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Radioactivity in the Underground Environment of the Cambric Nuclear Explosion at the Nevada Test Site

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PREFACE

The site of the Cambric underground nuclear test was re-entered nearly ten years after its detonation at the USERDA Nevada Test Site. The experimental results obtained from radiochemical analysis of sidewall cores and water taken during the re-entry drillback and sampling operations are summarized and discussed in this report. The investigation was part of the Radionuclide Migration Project sponsored by the Nevada Operations Office of ERDA. The entire report was reviewed and modified by all three of the authors, but primary responsibility for the compilation and interpretation of the data and for writing given sections was divided among the authors as follows:

Darleane C. Hoffman, Los Alamos Scientific Laboratory: Summary; Section I, Introduction and Background; Section V, Radiochemical and Chemical Analyses; Section VI, Discussion; Appendix, C, Procedures; Appendix D, Results of γ-Spectral and Radiochemical Analyses.

Randolph Stone, Lawrence Livermore Laboratory: Section III, Drilling and Construction of RNM-1; Section IV, Water Sampling Operations; Appendix A, Chronological History of RNM-1.

William W. Dudley, Jr., U.S. Geological Survey, Denver: Section II, Physical Setting; Appendix B, Selected Chemical Analyses of Water Samples from RNM-1.

Although the recommendations, Section VII, were written by D. C. Hoffman, they were the result of suggestions and input from many people, in particular, J. E. Sattizahn, LASL, R. J. Borg, LLL, H. B. Levy, LLL, and the other authors.

RADIOACTIVITY IN THE UNDERGROUND ENVIRONMENT OF THE CAMBRIC NUCLEAR EXPLOSION AT THE NEVADA TEST SITE

by

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Randolph Stone

William W. Dudley, Jr.

ABSTRACT

The experimental results obtained from investigation of the radionuclide distribution in the environment around the detonation point of the 0.75-kt nuclear test, Cambric, fired 300 m underground in alluvium at the Nevada Test Site in 1965, are presented and discussed. Analyses of sidewall cores obtained ten years later from near ground surface to below the explosion cavity showed that most of the radioactivity is still contained within solid material in the lower cavity region. Water pumped from the region of highest activity at the bottom of the cavity showed only T and ^{90}Sr at levels higher than the recommended concentration guides for drinking water in uncontrolled areas. Recommendations for future studies are given. The investigation is part of the Radionuclide Migration Project sponsored by the Nevada Operations Office of ERDA.

SUMMARY

Although nuclear tests have been conducted underground at the Nevada Test Site for more than 15 years, the Radionuclide Migration (RNM) Project is the first investigation designed specifically to characterize the radionuclide distribution in both the water and rubble around the detonation point after a nuclear test. Prior to this study, water had been pumped from the chimney of only one underground test. In Phase 1 of the RNM study, the site of the 0.75-kt Cambric event, conducted in Frenchman Flat some 300 m underground in alluvium *below the water table, was successfully re-entered ten years after the detonation. An extensive suite of sidewall core samples was obtained from near ground level to below the explosion cavity. A technique involving casing the drillback hole, appropriate placement of internal and external packers, and perforation of the casing at selected depths below the water table was successfully used to isolate five different zones from below the cavity to outside the chimney. Representative water samples were pumped from each zone in succession with apparently little cross-contamination, thus allowing a well-defined determination of the vertical distribution of the radioactivity in the ground water.*

No activity above background was observed in water pumped from the region below the cavity. Water from the region of highest radioactivity at the bottom of the cavity showed only tritium (T), ^{85}*Kr,* ^{90}*Sr,* ^{106}*Ru,* ^{125}*Sb,* ^{137}*Cs, and minimal amounts of* ^{144}*Ce and* ^{239}*Pu. Of these, only T and* ^{90}*Sr were present in levels higher than the recommended concentration guides for drinking water in uncontrolled areas.*

After ten years, most of the radioactivity is still retained in vitrified or fused debris within the region of the original cavity created by the explosion. Although some ^{85}*Kr and T were observed in water and core samples from above the cavity, there was no evidence that they had moved above the water table, and more than 99.9% of the T was present as HTO. By comparing the amounts of various radionuclides produced in the Cambric device with the amounts detected in the pumped water, using T as the reference nuclide, effective "retention" factors for the solid debris of* 10^2 *to* 10^4 *for* ^{90}*Sr,* ^{106}*Ru,* ^{125}*Sb,* ^{137}*Cs, and* ^{144}*Ce, and of* $>10^6$ *for* ^{147}*Pm and* ^{239}*Pu were estimated. The very high values for* ^{147}*Pm and* ^{239}*Pu may be related to the high pH of the water of 8 to 8.5 as well as to a low removal rate from the glassy material. Higher retention values for* ^{90}*Sr and* ^{137}*Cs were found in the puddle than in the chimney region, indicating that incorporation of the activity in the fused debris in the puddle region may retard dissolution of the radionuclides and result in higher retention factors.*

Water is now being pumped from a satellite well 91 m south of the Cambric detonation point in an attempt to draw HTO from the cavity and determine whether any of the other radionuclides accompany it.

Based on the RNM studies to date, the following recommendations have been made for future work:

1) *Complete the sampling at the satellite well and re-sample the original well in the Cambric cavity.*

2) *Initiate Phase 2 of the projected RNM program by selecting a suitable nuclear test for study of the early as well as the late-time radionuclide source term and migration. Consider the possibility of a study designed specifically to investigate migration of radionuclides above the water table.*

3) *Conduct studies similar to the Cambric investigation for nuclear devices tested in other media at the NTS, such as tuff and rhyolite.*

4) *Carry out laboratory studies to determine the effects of different variables on the interactions between water and various geologic media.*

5) *Perform modeling studies to predict migration rates of radionuclides of interest for various media at the NTS and determine the relative importance of the various parameters.*

I. INTRODUCTION AND BACKGROUND

The Radionuclide Migration (RNM) Project was initiated at the Nevada Test Site (NTS) in January, 1974 under the sponsorship of the Nevada Operations Office (NV) of ERDA with the participation of the Lawrence Livermore Laboratory (LLL), Los Alamos Scientific Laboratory (LASL), Desert Research Institute (DRI), U. S. Geological Survey (USGS), and selected support organizations. R. W. Newman, NV, was designated Project Manager, and J. E. Sattizahn, LASL, and R. H. Ide, LLL, were named Technical Directors. The stated intent of the project was "to provide data and interpretation thereof which will quantify the radionuclides which migrate away from underground nuclear explosion cavities and chimneys and will determine the time-distance relationships of such migration under the conditions of the test. This information may then be applicable to the hydrologic program studies which have been and are in progress relating to long-term safety with regard to contamination of water supplied both on- and off-site. It may also provide a base for studies relating to underground disposal of high-level radioactive waste."

The project was divided into two experiments. The first, called Experiment No. 1, was started at once and is the subject of this report. In Experiment No. 1, the site of the 0.75-kt nuclear test, Cambric, which was fired beneath the water table in alluvium was chosen for examination. The choice was based on several considerations. The Cambric cavity is within the Area 5 water-supply aquifer. It was predicted that sufficient time had elapsed so that the cavity and chimney had filled with ground water to the preshot static water level, 73 m above the detonation point. If so, radionuclides might be present in the water and constitute a potential source for migration. The Cambric detonation point is only 294 m below ground surface, and thus the re-entry drilling and sampling operations would be less difficult and expensive than for some of the more deeply buried tests. Although the Cambric chimney was believed not to have progressed to the surface, a small subsidence was detectable at the surface. The existence of some uncertainty concerning the stability of the area precluded drilling vertically through the chimney, and therefore, it was planned to drill a slant hole into the chimney-cavity region. The site was far enough from the areas of active nuclear testing so that damage or interruption of the re-entry and sampling operations from those activities would be unlikely. Sufficient tritium was present to provide an easily measurable tracer for water from the cavity region.

The postshot debris also contained plutonium and fission products whose concentrations in the rubble and ground water from the cavity and chimney regions could be measured and compared. The small yield was expected to have had little effect on the local hydrology. Further, it was judged that the alluvium consituted a good medium for hydrologic studies because it was more permeable than tuff and did not have large fissures or cracks through which the water might selectively flow. A satellite well was to be drilled some distance from the Cambric reentry hole; pumping of the satellite well was expected to induce a sufficient artificial gradient to draw water from the Cambric cavity and provide an opportunity for study of radionuclide migration under field conditions. Detection of tritium would signal the breakthrough of water from the Cambric cavity region.

The initial phases of Experiment No. 1 have now been successfully completed. The cavity region was re-entered and sidewall sampling was performed in order to measure the vertical distribution of radionuclides. The hole was cased and the casing perforated to permit pumping of water in different regions. In this way, variations in the radionuclide content of water from the various intervals were determined. The satellite well has been drilled and pumping is in progress. Much useful and interesting information has been obtained concerning the source term, i.e., the distribution and concentration of radionuclides around the Cambric detonation point ten years after the test. This report gives a detailed description of the physical setting, construction, and sampling of RNM-1, of the analyses performed on the samples, a discussion of the results, and recommendations for future studies.

The data from Experiment No. 1 will be used to plan Experiment No. 2. It is envisioned as a "cradle-to-grave" study in which preshot chemical, geologic, and hydrologic conditions, the radionuclide distribution in soil and water immediately after the test, the rate of infill of water, and early as well as late-time radionuclide migration will be studied.

II. PHYSICAL SETTING

A. Site Location

The Cambric device was detonated on May 14, 1965 with a yield of about 0.75 kt. The explosion point was at a depth of 294.3 m in alluvium in western Frenchman Flat, located in the southeastern part of NTS, about 100 km northwest of Las Vegas (Fig. 1). Frenchman Flat ranks fourth--behind Yucca Flat, Rainier

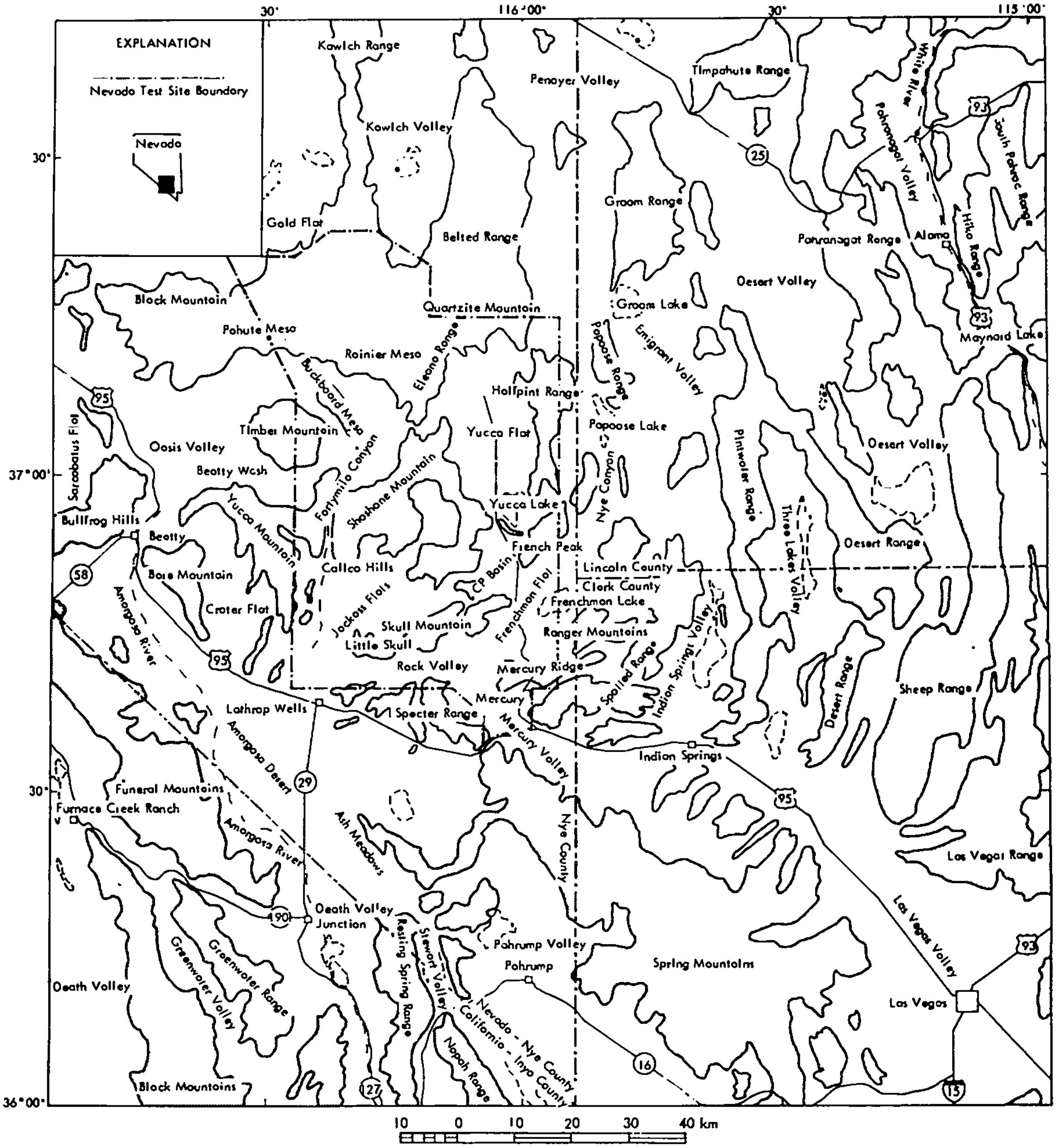
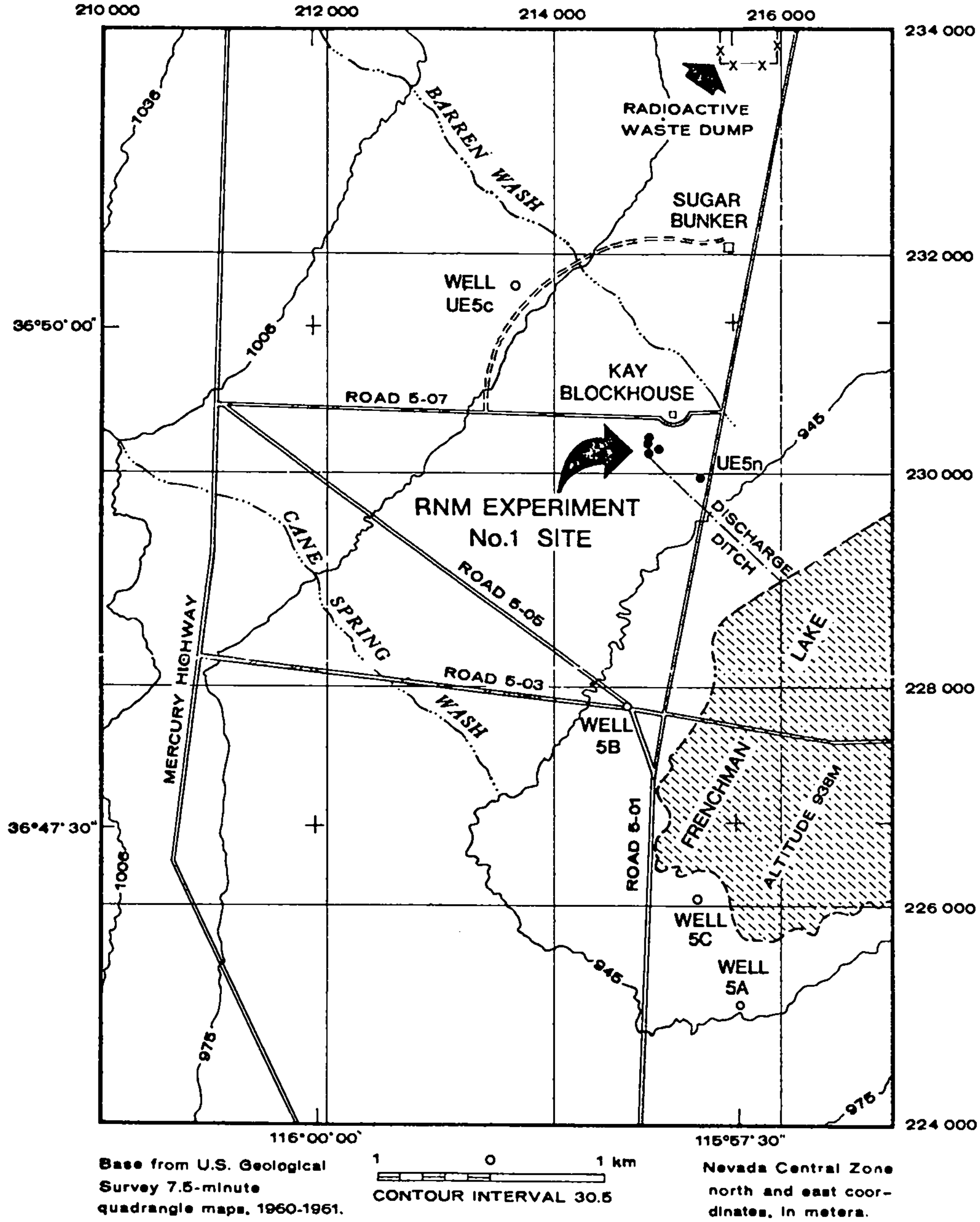


Fig. 1. Index map of Nevada Test Site and vicinity. Cambric site is in western Frenchman Flat in southeastern NTS.



Base from U.S. Geological Survey 7.5-minute quadrangle maps, 1960-1961.

Nevada Central Zone north and east coordinates, in meters.

Fig. 2. West-central Frenchman Flat, showing location of the RNM Experiment No. 1 site.

Mesa, and Pahute Mesa--as a testing locality; of 338 announced underground nuclear tests at NTS through June 30, 1975, only 10 were conducted in Frenchman Flat[1].

Three water-supply wells and one former well, shown in Fig. 2, are in western Frenchman Flat. Two of the supply wells, 5B and 5C, produce water from the alluvial materials in which Cambric was detonated. Wells 5B and 5C (and formerly Well 5A) are used for multiple purposes including the general water supply for Mercury, the housing and operational center of NTS. Distances from Cambric to Wells 5B, 5C, and 5A, respectively, are 2.5, 4.3, and 5.3 km. Well UE5c, about 1.8 km northwest of the Cambric site, is used as a source of construction water. Semi-annual monitoring of these wells by the Environmental Protection Agency has revealed no radioactivity above background.

