STORAGE OF LOW-LEVEL RADIOACTIVE WASTES IN THE GROUND

HYDROGEOLOGIC AND HYDROCHEMICAL FACTORS

with an Appendix on

THE MAXEY FLATS, KENTUCKY, RADIOACTIVE WASTE STORAGE SITE: CURRENT KNOWLEDGE AND DATA NEEDS FOR A QUANTITATIVE HYDROGEOLOGIC EVALUATION

By

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FOREWORD

The Office of Radiation Programs carries out a National Program designed to evaluate the exposure of man to ionizing and nonionizing radiation and to promote development of controls necessary to protect the public health and safety and assure environmental quality.

Within the Office of Radiation Programs, problem areas have been defined and assigned a priority in order to determine the level of effort expended in each area. One of these, the waste management problem area, has been assigned a high priority and requires the participation and cooperation of several Federal agencies. This report is directed at a specific Environmental Protection Agency task of establishing action guidelines based on radiation exposure levels. Other reports, recommendations, and State assistance will be developed and executed to fulfill EPA obligations under the interagency agreement.

I encourage users of this report to inform the Office of Radiation Programs of any omissions or errors. Your additional comments or requests for further information are also solicited.

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Deputy Assistant Administrator
for Radiation Programs

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CONVERSION FACTORS

Factors for converting English units to metric units are shown to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	Multiply by	Metric
inches (in)	25.40	millimetres (mm)
feet (ft)	0.3048	metres (m)
miles (mi)	1.609	kilometres (km)
cubic feet (ft^3)	0.02832	cubic metres (m^3)
gallons (gal)	3.785	litres (l)
gallons per minute (gpm)	0.06309	litres per second (l/s)
pounds per square inch (psi)	0.07031	kilograms (force) per square centimetre (kgf/cm^2)

STORAGE OF LOW-LEVEL RADIOACTIVE WASTES IN THE GROUND: HYDROGEOLOGIC AND HYDROCHEMICAL FACTORS

ABSTRACT

Hydrogeologic criteria presented by Cherry and others (1973) are adopted as a guideline to define the hydrogeologic and hydrochemical data needs for the evaluation of the suitability of proposed or existing low-level radioactive waste burial sites. Evaluation of the suitability of a site requires the prediction of flow patterns and of rates of nuclide transport in the regional hydrogeologic system. Such predictions can be made through mathematical simulation of flow and solute transport in porous media. The status of mathematical simulation techniques, as they apply to radioactive waste burial sites, is briefly reviewed, and hydrogeologic and hydrochemical data needs are listed in order of increasing difficulty and cost of acquisition.

Predictive modeling, monitoring, and management of radionuclides dissolved and transported by ground water can best be done for sites in relatively simple hydrogeologic settings; namely, in unfaulted relatively flat-lying strata of intermediate permeability such as silt, siltstone and silty sandstone. In contrast, dense fractured or soluble media, and poorly permeable porous media (aquitards) are not suitable for use as burial sites, first because of media heterogeneity and difficulties of sampling, and consequently of predictive modeling,

and second, because in humid zones burial trenches in aquitards may overflow. A buffer zone several thousands of feet to perhaps several miles around existing or proposed sites is a mandatory consequence of the site selection criteria. As a specific example, the Maxey Flats, Kentucky low-level waste disposal site is examined.

INTRODUCTION

Low and intermediate-level solid and liquid radioactive wastes have been released to the subsurface environment for over 2 decades during which dozens of reports, several symposia, and at least one short textbook (International Atomic Energy Agency, 1965) have been published on this practice.

In this paper no claim or attempt is made to summarize the voluminous literature on radioactive waste storage or disposal into the ground. First, an excellent summary is available (International Atomic Energy Agency, 1965). Second, conclusions based on even the most detailed of site studies are usually of only limited value for evaluation of the waste-containing properties of another site with differing hydrogeologic, pedologic or geochemical setting; that is, the transfer value of such studies is limited. The objective of this paper is to present a brief overview of some of the major hydrogeologic and hydrochemical factors bearing on radioactive waste storage in, and release from, the ground; special emphasis is placed on a review of the state of the art of simulation of solute transport, and on complications of data collection. As a specific example, the Maxey Flats, Kentucky low-level burial site is examined in the Appendix.

Some qualifications and definitions are needed at this point. First, a thorough evaluation of the potential hazard created by emplacement of radioactive wastes into the ground would consider critical nuclides, critical pathways, and critical population groups (International Atomic Energy Agency, 1971). We consider herein only those critical pathways suggested by hydrogeologic and, to a lesser degree, geomorphic factors. It is likely that burial trenches could be designed which would contain critical nuclides, for several hundred years, barring destruction of the site by an earthquake. Existing practices, however, are to bury the low-level wastes in unlined trenches or pits, a practice necessitating attention to hydrogeologic pathways of critical nuclide transport. Second, because of the operational and economic difficulties of determining a priori the critical nuclides in the effluent from waste dumps, our definition of low-level waste follows that of the US. Atomic Energy Commission (1967), namely wastes with about 1 μCi (microcurie) per gallon or cubic foot of waste. Lastly, although we restrict our discussion to shallow burial of low-level wastes (as defined) we are aware that, in practice, low-level wastes may, in fact, consist of any wastes not classified as high-level and may even contain quantities of the long-lived and extremely toxic transuranic radioelements.

POTENTIAL RELEASE MECHANISMS AND HYDROGEOLOGIC SITING CRITERIA

Potential mechanisms through which critical radioelements in low-level solid wastes may be released from a burial site and introduced into the hydrosphere, atmosphere or biosphere are: a) transport of dissolved nuclides by water to wells, gaining streams, or springs; b) transport upward to the soil zone by capillary flow followed by concentration of the nuclides in plants; and c) exposure and overland transport by normal erosion processes (water and wind), erosion due to floods, or erosion following disruption of landscapes by earthquakes.

The suitability of a site for shallow burial of low-level wastes, therefore, depends on the extent that its environs are capable of preventing the occurrence of these release mechanisms. Criteria for the evaluation of the suitability of a site for land burial operations have been presented in reports by Peckham and Belter (1962), Richardson (1962a, 1962b), Mawson and Russel (1971), and very recently by Cherry and others (1973). The report by Cherry and others categorizes burial sites as a) intermediate-term sites, suitable for wastes that decay to safe levels within several decades and for which protection is mainly provided by engineered structures in which the wastes are buried, and b) long-term sites, suitable for wastes with longer life, and which depend mainly on hydrogeologic conditions for protection. Hydrogeologic criteria are presented for both types of sites. We found the hydrogeologic criteria that they present to be very comprehensive, and we have adopted them as a guideline in defining the type of data that are needed for the evaluation of burial sites. Of course, assessment of a site as suitable for intermediate or long-term burial applies only to future sites. Inasmuch as the type of waste buried in existing sites has not been strictly controlled, these sites require treatment as long-term burial sites, although all of them may not meet the criteria for such sites.

