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UCRL-52078

INFORMATION PERTINENT TO THE MIGRATION OF RADIONUCLIDES IN GROUND WATER AT THE NEVADA TEST SITE

Part 1: Review and Analysis of Existing Information

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Preface

The intent of this study is to search and understand the technical literature that exists on the migration of radioactive contaminants through rock and water-saturated aquifers. In order to treat the subject in depth, portions of the study have been assigned to specialists within the group of authors. The hydrology and hydrogeology of the Nevada Test Site (II,B and C), hydraulic effect of underground nuclear explosions (III,E), portions of the section on transport of radioactivity in ground water (V,B, D, E, and F), and description of groundwater quality monitoring (IV,E) were written by Randolph Stone. The portions of the report that deal with nuclear testing and close-in water sampling at NTS (II,A; IV,A; VI) were written by Lawrence D. Ramspott. The section on sorption (V,C), the description of distribution of radioactivity at early times (IV,B), and the section on transfer of radioactivity to the ground water (IV,C) were written by Harris Levy. The phenomenology of nuclear explosions and limit of radioactivity (III,A, B, C, and D), composition of NTS rocks (II,D), and interpretation of radiochemical analyses (IV,D), and other sections not mentioned here, were written by I. Y. Borg. The Recommendations and Summary and Conclusions sections represent a joint effort. While all sections were reviewed and modified by all four authors, prime responsibility for errors and omissions rests with the individuals associated with the specific sections.

hydrologic studies in and near NTS have been purposely limited to meet the objective of defining the pattern of ground-water flow at NTS and in the nearby vicinity. With these limitations, complete determination of the extent of regional ground-water systems has not been possible.

Possible Boundaries of the Ash Meadow Ground-Water Subsystem - Winograd and Thordarson attempted to outline the areal extent of the Ash Meadows ground-water basin through analysis of the regional pattern of precipitation, the hydraulic head potentiometric map, and the major geologic features. No formal recourse to complete water-budget analysis was followed.

The Spring Mountains and the Sheep Range receive more precipitation (Fig. 4) than other upland areas and are composed of rocks making up the Lower Carbonate Aquifer. Hence they could act as recharge boundaries on the south and east of the basin.

The potentiometric map (Fig. 13) indicates that ground water flows to Frenchman Flat from the east and northeast, suggesting that at least northern Indian Springs Valley is a part of the basin. The contours of hydraulic head in Cenozoic rocks of Pahute Mesa and Emigrant Valley indicate the approximate position of a ground-water divide that may lie beneath the Belted Range. This portion of the western boundary of the Ash Meadows basin is depicted in Fig. 14. The potentiometric contours for Cenozoic units, the hydraulic barrier extending from Lathrop Wells south along the spring line, and the presence of the Lower Clastic Aquitard east of Lathrop Wells (Fig. 13) indicate that ground water beneath the central Amargosa Desert and southwestern Jackass Flats does not discharge in the springs at Ash Meadows and therefore does not reside in the Ash Meadows basin.

Winograd and Thordarson suggest that the geologic character and extent of the west-dipping Gass Peak thrust fault, whose surface trace generally coincides with the eastern base of the Sheep Range (Fig. 3), causes most of the recharge to the Sheep Range to be diverted westward to Three Lakes Valley and southern Desert Valley. They conclude that only a small portion of the Ash Meadows discharge comes from Pahrump Valley because of an apparent barrier to flow between the two areas formed by the Lower Clastic Aquitard. Malmberg (1967) asserts that most of the underflow from Pahrump Valley is toward the Nopah and Resting Springs Ranges to the southwest of Pahrump Valley.

