mg})_z (\text{NH}_4)_N^2}, 10300 = 1458 \frac{(\text{NH}_4)_z^2}{(\text{Mg})_z}, (\text{Mg})_z = \frac{(\text{NH}_4)_z^2}{7.064};$$

$$(\text{NH}_4)_z + (\text{Na})_z + (\text{K})_z + (\text{Ca})_z + (\text{Mg})_z = 1.$$

Substituting,

$$(\text{NH}_4)_z + \frac{(\text{NH}_4)_z}{2.105} + \frac{(\text{NH}_4)_z}{2.240} + \frac{(\text{NH}_4)_z^2}{0.2064} + \frac{(\text{NH}_4)_z^2}{7.064} = 1,$$

$$6.8748(\text{NH}_4)_z + 3.2659(\text{NH}_4)_z + 3.0691(\text{NH}_4)_z + 33.3081(\text{NH}_4)_z^2$$

$$+ 0.9732(\text{NH}_4)_z^2 = 6.8748,$$

$$34.2813(\text{NH}_4)_z^2 + 13.2098(\text{NH}_4)_z - 6.8748 = 0,$$

$$(\text{NH}_4)_z = \frac{-13.2098 + \sqrt{(13.2098)^2 - 4(-235.68)}}{2(34.2813)} = 0.295;$$

$$(0.295) (1.88 \text{ meq } \text{NH}_4^+/\text{g AW 400}) = 0.55 \text{ meq } \text{NH}_4^+/\text{g AW 400 estimated.}$$

TRACE STRONTIUM ADSORPTION
IN A PARTIALLY SATURATED TRANSIENT SYSTEM

B. F. Hajek

Usually in ground disposal of radioactive liquid wastes, the solution is disposed, initially, to a relatively dry soil with natural resident exchangeable ions on the exchange complex. Prediction of radionuclide movement in these systems is often based on small soil column studies using simulated or actual waste solutions and steady state saturated flow conditions.⁽¹⁾ In reality, steady state ion or solution movement conditions are seldom, if ever, attained beneath crib disposal facilities.

Column studies at Hanford have shown that relative strontium and cesium breakthrough concentrations of 10^{-3} can occur in the first volume of effluent reaching the end of a column of soil (unpublished results of B. F. Hajek and B. L. Carlile). This occurs regardless of the fact that distribution coefficients (K_d) for the soil-radionuclide system are greater than 20 ml/g.

In studies with 0.1N strontium solutions in saturated and partially transient systems, this "leakage" was not detected.^(2,3) The data also showed that concentration distributions could be predicted in saturated systems and that the movement of the 50% relative adsorption zone (average movement) could be predicted in partially saturated transient systems.

This report presents the results of a study on the movement of trace quantities of strontium in a sodium

solution invading dry soil. Trace amounts of radioactive strontium are frequently in the wastes disposed to the ground at Hanford and sodium is often the major competing ion in solution.

The experimental method has been fully described previously.⁽³⁾ Briefly, Burbank loamy fine sand is packed into horizontal trays. At one end of the tray a porous faced block (porvic membrane) is used to introduce the test solution into the air dry soil at tensions of 30 and 50 cm. The influent volume of 0.5N NaCl solution, traced with ^{85}Sr , and the wetting front positions are recorded as a function of time. After the desired wetting front positions are attained, flow is stopped and the moisture content and adsorbed ^{85}Sr concentrations determined and recorded as a function of distance from the influent end. The volumetric moisture content distributions are shown in Figure 1. Flow time is not shown; however, the wetting front advance rate is in direct proportion to the square root of time. This is generally the case in this type of transient system.

Strontium concentration distributions (counts/g) relative to the concentration per milliliter of influent solution are shown in Figures 2 and 3. The equilibrium distribution coefficient (K_d) for this soil-solution system was determined in a separate experiment. The K_d was found to be

FIGURE 1. Experimental Saturation Distributions

FIGURE 2. Experimental Trace Strontium Distributions at 50 cm Moisture Tension

FIGURE 3. Experimental Trace Strontium Distributions at 30 cm Moisture Tension

26 ml/g [(concentration/g)/(concentration/ml)]. The data show that this maximum sorption was not reached at any point in the column. The adsorbed concentrations do not reflect the volume of solution or wetting front advance within the first 2 cm sections. In all cases, the volume of influent or wetting front distance are qualitatively related at 4 cm, that is, columns receiving the most solution showed more strontium retained at this point.

The data show that prediction of trace strontium movement rates and concentration distributions (dispersion) in a transient flow system will be difficult. The amount of influent is not adequate for the formation of

a movement front from which some average migration rate value could be determined. The predictive model will have to be based on factors which influence the development of a dispersed front. Any predictive model must include the effect of a changing volumetric moisture content and the sorption effects of resident soil ions which compete with invading solution ions and the trace radionuclide. The fact that only 20% of maximum sorption was attained in Column 1 in the first centimeter increment after 47 pore volume displacements (based on a volumetric content of 20%) clearly indicates that considerable throughput is needed before an average frontal movement rate could be established.

Figure 4 shows the experimental points for Column 1 and a calculated strontium distribution obtained by use of a breakthrough prediction model developed by Dutt⁽⁴⁾ and modified for trace radionuclide systems by Hajek.⁽⁵⁾ The comparison can be evaluated in a qualitative manner only, since little consistent separation was obtained in the first 4 cm in any column.

This predictive method considers the soil column to be made up of n segments Δx in length. The total column length is given by the expression,

$$L = \sum_{i=1}^n \Delta x_i$$

where i designated the particular segment. If C is the initial concentration of the radionuclide in

FIGURE 4. Calculated and Experimental Trace Strontium Distributions at 50 cm Moisture Tension

solution and q is the amount of solution in each segment i , the final concentration C' in the first aliquot, q , coming from the column will be,

$$C' = C + \sum_{i=1}^n \Delta c_i$$

where Δc_i is the change in concentration of the radionuclide when the aliquot q is passed through segment i .

A method for calculating equilibrium solution concentration and quantities adsorbed on soil is available from the equilibrium distribution coefficient (K_d) expression,

$$K_d = \left(\frac{C - C_1}{C_1} \right) \left(\frac{ml}{W} \right)$$

in which W is the weight of soil in segment x , ml is the volume of solution in aliquot q and C_1 is the equilibrium solution concentration.

The distribution of ^{85}Sr between the solution and adsorbed phase was determined by solution displacement from sections removed from the columns after each run. The apparent distribution coefficients were 0.9 and 1.5 ml/g at 4 and 2 cm depths, respectively. At 1 cm, the K_d ranged from 4 to 16 ml/g. These values are considerably less than the 26 ml/g maximum determined by separate experiment in which a 2 g soil plug was loaded to equilibrium with the influent solution. Since the data showed that adsorption in

the transient system was less than at final steady state, the predictive model was modified to allow the use of different adsorption constants in each segment. The calculated distribution shown in Figure 4 was obtained by using constants of 20, 5.0 and 2.0 ml/g for the 1, 2 and 3 cm segments and 1 ml/g from 4 to 10 cm depths. A volumetric moisture content of 20% was used for the aliquot (q) volume. The agreement is good to 6 cm; however, it appears that still lower constants would be needed to predict the trace movement below 6 cm in the system.

The reasonably good qualitative agreement obtained between calculated and experimental results indicates that prediction of trace radionuclide movement could possibly be achieved by further modification of the model.

The modifications would have to include the effects of resident ions on trace ion coefficients and the effect of a changing moisture content. A model of this type would be especially useful in arid surface soil systems where partially saturated, transient conditions are generally the rule.

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