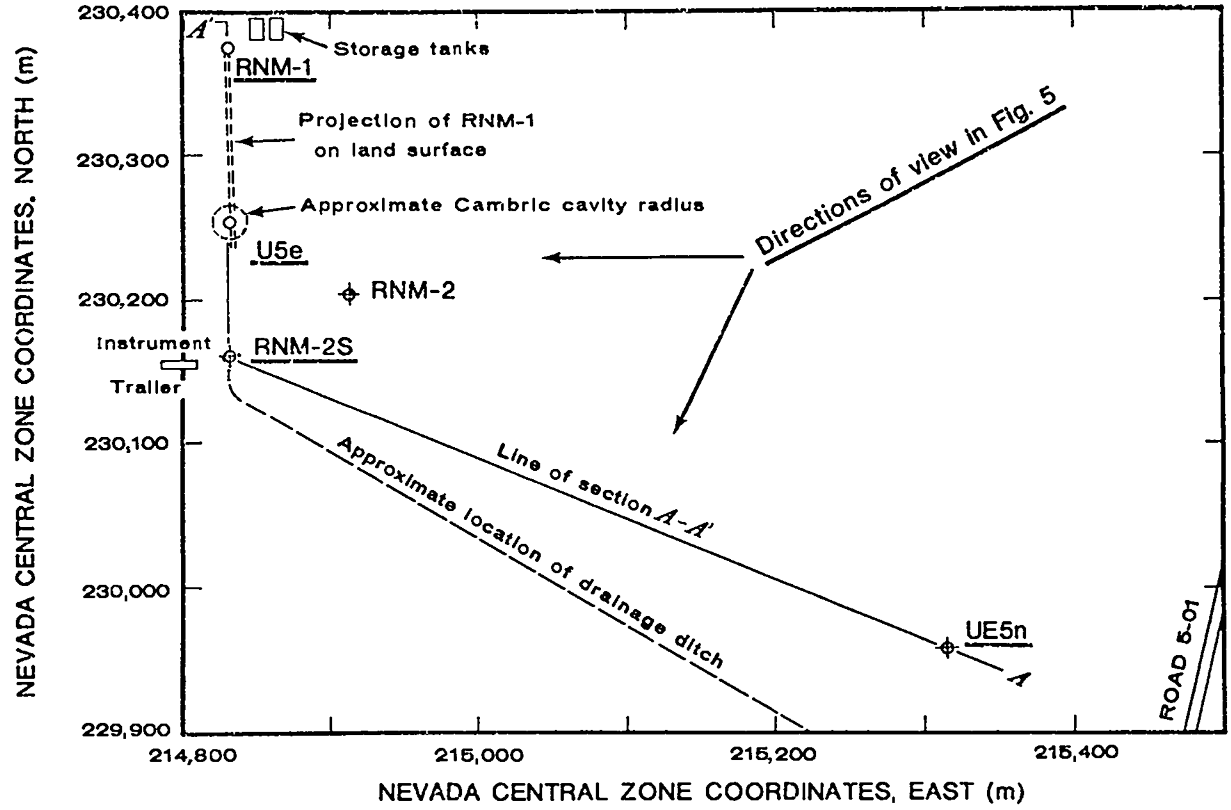


Fig. 3. Principal features of the RNM Experiment No. 1 site and nearby vicinity. Section A-A' is shown in Fig.. 5.

Figure 3 shows the Cambric site and the facilities constructed for RNM Experiment No. 1. Locations and depths of the drill holes and wells and their approximate land-surface altitudes are as follows:

U5e: Cambric emplacement hole
Nevada Central-Zone Coordinates: N230,251.7 m, E214,832.5 m
Approximate land-surface altitude: 956 m
Depth: 304.8 m

RNM-1: Re-entry sampling well
Nevada Central-Zone Coordinates (surface): N230,374.9 m, E214,832.5 m
Land-surface altitude: 956.0 m
Depth: 396.9 m (slant); 370.2 (vertical)

RNM-2: Water-level observation hole
Nevada Central-Zone Coordinates: N230,204.4 m, E214,910.7 m
Approximate land-surface altitude: 954 m
Approximate depth: 235 m

RNM-2S: Satellite well for pumping and sampling
Nevada Central-Zone Coordinates: N230,160.5 m, E214,832.6 m
Approximate land-surface altitude: 955 m
Depth: 341.4 m

UE5n: Nearby exploratory hole providing additional information
Nevada Central-Zone Coordinates: N229,959.4 m, E215,315.3 m
Approximate land-surface altitude: 951 m
Depth: 514.2 m

RNM-1 was drilled in May 1974 through and beneath the Cambric cavity for the purpose of obtaining sidewall cores and for subsequent water sampling. RNM-2 was an unsuccessful attempt to complete a satellite pumping well; after severe hole enlargement and caving, 6-cm tubing was installed to provide access for water-level measurements. The present satellite well for pumping and sampling, RNM-2S, was completed in April 1974. It was completed before drilling RNM-1 in order to avoid the possibility of contamination with radioactivity from Cambric.

B. Physiography

Frenchman Flat is a closed basin, having interior surface drainage to Frenchman Lake, a normally dry playa about 20 km^2 in area and about 938 m in altitude (Fig. 2). Gently sloping (10 to 20 m/km) desert of sparsely vegetated alluvial soil surrounds the central playa up to an average altitude of about 1030 m. Mountainous terrain that reaches about 1900 m in altitude surrounds most of the basin.

Well-defined drainage channels in the mountainous areas and uppermost alluvial slopes give way to braided and slowly migrating channels on the middle and lower desert floor. All channels are ephemeral, carrying runoff only during major storms and then losing it rapidly to infiltration and evaporation. Rarely, runoff reaches Frenchman Lake where it spreads over the wide playa surface and evaporates. While precipitation is a scant 150 mm per year, the potential evaporation rate is on the order of 3 m per year.

C. Geology

1. General

Frenchman Flat lies in the transitional zone between widespread exposures of Paleozoic rocks, primarily carbonates that characterize eastern Nevada, and Tertiary (younger) volcanic rocks of south-central Nevada. As shown in Fig. 4, which is adapted from Carr[2], the ranges to the south, southeast, and east of central Frenchman Flat are formed of lower Paleozoic limestone, dolomite, and quartzite. The hills to the west and north are composed of Tertiary volcanic rocks, although local exposures of Paleozoic rocks attest to their presence beneath the volcanic cover.

The Paleozoic carbonate rocks range in age from late Cambrian through Devonian and attain a total thickness of more than 5000 m (Ref. 3). Several episodes of mountain building folded, tilted, and uplifted these and younger, overlying rocks. Stresses of this tectonism also produced faults and joints in the rocks, in places thrusting rock masses as much as several kilometers over those below. Although the youngest Paleozoic rocks along the periphery of Frenchman Flat are about 300 million years old, younger rocks that are present elsewhere in the vicinity of NTS covered them but were later eroded.

Beginning about 25 million years ago[4], the area that is now NTS experienced a series of volcanic eruptions that covered the region with additional thousands of meters of tuffs and lava flows. Tuff, which is volcanic ash deposited under air or water or as a spreading hot, gaseous cloud (welded tuff), makes up the greatest thickness of the volcanic section.

At about the same time that volcanism began, tectonic forces initiated a period of faulting that continues to the present day. The surface of Nevada and adjacent states was broken into a series of mountain ranges trending generally north and surrounded by deep valleys into which additional volcanic material accumulated. Volcanism gave way to sedimentation of debris eroded from the

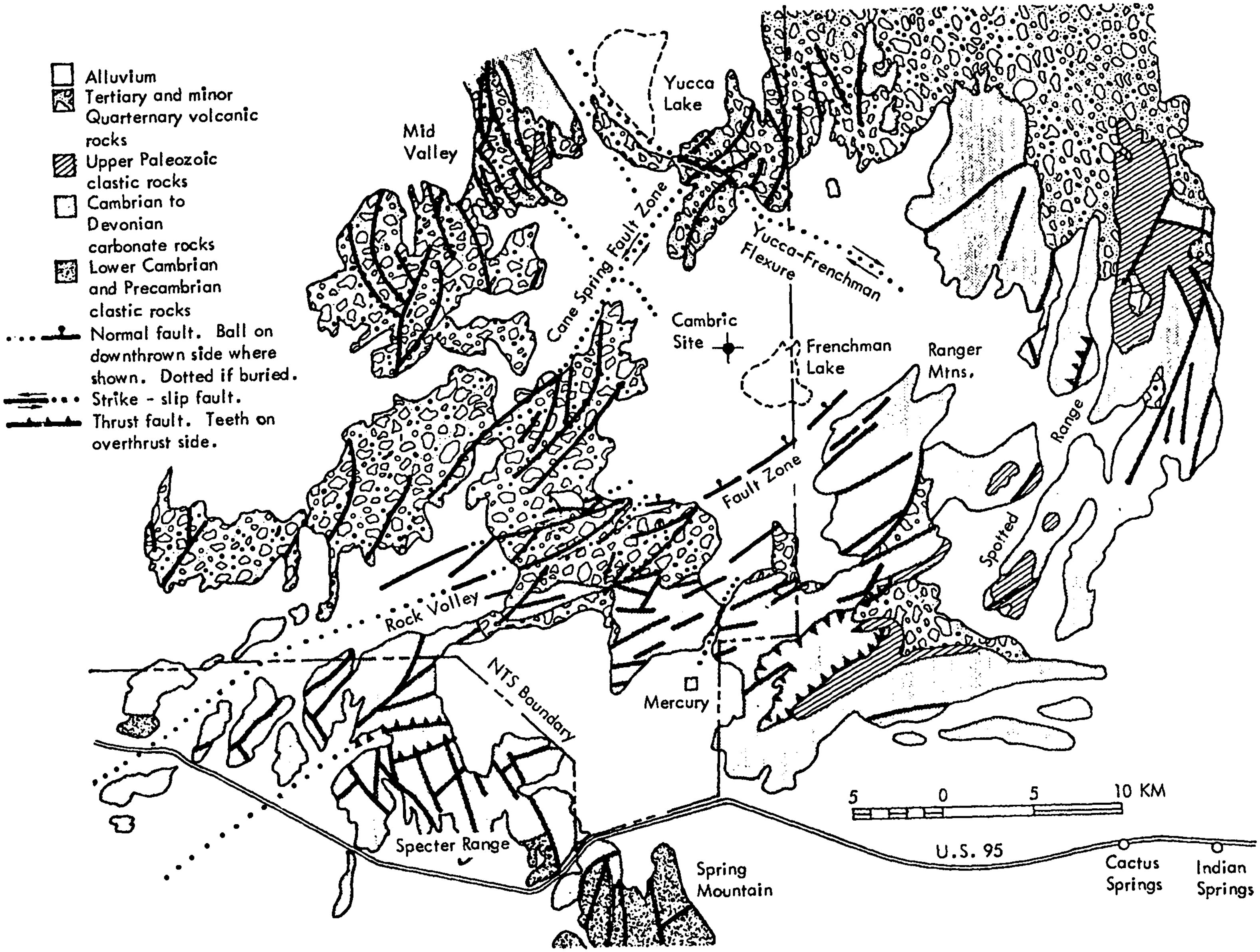


Fig. 4. General geology of Frenchman Flat and southeastern NTS (Carr, Ref. 2).

ranges as the major process of valley filling. Relative subsidence of the valley floor in Frenchman Flat was at least 2,500 m; the Paleozoic rocks are estimated from gravity measurements to be about 460 m below sea level beneath central Frenchman Flat, or about 1,400 m beneath land surface[5]. The relative thicknesses of the Tertiary volcanics and overlying Quaternary alluvium is not known, but in central Frenchman Flat the alluvium is at least 500 m thick and probably reaches a maximum thickness of 700 to 800 m.

All rock types in the vicinity except the youngest alluvium are cut by faults. Present-day tectonism in and around Frenchman Flat occurs mainly along two northeast-trending fault zones characterized by left-lateral, strike-slip movement with lesser dip-slip movement. These are the Rock Valley fault zone, which crosses southern Frenchman Flat, and the Cane Springs fault zone, which passes through northwestern Frenchman Flat[2]. The August 5, 1971, Massachusetts Mountain earthquake (magnitude 3-4) occurred in southernmost Yucca Flat, near the projected intersection of the Cane Springs fault zone and the Yucca-Frenchman flexure, a northwest-trending, right-lateral flexure with an offset of about 1.5 km. An earthquake of similar size occurred on February 19, 1973, about 1.5 km northeast of Frenchman Lake playa and near the projected intersection of the Yucca-Frenchman flexure with the Rock Valley fault zone. According to Carr[2], most of the more than 50 earthquake epicenters in southern NTS during the period 1961-1972 were located beneath alluvium, suggesting that present seismic activity represents shallow adjustment to previous deep subsidence of the basins.

A cross section showing the general geology at the site of the RNM experiment is provided in Fig. 5. The drill holes penetrate only alluvium, so the depths to Tertiary and Paleozoic rocks are speculative.

2. Character of Alluvium.

Information about the nature of the alluvium at the Cambric site was provided from the following sources: the lithology and grain size of 13 sidewall samples taken from RNM-1 between vertical depths of 103.6 and 319.9 m were examined at LLL; a lithologic log was prepared by USGS from cuttings from RNM-2; detailed sample descriptions and measurements of the physical properties[6] of alluvium from UE5n were made at LLL. Sample descriptions from all three of these sources indicate a remarkable uniformity in the alluvium. Medium to coarse sand is the dominant grain size, although a silty matrix occurs commonly in sidewall samples from RNM-1 and UE5n; no sidewall samples were collected from RNM-2.

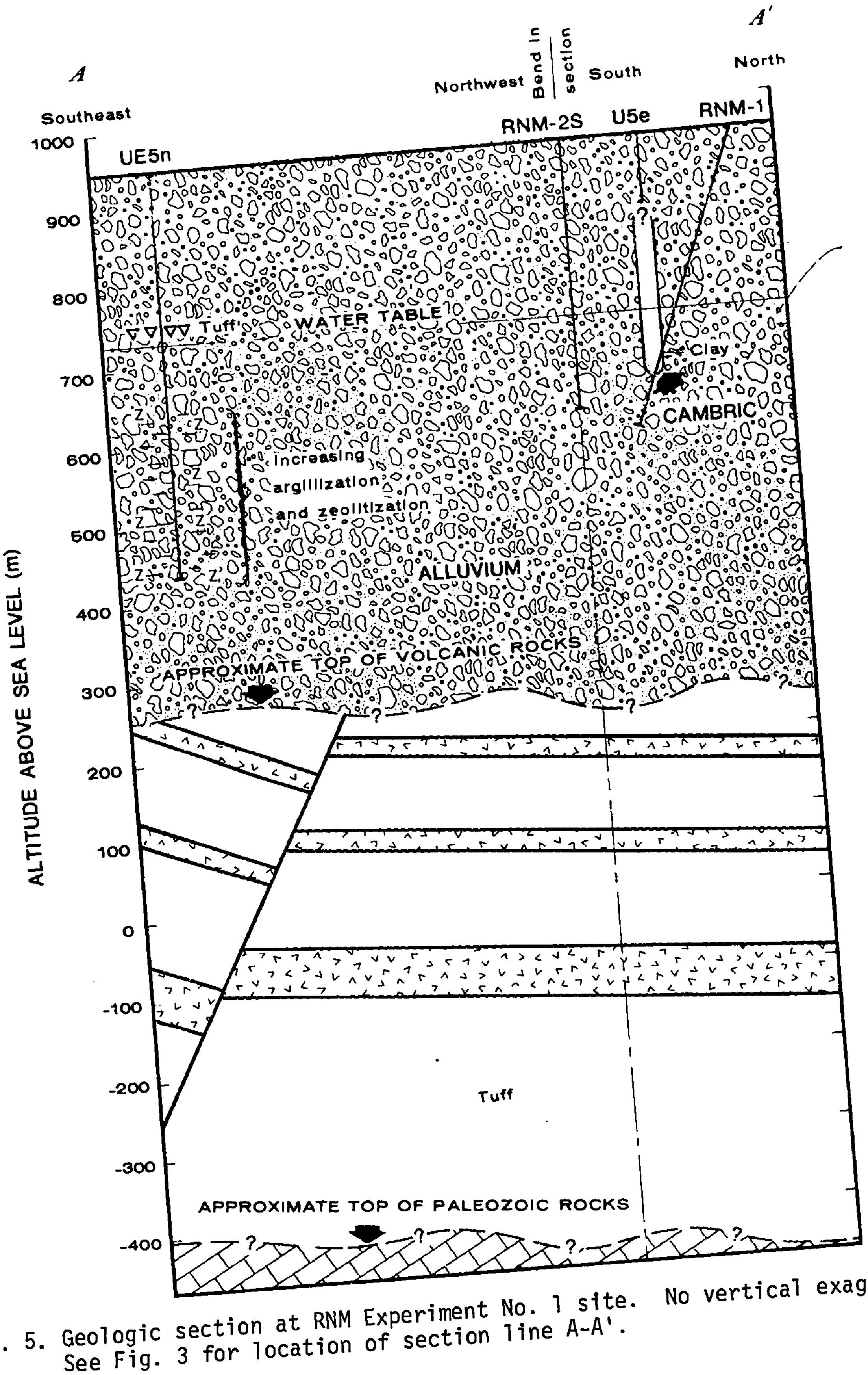


Fig. 5. Geologic section at RNM Experiment No. 1 site. No vertical exaggeration. See Fig. 3 for location of section line A-A'.

Pebbles were included in most of the samples and cuttings, and gravel and cobble beds were encountered in the upper 200 m. Lithologies of the sand particles and pebbles are diverse but were derived mainly from the Tertiary volcanics--Timber Mountain Tuff (mainly welded), Topopah Spring Member of the Paintbrush Tuff, lava and tuff of the Wahmonie Formation, and tuff breccia and tuffaceous sandstone of the Salyer Formation. Only a minor percentage of the clasts were of Paleozoic quartzite, dolomite, and limestone.

In RNM-2, the sediments were generally finer grained below 230 m, while the log of UE5n shows an increase of induration at about 287 m, accompanied by zeolitization and argillization of the sand-silt matrix. RNM-1 was in the presumed rubble chimney at this depth range; however, the sample obtained from alluvium beneath the cavity at a depth of 320 m had a median grain size of 0.32 mm, which was one of the smallest determined. One sample, from the upper-cavity region at 292 m in RNM-1, was composed of bluish-gray silty clay, and a very fine, rhyolitic ash-fall tuff of unknown age occurred from 195.1 to 199.6 m in UE5n.