To provide the background for what follows, the hydrogeologic criteria presented by Cherry and others (1973) are repeated here, with slight modifications:

> "*Criteria for Intermediate-Term Burial Sites*
>
> (1) *the land surface should be devoid of surface water, except during snowmelt runoff and exceptional periods of rainfall. In other words the sites should not be located in* [flood plain,]* *swamps, bogs, or other types of very wet* [or potentially very wet] *terrain.*
>
> (2) *the burial zone should be separated from fractured bedrock by an interval of geologic deposits sufficient to prevent migration of radionuclides into the fractured zone.*
>
> *Except in unusual circumstances the direction and rate of ground-water flow as well as the retardation effects are very difficult or impossible to predict in ground-water regimens in fractured rocks. This lack of predictability necessitates that fractured rock be regarded as a major hazard in terms of subsurface radioactive waste management. In fact, it is doubtful if contaminated ground water could be effectively detected and monitored in some types of fractured rock.*

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* Additions to the quote indicated by [ ], omissions by ......

(3) *the predicted rate of radionuclide transport in the shallow.... deposits at the site should be slow enough to provide many years or decades of delay time before radionuclides would be able to reach public waterways or any other area which might be considered hazardous in the biosphere. In other words considerable time would be available for detection of contamination and for application of remedial measures if necessary.*

(4) *the site should have sufficient depth to water table to permit all burial operations to occur above the water table, or as an alternative the site should be suitable for producing an adequate water-table depth by flow system manipulation.*

(5) *the site should be well suited for effective monitoring and for containment by flow-system manipulation schemes."*

"Criteria for Long-Term Burial Sites

(1) *the land should be generally devoid of surface water and be relatively stable geomorphically. In other words erosion and weathering should not be proceeding at a rate which could significantly affect the position and character of the land surface during the next few hundred years.*

(2) *the subsurface flow pattern in the area must be such that the flow lines from the burial zone do not lead to areas considered to be particularly undesirable, such as fractured bedrock, public waterways used by man, aquifers used for water supply, etc.*

(3) *the predicted residence time of radionuclides within an acceptable part of the subsurface-flow system must be of the order of several hundred years. The hydrogeologic conditions must be simple enough for reliable residence-time predictions to be made.* (underlining not in original quote)

(4) the natural water table should be below the burial zone by at least several meters and the hydrogeologic setting should be such that large water-table fluctuations are very unlikely. This condition would provide additional assurance that leaching of radionuclides would not occur quickly in the event of corrosion of the waste containers or in the event that low-level wastes are put directly in the ground."

As these criteria indicate, for a complete evaluation of the suitability of a site for land burial of wastes, it is necessary to predict the flow patterns and the rate of transport of radionuclides in the regional hydrogeologic system. Such predictions require the simulation of the hydrogeologic system by a mathematical model that describes the simultaneous transport of radioactive solutes and water in the system. A brief review of the state of the art in solute transport simulation is presented in the next section.

MATHEMATICAL SIMULATION OF SOLUTE TRANSPORT IN HYDROGEOLOGIC SYSTEMS: A BRIEF REVIEW

The processes that control the transport of solutes in a hydrogeologic system are: (a) convection by the moving fluid, (b) hydrodynamic dispersion, which combines the effects of mechanical dispersion and molecular diffusion, and (c) chemical reactions which may take place between various solutes, between solutes and the solid matrix of the system, and within the solute, namely radioactive decay. Mathematical simulation of solute transport in a hydrogeologic system, therefore, requires the simultaneous solution of the differential equations that describe the movement of the fluid in the system and the transport of each of the solutes in the fluid by one or more of the processes stated above. The simulation can be carried out, provided that the boundary conditions and the parameters defining the system and the processes that take place within the system are known and provided that the resulting equations are solvable by known mathematical techniques.

Simulation of fluid flow through porous media has received considerable attention in the past, and both analog and digital methods have been developed and extensively applied to analyze actual field problems. However, because of the difficulties in solving the solute transport equation and because of a lack of understanding of all the types and rates of chemical reactions that may take place as a solute moves through a porous medium, until recently little progress had been made in simulating solute transport. Only relatively simple problems could be handled by analytical techniques, and the finite difference methods, which were so successful in simulating fluid flow, did not always provide satisfactory solutions to the solute transport equation. Development of more accurate numerical methods, however, such as the method of characteristics (Gardner and others, 1964) and the Galerkin method (Price and others, 1968; Aziz and others, 1968), has recently made possible the solution of the solute transport equation and its application to actual field problems under certain conditions. Progress has also been made in the area of chemical reactions, and the transport of solutes with equilibrium controlled ion exchange type reactions has been simulated. Research is continuing in this area, and it is expected that solute transport with other types of reactions will be possible to simulate in the near future. A few selected examples of recent articles on solute transport that are indicative of the present state of the art are presented below.

In unsaturated systems, Bresler and Hanks (1969) considered the one-dimensional (vertical) transient convective transport of a nonreacting solute. Later, Bresler (1973) extended the solution to this problem to include ionic diffusion and mechanical dispersion (hydrodynamic dispersion) by using a high-order finite difference method.

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In saturated systems, assuming two-dimensional transient flow, Pinder and Cooper (1970) and, independently, Reddell and Sunada (1970) used the method of characteristics to study salt-water intrusion in an aquifer. Bredehoeft and Pinder (1973) used the same method to simulate aquifer contamination in Brunswick, Georgia, and Pinder (1973) used the Galerkin method to simulate aquifer contamination in Long Island, New York. In these problems the solute was assumed to be conservative (nonreacting), and transport by convection and hydrodynamic dispersion was considered.

Lai and Jurinak (1971) used finite-difference approximations to solve the one-dimensional solute transport equation for a single component, under steady fluid flow conditions, including the effects of ion exchange controlled by local equilibrium. Rubin and James (1973) also assumed one-dimensional steady water flow and local chemical equilibrium and applied the Galerkin method to cases involving (1) homogeneous or layered systems, (2) exchange reactions with constant or concentration dependent selectivity coefficients, (3) binary or multi-component exchange, and (4) systems in which one of the exchanging ions is also involved in a precipitation-dissolution reaction. Robertson and Barraclough (1973) used the method of characteristics model developed by Bredehoeft and Pinder (1973) and considered radioactive decay and instantaneous-equilibrium, linear-isotherm type reversible sorption to simulate the two-dimensional transport of radioactive wastes in the Snake Plain aquifer at the

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National Reactor Testing Station, Idaho.