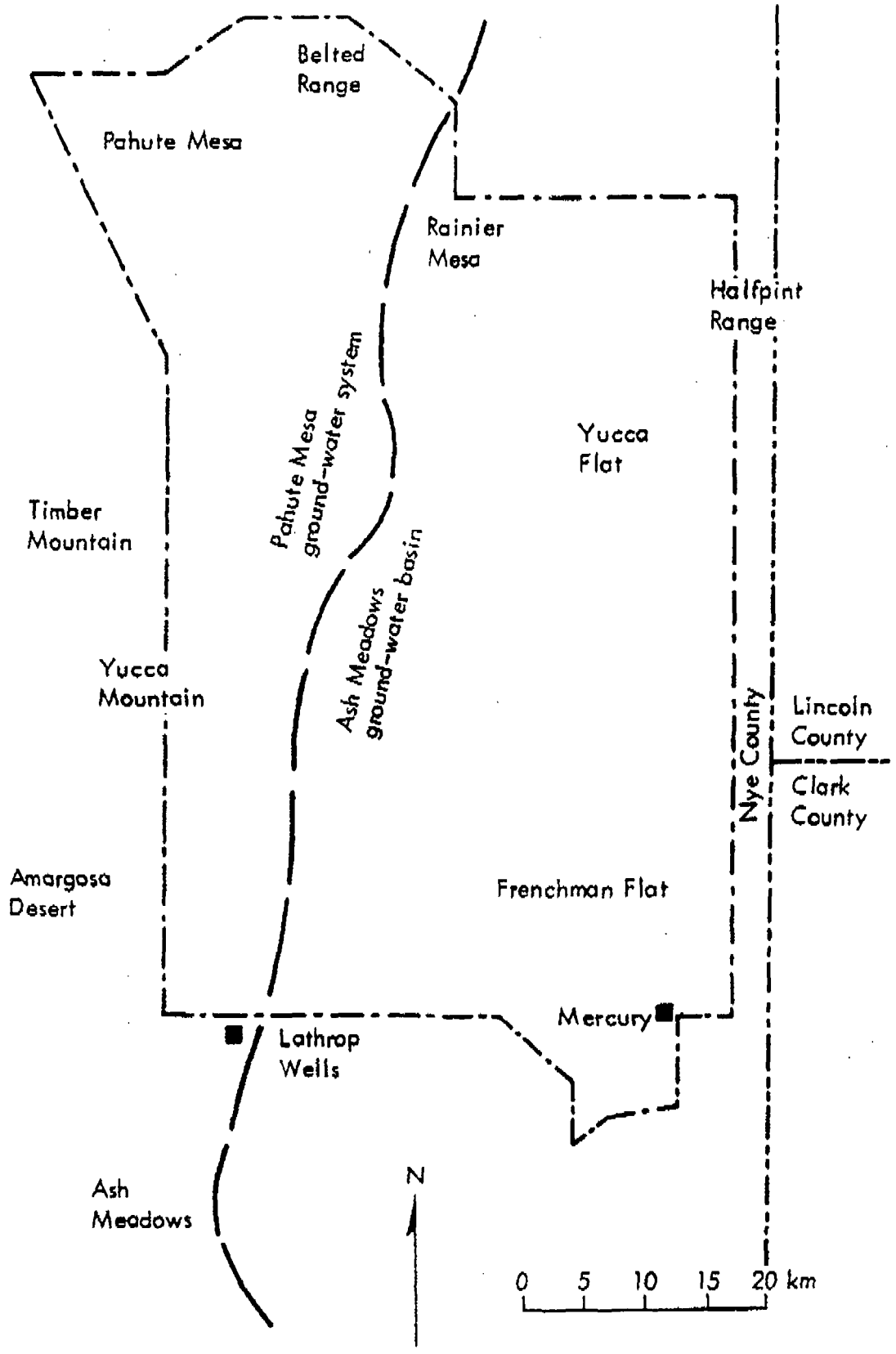

Fig. 14. Approximate location of boundary between Ash Meadows ground-water basin and Pahute Mesa ground-water system, Nevada Test Site.

point out, however, that in a nuclear explosion the number of neutrons (per kiloton of energy produced) actually escaping from the device is about the same for both fission and thermonuclear devices. Tewes and Schwartz (1975) conclude that approximately the same amounts of the various activation products are produced irrespective of the type of explosive. Thus, even if one assumed activation from several times as much thermonuclear yield as fission yield at NTS, radioactivity from the fission products would still be dominant at any time greater than 10 years.

The amount of tritium deposited below or near the water table at NTS through June 30, 1975, can be crudely estimated. It is about 10 kg at Pahute Mesa and about 3 kg at Yucca Flat. The amount at Frenchman Flat is negligible. These values are for the 78 tests detonated below the water table or with a cavity radius below the water table. These estimates are probably accurate to within a factor of 2 or 3 but should not be construed as a definitive catalog of tritium deposited at NTS. As tritium has an activity of about 10^4 Ci/g, 13 kg of tritium represents 1.3×10^8 Ci initially.