Water contents measured in the apparently least disturbed samples from UE5n ranged generally between 10% and 13% by weight above the water table and between 16% and 22% below the water table. Samples taken beneath the water table had calculated porosities between 31% and 41% and computed degrees of saturation greater than 80%. The probable range of interclast porosity, which is of primary concern to ground-water flow calculations, can be estimated from the relationship:

$$n = \frac{N-n_c}{1-n_c},$$

where n is interclast porosity, N is total porosity, and n_c is the porosity of the clasts. For assumed clast porosities of 5%, 10%, 15%, and 20%, respectively, the following values of n result.

n_c	Value of n (%)	
(%)	N=31%	N=41%
5	27	38
10	23	34
15	19	31
20	14	26

The clasts were derived for the most part from well-indurated rocks, which probably have porosities in the range of 5% to 15%. Consequently, 20% to 35% is the probable range for interclast porosity. This indicates a rather loose state of packing, which is borne out by caving problems encountered in the drill holes.

D. Hydrology

Frenchman Flat lies within the Ash Meadows ground-water system, an area of about 11,500 km^2 under which water flows generally in a southwesterly direction to discharge at Ash Meadows in the east-central Amargosa Desert. About 57,000 m^3/day flows from the springs at Ash Meadows, representing an average rate of recharge of only 1.8 mm/year over the basin. Winograd and Thordarson[7] have provided the most comprehensive description of this ground-water system and of the hydrology of NTS.

1. Hydrologic Units

The principal aquifer of southeastern Nevada, termed the lower carbonate aquifer, consists of thick carbonate rocks ranging in age from late Cambrian through Devonian. Although these limestones and dolomites are a thousand meters or more below land surface over much of the area and are dislocated by many faults, the long history of tectonism has produced extensive and probably well-integrated fracture systems. In places where flow is concentrated by the geometric setting, the faults and fractures are presumed to be enlarged by solution, creating highly transmissive pathways for ground-water flow. Where this has occurred, such as at an experimental USGS tracer site southwest of Mercury, transmissivity exceeds 10,000 m^2/day for intervals only a few tens of meters thick, giving an apparent average hydraulic conductivity of about 200 m/day. Well C, in southern Yucca Flat, produces from carbonate rocks with similar properties. More typically, the average hydraulic conductivity in wells and test holes penetrating this aquifer ranges from 0.2 to 4 m/day.

Beneath the lower carbonate aquifer are lower Cambrian and Precambrian quartzites, siltstones and shales that function as an aquitard, limiting the depth of flow and, where they are structurally high, also diverting flow laterally. Devonian and Mississippian argillite and quartzite of the Eleana Formation, termed the upper clastic aquitard[7], overlie the lower carbonate aquifer in the vicinity but are not known to be present at depth in Frenchman Flat.

The hydraulic conductivity within the volcanic rocks beneath Frenchman Flat undoubtedly varies widely. The dacite lava aquifer that yields water to Well

UE5c has an estimated average hydraulic conductivity of about 5 m/day, which is probably near the upper limit for fractured lavas and welded tuffs of the Tertiary sequence. Nonwelded (bedded) tuffs that are not zeolitized or argillized are less permeable[7], having transmissivities that correspond to hydraulic conductivities of 0.05 to 0.5 m/day.

The principal aquitards beneath Frenchman Flat are expected to be zeolitized tuff and argillized tuff or argillaceous sediments. For 34 core samples of zeolitized tuff from NTS, Winograd and Thordarson[7] report hydraulic conductivities ranging from 2×10^{-6} to 2×10^{-2} m/day, with a median value of 2.5×10^{-4} m/day. The argillaceous materials, as measured in 38 cores, displayed a range of hydraulic conductivity of from 1×10^{-9} to about 2×10^{-2} m/day with a median value of about 2.5×10^{-6}.

The RNM experiment at Cambric is being conducted in alluvium 200 m or more above the volcanic rocks. The average hydraulic conductivity of RNM-1 sidewall samples was estimated from analysis of grain-size distribution to be about 4 m/day, although some loss of the finer fraction might make this value too high by as much as an order of magnitude. However, the productivity of RNM-2S indicates a comparable value of about 1.5 m/day. Tests of Well 5B indicate a hydraulic conductivity of 1.4 m/day, but the less productive alluvium at Well 5C has a conductivity of about 0.2 m/day.

2. Water Table and Ground-Water Movement

As was stated above, Frenchman Flat is one of the areas contributing recharge, however small, to regional flow in the Ash Meadows ground-water system. Although the general direction of flow from the water table is downward toward the lower carbonate aquifer, the local direction of flow may be quite different. The probability that downward flow would meet highly impermeable zeolitized or argillized tuffs suggests that paths of water entry to the lower carbonate aquifer may be controlled mainly by local structural conditions. The southern part of Frenchman Flat, along the Rock Valley fault zone, offers the following features that favor it as the destination of water moving through the alluvium and volcanic rocks: (1) the Paleozoic rocks are highly faulted and susceptible to chemical solution; (2) differential movement along basin-boundary faults has left the carbonate rocks laterally contiguous to younger materials; and (3) the Rock Valley Fault Zone intersects other faults through Mercury Valley and the narrows between the Spring Mountains and the Specter Range, to which much evidence points as the principal path of discharge to Ash Meadows.

The hydraulic head potential in the lower carbonate aquifer beneath Frenchman Flat is about 726 m above sea level. At the RNM site the water table is at an altitude of about 736 m, which provides a downward gradient of about 8 x 10^{-3} m/m to the Paleozoic rocks at a depth of about 1,200 m. The gradient for lateral (southeastward) flow to the southern part of the basin is about 1 x 10^{-3}, or almost an order of magnitude less than that available for downward flow. However, if 1% of the stratigraphic units at depth have a hydraulic conductivity of 10^{-3} m/day, as compared with about 1 m/day for other units, the effective resistance to vertical flow is about the same as that for lateral flow. It seems likely, then, that the southward component of flow is significant in comparison with, and perhaps greater than, the downward component.

This line of reasoning is speculative, of course. It may be that there are no sufficiently permeable and continuous paths for easy lateral flow to the fault zone, that the fault zone itself is not the locus of greatest permeability in the lower carbonate aquifer, or that other equally attractive paths to the carbonate aquifer are available within the central basin.

An artificial southward gradient has been induced locally in modern times by pumping from Wells 5A, 5B, and 5C. From 1958 through 1971 a total of about 4.3 x 10^6 m^3 was pumped from these wells, at an average rate of about 850 m^3/day (Ref. 8). The static water level in Well 5C after 5 days of recovery in 1971 was at an altitude of 720.8 m, about 8 m below the level measured in 1961 after a 133-day recovery. Periodic measurements in Well 5B have shown little residual drawdown; static levels have ranged from 734.0 to 734.6 m in altitude, with 1959 and 1971 levels both being 734.3 m. This contrast is puzzling and effectively precludes prediction of the effect of the production on the hydraulic gradient at the RNM site. In such a porous, unconfined aquifer, however, it is unlikely that perceptible effects of pumping at this moderate rate have spread more than a kilometer.

Figure 6 shows the distribution of hydraulic head potential in the lower carbonate aquifer and a pattern of contours on the water table that is consistent with both downward flow and southeastward flow near the Cambric site in Frenchman Flat. Note that at the southern end of Yucca Lake and about 5 km south of Mercury, the two sets of contours coincide, indicating water table within the Paleozoic rocks.

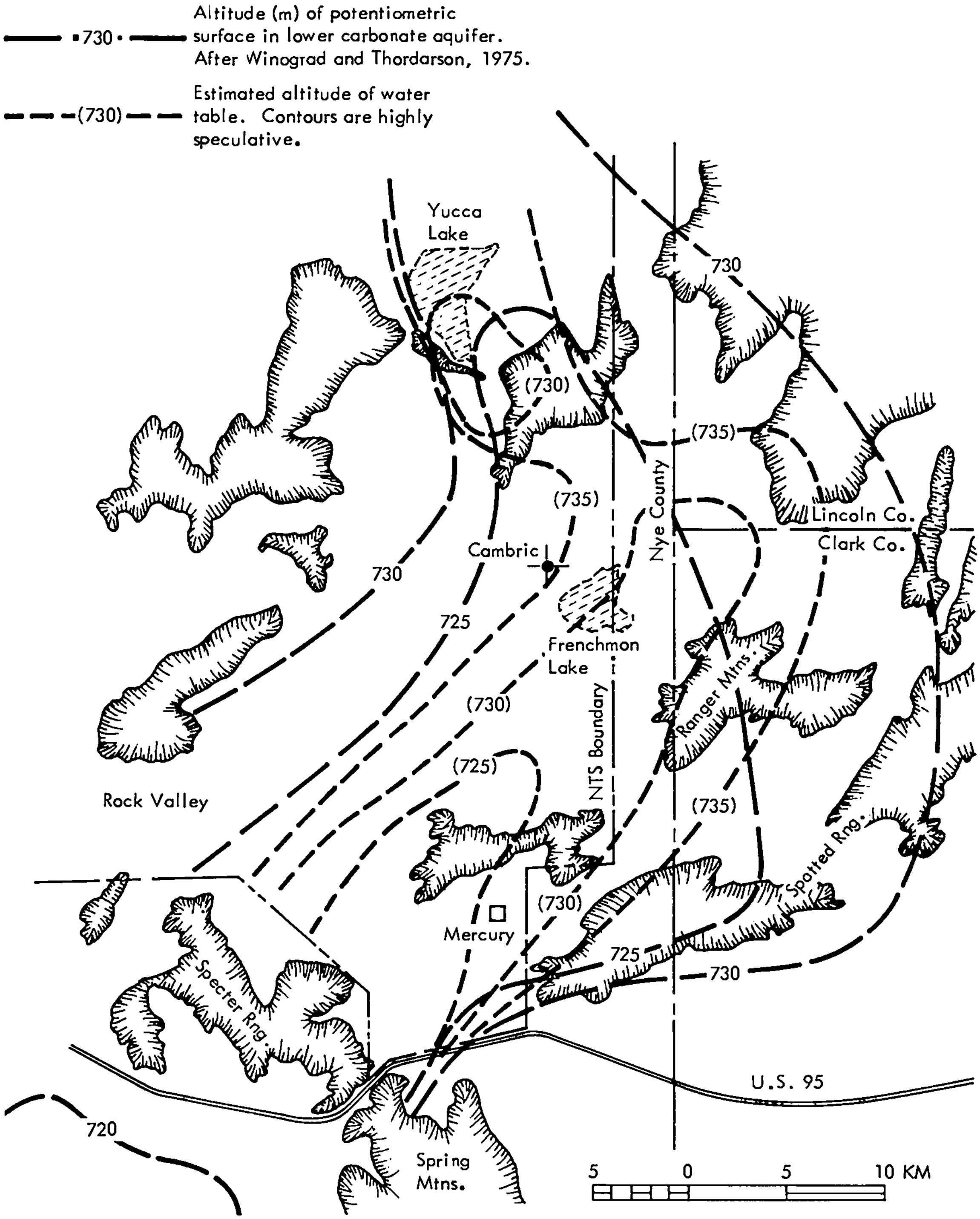


Fig. 6. Estimated altitudes of potentiometric surface in lower carbonate aquifer and of water table beneath southeastern NTS and vicinity.

III. DRILLING AND INITIAL CONSTRUCTION OF RNM-1

Sampling hole RNM-1 was drilled down and to the south through the Cambric chimney and cavity (Figs. 7 and 8) with an average inclination of about 21° from vertical. Starting at a surface location about 120 m north of the Cambric ground-zero position, RNM-1 followed the original post-detonation sampling borehole to a vertical depth of about 134 m, where it was sidetracked to penetrate fresh materials. Sidetracking was preceded by cementing to plug off sidetrack holes that remained from the original post-detonation drilling.

Drilling muds and most other fluids used in drilling and completing RNM-1 were labeled with lithium chloride to a calculated concentration of about 20 ppm of Li so that the Li content of ground water samples taken later could be used as an indication of the degree of contamination from added fluids. (The natural Li content of ground water in this region is only 0.01 to 0.05 ppm.) The hole was successively deepened in several stages so that sidewall core samples could be obtained after each deepening with a minimum of invasion and contamination by drilling fluids and radioactive material from deeper zones. The details of the drilling and construction operations are contained in Appendix A. The following discussion summarizes the important aspects of these operations.

Before drilling was started, sidewall core samples 1 through 6 were taken in the original postshot hole drilled for sidewall core sampling in 1965. Depths of these samples and of samples taken subsequently above the water table are shown in Fig. 8, together with a schematic representation of the chimney-cavity configuration. (Details of nuclear explosion phenomenology are given in Ref. 1.) The RNM-1 sidetrack hole was then drilled to a vertical depth of about 215 m, and sidewall sampling above the water table was completed. Core samples 7 through 18 were obtained in the freshly drilled hole, but cores 19 through 26 were taken from the original post-detonation exploratory hole above the RNM-1 sidetrack. Cores 19, 20, and 21 were contaminated by cement invasion.

Drilling beneath the water table progressed to about 232 m vertical depth, and sidewall samples 27 through 29 were obtained (Fig. 9). The hole was drilled further to about 256-m vertical depth, and samples 30 through 32 were taken. Further drilling deepened RNM-1 to about 265-m vertical depth, and sidewall coring yielded samples 33 through 35. The hole was then deepened to about 290 m, and sidewall samples 36 through 38 were obtained.

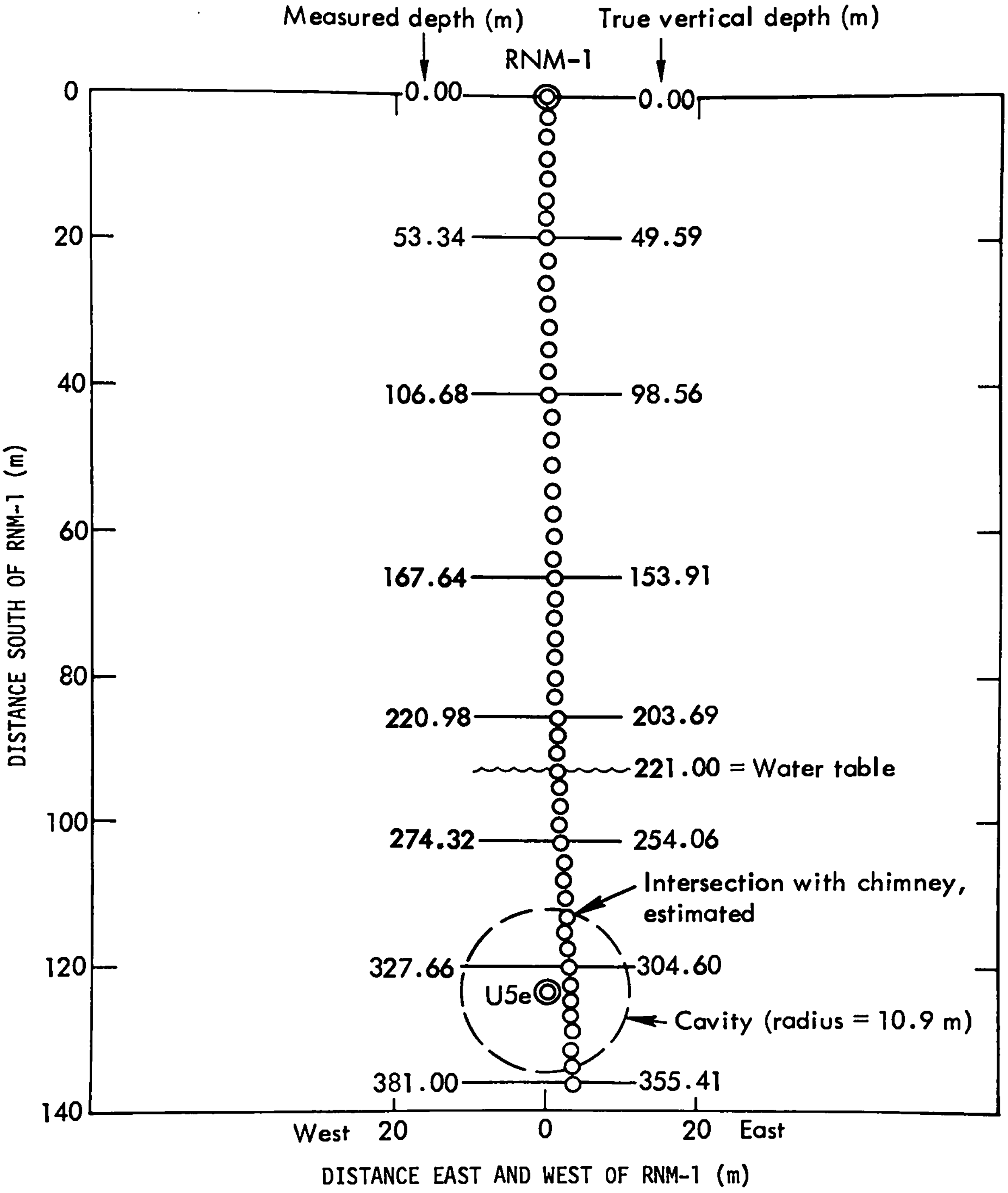


Fig. 7. Map showing position of RNM-1, with surface projections of selected depths in the drill hole.