Therefore, with the present state of the art of numerical simulation of solute transport, the movement of radionuclides leached from shallow land burial sites could be simulated by assuming that: (a) the flow is one-dimensional (vertical) in the unsaturated zone and two-dimensional (horizontal) in the saturated zone; (b) isothermal conditions prevail; (c) the solute transfer processes that take place are convective transport, hydrodynamic dispersion, radioactive decay, and instantaneous-equilibrium controlled reversible sorption; and (d) density variations due to changes in solute concentration are negligible. Under these assumptions the equations applicable to transient transport of radionuclides, formulated on the basis of the references cited above, are given below.

In the unsaturated zone:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_z}{\partial z} + W(z,t)$$

and

$$\frac{\partial}{\partial t} (\theta C_i + \rho_m \bar{C}_i) = \frac{\partial}{\partial z} \left(D_z \frac{\partial C_i}{\partial z}\right) - \frac{\partial}{\partial z} (q_z C_i)$$

$$+ W(z,t)C_i' - k_i (\theta C_i + \rho_m \bar{C}_i)$$

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where

θ = volumetric water content of the medium, dimensionless;

t = time, T;

q_z = $- K(\theta) \frac{\partial h}{\partial z}$ = vertical flux of solution, LT^{-1};

z = vertical space coordinate, L;

$K(\theta)$ = hydraulic conductivity of medium (a function of θ) LT^{-1};

h = hydraulic head, L;

W = $\sum_{j=1}^{m} W_j \delta(z-z_j)$ = rate of source terms, T^{-1};

m = number of sources;

W_j = flux due to source j located at z_j, LT^{-1};

δ = Dirac delta function;

C_i = mass of dissolved form of nuclide i per unit volume of solution, ML^{-3};

$\bar{C}_i$ = mass of sorbed form of nuclide i per unit mass of the porous medium, dimensionless;

ρ_m = bulk density of the medium, ML^{-3};

D_z = $d_z q_z + D_d(\theta)$ = effective coefficient of vertical hydrodynamic dispersion, L^2T^{-1};

d_z = vertical dispersivity coefficient, L;

$D_d(\theta)$ = molecular diffusion coefficient (a function of θ) L^2T^{-1};

C_i' = mass of nuclide i per unit volume of solution in the source fluid, ML^{-3};

k_i = $\ln 2/(t_{\frac{1}{2}})_i$ = radioactive decay rate of nuclide i, T^{-1}.

$(t_{\frac{1}{2}})_i$ = half life of nuclide i, T.

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In the saturated zone:

$$S \frac{\partial h}{\partial t} = - \frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} + Q(x,y,t)$$

and

$$\frac{\partial}{\partial t} (b\varepsilon C_i + b\rho_m \bar{C}_i) = \frac{\partial}{\partial x} (D_{xx} \frac{\partial C_i}{\partial x} + D_{xy} \frac{\partial C_i}{\partial y}$$

$$+ \frac{\partial}{\partial y} (D_{yy} \frac{\partial C_i}{\partial y} + D_{yx} \frac{\partial C_i}{\partial x}) - \frac{\partial}{\partial x} (q_x C_i) - \frac{\partial}{\partial y} (q_y C_i)$$

$$- b\varepsilon\gamma\alpha C_i \frac{\partial h}{\partial t} + Q(x,y,t)\ C_i' - k_i b(\varepsilon C_i + \rho_m \bar{C}_i)$$

where S = storage coefficient of medium, dimensionless;

x,y = space coordinates along principal axes of transmissivity, L;

$q_x, q_y = - T_{xx}\frac{\partial h}{\partial x}, - T_{yy}\frac{\partial h}{\partial y}$ = fluxes of solution in the x and y direction, respectively, L^2T^{-1};

$T_{xx}, T_{yy} = K_{xx}b, K_{yy}b$ = transmissivities of the medium in the x and y direction, respectively, L^2T^{-1};

K_{xx}, K_{yy} = hydraulic conductivities of the medium in the x and y direction, respectively, LT^{-1};

b = saturated thickness of the medium (equal to h in unconfined systems), L;

$Q = \sum_{j=1}^{m} Q_j \delta (x-x_j)\ \delta(y-y_j)$ rate of source terms, LT^{-1};

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Q_j = flux due to source j, located at x_j, y_j, L^3T^{-1};

ϵ = porosity of medium, dimensionless;

$D_{xx}, D_{yy}, D_{xy}, D_{yx}$ = components of the effective hydrodynamic dispersion coefficient for the entire saturated thickness of the medium (see below); L^3T^{-1};

γ = unit weight of solution, $ML^{-2}T^{-2}$;

α = compressibility of the medium, $M^{-1}LT^2$.

All other symbols are as defined previously. Following Scheidegger (1961) and Pinder (1973), the hydrodynamic dispersion coefficients can be expressed as

$$D_{xx} = D_L \frac{q_x^2}{q^2} + D_T \frac{q_y^2}{q^2} + D_d \tau$$

$$D_{yy} = D_L \frac{q_y^2}{q^2} + D_T \frac{q_x^2}{q^2} + D_d \tau$$

$$D_{xy} = D_{yx} = (D_L - D_T) \frac{q_x q_y}{q^2}$$

where $D_L = d_L q$ = effective longitudinal dispersion coefficient, L^3T^{-1};

$D_T = d_T q$ = effective transverse dispersion coefficient, L^3T^{-1};

D_d = effective molecular diffusion coefficient, L^3T^{-1};

q = $(q_x^2 + q_y^2)^{1/2}$ = magnitude of flux, L^2T^{-1};

d_L, d_T = dispersivity coefficients, L;

τ = tortuosity, dimensionless.

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For equilibrium reactions with linear adsorption isotherms, the concentration $\bar{C}_i$ of the sorbed form appearing in the solute transport equations can be expressed in terms of the concentration C_i of the dissolved form through use of the distribution coefficient K_d (Thompkins and Mayer, 1947; Kaufman, 1963), which is defined as

$$K_d = \bar{C}_i/C_i, \text{ dimension } L^3M^{-1}.$$

The distribution coefficient K_d is a lumped parameter which depends on many variables, including moisture content in the case of unsaturated flow. This parameter will be further discussed in the section that follows.

HYDROGEOLOGIC AND HYDROCHEMICAL DATA NEEDS FOR SITE EVALUATION

The types of hydrogeologic and hydrochemical data needed to determine whether proposed or existing sites meet the criteria stated earlier are listed below in approximate order of increasing difficulty and (or) cost of acquisition:

1. Depth to water table, including perched water tables, if present.
2. Distance to nearest points of ground water, spring water or surface water usage (Includes well and spring inventory).
3. Ratio of pan evaporation to precipitation minus runoff (by month for period of at least 2 years).
4. Water table contour map.
5. Magnitude of annual water table fluctuation.
6. Stratigraphy and structure to base of shallowest confined aquifer.
7. Baseflow data on perennial streams traversing or adjacent to storage site.
8. Chemistry of water in aquifers and aquitards and of leachate from the waste trenches.
9. Laboratory measurements of hydraulic conductivity, effective porosity, and mineralogy of core and grab samples (from trenches) of each lithology in unsaturated and saturated (to base of

shallowest confined aquifer) zone--hydraulic conductivity to be measured at different water contents and suctions.