Table 14 is a summary of the tritium activity at various times after a hypothetical single deposition. The table neglects the fact that these tests started in 1962 and have continued to the present, i.e., that they have extended more than one half-life. For that reason, the table is realistic only at D + 100 years, when the 13-year span of decay-start-times begins to be less important. The earlier times are included only to illustrate the effect of the slow initial decay due to the 12-year half-life.

The final category of radionuclides for the source term is original nuclear material. No data are known to the authors, so the following crude estimate was made. A reasonable value for the tamped critical mass* of ^{239}Pu is 10 kg. If one assumes that this much was used for each of the 78 tests - and the further balancing assumptions are made that 1) none of this was consumed in the test and 2) notwithstanding the low-intermediate to intermediate yields of some of these tests, no additional ^{239}Pu was present - then 780 kg of ^{239}Pu can be used as a radionuclide source term. The error assigned to this estimate must be at least an order of magnitude, but some value is needed for illustrative purposes. In a similarly arbitrary fashion, we will also assume

*The critical mass when surrounded by a "tamper" or neutron reflector.

Table 14. Activity of tritium deposited at NTS below or near the water table.

Time after deposition[a] (years)	Activity (Ci)	
	Yucca Flat	Pahute Mesa
1	2.8×10^{7}	9.2×10^{7}
5	2.2×10^{7}	7.5×10^{7}
10	1.7×10^{7}	5.6×10^{7}
25	7.0×10^{6}	2.4×10^{7}
100	9.0×10^{4}	3.1×10^{5}
200	2.8×10^{2}	9.2×10^{2}
300	9.0×10^{-1}	3.0×10^{0}
400	2.8×10^{-3}	0.2×10^{-3}
500	9.0×10^{-6}	2.8×10^{-5}
600	2.5×10^{-8}	8.4×10^{-8}
700	8.0×10^{-11}	2.8×10^{-10}

[a]The table is constructed assuming all ^{3}H was deposited simultaneously rather than intermittently over a 13-year period (1962 to 1975).

deposition of an arbitrary 10 kg of ^{235}U at each test site. Neither of these values should be construed as an actual inventory of ^{239}Pu or ^{235}U. Because of the long half-lives of ^{239}Pu and ^{235}U, no table showing decay for the first hundred years has been constructed. However, ^{239}Pu displays a specific activity of 61.3 Ci/kg, and ^{235}U produces 2.1×10^{-3} Ci/kg.

The initial NTS deposition at D + 180 days for the 78 tests near or below the water table can be summarized as follows:

Source	Activity (Ci)	Uncertainty factor*
^{3}H	1.3×10^{8}	0.3 to 3.0
^{239}Pu	4.8×10^{4}	0.1 to 10.0
^{235}U	1.6	0.1 to 10.0
Fission products	1.8×10^{8}	0.5 to 1.5
Rock activation products	5.6×10^{6}	0.5 to 2.0

*For example, the ^{3}H activity is somewhere between $0.3(1.3 \times 10^{8})$ and $3.0(1.3 \times 10^{8})$Ci.

At first glance, the presence of ^{235}U would seem to be trivial, but because of its extremely long half-life (7.13×10^8 years), it cannot be ignored.

The final step of this analysis is looking at the effect of longer times on the radionuclide source term. Tables 15 and 16 are constructed for Yucca and Frenchman Flats and Pahute Mesa, respectively, for nuclides with greater than one curie total activity at D + 100 years. (Tables 12, 13, and 14 show activities at times less than 100 years, except for ^{239}Pu and ^{235}U.) Fifty-three tests in the Yucca Flat system, three at Frenchman Flat, and twenty-two at Pahute Mesa were considered in Tables 15 and 16.

These tables were constructed to show the general effect of radioactive decay. No judgment as to biological significance was exercised in selection of radionuclides for inclusion in the table. For example, ^{85}Kr and ^{39}Ar were included. Significance of the data in the tables depends on assumptions about the length of time before contaminated water might reach an off-site aquifer. It is worth noting that for the 78 tests below or near the water table, only 6 radionuclides will be present in greater than millicurie amounts after 1000 years.