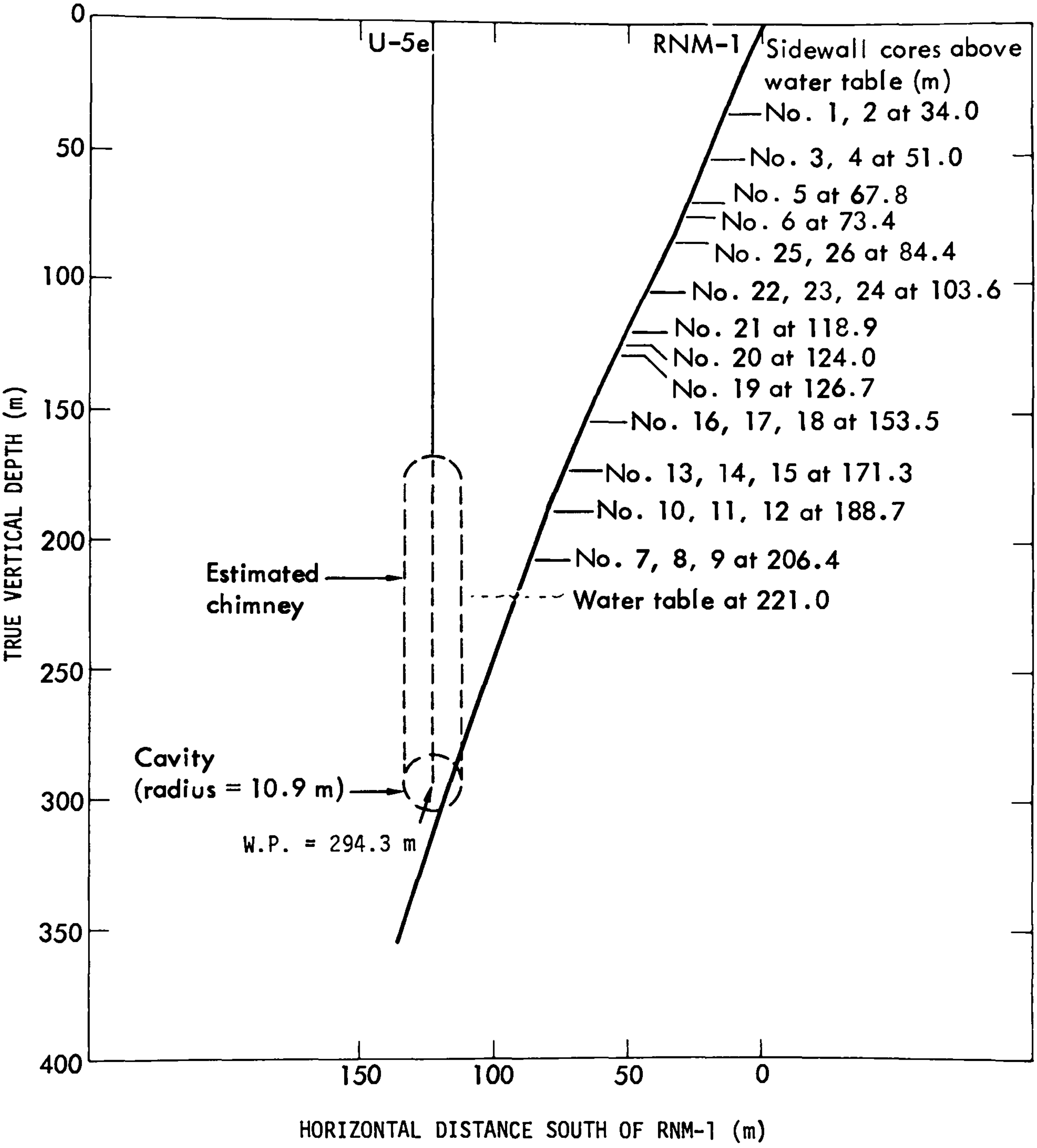


Fig. 8. Cross section through RNM-1 and U5e, drawn along average bearing of RNM-1 shown in Fig. 7. Locations of sidewall samples taken above the water table are shown.

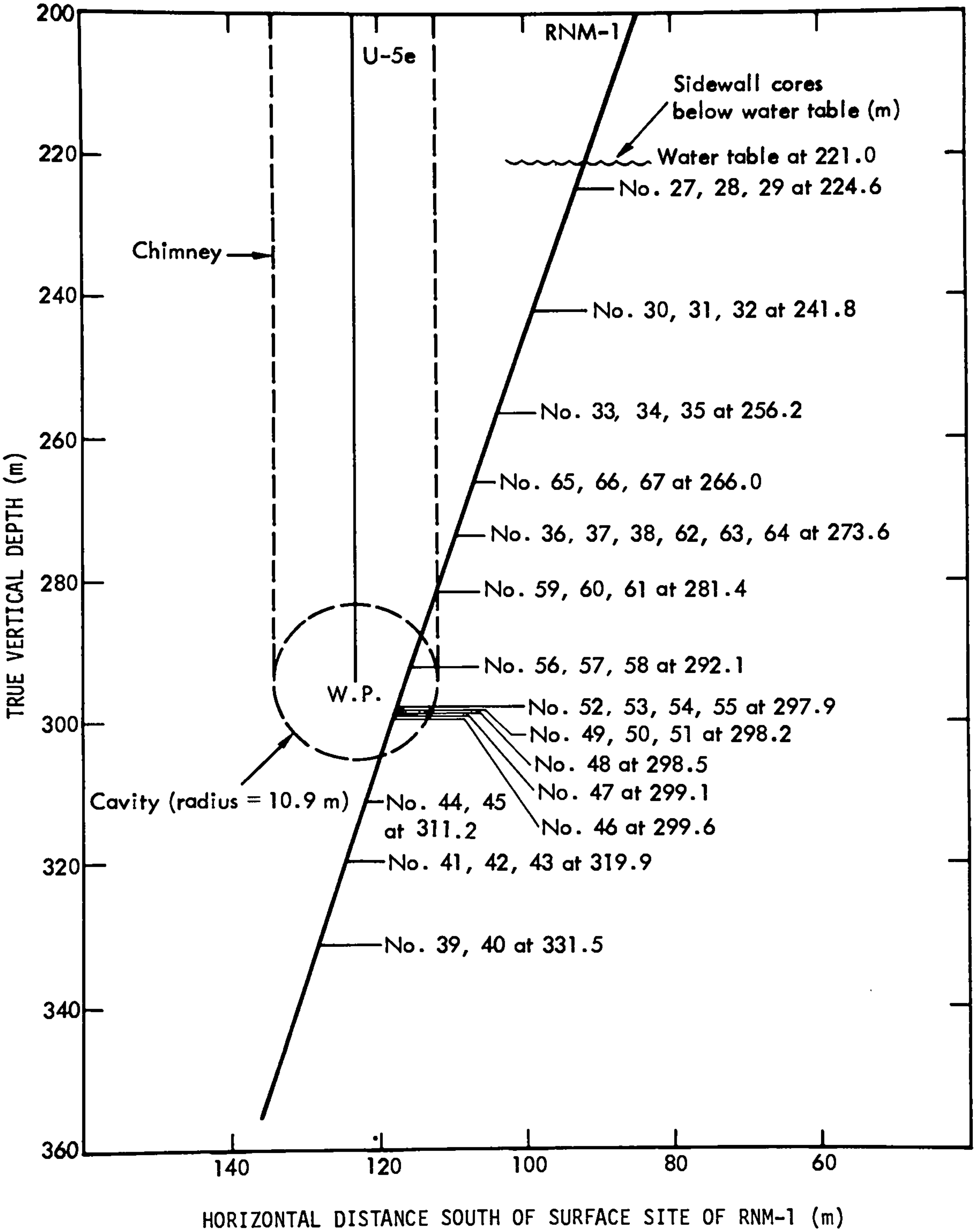


Fig. 9. Cross section through RNM-1 and U5e, drawn along average bearing of RNM-1 shown in Fig. 7. Locations of sidewall samples taken below the water table are shown.

RNM-1 was next drilled to a vertical depth of about 355 m, passing through the Cambric cavity and to about 50 m beneath it. A γ-ray log of the radioactivity in the hole was taken and is shown in Fig. 10. This log influenced the selection of additional sampling positions. Sidewall sampling then proceeded without interruption, and samples 39 through 67 were taken in numerical order, most of them at positions corresponding to peaks in the γ-ray log.

The γ-ray log also provided the basis for estimation of the radius of the cavity produced by the Cambric device. The point of intersection of RNM-1 with the lower hemisphere of the cavity, or bottom of the puddle,[a] was taken from an inspection of the log to be at 304.4-m true vertical depth. The position of this piercing point relative to the device working point was determined using RNM-1 hole deviation survey results and knowledge of the working point position. Three-dimensional trigonometric calculations led to an estimate of 10.9 m for the cavity radius. RNM-1 did not pierce the Cambric cavity at its lowest point, but at a point approximately 1 m above the lowest point on the lower hemisphere of the cavity.

After completion of sidewall sampling, RNM-1 was cleaned out to its total depth of 355 m, and casing was installed. The casing string was 140 mm in diameter and included three external casing packers. As shown in Fig. 11, the external casing packers were seated at approximate vertical depths of 270 m, 285 m, and 300 m. The external casing packers each consisted of an annular, composite rubber and fiber element that was expanded to fit against the hole wall after being placed in position along with the casing string. The external packers were used to minimize vertical movement of water in the annular space between the casing and the hole wall. The results of chemical and radiochemical analysis of the water samples eventually pumped from various zones in RNM-1 seem to indicate that the external casing packers served the intended purpose.

The annulus between the borehole and the casing was then cemented from the borehole total depth of 355 m up to the lowest external casing packer at about 300 m as illustrated in Fig. 11. Finally, RNM-1 was drilled to a vertical depth of 370 m, leaving about 15 m of open hole beneath the cemented casing. A fluid density log was run and showed the fluid level at 239.6-m measured slant depth,

[a] Puddle is defined here as the region at the bottom of the explosion cavity which originally contained molten rock. It normally contains large quantities of refractory fission products, activation products, and fissile materials. See Ref. 1.

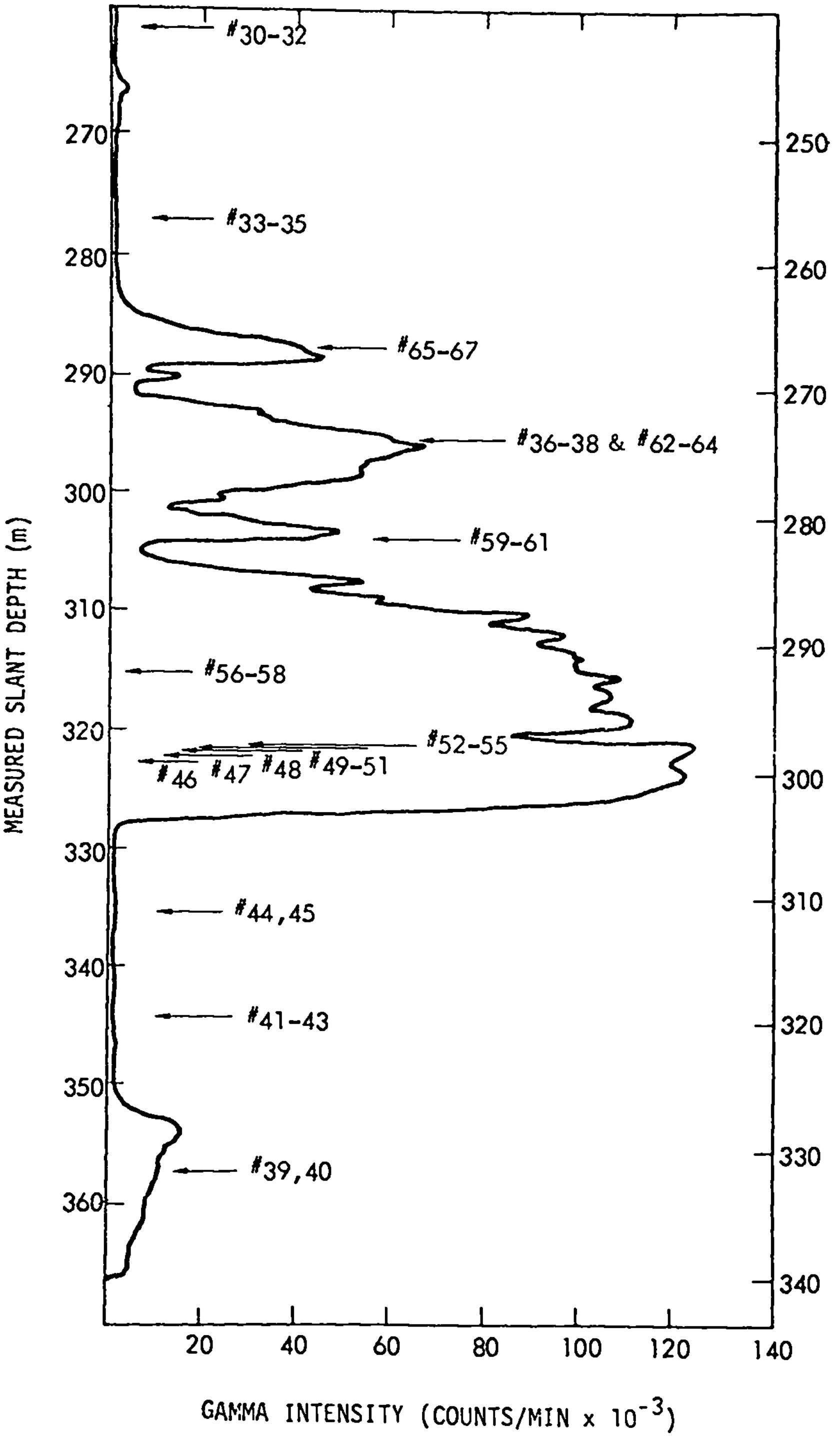


Fig. 10. Log of γ-radioactivity in RNM-1 drillback hole. Positions and numbers of sidewall core samples indicated.

corresponding to a true vertical depth of 221 m. This is consistent with the estimated preshot static water level of 221 m below land surface, and indicates complete infill of the cavity-chimney region. Subsequent water sampling and recompletions of RNM-1 are described in the following section.

IV. GROUND-WATER SAMPLING FROM THE VICINITY OF THE CAMBRIC UNDERGROUND NUCLEAR EXPLOSION

A. Introduction

Ground-water samples were obtained from each of five different zones (Fig. 11) in the Cambric chimney well (RNM-1) by means of 2-liter samplers which were lowered into the well and retrieved by wireline, and by pumping from each zone using a submersible pump which discharged at the surface through a pipe. The samples were sealed in the sample containers at the position and time of sampling so as to retain the pressure extant at the sampling point.

The zones from which water samples were obtained, together with the series designation of the samples, are listed in Table I and illustrated in Fig. 11. The mechanics of ground-water sampling from each of the five zones is briefly described in the following sections. A more detailed account of operations at RNM-1 during the period of water sampling is contained in Appendix A.

TABLE I

ZONES SAMPLED IN CAMBRIC (RNM-1) CHIMNEY WELL WITH CORRESPONDING WATER-SAMPLE SERIES DESIGNATIONS

Zone	Position of Internal Casing Packer at Bottom of Zone		Perforated Intervals				
	Measured depth (m)	Vertical depth (m)	Measured depth (m)	Vertical depth (m)	Sample Series	Dates Pumped	Volume Pumped (m^3)
I	open hole		No perforations; tested from:		A	7-10-74	53
(below cavity)	396.9	370.2	381.6 - 396.9	355.0 - 370.2			
II	373.4	347.6	324.0 - 327.7	300.4 - 303.9	B	9-5,6-74	1.86
(lower cavity)					C	11-5-74 to 1-31-75	19.9
III	319.4	296.0	309.3 - 312.4	286.4 - 289.4	D	4-29-75	18.9
(upper cavity)			315.4 - 318.5	292.2 - 295.2			
IV	304.8	282.7	295.0 - 298.0	272.9 - 275.7	E	8-7,8-75	45.7
(chimney)			300.5 - 303.5	278.1 - 280.9			
V	289.3	267.5	280.1 - 282.6	258.8 - 261.1	F	8-13,14-75	18.6
(adjacent to chimney)			285.9 - 288.6	264.3 - 266.8			

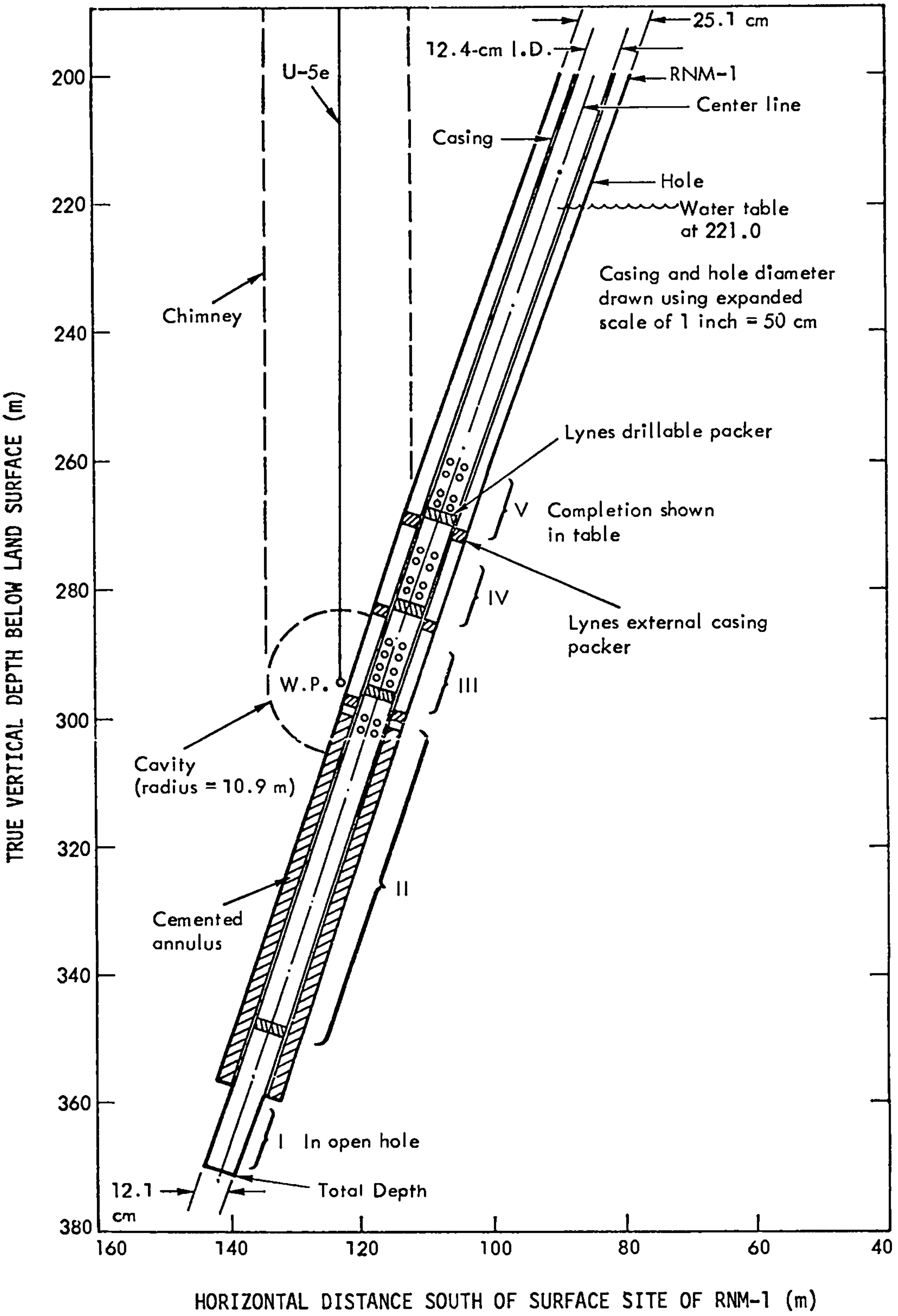


Fig. 11. Construction details of RNM-1 in and near the lower part of the Cambric chimney.

B. Zone I - Below Cavity

At the time of initial completion, RNM-1 was cased through the lower part of the Cambric chimney to a vertical depth of 355.0 m and had been deepened below the bottom of the casing to a vertical depth of 370.2 m. The uncased portion of the well was developed by air-lift pumping prior to water sampling with the wireline sampler at a vertical depth of 359.3 m. Water was then removed from the uncased interval of the well, located approximately 60 m below the Cambric lower cavity boundary, using a submersible pump that had been lowered into the well. A total of about 53 m^3 of water was pumped from Zone I in 8 hours. Water samples were taken hourly from the pumped discharge.