10. Neutron moisture meter measurements of moisture content of unsaturated zone. Measurements to be made in especially-constructed holes; at least 2 years' record needed.
11. In situ measurements of soil moisture tension in upper 15-30 feet (4.5-9.0 m) of unsaturated zone; at least 2 years' record necessary.
12. Three-dimensional distribution of head in all saturated hydrostratigraphic units to base of shallowest confined aquifer.
13. Pumping, bailing, or slug tests to determine transmissivity and storage coefficients.
14. Definition of recharge and discharge areas for unconfined and shallowest confined aquifers.
15. Field measurements of dispersivity coefficients.
16. Laboratory and field determination of the distribution coefficient (K_d) for movement of critical nuclides through all hydrostratigraphic units.
17. Rates of denudation and (or) slope retreat.

These data are necessary for a complete definition of flow and nuclide transport through both the unsaturated and saturated zones. To obtain such information, exploration costs could total several tens to several hundreds of thousands of dollars, dependent upon depth to water table and complexity of the flow system. However, not all the outlined information is likely to be needed at all sites. For example, in the arid or semi-arid zones, data types 1 and 3 may strongly indicate the absence of any net flux of water in the unsaturated zone below a depth of a few feet (Winograd, 1974) and, hence, the probable suitability of the site for storage of solidified wastes, at least in the short term, say less than 100 years. Should some liquid wastes also be placed in the same trench, data of the type listed in items 1, 9, 10 and 11 might permit an estimate of the volume of liquid waste that the unsaturated zone might accept before flow reaches the water table. Even in sub-humid terrane, the presence of interbedded fine and well-sorted coarse-grained sediments within the unsaturated zone might, when coupled with a moderate depth to water table (say 30 feet or 9 m), preclude natural recharge during all but the wettest of years (Winograd, 1974). As another example, field measurements of hydraulic conductivity and dispersivity at a storage site excavated in a thick aquitard, say a 60-foot (18 m) thick glacial till, is impractical, as might be the attempt to measure the three-dimensional distribution of heads. In such a medium, perhaps only a long-term monitoring may permit determination of velocity, flow direction, and dispersion.

To determine the extent to which sorption processes retard the movement of a given critical nuclide, the four principal types of geochemical information necessary are: a) the mineralogy (by size fraction including colloidal materials) of all hydrostratigraphic units traversed by the water, including units in the unsaturated zone; b) chemistry of water in aquifers and aquitards; c) chemistry of representative samples of leachate from the waste field; and d) laboratory experiments to determine the distribution coefficients (K_d) for the critical nuclides in representative samples of each hydrostratigraphic unit.

In some of the qualitative literature on waste disposal a panacealike aura surrounds the term ion-exchange. In such literature it is implied that when all else fails, ion-exchange processes will prevent movement of contaminants to points of water use. A few caveats are in order. First, there are several sorption processes, of which ion-exchange is but one. Some processes will capture and "fix" or hold a given nuclide "irreversibly" within the crystal lattice of a clay mineral; but other processes provide only a temporary home for undesirable elements, which after a while reappear in solution (Tamura, 1972). For this reason the parameter K_d, or distribution coefficient, is a markedly superior means with which to evaluate nuclide transport through a given medium. This coefficient is the ratio of activity, concentration or mass of a sorbed nuclide per unit mass of solid to the activity or concentration of dissolved nuclide per unit volume of water (Thompkins and Mayer, 1947; Kaufman, 1963). Explicit in the definition is the statement that sorption of a nuclide from waste-bearing water is incomplete; some fraction will always reside in the water. Second, as is ion-exchange, K_d is a lumped parameter -- one that is a function of many variables, including pH, redox potential, solute chemistry, concentration of the nuclides, chemistry of leachate, mineralogy (including solid solution), and, in the unsaturated zone, moisture content. For a given mineralogy it is also a function of surface area of the porous medium. Hence, predictions of nuclide travel based on laboratory measurements of K_d are valid only to the degree to which field conditions are duplicated. A major change in leachate chemistry may, in some cases, result in an order of magnitude decrease in the K_d determined in the laboratory (Tamura, 1972, fig. 1). Likewise, extrapolation of K_d values from one area to another is valid only if the natural water chemistry and fine grained alumino-silicate and (or) oxyhydroxide mineralogy in both areas is similar. Third, sorption is an important retardant of nuclide movement, principally in rocks with intergranular or intercrystalline porosity,-- rocks with considerable surface area. Sorption is considerably less effective in fractured or cavernous media due to minimal surface area and maximum velocity (that is, minimal contact time with minerals on fracture or cavern walls). Yet, even granular media, such as till, contain open fractures (Cherry, and others, 1973; Williams and Farvolden, 1967); where such fractures are present, the predictive value of K_d data determined from core samples may be marginal.

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CONCLUDING REMARKS

In our brief overview we have considered the hydrogeologic, and to a lesser extent the hydrochemical, aspects of subsurface movement of radionuclides dissolved from low-level wastes buried at shallow depths. The reader is reminded that a complete safety analysis of a low-level radioactive burial site would also have to explicitly consider the following matters: a) introduction of radionuclides to the atmosphere and surface water through long-term erosion and catastrophic erosion due to floods and earthquakes; b) uptake of radionuclides from the soil zone by plants; c) identification of critical nuclides within, and of the critical population group in the vicinity of, proposed burial sites (International Atomic Energy Agency, 1971); d) long term monitoring of the site to prevent vandalism and blundering by unaware descendents; and e) methods of trench construction and waste emplacement designed to reduce or exclude entry of water into the trenches.

Within the hydrogeologic domain of concern here, it is emphasized that predictive modeling, monitoring, and management of dissolved nuclides are most effective if wastes are emplaced in relatively simple hydrogeologic settings; namely, in unfaulted, relatively flat-lying strata of intermediate permeability (for example, silt, siltstone, and silty sandstone) in a region of low relief. In such a setting, a modest amount of background hydrogeologic and hydrochemical data of the types outlined in the previous section of this report may permit modeling of the rates and directions of movement of selected critical radionuclides prior to a commitment to use of the site. In contrast, fractured or soluble media and aquitards utilized as burial sites are difficult to monitor, sample, and model. Moreover, in humid zones, sites in aquitards may overflow. That is, due to the considerably higher permeability of the trenches than the surrounding strata, the trenches act as infiltration galleries, fill with precipitation, and may spill over through seeps at the trench-fill contacts. The hydrogeologic suitability of existing sites in aquitards can perhaps best be studied, ex post facto, by long term (one to several decades) monitoring of nuclide movement through sampling of water and cores from carefully designed and constructed test wells. Such long term records of nuclide distribution may then be used to empirically predict future rates and directions of nuclide travel.