2. Hydrologic Source Term

So far, no consideration has been given to the amount of radionuclides which might actually enter the water - the hydrologic source term. In following sections, it will be pointed out that the radionuclides are generally divided into refractory and volatile species, with refractories concentrated in the puddle glass near the cavity bottom and volatiles distributed through the chimney. Information on the relative solubility of these materials is sparse; however, the data are consistent with assertions in the Plowshare literature (Higgins, 1959, p. 1511; Tewes et al., 1974, p. 10; Miller, 1973, p. 9) that 1) less than 1% of the radionuclides in the melt glass near the bottom of the chimney will be dissolved, 2) much of the soluble long-lived radionuclides in the chimney water will be sorbed on the chimney rubble, and 3) most of the tritium will be mixed with chimney water at times on the order of a year. However, there are some data (Borg, 1975) suggesting that some portion of the tritium may be trapped in explosion-produced glass. In later sections it will be pointed out that some fraction of the material dissolved will be sorbed within the chimney.

Table 15. Total radionuclide source term[a] for Yucca Flat and Frenchman Flat at indicated times after time zero (D).

Nuclide	Half-life (years)	Activity (Ci)[b] at time D plus			
		100 yr	200 yr	500 yr	1000 yr
^{3}H	12.3	1.1×10^{5}	3.8×10^{2}	-	-
^{239}Pu	2.4×10^{4}	3.41×10^{4}	3.40×10^{4}	3.37×10^{4}	3.32×10^{4}
^{235}U	7.1×10^{8}	1.176	1.176	1.176	1.176
^{99}Tc	2.13×10^{5}	70	70	70	70
^{151}Sm	87	6.9×10^{3}	3.1×10^{3}	2.8×10^{2}	5.3
^{137}Cs	30	5.4×10^{4}	5.4×10^{3}	5.2	-
^{90}Sr	28	3.9×10^{4}	3.3×10^{3}	2.0	-
^{85}Kr	10.8	1.2×10^{2}	2.0×10^{-1}	-	-
^{14}C[c]	5730	4.2×10^{2}	4.2×10^{2}	4.0×10^{2}	3.8×10^{2}
^{39}Ar[c]	270	3.8×10^{2}	2.9×10^{2}	1.4×10^{2}	3.8×10^{1}
^{152}Eu[c]	12	1.2×10^{2}	3.7×10^{-1}	-	-

[a]Only nuclides with >1 Ci activity at 100 years are included; thus ^{144}Ce, ^{106}Ru, ^{129}I, and other nuclides listed in Tables 12 and 13 are not included.

[b]A dash (-) indicates less than 10^{-3} Ci.

[c]Activity calculated from fission yield has been arbitrarily doubled to allow for activation due to thermonuclear yield.

In the simplest case, the slug of radionuclide-bearing water which starts to migrate from the chimney is the hydrologic source term. However, while instantaneous slug injection is used for purposes of transport calculations, it is only an approximation of what happens for radionuclides with the possible exception of tritium. The process whereby radioactivity is portioned between glass, rubble, and water will be treated in the following sections.

B. DISTRIBUTION OF RADIOACTIVITY AT EARLY TIMES

Immediately after detonation, the device and the surrounding rock have been vaporized. All or nearly all of the radioactive species

Table 16. Total radionuclide source term[a] for Pahute Mesa at indicated times after time zero (D).

Nuclide	Half-life (years)	Activity (Ci)[b] at time D plus			
		100 yr	200 yr	500 yr	1000 yr
^{3}H	12.3	3.5×10^{5}	1.3×10^{3}	-	-
^{239}Pu	2.44×10^{4}	1.34×10^{4}	1.34×10^{4}	1.33×10^{4}	1.31×10^{4}
^{235}U	7.13×10^{8}	0.462	0.462	0.462	0.462
^{99}Tc	2.13×10^{5}	93	93	93	93
^{151}Sm	87	9.2×10^{3}	4.1×10^{3}	3.8×10^{2}	7.1
^{137}Cs	30	7.2×10^{4}	7.1×10^{3}	7.0	-
^{90}Sr	28	5.2×10^{4}	4.4×10^{3}	2.6	-
^{85}Kr	10.8	1.6×10^{2}	2.6×10^{-1}	-	-
^{14}C[c]	5730	5.5×10^{2}	5.4×10^{2}	5.2×10^{2}	4.9×10^{2}
^{39}Ar[c]	270	5.0×10^{2}	3.9×10^{2}	1.8×10^{2}	4.9×10^{1}
^{152}Eu[c]	12	1.6×10^{2}	5.0×10^{-1}	-	-

[a]Only fission and activation products with >1 Ci activity at 100 years are included.