Water-level drawdown response in RNM-1 during the eight-hour pumping period was not obtained because of a malfunction of the pressure-sensing equipment. Drawdown response to pumping RNM-1 was obtained in RNM-2S, however. The drawdown response at RNM-2S to pumping RNM-1 at an average rate of about 136 m^3 per day (Fig. 12) was analyzed to yield estimates of the transmissivity and hydraulic conductivity of the alluvium beneath the Cambric chimney. The drawdown data corresponding to the last 100 minutes of pumping fall along a straight line on the semilogarithmic drawdown response curve. These data were treated according to the modified Theis nonequilibrium method[9] to yield estimates of 46 m^2/day for the transmissivity and 3 m/day for the hydraulic conductivity of the alluvium. The effective thickness of the tested alluvium is assumed to be 15.5 m, based on

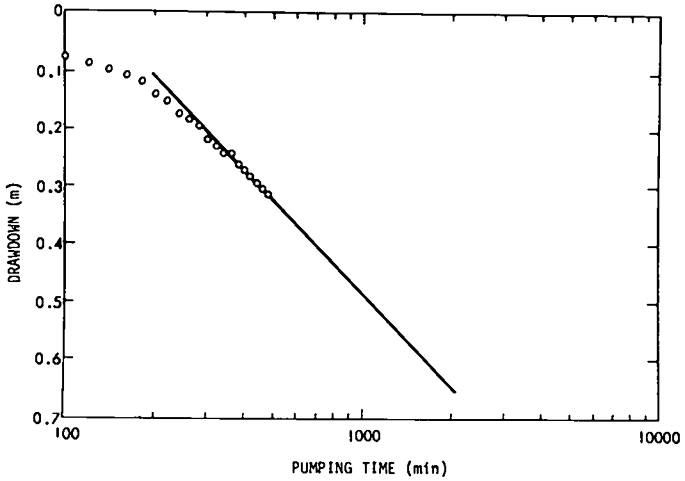


Fig. 12. Drawdown response in RNM-2S to pumping RNM-1, Zone I, at 136 m^3/day.

the length of open hole below the casing. Application of the Theis method in this instance is intended only as a vehicle by which to obtain an order-of-magnitude estimate of transmissivity and hydraulic conductivity. The actual conditions during the pumping of RNM-1 and observation of drawdown at RNM-2S almost certainly do not correspond to the model on which the Theis method is based.

C. Zone II - Within Lower Cavity Region

After completion of water sampling from Zone I, a packer was set inside the casing in RNM-1 at a vertical depth of 347.6 m, thus sealing off Zone I. The inside of the casing above the packer was rinsed with uncontaminated water tagged with LiCl, and the casing in Zone II was perforated with shaped explosive charges in the interval from 300.4-m to 303.9-m vertical depth. Two water samples were taken with the wireline sampler, one each from 299.0-m and 302.1-m vertical depths. Water was then removed from Zone II using a submersible pump. The inflow rate through perforations in Zone II was less than the minimum pump discharge rate; hence, Zone II was pumped and sampled intermittently over a period of several months, during which a total of 21.8 m^3 of water was removed from the zone. Sampling from Zone II was believed important because the perforated interval was within the lower portion of the Cambric cavity.

Upon completion of pumping water from Zone II, two samples were retrieved using the wireline sampler. The water level in RNM-1 was then depressed using air pressure. When the water level had stabilized, air pressure was suddenly released and recovery of the water level was measured. The water-level recovery as a function of time was treated as a "slug withdrawal test".[10,11] The casing in Zone II was reperforated and the well was surged by applying and releasing air pressure at the casing head in several cycles. A second slug withdrawal test was performed. The water-level recovery in this test is depicted in Fig. 13 where the observations are plotted. Analysis of the recovery data showed the apparent transmissivity in Zone II to be 0.57 m^2/day. Assuming the effective thickness of material adjacent to Zone II to be 3.7 m, the length of perforated casing, the apparent hydraulic conductivity in the zone is 0.15 m/day.

Because reperforation and surging of Zone II resulted in only a twofold increase in apparent transmissivity, it was decided to pump from the zone no further.

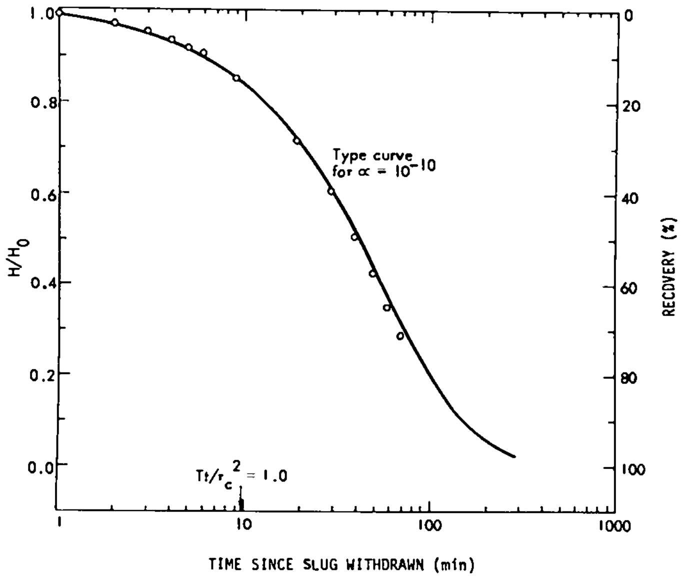


Fig. 13. Water level recovery in RNM-1 after slug withdrawal from Zone II.

D. Zone III - Within Upper Cavity Region

After completion of water sampling from Zone II, a packer was set inside the well casing at 296.0-m vertical depth, sealing off Zone II. Attempts were made to rinse the inside of the casing with uncontaminated water, but the effort was abandoned because of operational difficulties. The casing in Zone III was perforated in the intervals from 286.4-m to 289.4-m and 292.2-m to 295.2-m vertical depths. The well was surged by applying and releasing air pressure at the casinghead in several cycles. Water-level recovery following the final casing pressurization was measured. The zone was then reperforated and surged again. Reperforation and surging had little effect on the apparent transmissivity of Zone III.

Water-level recovery from air pressurization of the casing following the initial perforation in Zone III is shown in Fig. 14. Analysis of the recovery data revealed the apparent transmissivity in Zone III to be 1.46 m^2/day. Assuming the effective thickness of material adjacent to Zone III to be 6.5 m, the apparent hydraulic conductivity in the zone is 0.22 m/day.

After perforating and surging Zone III, water samples were retrieved using the wireline sampler. The submersible pump was installed and 18.9 m^3 of water was pumped from Zone III within a day. Water samples of the pumped discharge were obtained. Subsequent to pumping from Zone III, two water samples were obtained from 290.8-m vertical depth with the wireline sampler.

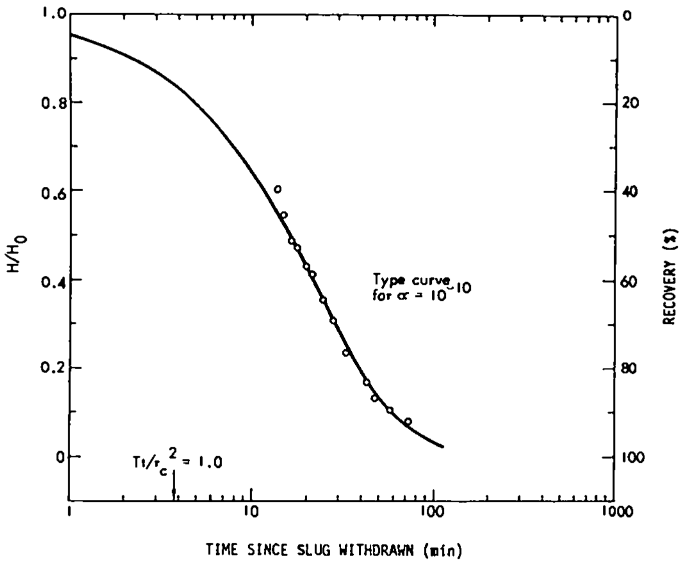


Fig. 14. Water level recovery in RNM-1 after slug withdrawal from Zone III.

E. Zone IV - Chimney

Upon completion of water sampling from Zone III, a packer was set inside the casing at 282.7-m vertical depth, sealing off Zone III. The inside of the casing was rinsed with uncontaminated water and perforated in the intervals from 272.9 m-to 275.7-m and 278.1-m to 280.9-m vertical depth. A water sample was retrieved from 278.1-m vertical depth using the wireline sampler. The well was surged with air pressure. Very slow water-level recovery was measured and the zone was reperforated in the interval from 278.1-m to 280.9-m vertical depth. Again the well was surged with air pressure with very slow water-level recovery following pressurization. Alluvial material apparently had intruded into the casing through the perforations. The material was circulated out of Zone IV by pumping LiCl-tagged water down tubing which had been lowered into the well. Finally, the submersible pump was installed in Zone IV and a total of 45.7 m^3 of water was pumped and sampled within a day. Two water samples were retrieved from 276.7-m vertical depth using the wireline sampler.

F. Zone V - Adjacent to Chimney

The last internal casing packer was set at 267.5-m vertical depth, sealing off Zone IV. The inside of the casing was rinsed twice with uncontaminated water and perforated in the intervals from 258.8-m to 261.1-m and 264.3-m to 266.8-m vertical depths. The well was surged with air pressure and two water samples were obtained from 259.9-m vertical depth using the wireline sampler. The submersible pump was installed in Zone V and 18.6 m^3 of water was pumped from the zone, and sampled, within a period of two days. Following the pumping operation, two more water samples were obtained from the zone with the wireline sampler.

G. Comments on Hydraulic Characteristics of Material in Zones II and III

Zone II was perforated in the region of highest γ-activity, according to the γ-log of RNM-1 shown in Fig. 10. This region is thought to contain the greatest accumulation of solidified melt resulting from the Cambric explosion. The lower portion of the region is believed to be the lower cavity boundary. Zone III was perforated above the lower cavity boundary in a region of lower, but substantial γ-activity as shown by the log. Perhaps the somewhat lower hydraulic conductivity in Zone II (0.15 m/day), compared with that in Zone III (0.22 m/day), is a consequence of the greater concentration of solidified melt in Zone II, the greater compaction of material in the bottom of the cavity, and the proximity of Zone II to the zone of compaction outside the lower hemisphere of the cavity.

V. CHEMICAL AND RADIOCHEMICAL ANALYSES

A. Introduction

Radiochemical analyses were performed on a variety of core and water samples in order to determine the distribution and identity of radionuclides in and around the original Cambric detonation point. Major objectives included measurement of the radionuclide content of water from the Cambric cavity and chimney regions below the water table in order to determine the potential source term for migration in the water and estimation of the partition of the various radionuclides between the water and solid material.

Although measurements of fluid level indicated complete infill of the cavity-chimney region to the preshot static water level of about 221 m, the question of whether the chimney extended above the water table remains. The vertical extent and radius of the chimney shown in Figs. 8 and 9 are schematic only. There is very little experience with tests of this yield buried in saturated alluvium. Existing data for chimney height, measured from the detonation point, have been plotted as a function of cavity radius (see Ref. 1, p. 79). From this plot a chimney height of about 90 m in dry alluvium,or 32 m in tuff, granite, dolomite, or sandstone-shale, can be estimated for a cavity radius of 11 m. However, the plot in Ref. 1 shows chimney heights of 23 m and 75 m for two different nuclear explosions in dry alluvium, both having cavity radii of 9 m. Although estimates of the extent of the chimney can be seen to be somewhat uncertain, a maximum value would seem to be about 90 m above the detonation point of 294 m, or about 204 m below land surface. Even if the chimney did extend above the water table for 15 to 20 m as this maximum estimate indicates, it seems unlikely that a significant fraction of the steam or volatile radioactive species from the relatively small cavity volume would penetrate through the 60 m of saturated alluvium above the top of the cavity. The formation of extensive fractures or fissures through which volatile radionuclides could escape would not be expected in the collapsing alluvium. Assuming some very small fraction of the volatile radionuclides were deposited in the alluvium above the water table, these nuclides still would not constitute a potential source term for migration in ground water until they were transported into the aquifer. Radionuclide movement via surface water drainage appears remote as the potential evaporation rate greatly exceeds the annual precipitation rate of only 150 mm (see Section II B), and the top of the chimney is more than 200 m below ground surface.

B. Chemical Analyses

The pH and conductivity of water pumped from the various zones were measured in the field by standard methods. Rather complete chemical analyses of the pumped water samples were also made to help in correlation of radionuclide content with water characteristics and to see if the chemical composition of the water varied from zone to zone. The Li and Ca contents were measured at the various laboratories by atomic absorption techniques. Chemical analyses of the water were made by the USGS and the results of these analyses are given in Appendix B. Representative analyses for water from each of the five zones and for nearby wells are given in Table II. (See Table I, Section IV for a summary of the position of the zones and the pumping history.) As discussed in Section III, fluids added during drilling and completion of RNM-1 were tagged with 20 ppm of Li, and the Li concentration of the water samples was used as an indication of the degree of contamination from added fluids.

The A-series water samples were pumped from Zone I and showed ≤ 0.05 ppm Li, indicating little contamination from drilling fluids. The Ca content was ≈ 15 ppm and the pH was nearly constant at 8.1.

The B-series samples were taken from Zone II, the bottom cavity region, and represented only about 1.86 m^3 of pumped water. They showed higher Li and Ca

TABLE II

ANALYSES OF REPRESENTATIVE WATER SAMPLES PUMPED FROM RNM-1

Zone	Sample Series	Pumping Dates	Volume Pumped (m^3)	Conductivity (μmhos/cm)	pH	Ca (ppm)	Li (ppm)
I (below puddle)	A	7-10-74	≈53	≈ 420	8.1	≈ 15	≤0.05
II (bottom cavity)	B	9-5,6-74	1.86	≈2000	11	≈150	3-7
	C	11-5-74 to 1-31-75	21.8	≈1000	8.3	≈50	0.4
III (top cavity)	D	4-29-75	18.9	≈1100	7.2	≈70	0.2
IV (chimney)	E	8-7,8-75	45.7	≈1100	7.0-7.1	≈90	≈1.5
V (adjacent to chimney)	F	8-13,14-75	18.6	≈ 670	7.3-7.5	≈50	0.3-0.4
	Depth (m)						
Well 5A	238 m	6-4-64	--	687	8.2	3	0.01
Well 5B	230 m	3-25-71	--	482	7.9	7	0.04
Well 5C	314 m	3-22-71	--	547	8.1	1	<0.01
Hole UE5c	--	3-23-71	--	428	7.8	9	0.01

values than Zone I. These high Ca contents and the high pH (≈11) and conductivity (≈2000 μmho/cm) values seemed to indicate some dissolution of the large amount of cement pumped into the hole and annular space between the casing and drilled hole during drilling and casing operations. Because these analyses indicated that representative ground-water samples had not yet been obtained, pumping of Zone II was resumed some 2 months later (C-series samples). After pumping 7.5 m^3 of water, the pH dropped to 8.9 and the Ca to 64 ppm. After pumping about 15 m^3, the values stabilized at pH = 8 to 8.5, at Li ≈0.4 ppm, and at Ca ≈ 50 ppm.

The D-series samples were taken in Zone III, the upper cavity region. The Li content dropped to less than 0.4 ppm and the pH to 7.2 after pumping 6.4 m^3 from this zone, but the Ca content remained between 60 and 75 ppm.

The E-series samples were pumped from Zone IV, the chimney region. The initial Li content of 11 ppm dropped to 3 ppm or less after pumping ≈15 m^3, but seemed to level off at 1.5 ppm even after 40 m^3 of water had been removed. The Ca content remained in the 90-to 95-ppm range, and the pH was 7.0 to 7.1.

The F-series samples were taken in Zone V, adjacent to the chimney region, and showed Li contents of 0.5 ppm or less after pumping only 3.8 m^3. The Ca content was about 50 ppm and the pH was 7.3 to 7.5.

The Ca contents of the water samples pumped from RNM-1 seemed to be generally higher than those for water from other wells in the area (Table II), perhaps again reflecting some effect from the cement used in the drilling and casing operations. The pH in Zones III, IV, and V was somewhat lower than in Zones I and II and water wells 5A, 5B, and 5C.

C. Radiochemical Analyses and Results

Three types of samples were obtained for radiochemical analyses: 1) Sidewall cores taken during re-entry to the Cambric site; 2) "Pressurized" water samples retrieved before and after pumping each of the zones as described in Section IV and Appendix A; 3) Pumped water samples removed in each zone by means of a submersible pump as described in Section IV and Appendix A.

1. Sidewall Cores.

A total of 67 sidewall core samples was taken as described in detail in the chronological history given in Appendix A. They were numbered in order of recovery and their positions are shown schematically in Figs. 8 and 9. The sampling positions are indicated in Fig. 10 on the γ-intensity log taken after completion of re-entry drilling. The original Cambric emplacement depth was 294 m and from the γ-log the cavity radius was calculated to be 10.9 m (Section III). All of the core samples, their depths, and subsequent treatment are listed in Table III.

Duplicate or triplicate samples were taken at most depths. One of the cores at each depth (in its coreshoe) was immediately placed in a gas-tight, nitrogen-flushed, stainless steel container. These cores were shipped to LASL for analyses of ^{85}Kr, HT, and HTO, and for γ-spectral analyses of representative dried and ground core material. Complete procedures are given in Appendix C. The other samples (in their coreshoes) were sealed in water-tight plastic bags for shipment to LLL and LASL for γ-spectral and radiochemical analyses of the cores and contained fluid.