A buffer zone several thousands of feet to several miles around new and existing sites is a mandatory consequence of the site selection criteria outlined in the section, "Potential release mechanisms and hydrogeologic siting criteria." The minimum width of the buffer zone would be governed at each prospective site by the calculated length of ground-water flow path needed to permit decay to safe levels of the identified critical nuclides. A buffer zone 20-50 percent greater than that calculated is probably advisable, so that: a) a safety factor is provided in the event that unknown aquifer heterogeneities result in longitudinal dispersion considerably greater than calculated; and

b) construction of additional disposal sites adjacent to the original site is possible should the predictions of solute movement prove conservative.

Finally, the commonly made distinction between storage versus disposal of radioactive wastes appears questionable for low-level wastes. This distinction, though applicable to problems concerning the handling of the relatively small volume of high-level radioactive wastes (see for example, Winograd, 1974), does not appear realistic for the relatively large volumes of low-level waste production projected for the years 1976-80, 1981-90, and 1991-2000, namely 3.6 X 10^6, 14.5 X 10^6, and 79 X 10^6 ft^3 per year (O'Connell and Holcomb, 1974). It appears improbable on economic, logistical, or radiological safety grounds, that the contents of an existing low-level waste site would be exhumed even in the event of extensive leakage of contaminated ground water from the site. Hence, in reality, the term "waste disposal" may be more correct for shallow burial of low-level wastes than the term "waste storage". Granting that such emplacement is to all intents and purposes permanent (in a human time frame) it becomes mandatory that: a) intensive hydrogeologic and hydrochemical studies precede choice of all new sites and that they be completed at any existing, but heretofore un-studied, sites; and b) that intensive radiochemical monitoring of ground and surface waters be done during and after the lifetimes of all operational sites.

APPENDIX

THE MAXEY FLATS, KENTUCKY, RADIOACTIVE WASTE STORAGE SITE: CURRENT KNOWLEDGE AND DATA NEEDS FOR A QUANTITATIVE HYDROGEOLOGIC EVALUATION

Current Knowledge of Site Hydrogeology

Maxey Flats, a low-level radioactive waste storage site administered and monitored by the State of Kentucky and operated by Nuclear Engineering Co. (NECO) is located atop a dissected plateau in Fleming County near Morehead, Kentucky. The site, approximately 2,500 feet (760 m) long and 1,200 feet (370 m) wide, is bounded by scarps and steep slopes on the east, south and west (fig. 1). The upland is about 250-350 feet (76-110 m) above the surrounding valleys (locally called hollows), which contain small perennial creeks. Average annual precipitation is 46 inches (1,170 mm). Storage of wastes began in May 1963, and about 2.5 million cubic feet (70,000 m^3) of radioactive wastes have been buried in trenches through 1971. An inventory of type and quantity of wastes buried is available in a report by Clark (1973).

The stratigraphy of the site and surrounding regions is well known and clearly depicted on a 1:24,000 geologic map (McDowell, Peck and Mytton, 1971). The site is underlain by gently dipping (25 feet per

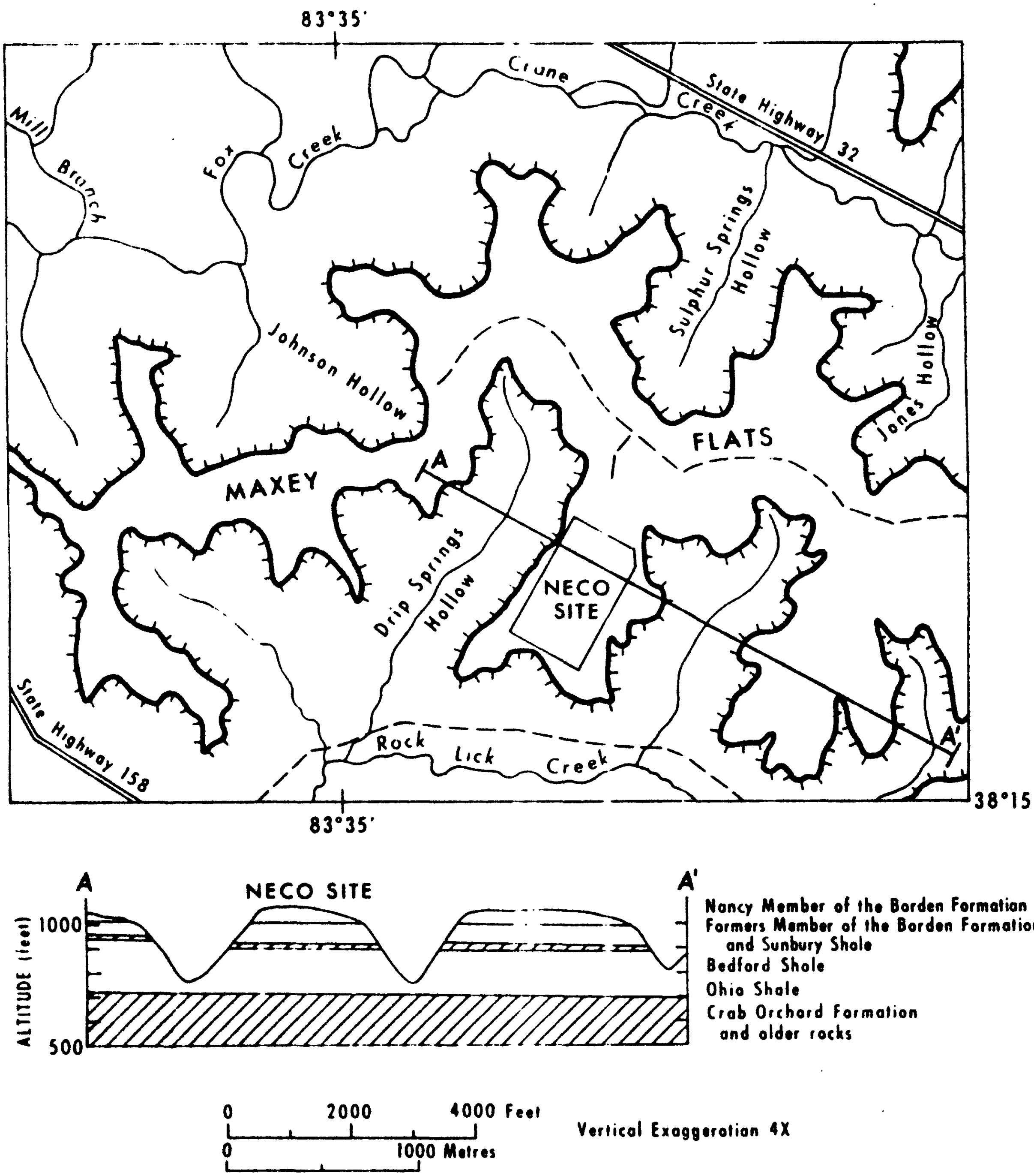

Figure 1. Sketch map and geologic section, Maxey Flats, Kentucky (base map, USGS 1:24,000 Plummers Landing quadrangle; geology simplified after McDowell and others, 1971).

mile of 4.7 m/km to the east-southeast) Silurian, Devonian, and Mississippian rocks consisting chiefly of fissile carbonaceous shale, clay-shale, and some siltstone and sandstone. These rocks comprise the following formations, listed in order of decreasing age: Crab Orchard Formation (upper part, 80-130 ft or 24-40 m thick); Ohio Shale (150-220 ft or 46-67 m thick); Bedford Shale (10-40 ft or 3-12 m thick); Sunbury Shale (15-20 ft or 5-6 m thick); and the Farmers (33-95 ft or 10-29 m thick) and Nancy (155-195 ft or 47-59 m thick) Members of the Borden Formation. At Maxey Flats only the lower 40 feet (12 m) of the Nancy Member is present. The trenches are entirely within the Nancy Member.