[b]A dash (-) indicates less than 10^{-3} Ci.

[c]Activity calculated from fission yield has been arbitrarily doubled to allow for additional activation due to thermonuclear yield.

produced by the explosion are contained in gaseous form in the superheated expanding gas. When the cavity ceases to grow, the temperature and pressure continue to drop as heat is given up to the surrounding rock. Until now the radioactive gases have been held within the cavity walls (Teller et al., 1968).

When the melt flows to the bottom of the cavity and the walls begin to spall, gas may escape. By this time the cavity has cooled sufficiently so that the chemical species with higher boiling points, the so-called refractory nuclides, have condensed in the melt or are present in fine droplets still in

values of effective porosity from 0.01 to 1%. Similarly, flow rates of 180 to 18,000 m/year beneath the Specter Range have been estimated. If the range is limited to effective porosities between 0.1 and 1%, as we believe to be more nearly the case, the estimates of rate of movement of water in the Lower Carbonate Aquifer beneath central Yucca Flat and beneath the Specter Range become 1.8 to 18 m/year and 180 to 1800 m/year, respectively. An independent estimate of the rate of movement in one formation of the Carbonate Aquifer between the Specter Range and Ash Meadows, not dependent on an estimate of effective porosity by itself, was recently given as 18 to 410 m/year. There are large gaps in the knowledge of the areal variation of hydraulic characteristics of the Lower Carbonate Aquifer in Frenchman Flat and Mercury Valley, where only one well in each valley has served to test the Aquifer.

Not much movement in Yucca Flat it may take 1000 yrs to leave Yucca Flat

The general direction of ground-water movement beneath eastern Pahute Mesa is inferred to be to the south-southwest. Ground water is presumed to move southward from Pahute Mesa toward the Amargosa Desert through Oasis Valley, Crater Flat, and western Jackass Flats. The Pahute Mesa system apparently discharges in Oasis Valley and in the Amargosa Desert, west of the Ash Meadows springs. There are large gaps in factual knowledge of the pattern of ground-water flow in the area between and including Timber Mountain and southern Crater Flat. Little, if any, subsurface information exists on the geology and hydrology of this area. South-southwesterly ground-water movement beneath eastern Pahute Mesa is estimated to occur at rates of from 2 to 76 m/year.

Most tests in Yucca Flat, which is the major test area, have been located in the vadose zone. In developing the radionuclide source term presented in this report, only those tests detonated below the water table, or with a lower cavity boundary below the water table, were included. Therefore, it is important to establish that tests in the vadose zone are in fact relatively isolated from the saturated ground-water system.

There are a number of lines of evidence which suggest that there is no recharge to the water table from the surface of Yucca and Frenchman Flats downward: 1) Although site-specific measurements are lacking, the general climatic data and observations on the climate and botany of NTS indicate that evapotranspiration equals or exceeds annual infiltration in the test areas (there may be some recharge in the fringing bahadas).

in the vicinity of outcrops or subsurface structural highs of the underlying Lower Clastic Aquitard. Ground-water flow in the Lower Carbonate Aquifer is mainly through interconnected fractures and serves to link the valleys of the eastern part of NTS into the Ash Meadows system. Hydraulic testing of the Lower Carbonate Aquifer has been restricted to fewer than two-dozen wells or test holes at NTS and vicinity. These tests have enabled an evaluation of hydraulic head and transmissivity, but measurement of the coefficient of storage or effective porosity of the Lower Carbonate Aquifer has not been generally possible because of nonideal test conditions. The longitudinal dispersivity of one formation of the Lower Carbonate Aquifer has been evaluated in a two-well tracer test. Other results of this test permit estimation of the effective porosity of the formation as about 1.5%

The Tuff Aquitard overlies the Lower Carbonate Aquifer in much of the eastern portion of NTS. The Aquitard contains substantial quantities of zeolite and clay minerals, and ground water presumably moves downward through it by means of interstitial flow. Measurement of hydraulic head in the Tuff Aquitard has been carried out in the field, but most knowledge of its hydraulic conductivity and effective porosity comes from laboratory tests of core materials. Overlying the Tuff Aquitard are various other volcanic aquifers and minor aquitards as well as valley-fill aquifers.