TABLE III

SUMMARY OF CORE SAMPLES, TREATMENT, AND ^{137}Cs CONTENT

Core Sample No.	Depth[a] (m)	^{137}Cs dpm/g at t_o
1[b],2	34.1 (36.6)	n.d.[c]
3,4[b]	51.0 (54.9)	n.d.
5	67.8 (73.2)	n.a.[d]
6[b]	73.4 (79.2)	n.a.
25,26[b]	84.4 (91.4)	13
22,23[e],24[b]	103.6 (112.8)	13
21[b]	118.9 (129.8)	13
20[e]	124.0 (135.6)	n.a.
19	126.7 (138.7)	n.a.
16,17[b],18[e]	153.5 (167.9)	9
13,14[b],15[e]	171.3 (187.1)	9
10,11[b],12[e]	188.7 (205.7)	13
7,8[b],9[e]	206.4 (224.6)	n.a.
27,28[b],29[e]	224.6 (243.8)	9
30,31[b],32[e]	241.8 (262.1)	9
33[f],34[b],35[e]	256.2 (277.4)	40
65,66[b],67[e]	266.0 (287.7)	4.9 x 10^2
36[e]37[b],38	273.6 (295.7)	6.3 x 10^3
62,63[b],64[e]		2.1 x 10^3
59,60[b],61[e]	281.4 (303.9)	1.3 x 10^3
56,57[b]58[e]	292.1 (315.2)	5.5 x 10^3
52[e],53,54[b],55[e]	297.9 (321.3)	1.8 x 10^4
49[e],50[b],51[e]	298.2 (321.6)	2.4 x 10^4
48	298.5 (321.9)	n.a.
47	299.1 (322.5)	n.a.
46	299.6 (323.1)	n.a.
44[f],45[b]	311.2 (335.3)	75
41,42[b],43[e]	319.9 (344.4)	9
39[f],40[b]	331.5 (356.6)	13

[a] All depths are true vertical depths measured from ground level. The depths measured from ground level reference along the non-vertical path followed by the borehole are given in parentheses.

[b] These cores were placed immediately in nitrogen-flushed, gas-tight, stainless steel containers for subsequent gas analysis at LASL.

[c] Not detected.

[d] Not analyzed.

[e] These cores were sent to LLL; all others went to LASL.

[f] Half of each sample was later sent to LLL for lithologic description.

Results of the ^{85}Kr, HT, and HTO analyses of water removed from the cores are given in Table IV. The water from cores taken in the original postshot sampling hole between 34 and 120 m appears to be contaminated with T. This contamination probably occurred during the initial postshot drilling operation some ten years ago. Cores taken between 154 and 242 m showed very low T levels. Because the re-entry hole was slant drilled from a point about 120 m north of the Cambric detonation point rather than vertically from directly above, neither the distribution of radioactivity directly above, nor the height of the chimney, could be determined from measurements of the material obtained by core sampling. The first radioactivity was detected on the γ-log (Fig. 10) at a vertical depth of about 245 m, which might signal entrance of the drill hole into the chimney. The first definite indication of radioactivity in the cores was found in core 34, taken at a vertical depth of 256 m. These results indicate that the chimney radius may be somewhat larger than the 11 m shown in Fig. 9. Cores taken below this depth show increasing levels of activity. Although they are considered to be volatile species and are found outside the cavity region, by far the highest levels of T and ^{85}Kr were found in core 57 taken at 292 m and in cores 50 and 54 which were taken at 298 m, near the bottom of the cavity. No cores were obtained between 298 m and the estimated cavity bottom at 305 m, and they might have been expected to have shown somewhat higher levels of activity. Cores removed 6 m and 15 m below the bottom of the cavity showed levels of T and ^{85}Kr activity as low as those taken 27 m or more above the top of the cavity, illustrating the rather abrupt drop in radioactivity below the cavity. These very low levels also show that very little radioactivity has moved below the bottom of the cavity, even ten years after the test.

The measured HT/HTO values are also given in Table IV. In the active region from within the puddle up to about 265 m, only 0.01% to 0.1% of the T activity is in the form of HT (or CH_3T). This is consistent with the value of 0.07% which can be estimated for an NTS test of this yield under standard emplacement conditions[12], assuming the density of the alluvium is 2.0 g/cm^3 and the water content is 15% by weight. It is assumed that there are no significant concentrations of T in other species, and that, therefore, 99.9% or more of the T is incorporated in the water.

The observed ^{85}Kr/T atom ratios (Table IV) are in the range of $(0.4 - 5.0) \times 10^{-4}$ while the calculated value is 1.2×10^{-4} for Cambric. Although the measured values show considerable scatter, there is no real indication that the ^{85}Kr and

TABLE IV

RESULTS OF ^{85}Kr, HT, AND HTO ANALYSES OF CORE SAMPLES

Core #	Vertical Depth (m)	Dry wt (g)	H_2O (ml)	HTO[a] at t_o (μCi/ml)	HT/HTO	σ[b] (%)	Σ Atoms at t_o T ($\times 10^{-13}$)*	Σ Atoms at t_o ^{85}Kr ($\times 10^{-10}$)*	R[c]
1	34.1	158	10.5	6.56×10^{-2}	8.29×10^{-4}	1.2	1.42	8g	---
4	51.0	426	28.5	8.72×10^{-2}	8.91×10^{-5}	2.8	5.13	8g	---
6	73.4	256	19.0	9.43×10^{-2}	1.19×10^{-4}	3.0	3.70	8g	---
26	84.4	520	136	1.52×10^{-2}	3.05×10^{-4}	1.2	4.27	8g	---
24	103.6	1140	181	4.91×10^{-3}	2.33×10^{-4}	2.9	1.83	8g	---
21	118.9	1010	142	5.89×10^{-3}	1.10×10^{-3}	0.8	1.73	8g	---
17	153.5	682	74	1.55×10^{-4}	1.94×10^{-2}	2.7	0.024	Bg	---
14	171.3	643	147	2.42×10^{-4}	1.60×10^{-2}	2.1	0.073	8g	---
11	188.7	694	139	2.18×10^{-5}	6.59×10^{-2}	3.0	0.006	Bg	---
8	206.4	371	98	5.36×10^{-6}	8.47×10^{-1}	1.5	0.001	8g	---
28	224.6	682	139	5.87×10^{-6}	2.43×10^{-1}	3.0	0.002	8g	---
31	241.8	630	153	1.28×10^{-5}	2.01×10^{-1}	1.4	0.004	8g	---
34	256.2	741	157	1.78×10^{-4}	5.52×10^{-3}	3.8	0.058	0.036	5.17
66	266.0	895	278	9.31×10^{-3}	6.01×10^{-4}	0.6	5.34	1.45	2.25
37	273.6	781	160	4.04×10^{-2}	6.52×10^{-4}	0.3	13.3	4.41	2.74
63	273.6	563	200	1.54×10^{-2}	1.14×10^{-3}	0.3	6.36	2.64	3.44
60	281.4	584	190	1.48×10^{-1}	2.50×10^{-4}	0.2	58.1	2.82	0.405
57	292.1	370	185	2.02	1.43×10^{-4}	0.1	772.	36.2	0.396
54	297.9	950	262	4.33	7.82×10^{-5}	0.1	2343.	335	1.19
50	298.2	385	157	2.95	8.19×10^{-5}	0.1	956.	161	1.40
45	311.2	384	154	3.25×10^{-4}	5.23×10^{-2}	0.4	0.103	0.044	3.36
42	319.9	486	180	1.76×10^{-4}	7.86×10^{-2}	0.2	0.065	0.019	2.23
40	331.5	1013	260	3.25×10^{-3}	2.54×10^{-3}	0.5	1.75	0.260	1.24

---

[a] The standard deviations for these counting data are $\leq$ 1% except for cores 8 and 10 where they are 2%.

[b] σ is the standard deviation for the counting data and is $\leq$ 1% unless otherwise stated.

[c] R is the ratio of observed to calculated atom ratios for ^{85}Kr to T at t_o.

*All entries have been multiplied by the factor in parentheses. Divide each entry by this factor to get the actual value.

HTO have separated. Thus,it appears that most of the ^{85}Kr as well as the T is associated with the water.

Gamma-spectral analyses were made of representative 7-g samples, taken after grinding the cores from which the water and gases had been removed. Representative samples of ground, dried, longitudinal core slices were analyzed at LLL. Only ^{137}Cs activity was detected in the γ-spectra of cores taken outside the estimated original cavity region of 283 to 305 m. The specific activity of ^{137}Cs in these samples is reported in Table III. The fission products ^{106}Ru, ^{125}Sb, ^{144}Ce, ^{155}Eu, the neutron activation products ^{54}Mn, ^{60}Co, ^{134}Cs, ^{152}Eu,

^{154}Eu, and ^{239}Pu and ^{241}Am were detected only in cores taken from the cavity region. (See Appendix D-VI for complete results.)

The material from cores 38 and 48, which had been stored in plastic containers to retain water, was removed from the core shoes, weighed and thoroughly mixed with a measured volume (150 to 200 ml) of distilled water. After equilibration overnight, the mixture was filtered on 0.5-μ Nuclepore filters, and radiochemical and γ-spectral analyses of the water were performed. The results of T analyses, corrected for dilution from the added water, are shown in Table V.

TABLE V

TRITIUM RESULTS FOR WATER REMOVED FROM CORES

Core	Vertical Depth (m)	H_2O (ml) Original	H_2O (ml) added	T at t_0[a] (μCi/ml)[b]
33	256.2	49	150	1.48×10^{-2}
38	273.6	130	200	4.19×10^{-2}
48	298.5	105	205	3.01
44	311.2	26	150	5.45×10^{-2}
39	331.5	40	150	5.08×10^{-2}

[a] Corrected to specific activity of original volume of water.

[b] Standard deviations of counting data are all ≤0.1%.

Most of the values agree with the results shown in Table IV for water removed from other cores taken at similar depths and placed immediately in gas-tight containers.

The dried, solid material from cores 38, 48, and 53 was visually graded into several fractions: material which had been altered by the nuclear explosion, and is presumably refractory, i.e., black, glassy, or fused in appearance; fine, apparently unaltered material; and coarser, unaltered material. No fused material could be picked out from core 38 which was taken from the chimney region. The material from these fractions was pulverized, and representative 7-g samples of each were completely dissolved according to the usual LASL dissolving procedure (Ref. 13, p. 261). The ^{106}Ru and perhaps some of the ^{125}Sb would be lost during the dissolving procedure. The results of γ-spectral analyses for ^{125}Sb, ^{137}Cs, ^{144}Ce, and ^{155}Eu, and radiochemical analyses for ^{90}Sr, ^{147}Pm, ^{239}Pu, and ^{241}Am in these fractions are given in Table VI. (The ^{90}Sr procedure is outlined

TABLE VI
ACTIVITY DISTRIBUTIONS FROM ANALYSES OF DISSOLVED SAMPLES FROM CORES 38, 53, AND 48

Core	Fraction	Activity at t_0 (dpm/g)							
		^{90}Sr	^{125}Sb	^{137}Cs	^{144}Ce	^{147}Pm	^{155}Eu	^{239}Pu	^{241}Am
38 273.6 m (chimney)	Coarse sand	4.3×10^{2}	n.a.[c]	3.4×10^{3}	1.10×10^{5}	2.5	n.a.	3.6	n.a.
		(1.2×10^{2})[a]		(9.4×10^{2})	(3.1×10^{4})	(0.69)		(1.0)	
	Fines	5.5×10^{2}	n.a.	5.3×10^{3}	1.20×10^{5}	0.6	n.a.	6.9	n.a.
		(8.0×10^{1})		(7.7×10^{2})	(1.7×10^{4})	(0.09)		(1.0)	
53 297.9 m (high puddle)	cold "native"	1.0×10^{4}	7.9×10^{3}	4.0×10^{3}	n.d.[d]	n.a.	3.9×10^{3}	3.8×10^{4}	4.4×10^{3}
		(0.26)	(0.21)	(0.11)			(0.10)	(1.00)	(0.12)
	Fines	2.2×10^{3}	3.9×10^{4}	1.5×10^{4}	n.d.	n.a.	1.5×10^{4}	1.4×10^{5}	1.9×10^{4}
		(0.016)	(0.28)	(0.11)			(0.11)	(1.00)	(0.14)
	Fused	7.7×10^{4}	n.d.	6.9×10^{4}	1.40×10^{7}	4.5×10^{6}	1.7×10^{5}	1.5×10^{6}	2.0×10^{5}
		(0.051)		(0.046)	(9.3)	(3.0)	(0.11)	(1.00)	(0.13)
48 298.5 m (high puddle)	cold "native"	3.1×10^{3}	n.d.	3.8×10^{3}	n.d.	n.a.	n.d.	2.6×10^{2}	n.d.
		(12)		(15)				(1.00)	
	Fused	6.1×10^{4}	7.6×10^{4}	5.3×10^{4}	1.18×10^{7}	3.6×10^{6}	1.3×10^{5}	1.2×10^{6}	1.7×10^{5}
		(0.051)	(0.063)	(0.044)	(9.8)	(3.0)	(0.11)	(1.00)	(0.14)
$(A_x/A_{Pu})_{calc}$[b]		0.223	0.213	0.649	14.1	2.45	0.134	1.00	-----

[a] Values in parentheses are the activity ratios for the indicated nuclides relative to the ^{239}Pu in the sample.

[b] $(A_x/A_{Pu})_{calc}$ is the ratio calculated for Cambric from values given in Table VII.

[c] n.a. = not analyzed for this nuclide.

[d] n.d. = not detected.

in Appendix C-IV, and other radiochemical procedures are given in Ref. 13.) The highest specific activities for all nuclides were found in the fused material removed from cores 48 and 53 which came from the lower cavity region, but significant levels of ^{90}Sr, ^{137}Cs, and ^{144}Ce were also found in the rubble or apparently unfused material from these cores and chimney core 38. Activity ratios were calculated relative to ^{239}Pu which is refractory, i.e., its boiling point is high enough so that it has condensed out of the vapor phase by the time of cavity collapse and is normally retained[1] in the puddle at the bottom of the explosion cavity. A comparison with the postshot ratios calculated[14] for Cambric (Table VII) shows that ^{90}Sr and ^{137}Cs are highly depleted in the fused material, but that these nuclides are highly enriched relative to ^{239}Pu in the unfused material from cores 48 and 53 and in the material from chimney core 38. The ratios shown in Table VI indicate that only about 7% of the ^{137}Cs and 23% of the ^{90}Sr relative to ^{239}Pu remain in the fused material. However, they are greatly enriched in the rubble from the cavity as well as chimney regions. Thus, although only a small

TABLE VII

RATIOS FOR RNM-1 SOURCE AT t_0 (5-14-65)

Nuclide	$T_{1/2}$ (years)	$(N_X/N_T)^a$	$(A_X/A_T)^b$
T	12.26	1.00	1.00
^{85}Kr	10.74	1.22×10^{-4}	1.38×10^{-4}
^{90}Sr	28.9	1.66×10^{-3}	7.05×10^{-4}
^{106}Ru	1.010	3.68×10^{-3}	4.46×10^{-2}
^{125}Sb	2.77	1.52×10^{-4}	6.73×10^{-4}
^{137}Cs	30.0	5.03×10^{-3}	2.05×10^{-3}
^{144}Ce	0.779	2.84×10^{-3}	4.47×10^{-2}
^{147}Pm	2.62	1.65×10^{-3}	7.74×10^{-3}
^{155}Eu	5.00	1.73×10^{-4}	4.24×10^{-4}
^{238}U	4.5×10^{9}	1.78×10^{2}	4.9×10^{-7}
^{239}Pu	2.44×10^{4}	6.28	3.16×10^{-3}
^{241}Am	4.2×10^{2}	$\approx 2.5 \times 10^{-2}$	$\approx 7.7 \times 10^{-4}$

---

[a] This is the atom ratio of the indicated nuclide to the post-detonation tritium of ≈6.3 g or 1.25×10^{24} atoms. The atoms of fission-product nuclides were calculated using a total yield of $\approx 10^{23}$ fissions for Cambric and the cumulative fission yields given in Meek and Rider, Ref. 14.

[b] This is the ratio of the disintegration rate for each nuclide relative to tritium calculated from the indicated half lives.

fraction of the ^{90}Sr and ^{137}Cs remained in the fused material from the cavity, the remainder seems to have condensed and been contained on rubble in the cavity or lower chimney (Table III). The ^{147}Pm, ^{155}Eu, and ^{241}Am seem to stay with ^{239}Pu as expected.

A summary of data from γ-spectral analyses of the 7-g samples and of γ-spectral and radiochemical analyses of the graded, dissolved samples is given in Table VIII. Ratios of the various activities were calculated relative to ^{155}Eu because it was measured in both types of samples and is believed to be relatively refractory. Comparison of these ratios with the unfractionated ratios for Cambric show that ^{106}Ru and ^{137}Cs are severely depleted in cores taken from below

TABLE VIII

ACTIVITY RATIOS IN SELECTED CORES FOR VARIOUS NUCLIDES RELATIVE TO ^{155}Eu

Vertical Depth (m)[a]	Core	^{60}Co	^{106}Ru	^{125}Sb	^{137}Cs	^{144}Ce	^{152}Eu	^{154}Eu	^{239}Pu	^{241}Am
292.1	57[b]	0.75	n.d.[c]	2.5	45.8	n.d.	n.d.	0.58	n.a.[d]	n.a.
297.9	53 - "native"[e]	0.48	n.a.	2.0	1.0	n.d.	n.d.	n.d.	9.1	1.12
	53 - fines[e]	0.73	n.a.	2.5	0.97	n.d.	0.030	n.d.	9.2	1.25
	53 - fused[e]	0.63	n.a.	n.d.	0.41	82.1	0.016	0.018	9.8	1.23
297.9	54[b]	0.89	32.8	2.1	0.67	87.6	0.020	0.027	n.a.	n.a.
298.2	50[b]	0.72	27.6	2.0	0.66	99.4	0.023	0.028	n.a.	n.a.
298.5	48 - fused[e]	0.72	n.a.	0.59	0.41	91.7	0.033	0.033	9.0	1.30
311.2	45[b]	n.d.	n.d.	n.d.	0.68	n.d.	n.d.	n.d.	n.a.	n.a.
$(A_x/A_{^{155}Eu})^f_{calc}$		---	105	1.59	4.83	105	---	---	7.45	---

[a] Bottom of puddle estimated from γ-log to be 305 m and cavity radius estimated to be 10.9 m. Original cavity then extended from about 283 to 305 m.

[b] Representative 7-g samples of the ground core were analyzed by γ-spectroscopy.

[c] n.d. = not detected.

[d] n.a. = not analyzed for this nuclide.

[e] Samples were dissolved prior to γ-spectral or radiochemical analysis.

[f] $A_x/A_{^{155}Eu}$ calculated for Cambric from values in Table VII.

the original emplacement depth of 294 m. ^{125}Sb seems to be depleted in the fused material only, as though it were volatilized out of the melt but then deposited on nearby, unaltered alluvium. The ^{239}Pu and ^{241}Am ratios are relatively constant as might be expected for non-volatile species. The ^{239}Pu values are all higher than the calculated value, possibly indicating some depletion of ^{155}Eu in the cavity region. ^{144}Ce is also somewhat depleted in these cores and is enriched in chimney core 38 (Table VI) as are ^{90}Sr and ^{137}Cs. Presumably, they are in the chimney as a consequence of the movement of their rare gas or alkali metal precursors.