The hydrogeology of the site is poorly understood. A summary of several reconnaissances (Hopkins, written commun. 1962; Walker, 1962; and Whitman, written commun. 1971) and observations made during a 2-day traverse of the site by I.J. Winograd follows.

All the cited stratigraphic units are aquitards, and only one of these has been hydraulically tested at the storage site. The Ohio Shale is probably the most transmissive of the strata beneath the site by virtue of its highly fissile nature, general absence of interbedded clay-shales (some which are slightly to very plastic when wet), and great thickness (150-200 ft or 46 to 67 m). In areas adjacent to the site, this formation reportedly yields 100 to 500 gallons (400-2000 litres) per day to wells, particularly those dug or drilled in valleys (Hall and Palmquist, 1960); water quality is marginal. The Crab

Orchard Formation, in contrast, consists predominantly of expansive clay-shale, reported to be very plastic when wet, and to flow and slump into excavations (McDowell, Peck and Mytton, 1971; Dobrovolny and Morris, 1965); open fractures are therefore unlikely in this formation within the zone of saturation, and it may be the least permeable of the aquitards beneath the site. The Crab Orchard Formation apparently controls the occurrence of the numerous springs and seeps reportedly emerging from the base of the overlying Ohio Shale (Dobrovolny and Morris, 1965); such control, if documented by a detailed inventory of springs at and around the site, suggests that the Crab Orchard, by virtue of its stratigraphic position, may be considered the "hydraulic basement" for significant movement of ground water in the region.

The transmissivity of the remaining four formations or members is probably intermediate between that of the Crab Orchard and the Ohio Shale. Sandstone and siltstone near the base of the Nancy Member and in the Farmers Member of the Borden Formation contain open joints and bedding planes in outcrop and in exposures. But these competent strata are interbedded with clay-shales, which may retard and control the vertical movement of water beneath Maxey Flats. Open bedding planes observable in the Farmers Member along the eastern scarp of Maxey Flats appear to be due to removal, by mechanical weathering, of the soft interbedded clay-shales, which are in place a few yards in from the outcrop face.

The highly fissile nature of the Ohio and Sunbury Shales and the high degree of induration of siltstones and sandstones of the Nancy and Farmers Members of the Borden Formation suggest that flow through these strata occurs principally via secondary openings, namely joints and planes of fissility. Whether water flow in the clay-shales of the Nancy and Farmers Members and the Bedford Shale also occurs principally through fractures rather than interstices is an open question; some of these clay shales are plastic when wet (particularly those in the Bedford Shale) and may contain no open fractures when saturated.

A well inventory and test drilling in 1962 (Hopkins, written commun. 1962; Walker, 1962) suggest that many shallow dug wells tapping the basal Nancy Member on the Flats are actually cisterns periodically recharged with water from the soil zone. Pressure injection tests were conducted by Walker (1962) on several 40 to 50 foot (12-15 m) test holes at the NECO site. Assuming that no leakage occurred around the packers, the results of these tests indicate that injection rates ranged from 0.00002 to 0.005 gallons per minute per foot of injected interval per pound per square inch of injection pressure (0.00006-0.015 $[(l/s)/m]/(kgf/cm^2)$); the median value for 10 tests was 0.0002 gallons per minute per foot per pound per square inch (0.0006$[(l/s)/m]/(kgf/cm^2)$). After drilling, but prior to the pressure injection testing in 1962, water was not detected in any of the test holes. The reported absence of a measurable water level in the test holes may support the cistern concept or may simply reflect inadequate time for recovery of water level after completion of the drilling. In aquitards such recovery may take hours to days (Winograd, 1970) even in holes drilled by the air-rotary or cable tool methods. The drill holes contained water when measured by H. Hopkins in October 1963.

Based on water level data from shallow dug and drilled wells, from two deep wells, and upon hydrogeologic inference, the following model of ground-water flow may be postulated for the Maxey Flats area. Ground water in the soil zone is perched above the poorly permeable Nancy Member of the Borden Formation (Hopkins, written commun. 1962). It is this water that supplies shallow dug wells on Maxey Flats. This perched water table (altitude 1,035-1,055 ft, or 315-322 m) slopes southeastward, paralleling the regional dip of the Nancy Member (Hopkins, written commun. 1962)[2/]. Water levels in the two "deep" wells (reportedly drilled to 110 and 165 feet or 34 and 50 m, but only open to 59 and 64 feet or 18 and 20 m, at the time of measurement in 1962) were as much as 30 feet (9 m) lower than the perched water table in 1962. The lower levels may represent a lower water table, as suggested by Hopkins (written commun. 1962), or be evidence of decreasing heads with depth, namely suggestive of vertical ground-water flow within the Nancy Member.

2/ In October 1963 Hopkins also measured water levels in 7 of the 8 test holes drilled at the site. Water level altitudes in these 40-50 foot (12-15 m) holes range from 1,025-1,040 feet (312-317 m) with depths to water of 6-20 feet (2-6 m). Interpretation of these water levels will require detailed study of waste burial operations during the months preceding the measurements.

The emergence of springs and seeps from the Ohio Shale around the periphery of Maxey Flats and adjacent regions (McDowell, Peck, and Mytton, 1971) indicate the presence of a water table in this formation, but its altitude and configuration beneath the Flats or adjacent areas is unknown. Whether any perched zone(s) of saturation exists between the perched water in the soil zone and the postulated water table in the Ohio Shale is conjectural. Whitman (1971, written commun.) postulated such a zone within siltstones of the Farmers Member of the Borden Formation. A perched zone of saturation conceivably might also exist in the Sunbury Shale, above the reportedly expansive clay-shales of the Bedford Shale. Also unknown is the magnitude of interflow, namely ground-water flow within the relatively permeable soil and colluvium blanketing parts of the slopes surrounding the Flats.