The portion of the Pahute Mesa ground-water system that has been explored in any detail at depth is limited to eastern Pahute Mesa. Fractured rhyolitic lava flows and welded tuffs are considered to be the aquifers; the pathways are believed to be fractures within the units. Nonwelded and altered tuffs generally act as aquitards. Fewer than two-dozen wells and test holes on eastern Pahute Mesa have provided data for evaluation of hydraulic head and transmissivity of the interbedded rhyolites and welded tuffs. No measure of the coefficient of storage or of the effective porosity of these units has been possible, and evaluation of dispersivity has not been attempted.

Ground water is estimated to move downward through the Tuff Aquitard beneath Yucca Flat at average rates of 1.5×10^{-4} to 6×10^{-2} m/year. The rate of lateral movement to the south in the Lower Carbonate Aquifer beneath central Yucca Flat has been estimated to range from 1.8 to 180 m/year, on the basis of a range of

equilibrium with the vapor. As the roof and walls of the cavity collapse, the escaping gases move through the forming chimney. Many of the lower-boiling species, the volatile nuclides, will condense on the surface of the chimney rubble, while some of the radioactive species remain gaseous. A high percentage of the refractory species will be trapped in the solidified melt (Levy, 1972; Tewes and Schwartz, 1975). Amounts found in the chimney most likely have come from splashes or extrusion of melt or the entrainment of fine droplets of melt in the escaping cavity gases.

Examples of species present in high-boiling, refractory forms are the rare earths, zirconium, the alkaline earths, and plutonium. Examples of species present in lower-boiling forms that behave in a partly volatile fashion are the alkali metals, ruthenium, uranium, antimony, tellurium, and iodine. Then there are radioactive isotopes of argon, krypton, and xenon, which are permanently gaseous.

Certain fission-product mass chains behave chemically in a rather mixed fashion. Fission fragments of a given mass will have a distribution over a small range of atomic numbers. These initial products will be part of a chain which decays by beta-emission until a stable (or long-lived) member of the mass chain is reached. At the time of escape of the cavity vapor, the mass chain will still be distributed among chemical elements with different behavior. For example, consider the mass chain 140, which at later times we observe as ^{140}Ba. At the time of collapse of the cavity walls, the available ^{140}Ba will be associated with the melt. Some of the ^{140}Cs will also remain in the melt, while some will be in the escaping vapor, will condense on the cooler chimney rocks, and then decay to ^{140}Ba. The ^{140}Xe will escape the cavity region, and as it decays to ^{140}Cs and then ^{140}Ba, the nongaseous decay products will deposit upon the cooler surfaces of the chimney rocks (Levy, 1972).

Gaseous species not only will percolate upward through the chimney, but some may find their way into the cracks of the fracture region around the chimney. Unless they are formed directly, the final distribution (before contact with water) of the longer-lived radioactive species of primary concern to us will depend on the distribution and chemical behavior of their shorter-lived predecessors, as exemplified by the case of ^{140}Ba described above.

Radioactive species which may be produced in device materials and

thermonuclear reaction; direct products of the nuclear reactions (the fission products and tritium); and the radionuclides produced by neutron activation in the immediate vicinity of the explosion.

The radionuclide source term at NTS has been estimated for the 78 events detonated below the water table or having a cavity edge below the water table. The total fission yield for all events detonated at NTS below the water table or that had a cavity edge below the water table is slightly over 3 Mt at Yucca Flat, slightly over 4 Mt at Pahute Mesa, and less than 10 kt at Frenchman Flat. Approximations of the fission and activation products were made from the total fission yield. The amounts of tritium deposited at Yucca Flat and Pahute Mesa were estimated to be 3 and 10 kg, respectively. Crude estimates of the amounts of ^{239}Pu and ^{235}U were also made. The results of all these estimates were then assigned to the two ground-water systems (Pahute Mesa and Ash Meadows) and decayed to 1000 years, assuming that all nuclides had been deposited simultaneously. Some general features emerged from this analysis which are pertinent to considerations of underground migration of radionuclides at NTS. First, there is a very considerable reduction in the radioactivity even in the first 10 years. For example, at 10 years, there is only 1% as much fission-product activity as there was at 180 days, and only 4% as much activation-product activity. Even for tritium, there is about a 40% reduction in activity. Since underground testing at NTS has spanned a 14 year period, these figures are relevant. After 100 years, only 10 nuclides are present in amounts exceeding 1 curie. The most mobile of these is ^{3}H. The analysis indicates that the long-term problem (that is, on a time scale of centuries) is likely to be with plutonium.