As mentioned earlier, the water removed from cores 38 and 48 was analyzed radiochemically for ^{90}Sr and ^{239}Pu and by γ-spectrometry for other nuclides. The results of these analyses are given in Table IX. Effective distribution coefficients were estimated according to the expression,

$$K_d = \frac{(\text{dpm/g soil})}{(\text{dpm/ml } H_2O)}.$$

TABLE IX

ANALYSES OF WATER FROM CORES 38 AND 48

Core	Vertical Depth (m)	Activity at t_0 (dpm/ml H_2O) ^{90}Sr	^{137}Cs	^{239}Pu
38	273.6	n.d.[a]	0.4 (20%)[b]	$\leq 10^{-3}$
48	298.5	2.22 (10%)[b]	≤ 4	6.2×10^{-3} (20%)[b]

[a] n.d. = not detected.

[b] Standard deviation of counting data.

It was hoped that the K_d's for core 38 from the chimney could then be compared with those for core 48, taken from the high puddle region. However, due to the long decay period the sensitivity for many shorter lived species was very low, and the specific activity of core 38 was too low to detect many of the longer lived activities. K_d's for ^{137}Cs and ^{239}Pu of $\approx 10^4$ and $\geq 5 \times 10^3$, respectively, were estimated for core 38. The K_d's for ^{90}Sr, ^{137}Cs, and ^{239}Pu of $\approx 10^4$, $\geq 10^4$, and $\approx 10^8$, respectively, which were estimated for core 48, are consistent with the results for core 38.

2. Pumped Water Samples

Water samples were pumped from each zone after perforation and cleaning as outlined in Appendix A and Section IV. The perforated intervals, volume of water pumped, and sample designations are given in Table I, Section IV.

The 53 m^3 of water pumped from Zone I, some 50 m below the cavity region, showed no T activity above background. The Li content indicated negligible dilution with drilling fluids.

The B-series water samples were pumped from Zone II, the lower cavity region. Because of the low inflow rate, only 1.86 m^3 of water was removed. A portion of each sample was filtered through a 1-μ Nuclepore filter in the field, and some samples were made 0.1 N in HCl prior to filtration in order to see if these variables affected the results of subsequent radiochemical and γ-spectral analyses perfomed at LLL and LASL. The amount of γ-activity on the filters was found to be a small fraction of that in the water, and no significant difference in γ- or T analyses between acidified and non-acidified samples could be found. (See Appendix D-VII A.) Comparison of LASL results to LLL results for T gave an overall ratio of 0.998 for the filtered samples, indicating no bias between the analyses at the two laboratories. Because the Li content had not dropped below 3 ppm, further pumping seemed necessary to reduce the dilution from drilling fluids, and pumping was resumed some two months later. The C-series samples were pumped intermittently over a period of several months until a total of 21.8 m^3 of water was removed and the Li content had dropped to 0.4 ppm. The zone was then reperforated, but because the transmissivity increased by only a factor of two, pumping in this zone was not resumed.

The results of γ-spectral, T, and ^{90}Sr radiochemical analyses of the B-and C-series samples from Zone II are plotted in Fig. 15. Complete results are tabulated in Appendix D and methods of analysis are given in Appendix C. Only ^{106}Ru, ^{125}Sb, and ^{137}Cs could be detected in the γ-spectra. After pumping 3.8 m^3, the various activity levels seemed to stabilize, although some fluctuations were still observed. Results for ^{125}Sb were rather erratic, but the agreement between LLL and LASL analyses was satisfactory.

The results for γ-spectral, T, and ^{90}Sr analyses for the D-series samples (Zone III) are shown in Fig. 16. The T and ^{90}Sr levels remained quite constant after pumping 2 m^3 of water, but the ^{106}Ru and ^{137}Cs levels continued to decrease until 6 to 8 m^3 of water had been pumped. The ^{125}Sb actually showed a slight increase with volume of water pumped.

Radiochemical analyses for ^{144}Ce, ^{147}Pm, and ^{239}Pu were also performed on selected B-, C-, and D-series samples. The observed activity ratios in the water for these nuclides relative to T were compared with the calculated ratios for Cambric. Assuming that essentially all the T is present as HTO (see Tables IV and X) and is contained below the water table, a "depletion" factor for each nuclide relative to T in the water was calculated by dividing the measured ratio to T by the calculated ratio for Cambric given in Table VII. The inverse of this can be regarded as the retention factor for a given nuclide on the solid debris and will be denoted by E_d. These experimentally determined E_d's for several nuclides are given in Table XI.

A rather constant level of T activity was obtained from Zone IV after pumping about 6 m^3 of water and from Zone V after about 1 m^3. (See Fig. 17.) Only

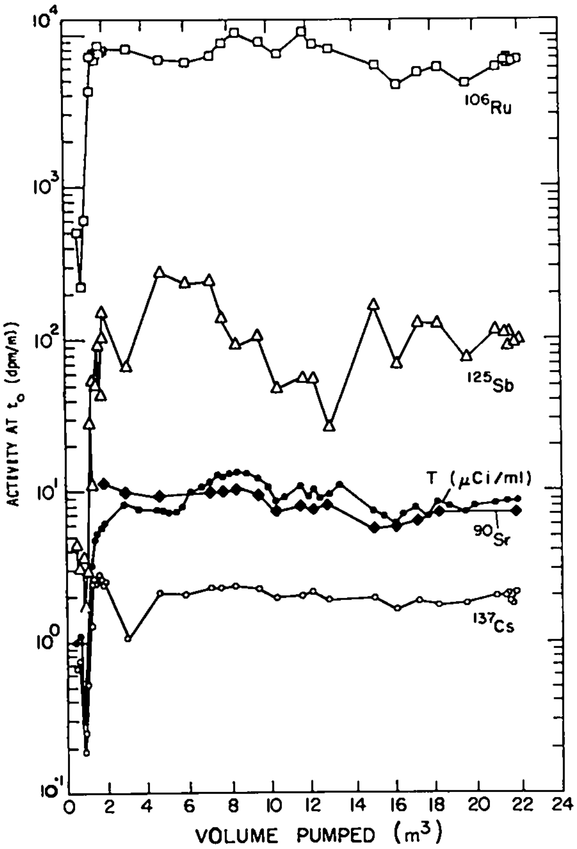


Fig. 15. Analyses of B- and C-series water samples, Zone II.

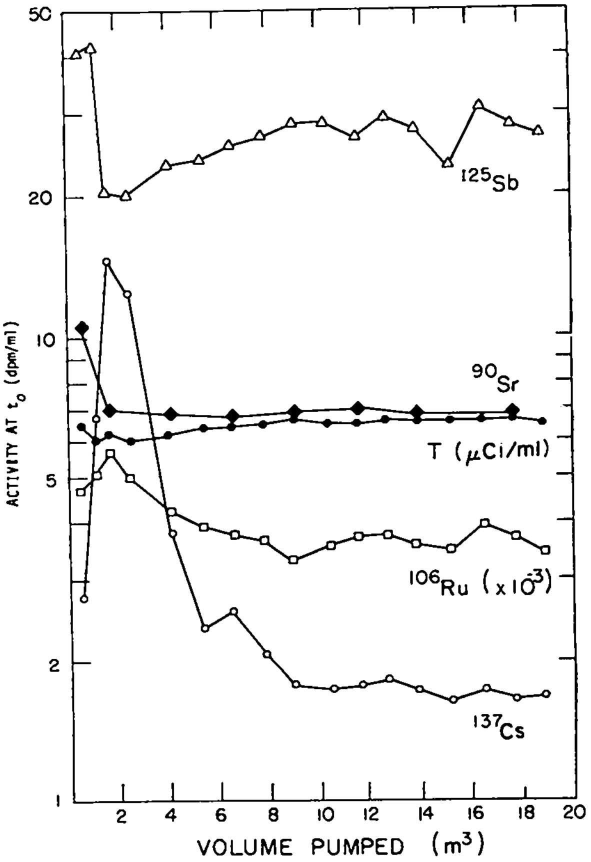


Fig. 16. Analyses of D-series water samples, Zone III.

TABLE X

ANALYSES OF PRESSURIZED WATER SAMPLES

Sample Description	Sample Number[c]	H_2O (ml)	T as HTO[a] µCi/ml at t_o	T as HTO[a] atoms/ml at t_o	HT/HTO	^{85}Kr[a] at t_o Σdpm	^{85}Kr[a] at t_o dpm/ml	^{85}Kr[a] at t_o atoms/ml	^{85}Kr/T at t_o	R[b]
Zone I										
5-10-74 (before pumping A-Series samples)										
385.6 m MSD[d]	1070	2200	Bg	----	----	----	----	----	----	----
	1071	2125	Bg	----	----	----	----	----	----	----
Zone II										
8-6-74 (before pumping B-& C-Series samples)										
322.5 m MSD	1101	1850	1.27×10^{-3}	2.7×10^{10}	1.7×10^{-5}	2.24×10^{3}	1.21	9.8×10^{6}	3.6×10^{-4}	3.00
325.8 m MSD	1102	1972	9.48×10^{-3}	2.0×10^{11}	9.7×10^{-7}	5.63×10^{3}	2.85	2.3×10^{7}	1.2×10^{-4}	1.00
4-11-75 (after pumping B-& C-Series samples)										
304.8 m MSD	1170	2200	9.70	2.01×10^{14}	2.1×10^{-7}	1.19×10^{6}	5.39×10^{2}	4.39×10^{9}	0.22×10^{-4}	0.18
309.4 m MSD	1171	2190	9.53	1.96×10^{14}	1.1×10^{-7}	1.73×10^{6}	7.91×10^{2}	6.45×10^{9}	0.33×10^{-4}	0.28
Zone III										
4-26-75 (before pumping D-Series samples)										
315.5 m MSD	1189	2190	9.03	1.87×10^{14}	1.8×10^{-6}	2.62×10^{6}	1.20×10^{3}	9.78×10^{9}	0.52×10^{-4}	0.43
	1190	2040	8.57	1.76×10^{14}	3.8×10^{-6}	2.46×10^{6}	1.21×10^{3}	9.86×10^{9}	0.56×10^{-4}	0.47
7-29-75 (after pumping D-Series samples)										
313.9 m MSD[d]	1194[c]	2290	6.73	1.39×10^{14}	0.96×10^{-6}	2.40×10^{6}	1.05×10^{3}	8.54×10^{9}	0.61×10^{-4}	0.51
	1192	2290	6.95	1.43×10^{14}	5.67×10^{-6}	2.06×10^{6}	9.0×10^{2}	7.33×10^{9}	0.51×10^{-4}	0.43
Zone IV										
7-31-75 (before reperforation and pumping of E-Series samples)										
300.5 m MSD	1193	2190	2.95	6.09×10^{13}	7.69×10^{-6}		- lost in analysis -			
8-8-75 (after pumping E-Series samples)										
299.0 m MSD	1196	2275	0.150	3.12×10^{12}	1.81×10^{-4}	1.61×10^{5}	7.06×10^{1}	5.76×10^{8}	1.85×10^{-4}	1.54
	1195	2300	0.156	3.21×10^{12}	1.84×10^{-4}	1.62×10^{5}	7.04×10^{1}	5.73×10^{8}	1.79×10^{-4}	1.49
Zone V										
8-12-75 (before pumping F-Series samples)										
281.3 m MSD	1197	2010	0.0417	8.63×10^{11}	9.75×10^{-4}	3.90×10^{4}	1.94×10^{1}	1.58×10^{8}	1.80×10^{-4}	1.50
	1198	2280	0.0398	8.19×10^{11}	7.52×10^{-4}	3.17×10^{4}	1.39×10^{1}	1.13×10^{8}	1.38×110^{-4}	1.15
8-15-75 (after pumping F-Series samples)										
280.4 m MSD	1199	1920	0.0374	7.74×10^{11}	11.1×10^{-4}	2.31×10^{4}	1.20×10^{1}	0.98×10^{8}	1.27×10^{-4}	1.06
	2000	1900	0.0378	7.80×10^{11}	3.55×10^{-4}	2.45×10^{4}	1.29×10^{1}	1.05×10^{8}	1.35×10^{-4}	1.13

[a] Standard deviations of counting data $\leq 0.1\%$.

[b] This is the ratio of the measured to the calculated ^{85}Kr/T atom ratio of 1.2×10^{-4} at t_o.

[c] LASL i.d. number.

[d] Depth of bottle intake, measured slant depth.

TABLE XI

E_d's FOR B-, C-, AND D-SERIES WATER SAMPLES

Sample	T at T_0 (dpm/ml) $(\times 10^{-7})$*	Measured A_x/A_T			E_d[a]		
		^{144}Ce	^{147}Pm	^{239}Pu $(\times 10^{10})$*	^{144}Ce	^{147}Pm	^{239}Pu $(\times 10^{-7})$*
B12	1.23	n.a.[d]	n.a.	2.8±20%	n.a.	n.a.	1.1
B12[b]	1.26	↓	↓	3.2±20%	↓	↓	1.0
B13[c]	1.33			12±10%			0.26
B13[b,c]	1.33			9.0±10%			0.36
C24	2.90			1.0±40%			3.2
C33	2.42	5.3×10^{-5}	$\leq 8\times 10^{-9}$	n.a.	8.4×10^{2}	$\gtrsim 10^{6}$	n.a.
C35	2.21	2.7×10^{-5}	$\leq 9\times 10^{-9}$	n.a.	1.7×10^{3}	$\gtrsim 10^{6}$	n.a.
D13	1.50	n.a.	n.a.	1.7±30%	n.a.	n.a.	1.9

---

[a] E_d is the "retention factor" obtained by dividing the A_x/A_T ratio for Cambric (Table VII) by the A_x/A_T ratio measured for the water.

[b] Samples were filtered through 1-µm Nuclepore filters in the field.

[c] Samples were made 0.1 M in HCl in the field.

[d] n.a. = not analyzed for this nuclide.

*All entries have been multiplied by the factor in parentheses. Divide each entry by this factor to get the actual value.

very low levels of T, ^{90}Sr, and ^{137}Cs could be detected in the E- and F-series samples pumped from these zones. (See Fig. 18.)

Representative values of the activity levels observed in the water pumped from each zone ten years after the Cambric event are given in Table XII. No activity above background could be detected in water pumped from Zone I, only 50 m below the bottom of the estimated cavity. Water pumped directly from the cavity region (Zones II and III) shows a maximum concentration of T of ≈ 6 µCi/ml which is about 2×10^3 higher than the recommended[15] concentration guide (CG) applicable to water in an uncontrolled area. The levels of ^{106}Ru, ^{125}Sb, and ^{137}Cs of only 2 to 12 dpm/ml are all well below the CG's for these nuclides. The ^{90}Sr level is about 10 times the CG. The ^{239}Pu levels are all less than the CG for drinking water by more than a factor of 600.

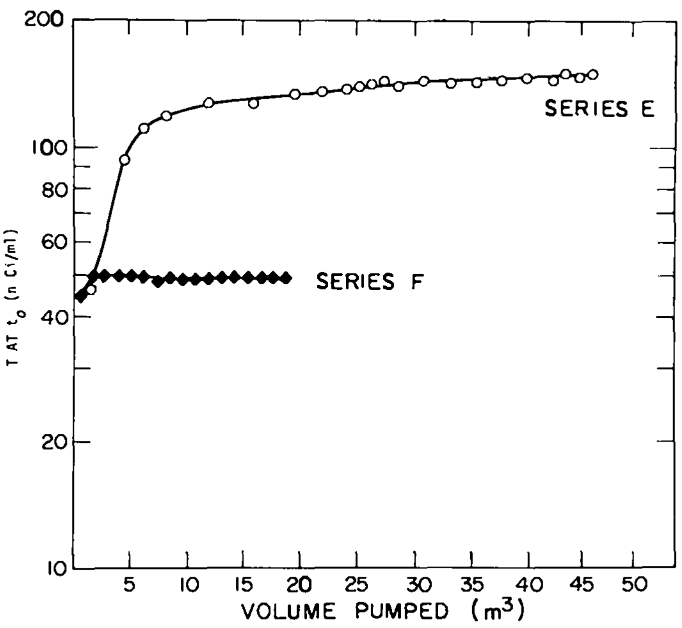


Fig. 17. T Analyses of E-(Zone IV) and F-(Zone V) series water samples.

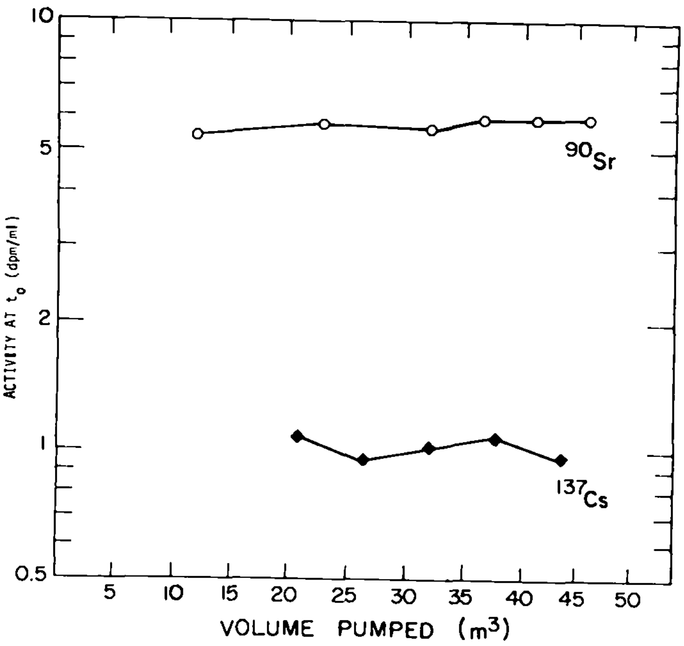


Fig. 18. ^{90}Sr and ^{137}Cs analyses of E-series water samples, Zone V.

E_d values for the various nuclides detected in each zone were also calculated and these are given in Tables XI and XIII. The highest E_d's ($\gtrsim 10^6$) were observed for ^{239}Pu and ^{147}Pm. Probably at the relatively high pH of this water these nuclides are precipitated as the hydroxides or are present as colloidal species, and only very small concentrations are in solution in the water. Incorporation of these refractory species in fused material may also reduce their dissolution or leach rates. E_d's of the order of 10^2 were calculated for ^{90}Sr, ^{106}Ru, and ^{125}Sb, and of 10^4 for ^{137}Cs and of 10^3 for ^{144}Ce. The values for ^{90}Sr and ^{137}Cs are significantly lower for the E- and F-series samples which were pumped in the chimney zones. Perhaps these activities moved out of the cavity region as the gaseous species ^{90}Kr ($T_{1/2}$ = 32.3 sec) and ^{137}Xe ($T_{1/2}$ = 3.8 min), and were then deposited on the surface of the alluvium, rather than incorporated in the glassy, fused debris in the puddle region.