To a first approximation, the perennial creeks west and northwest (Drip Springs Hollow), east and southeast (an unnamed creek), and south (Rock Lick Creek) of the site (fig. 1) comprise the hydrologic boundaries of the local ground-water flow system. The first two creeks reportedly are perennial except for a 2- to 4-week period each year; water persists in depressions in the creeks during periods of no flow (Hopkins, written commun. 1962). The near-perennial nature of these creeks suggests, in this area of probably low infiltration rates and high runoff, that the creek discharge is primarily baseflow from the Ohio Shale and (or) the Crab Orchard Formation and possibly from the colluvium blanketing parts of the slopes around the site.

The discharge in Drip Springs Hollow was about 1.7 cubic feet per second (0.048 m^3/s) on August 1, 1962, and that in the unnamed hollow east of Maxey Flats, 2.2 cubic feet per second (0.062 m^3/s) on the same date; both creeks were dry near their heads (Hopkins, written commun. 1962).

In summary, the stratigraphy of Maxey Flats is well known and its local hydrologic boundaries approximately defined. No data are available, however, on the depth to or configuration of the water table(s), head changes with depth within the zone of saturation, transmissivities, or porosities of any of the strata older than the Nancy Member of the Borden Formation; and data for the Nancy Member are marginal. The absence of substantive hydrogeologic data reflects, in part, the difficulties of obtaining hydraulic data from wells penetrating only aquitards and, in part, the absence of wells or test holes of proper construction tapping units older than the Nancy Member, either at or in the immediate vicinity of the site.

Inherent Obstacles to a Quantitative Evaluation of the Maxey Flats Hydrogeology

An outline of data needs and methodology for a quantitative evaluation of the hydrogeology of Maxey Flats is presented in the next section. Here we list several caveats which merit careful consideration prior to a commitment to a costly subsurface exploration program of the type outlined below. The study of and predictions of nuclide movement away from potential waste storage sites can be expedited for sites with relatively simple hydrogeology namely, sites underlain by non-fractured aquifers of moderate permeability. The strata beneath Maxey Flats, by contrast, are aquitards whose fractured nature and low permeability constitute major obstacles to successful quantitative definition of the hydrogeology of the region, regardless of funding levels. The low permeability of these strata constitutes an obstacle in two ways. First, determination of static water levels of, or the obtainment of representative samples of formation water from, selected depth intervals in the aquitards may take days or possibly weeks. Second, determination of transmissivities by pumping may not be feasible, necessitating use of less satisfactory techniques, such as slug injection testing. (See below.) Similarly, the low transmissivities may preclude utilization of two-well tracer tests for in-situ measurements of aquifer dispersivity and distribution coefficients.

The high probability of ground-water flow through fractures, particularly in the Ohio Shale, the Sunbury Shale, and the Farmers Member of the Borden Formation, constitutes the second major obstacle. First, the fractures introduce a measure of heterogeneity that may not readily be handled using the assumptions of flow through intergranular porous media. Ground-water velocities, computed using such an assumption, may be two or more orders of magnitude less than the maximum velocity. Second, data from two-well tracer tests are inherently difficult to interpret in fractured media, and the transfer value of such data is uncertain.

In view of the above considerations it might be preferable that the detailed hydrogeologic subsurface exploration program outlined in the next section is implemented in several phases. If initial phases of the drilling and testing program support our reservations on the possibility of a meaningful quantitative evaluation of the hydrogeology of the site, the program could be discontinued. In this event, consideration could be given to preventive measures that would: a) retard or exclude entry of water into the trenches for decades; b) retard movement of radionuclides out of the trenches even in the presence of ponded water; and c) retard exhumation of the wastes by erosion for decades. Such measures might, for example, include: a) placement of a concrete and (or) asphalt cover over all filled trenches; b) stratification of the wastes, in active and future trenches, with layers of soil or crushed shale, and c) exclusion from future burial of wastes containing the long-lived transuranic radioelements, such as plutonium and americium.

Outline of Data Needs and Methodology for an Evaluation of Site Hydrology

Studies necessary for an evaluation of the hydrogeology of Maxey Flats, as it relates to modeling and monitoring of the movement of dissolved radionuclides from the trenches to off-site areas, fall into three general categories: a) definition of the local and regional ground-water flow system; b) determination of magnitude of vertical and lateral leakage of ground water from the trenches; and c) measurement of the degree of retardation of specific nuclides during their migration through the aquitards underlying the site. The types of data necessary and methodology commonly used to obtain such data are outlined in this section, but such an outline should not be construed as being fixed. It is expectable that, in practice, the methodology will have to be tailored in varying degrees to meet the hydrogeologic conditions at the Maxey Flats site.

Definition of Ground-water Flow System

Definition of the local and regional ground-water flow systems, specifically the rates and directions of ground-water movement beneath and along the periphery of the site, is a prerequisite for any mass-transport modeling of nuclide movement. Definition of the flow systems requires information on the head distribution in and the transmissivity and porosity of each water-bearing stratigraphic unit beneath and in the region surrounding the site.

Head distribution within a water-bearing unit is commonly determined using: a) piezometers (namely cased and cemented wells open to the formation tapped only at the bottom) drilled to different depths; b) cased and cemented wells of differing depth open to the formation only opposite the bottom few feet to tens of feet of hole; and c) uncased holes completely penetrating the aquifer or aquitard, but in which selected zones are isolated for head measurement using inflatable packers. Because of the probable sparsity of water-bearing fractures in the aquitards beneath Maxey Flats, and the probable low permeability of such fractures, method "b" appears well suited for use at this site.

Several groups or nests of wells will probably be needed to define the three-dimensional distribution of head. Data obtained from the first group would determine that needed from the second group, etc. The first well in a group of six might, for example, be completed to determine the head in the first detectable water-bearing fracture in the Nancy or Farmers Member of the Borden Formation; such a well would be drilled, cased and cemented to the top of the members and then air-rotary drilled deeper till water entered the bore. An adjacent well of similar construction might test the water-bearing fractures in fissile shales of the Sunbury Shale. Successive wells might test the upper, middle and basal parts of the relatively thick fissile shales of the Ohio Shale and the clay-shales in the underlying Crab Orchard

Formation. Perhaps as many as four such groups or nests of wells might be needed at the NECO site.

After the head has been determined in each isolated zone, swabbing to obtain water samples may be feasible in the most permeable fractured intervals, as well as determination of permeability via slug injection tests. (See below.)

Determination of the head distribution in the aquitards will probably be extremely time-consuming, owing to the low permeability of these strata and to the influence of the drilling itself (Winograd, 1970). It is, therefore, necessary that modern air-rotary drilling, cementing, and testing equipment be used and that the entire operation be under the supervision of an experienced hydrogeologist. Rotary drilling with water or mud or drilling with cable tools would not be practical.