The hydrologic source term is less than the radionuclide source term. Many factors are responsible for the difference, including the "sealing" of radionuclides in the puddle glass, low solubility in water of some of the radionuclides, and sorption processes within the chimney rubble itself. In transport calculations, the source term used is the hydrologic source term or an estimate of it, not the radionuclide source term.

Distribution of Radioactivity within Chimney

The radioactivity which constitutes the radiochemical source term

is heterogeneously distributed throughout the chimney. In general it is fractionated according to the volatility of the nuclide or of a parent nuclide which existed early in the formation of the cavity and chimney. Elements with high boiling points or refractory elements are concentrated in the melt at very early times, whereas lower-boiling elements or nuclides with volatile precursers tend to disperse into the chimney rubble. Noncondensable gases such as krypton and xenon will tend to migrate farthest; condensable gases such as steam are also highly mobile. Because each chimney has a slightly different time-history, the exact distribution of radionuclides within it is unique. However, the general observation that refractory materials are concentrated in the melt and volatile materials in the chimney is valid for all.

Transfer of Radioactivity to Ground Water

The net transfer of radioactivity from the debris of an underground nuclear explosion to ground water can be considered the result of a two-stage process. The first stage is the transference of the radioactive species from a melt matrix and/or from the surface of contaminated rubble to the solution. The second stage is the interaction of the species in solution with the rocks in the chimney environment, attended by resorption of some of the radioactivity. To understand the transfer of radioactivity to ground water, leaching experiments must be carried out. These experiments should differentiate between the two stages, give results that can be expressed as a rate, and be carried out over a sufficiently long period of time to be meaningful. There seem to have been no experiments which meet all of these qualifications; however, leaching experiments on puddle glass by both the U.S. and the French have indicated that only a small portion of the available activity is leached, in all cases less than 1%.

The radioactivity on chimney rubble is on the surfaces of the pieces of rock and is readily accessible to ground water. There is a lack of experimental data on leaching of chimney rubble.

The Soviets have measured radioactivity in water in a nuclear explosion crater. By necessity, the effect of sorption could not be dissociated from leaching. At the same time, they did leaching experiments on both melt samples and contaminated rock samples. Together, these experiments showed that species having volatile precursors had a

the historical record at a site (Has the decline in activity been such as to have been expected from natural decay, or are other processes active?). If specific radionuclides are measured, a more sophisticated interpretation is possible, especially if additional information is available or can be estimated. What are the dimensions of the cavity and chimney; has the chimney completely filled; how much of the chimney is below the water table; what is the radioactive source term; how much melt was formed by the explosion; and how much radioactivity was trapped in the melt? Of the above questions, the greatest uncertainties are associated with the last two: how much melt per kiloton was formed, and what proportion of radioactivity trapped in the melt cannot be leached by the ground water. Given reasonable estimates for all but the last two variables, the maximum possible concentration (i.e., assuming that all is dissolved) of any particular radionuclide can be calculated. The difference between this calculated value and the measured value represents the summation of all processes which reduce the amount of radionuclides in the hydrologic source term. Comparison of ratios between nuclides present in the water and in the radionuclide source term can be equally informative.

D. TRANSPORT OF RADIOACTIVITY IN GROUND WATER

The movement of nongaseous radioactivity underground depends on the movement of flowing water and the interaction of the surrounding solid medium with species moving with the liquid phase. The rate of movement of the radioactivity can be retarded by its sorption on the rock medium through which the water flows.