Transmissivity may be determined by means of pumping or injection tests of selected zones. Determination of transmissivity by pump testing may not be feasible in the aquitards because they may not yield even a few gallons a minute to a pump for periods in excess of a few minutes to tens of minutes. Accordingly, a series of slug injection tests may be necessary; methodology and interpretation of slug testing are discussed by Cooper and others, 1967; Blankennagel, 1967, 1968; Papadopulos, and others, 1973. As mentioned previously, slug tests can be made in the nests of wells drilled for head determination. However, because such holes are designed to sample only a fraction of the thickness of each aquitard, tests in these holes may be adequate only for the thinner aquitards. Determination of the transmissivity of the Ohio Shale, Crab Orchard Formation, and perhaps the Farmers Member of the Borden Formation will require several additional holes penetrating the entire thickness of these aquitards.

Assuming the water table divide in the Ohio Shale parallels the long axis of the NECO site, that baseflow data from the creeks bounding the site (on east and west) are available, and that water in this shale is the principal source of the baseflow, then the gross transmissivity of this formation might also be determined using the drain method of Jacob (1943).

As in all fractured media, field determination of porosity will be extremely difficult. The difficulty will be compounded if the thick aquitards, such as the Ohio Shale, are too impermeable to pump. If the fracture porosity cannot be determined by field tests, limits can probably be placed on this parameter by examination of cores, outcrop and exposures.

An up-to-date bibliography of the methodology of aquifer testing, laboratory measurements of porosity and permeability, and geophysical borehole logging is presented in the report, "Recommended Methods for Water-Data Acquisition" (U. S. Geol. Survey, 1972, chapter II).

In summary, hydraulic testing methodology is available for determination of head, transmissivity, and porosity needed for the evaluation of the local and regional ground-water flow systems beneath Maxey Flats. Undoubtedly such methodology will require modification when applied to the aquitards. Use of highly trained drilling and hydrogeologic personnel and modern air drilling technology is probably necessary to assure success of such a study.

In addition to the cited data obtained by drilling, certain other types of data are necessary to complete a study of site hydrogeology.

1. A modern inventory of wells and springs within a 4-mile (6 km) radius of the site may prove helpful, first to verify and expand upon certain conclusions of the 1962 reconnaissances, and second to determine what geologic controls localize the springs and seeps of the region.

2. Placement of a recording gage above the mouth of Drip Springs Hollow and the creek in the unnamed hollow east of Maxey Flats. As mentioned previously, the baseflow characteristics of these creeks are potentially valuable, when coupled with head data, for a determination of the gross transmissivity of the Ohio Shale. In addition, several seepage runs made in the Drip Springs Hollow could determine whether the bulk of baseflow is derived from the Ohio Shale, or the Crab Orchard Formation.

3. Placement of a recording raingage at the NECO site on Maxey Flats.

4. Determination of the water chemistry of the creeks, particularly during periods of baseflow, and springs around the Flats. Selected chemical constituents, for example, Cl^-, Na^+, NO_3^-, and SO_4^{2-}, might prove as useful as nuclides in long-term monitoring of waste movement from the site, hence the need to establish the background chemistry at these sources. Chemistry of water in the aquitards and in the

trenches will be determined as part of the test drilling program and that program (described below) designed to study leakage from the trenches.

5. Map extent, thickness, and gross beta-gamma activity of colluvium on slope of Maxey Flats to determine if this material might under certain circumstances be capable of conducting ground water (namely interflow) off site. (See below.)

6. Laboratory measurements of effective intergranular porosity and permeability and X-ray study of the mineralogy of cores obtained from the test holes; the mineralogic analysis would be principally of the clay and colloidal size fractions.

7. Measurement of rates of slope retreat.

<u>Determination of the Magnitude of Vertical and Horizontal Leakage from the Trenches</u>

Definition of the local and regional ground-water flow systems is only the first step in an analysis of radionuclide movement from a burial site. Nuclides dissolved in water in the trenches may leave the trenches in several ways: a) vertical movement into the underlying aquitards and thence to the perennial creeks flanking the burial site; b) lateral movement, via the soil and colluvium, namely interflow, on the slopes flanking the site and thence to the creeks; and c) surface runoff, should both the trenches and soil zone become waterlogged. Which of these routes is likely to dominate under a worst-case condition, namely when water is permitted to pond in the trenches after abandonment of the site, and to what degree might vertical leakage modify natural ground-water gradients necessitate study. It is recognized that, as a result of the reported ponding of water in some trenches prior to 1971, the ground-water flow system, as defined today, may already reflect leakage from the trenches.

The magnitude of expectable vertical infiltration into the Nancy Member of the Borden Formation at the bottom of the trenches can be estimated via a series of infiltration tests using double ring infiltrometers. Infiltrometers are placed over visible fracture traces, or, if none are visible, at random. Methodology of such tests has been described by Johnson (1963).

Infiltration and laboratory tests of soil between trenches should permit a direct comparison of the relative permeability of the soil and the Nancy Member and an estimate of the magnitude of lateral interflow through the soil zone. Infiltration tests of the colluvium will be difficult due to its occurrence only on slopes; laboratory analyses of permeability of this bouldery material will be difficult.

The depth of vertical and lateral movement of nuclides beneath and adjacent to the trenches to date (1973) may be determined either by: a) water sampling, if a ground-water mound is found beneath the trenches; b) by means of periodic gamma ray logging of specially designed holes, if flow is unsaturated; and c) radio-chemical analyses of cores from the test holes and of samples of soil and colluvium.

Sorption Characteristics of the Aquitards

Sorption properties of porous media are usually investigated in the laboratory by batch mixing or column studies. (See, for example, Schroeder and Jennings, 1963; Wahlberg and Dewar, 1965 and Kaufman, 1963.) Field measurements are few. (See, for example, Parsons, 1961; Robertson and Baraclough, 1973.) If water movement through the aquitards beneath Maxey Flats is principally via joints, as suggested by the reconnaissances of Walker (1962) and Whitman (written commun. 1971), then determination of sorption by lab methods (designed solely for granular media) will not yield meaningful results except for soil and colluvium samples. Similarly, paired well tests will probably not be applicable unless transmissivities are high enough to permit pump testing. It appears likely that the sorption characteristics of the aquitards at Maxey Flats will have to be determined by comparison of the measured nuclide content of water in trenches with that sampled from springs and wells in the aquitard, and from soil moisture suction cups placed in the soil and colluvium. The activity distribution so sampled will be a net result of sorption and hydrodynamic dispersion properties of the media traversed.

Monitoring

Calibration of a mass-transport model of the Maxey Flats site will require several to many years of water level, baseflow, radiochemical and chemical data from selected wells, springs, creeks, and burial trenches at and around the site. An intensive and thorough radio-chemical monitoring program has been conducted at the site by the Kentucky Department of Health since the start of waste burial at the site. This program could be expanded to sample water from selected test wells and the baseflow in the creeks flanking the site. Periodic measurements of water levels and gamma radiation in the test holes would have to begin after completion of drilling programs.

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