Dispersivity

The water molecules have a distribution of flow velocities that transfer to a radioactive solute in the flow domain, so that not all the radioactivity will move at the same velocity. This and other effects give rise to hydrodynamic dispersion of the solute. This dispersion creates a concentration distribution, with the result that the peak concentration of a species cannot be greater than that of the source; and, as dispersion increases, the concentration distribution widens, with a consequential attenuation of the peak values. The average rate of movement of the radioactive solute will be the same as the average rate of movement of water if there is no sorption retardation by the surrounding medium.

In isotropic media dispersivity has two components: the longitudinal

dispersivity and the transverse dispersivity, which are described with reference to the direction of liquid flow. Useful values of dispersivity can only be obtained from field data. Estimates have been made by calibrating mathematical solute transport models against observed ground-water solute transport. The range of dispersivity values so obtained for a variety of aquifers in various geologic settings spans only an order of magnitude (12-137 m). The longitudinal dispersivity of one formation of the Lower Carbonate Aquifer was determined in a test near NTS to be 15 m.

Sorption

The term sorption has been used to describe in a nonmechanistic way reactions whereby a species is removed from a liquid phase and held in some manner by a solid. Radioactive species may be sorbed from ground water by several different means. Surface charges on solid material may attract and hold from solution oppositely charged ions. The type of reaction with greatest significance to migration of radionuclides in ground-water flow is some form of ion exchange. The term "ion exchange" is generally reserved for reactions that are reversible; thus ion-exchange sorption will serve to retard, but not to stop, the flow of radioactive ions. When ion exchange occurs under at least quasi-equilibrium conditions, it can be described by the distribution coefficient, K_d. The distribution coefficient is a lumped parameter defined as

$$K_d = \frac{\left(\begin{matrix}\text{amount of A}\\ \text{in solid phase}\end{matrix}\right) \Big/ \left(\begin{matrix}\text{weight}\\ \text{of solid}\end{matrix}\right)}{\left(\begin{matrix}\text{amount of A}\\ \text{in liquid phase}\end{matrix}\right) \Big/ \left(\begin{matrix}\text{volume}\\ \text{of liquid}\end{matrix}\right)} .$$

K_d values for each combination of rock type and radioisotope of interest are required as input parameters in transport predictions. Values of the distribution coefficient can be measured fairly easily in the laboratory. Although the validity of applying laboratory measures of the parameter to field situations is often questionable, the greater difficulties of direct field measurement makes laboratory measurement attractive. Measured values of the distribution coefficient are strongly dependent on the physical and chemical conditions of measurement. Among other variables, mineralogy, particle size, nature of solution, and chemical nature of radioactive species are important. The following examples can be cited: In general, a decrease in particle size results in an increase in K_d. Fresh silicate rocks have lower K_d's than their altered counterparts. For the same reasons, old

fractures absorb more than fresh fractures in a given rock. The sorption of Cs and Sr is greater than that of Ru and Sb and is probably related to the fact that the latter two elements form anionic complexes which do not readily take part in ion-exchange processes. Cs in clay-rich rocks often is sorbed more than Sr because of lattice shrinkage that traps the larger ion. Pu forms a positively charged polymer that is highly sorbed in the pH range of 2 to 8. However, because of the complexity of the processes influencing the distribution coefficient in poly-mineralic rocks, it has been customary to determine K_d's for each rock and site of concern. Rarely can such data be used elsewhere with confidence. The K_d's measured for NTS, which are tabulated here (Table 23), also indicate considerable variability for single NTS rock types.

One- and Two-Dimensional Transport Models

One- and two-dimensional mathematical models exist that could be used for the prediction of transport of radionuclides in ground-water flow from sites of underground nuclear explosions. One-dimensional models are probably sufficient. Their use can account for hydrodynamic dispersion, radioactive decay, convective transport, and instantaneous-equilibrium and linear-isotherm types of reversible sorption of a radioactive solute in ground-water flow. Both models require as input parameters known or estimated values of transmissivity, storage coefficient, hydraulic head, ground-water flow velocity, dispersivity, distribution coefficients, medium effective porosity, medium bulk density, initial source radionuclide concentrations in ground water, radionuclide decay constants, and dimensions of the radioactive contaminant pulse. With the exception of radionuclide decay constants and medium bulk densities, values of the parameters are either lacking altogether or are known imperfectly. Thus, currently only crude predictions of radionuclide transport at NTS can be made. Reliable and convincing predictions await further evaluation of the parameters that control transport in the NTS area.

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