The C-series samples which were pumped from the puddle region showed the highest T levels, about 11 µCi/ml corrected to zero time. Assuming the T to be uniformly distributed in the water, 15% water by weight and an average density of 2.0 g/cm^3 for the alluvium, a tritium-exchange radius of ≈16 m can be calculated, compared with the estimated cavity radius of 10.9 m. This is consistent with previous observations[12] that the T-exchange radius is somewhat larger than

TABLE XII

REPRESENTATIVE ACTIVITY LEVELS IN PUMPED WATER SAMPLES

Zone, Sample, Volume pumped	T (µCi/ml)	dpm/ml at t_0 + 10 years					
		T	^{90}Sr	^{106}Ru	^{125}Sb	^{137}Cs	^{239}Pu
Zone I							
A-8, 53 m^3	Bg[a]	Bg	Bg	Bg	Bg	Bg	Bg
Zone II							
B-13, 1.86 m^3	3.4	7.56×10^6	8.8	8.3	12.0	1.98	0.014
C-33, 11.5 m^3	6.1	1.36×10^7	7.9	10.9	4.6	1.58	0.0029 (C-24)
Zone III							
D-13, 14.0 m^3	3.8	8.52×10^6	5.3	3.8	2.3	1.35	0.0026
Zone IV							
E-30, 41.1 m^3	0.084	1.84×10^5	4.6	n.d.[b]	n.d.	0.79	n.d.
Zone V							
F-11, 11.9 m^3	0.028	6.2×10^4	0.20	n.d.	n.d.	0.16	n.d.
CG[c]	0.003	6.7×10^3	0.67	22.2	2.22×10^2	44.4	11.1

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[a] Bg = background

[b] n.d. = not detected.

[c] This is the recommended concentration guide (CG) applicable to water in uncontrolled areas.

TABLE XIII

E_d's FOR ^{90}Sr, ^{106}Ru, ^{125}Sb, AND ^{137}Cs FROM WATER SAMPLES

		Measured A_x/A_T				E_d[a]			
Sample	T at t_0 (µCi/ml)	^{90}Sr ($\times 10^7$)*	^{106}Ru ($\times 10^4$)*	^{125}Sb ($\times 10^6$)*	^{137}Cs (10^7)*	^{90}Sr ($\times 10^{-2}$)*	^{106}Ru ($\times 10^{-2}$)*	^{125}Sb ($\times 10^{-2}$)*	^{137}Cs ($\times 10^{-4}$)*
A-8	Bg	---	---	---	---	---	---	---	---
B-13	5.97	8.42	5.94	11.0	1.88	8.4	0.75	0.61	1.1
C-33	10.8	3.38	4.33	2.33	0.83	21.	1.0	2.9	2.5
D-13	6.74	4.53	2.40	1.87	1.13	16.	1.9	3.6	1.8
E-30	0.146	182	---	---	30.9	0.39	---	---	0.066
F-11	0.0491	22.9	---	---	18.3	3.1	---	---	0.11

---

[a] $E_d = (A_x/A_T)_{calc} \div (A_x/A_T)_{obsd.}$

*All entries have been multiplied by the factor in parentheses. Divide each entry by this factor to get the actual value.

the cavity radius. The total amount of T pumped from RNM-1 was $\approx 3.6 \times 10^8$ μCi ($\approx 7.4 \times 10^{21}$ atoms) or ≈0.6% of the total Cambric source term.

3. Pressurized Water Samples

A total of 17 pressurized water samples was obtained from the various zones of RNM-1 and returned to LASL for analysis of ^{85}Kr and of T in the water and in hydrogen removed from the water. (See Appendix C for the procedures used.) Usually two pressurized samples were taken after perforating and cleaning each zone, but before pumping the water samples, and two were taken after pumping to see if the ^{85}Kr and T contents before and after pumping were the same. The results of these ^{85}Kr and T analyses are shown in Table X.

Since no ^{85}Kr or T activity above background could be detected in Zone I, only one set of pressurized samples was taken there. The pressurized water samples taken before pumping Zone II had a Li content >20 ppm, indicating severe contamination from added drilling fluids. This probably accounts for the observation of very low levels of ^{85}Kr and T activity in these samples compared to those taken after pumping. The before and after values for Zones III and V are comparable. In Zone IV, samples were not taken just after reperforation and the single sample taken after initial perforation when the water inflow was very small is understandably not representative of Zone IV water. Results for the two samples taken after pumping Zone IV agree very well. They appear to be representtative of Zone IV water as the T content of 0.15 μCi/ml is the same as that of the pumped water samples from Zone IV (Table XIII). They are at least two to three times higher than those for water removed from cores taken from these zones. This may indicate dilution of water from the cores with drilling fluids.

The measured specific activity of T, corrected to t_0, in the pressurized water samples taken after pumping each zone is: Zone I, background; Zone II, 9.6 μCi/ml; Zone III, 6.7-7.0 μCi/ml; Zone IV, 0.15 μCi/ml; Zone V, 0.04 μCi/ml. The values are very similar to those for the water samples pumped from these zones (Table XIII, Figs. 15-17, Appendix D-VII). They are at least two to three times higher than those for water removed from cores taken from these zones. This may indicate dilution from drilling fluids. The HT/HTO ratios (Table X) show that 99.9% or more of the T is present as HTO rather than as HT or CH_3T, consistent with the results of measurements on water removed from the core samples (Table IV).

The measured-to-calculated ^{85}Kr/T ratios for the pressurized samples are given in Table X and indicate some depletion of ^{85}Kr relative to T in Zones II and III and perhaps slight enrichment in Zone IV. However, in Zone V, the ratio is nearly unchanged which indicates little or no upward movement of ^{85}Kr relative to HTO. Water removed from the core samples also showed no evidence for upward movement of ^{85}Kr. No ^{85}Kr was detected above the water table (see Section V, C-1), but it should be remembered that the core samples taken above the water table also came from outside the chimney. The following concentrations of ^{85}Kr, measured in the pressurized water samples, are believed to be representative of the various zones: Zone I, background; Zone II, 6.5×10^9 atoms/ml; Zone III, 9.8×10^9 atoms/ml; Zone IV, 5.7×10^8 atoms/ml; Zone V, 1.0×10^8 atoms/ml. The ^{85}Kr concentrations for Zones III, IV, and V are two to four times higher than those measured for water removed from cores taken in these zones. This might be a consequence of dilution of the water in the cores by drilling fluids or by loss of ^{85}Kr before the cores were placed in gas-tight containers. However, the ^{85}Kr concentration in the pressurized samples from Zone II perforated from 300.4 to 303.9 m, the region of the bottom of the cavity, is about a factor of two lower than in water from cores 50 and 54 obtained at 298 m. There is no obvious explanation although it might be postulated that because water production was so low and pumping extended over a period of several months, ^{85}Kr was lost from the water before the pressurized water samples were taken. (No pressurized samples were obtained just after reperforation of Zone II and before pumping.) The ^{85}Kr/T ratios for these Zone II pressurized samples were very low (Table X), also indicating loss of ^{85}Kr.

VI. RESULTS AND DISCUSSION

Re-entry drillback into the region of the Cambric nuclear test which was detonated 73 m below the water table in alluvium in May 1965, was accomplished in May 1974. Sidewall cores were retrieved at selected intervals from 34 m below ground level to 38 m below the detonation point at 294 m. Analysis of these cores and the contained water and gases provided the following information.

1. Most of the radioactivity is still confined in the region of the original cavity after 10 years. The highest specific activities of all radionuclides were found in the lower cavity region.

2. Analyses of various fractions separated from core samples removed from the lower cavity region indicate that only 23% of the ^{90}Sr and 7% of the ^{137}Cs, relative to ^{239}Pu, remained in fused material. However, these nuclides were greatly enriched, relative to ^{239}Pu, in the rubble from these cores and in all of the material from the chimney cores. The ^{90}Sr and ^{137}Cs appear to have condensed and been contained on nearby rubble in the cavity and lower chimney regions, and the highest specific activities are observed in the lower cavity region.

3. Measurements of HT and HTO from the cores and pressurized water samples show that more than 99.9% of the T is present as HTO.

4. Although some T and ^{85}Kr were found in the chimney, they were concentrated in the cavity region, and neither was found above the water table. The measured ^{85}Kr/T ratios are consistent with the calculated ratio for Cambric, and there is no indication that the ^{85}Kr has moved above the water table.

5. "Effective distribution coefficients" of $\approx 10^4$, $\geq 10^4$, and $\approx 10^8$ for ^{90}Sr, ^{137}Cs, and ^{239}Pu, respectively, were estimated by comparing the specific activities of the solid material and water from a puddle core.

Representative water was pumped from five different zones, ranging from below the cavity to above the chimney, by utilizing the technique of casing the drillback hole to the desired depth, pumping from the open hole to obtain background water, then placing an internal packer at the position corresponding to an external packer which had been positioned during the casing operation at the appropriate level for isolation of the next zone. Perforations were made at appropriate intervals, and the desired amount of water was pumped. Upon completion of pumping, the next packer was positioned, and the procedure was repeated until all zones had been sampled. Judging from the widely varying radionuclide content of the water pumped from the different zones, the isolation and clean-out procedures were quite successful, and relatively little cross-contamination between zones occurred. In this way, it was possible to obtain information concerning the vertical distribution of radioactivity in the ground water. Pressurized water samples were also obtained from each zone so as to retain any HT or ^{85}Kr present in the water.

Some of the most important results from measurements of the pumped and pressurized water samples are:

1. Detection of ^{85}Kr in pressurized water samples shows that the ^{85}Kr is indeed dissolved in the water. Again, as in water from the cores, the measured

^{85}Kr/T ratios are consistent with the calculated ratio for Cambric.

2. No T or other radioactivity above background was detected in $\approx$53 m^3 of water pumped from the background zone, 50 m below the cavity.

3. Water pumped from the region of the bottom of the cavity (the region of highest radioactivity) showed only T and ^{90}Sr in concentrations higher than recommended for uncontrolled areas. The ^{106}Ru concentration was a factor of two lower, ^{125}Sb and ^{137}Cs concentrations were factors of 20 or more lower, the ^{144}Ce concentration was more than 100 times lower, and the ^{239}Pu concentration was more than 600 times lower than the respective concentration guides recommended for uncontrolled areas. No other radioactivities were detected in the pumped water.

4. By comparing the ratios of the various nuclides detected in the water, relative to T, with the calculated ratios for the Cambric source term, effective retention factors for each nuclide on the solid debris were estimated. These ranged from $>10^6$ for ^{239}Pu and ^{147}Pm to 10^2 to 10^4 for ^{90}Sr, ^{106}Ru, ^{125}Sb, ^{137}Cs, and ^{144}Ce. Lower retention values for ^{90}Sr and ^{137}Cs were found in the chimney than in the puddle region, presumably because the activity in the chimney rubble is adsorbed on the surface of the alluvium rather than incorporated in fused, glassy material.

Only about 0.6% of the T from Cambric has been pumped from RNM-1, and water is now being pumped from RNM-2S, a well 91 m away, in an effort to pump HTO from the Cambric cavity and determine whether any other radioactivities accompany it. Based on the large depletion factors for the other activities observed in the water pumped from RNM-1, it seems unlikely that other activities will be detected.

VII. RECOMMENDATIONS

1. Upon detection of T at RNM-2S, analyses for other radionuclides should be performed. When sampling has been completed at RNM-2S, or if T is not detected after a reasonable length of time, water should again be pumped from RNM-1 to ascertain whether the source term has been depleted.

2. RNM Experiment No. 2 should be initiated. A suitable site for a 1—10-kt test should be chosen and several preshot satellite holes drilled in order to obtain complete preshot chemical, geologic, and hydrologic data. Postshot drillback and core sampling should be conducted as for RNM-1. As infill proceeds, water should be pumped from various zones isolated as in RNM-1. Anal-

sis of samples taken from the satellite holes will be performed to monitor the movement of T and other radionuclides. Re-entry drillback and sampling should be accomplished as soon as practical so that the behavior of shorter lived species such as 66-hour ^{99}Mo-^{99}Tc, 65-day ^{95}Zr, 40-day ^{103}Ru, 8-day ^{131}I, 11-day ^{147}Nd, and 7-day ^{237}U can be studied. Although these nuclides themselves have such short half lives that they are not likely to be moved off-site, they would constitute sensitive monitors of the behavior of longer lived activities of the same element which may be of interest on a very long time scale; for example, 1.6 x 10^7-year ^{129}I, 2 x 10^5-year ^{99}Tc, and ^{235,238}U.

3. Studies similar to those conducted at the site of the Cambric event, tested in alluvium, should be carried out for nuclear devices tested in other media such as tuff and rhyolite, to determine whether the same conclusions apply. The effect of nuclear yield should also be investigated.

4. Additional studies, probably in the laboratory, should be undertaken to determine whether the very high retention factors estimated for some nuclides, such as ^{239}Pu and ^{147}Pm, are a consequence of the nuclides being incorporated in fused debris or are related to the actual interactions occurring between the water and the geologic medium. The effect of pH, water composition, temperature, mineralogical composition, and particle-size distribution should be systematically studied.

5. Computer modeling studies of chemical reactions and nuclide transport using the best available data for distribution coefficients and ground-water flow velocities should be undertaken in order to predict the migration of various radionuclides as a function of time. A study to determine which parameters are most important should also be performed.

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APPENDIX A

CHRONOLOGICAL HISTORY - RNM-1

(WELL COMPLETED IN CAMBRIC CHIMNEY)

Note: All depths are measured from ground-level reference along the non-vertical path followed by the borehole. Depths given in parentheses are true vertical depths measured from ground level.

Date

5/1/74 Moved in and rigged up Hycalog drilling rig. Birdwell rigged up for fluid-level measurement and depth check. Tool stopped at 237.4 m; no fluid indicated.

5/2/74 Ran drill pipe to about 176.8 m for plugback operations. Mixed and pumped stage #1 consisting of 2.8 m^3 of slurry (neat cement with 3% $CaCl_2$). After waiting on cement, tagged plugback total depth with drill pipe at 246.0 m.

With bottom of drill pipe at 176.8 m, mixed and pumped stage #2 consisting of 2.8 m^3 of slurry (neat cement with 3% $CaCl_2$). After waiting on cement, tagged cement, top at 240.2 m.

With bottom of drill pipe at 176.8 m, mixed and pumped stage #3 consisting of 2.8 m^3 of slurry (neat cement with 3% $CaCl_2$ plus 113 g Flocele per sack).

5/3/74 After waiting on cement, tagged top of stage #3 at 211.5 m. Depth of 211.5 m is close to a reported sidetrack at 209.4 m.

With bottom of drill pipe at 149.4 m, mixed and pumped stage #4 consisting of 2.8 m^3 of slurry (neat cement with 3% $CaCl_2$ plus 113 g Flocele per sack). After waiting on cement, tagged top of cement at 211.5 m. Apparently cement going down sidetracked hole at 209.4 m.

Ran Lynes packer into hole on drill pipe. Packer stopped at 176.8 m where it stuck in hole. Tried to set packer using the rig pump and mud. Pressure rose too high and packer ruptured. Backed off and retrieved packer. Mixed and pumped stage #5 consisting of 0.7 m^3 of slurry (50% neat cement; 50% gypsum). Tagged top of stage #5 at 175.0 m.

Mixed and pumped stage #6 consisting of 1.4 m^3 of slurry (50% neat cement; 50% gypsum). Tagged top of stage #6 at 171.9 m.

Mixed and pumped stage #7 consisting of 1.4 m^3 of slurry (50% neat cement; 50% gypsum). Tagged top of stage #7 at 143.0 m. Plugback complete.

5/4/74 Went in hole with Dyna-Drill, 1.5° kick sub, Hunt tool and two Monel drill collars. Recovered two sidewall samples at each of the following depths: 36.6 m (34.1 m), 54.9 m (51.0 m), one at 73.2 m (67.8 m) and one at 79.2 m, (73.4 m).

Encountered bridge at 90.5 m. Activated Dyna-Drill. Cleaned out hole using mud tagged with LiCl (142 g per m^3), down to 98.1 m where hole started circulating.

Drilled down to 145.7 m where it was decided to sidetrack the hole off the cemented plugback total depth and forego any further sampling in the old hole.

Lost returns at 182.9 m. Drilled to 231.6 m without returns. Recovered three sidewall samples from each of the following depths: 224.6 m (206.4 m) 205.7 m (188.7 m), 187.1 m (171.3 m), and 167.9 m (153.5 m).

Recovered one sidewall sample from each of the following depths: 138.7 m (126.7 m), 135.6 m (124.0 m) and 129.8 m (118.9 m). These three samples were cement contaminated.

Recovered three sidewall samples from 112.8 m (103.6 m); recovered two sidewall samples from 91.4 m (84.4 m). Cleaned out fill and drilled new hole, using mud tagged with LiCl, from 231.6 m to 250.0 m.

5/5/74 Recovered three sidewall samples from 243.8 m (224.6 m). Ran directional survey for orientation. Drilled new hole from 250.9 m to 278.9 m. Recovered three sidewall samples from 262.1 m (241.8 m).

At this point there were indications of magnetic interference in the directional survey and control techniques. Records of the original hole reflected similar directional problems at about the same depth. Went into hole with a stiff assembly.

Drilled to 285.6 m. Recovered one sidewall sample at 277.4 m (256.2 m). Cleaned out hole and deepened to 294.7 m. Recovered two additional Sidewall samples at 277.4 m (256.2 m).

Cleaned out hole and deepened to 313.9 m. Recovered three sidewall samples from 295.7 m (273.6 m).

Drilled to 362.1 m. Ran directional survey. On the basis of actual survey data, the hole is 4.9 m to the left and 1.2 m below the target. On basis of other estimates, hole is only 2.1 m to the east and 1.2 m below the target.

Drilled to 381 m. Ran Birdwell high and low sensitivity High Intensity Gamma Ray log through drill pipe.

No anomaly indicated on either trace. Birdwell ran natural γ-ray log. (See Fig. 10, Section III.) This log was satisfactory. Pumped 44.5 m^3 of viscous mud, tagged with LiCl into the bottom of the hole.

5/6/74 Recovered two sidewall samples from 356.6 m (331.6 m). Recovered three sidewall samples from 344.4 m (319.9 m). Recovered two side wall samples from 335.3 m (311.2 m). Recovered ten sidewall samples from 323.1 m to 321.3 m (299.6 m to 297.9 m). Recovered three sidewall samples from 315.2 m (292.1 m). Recovered three sidewall samples from 303.9 m (281.4 m). Recovered three sidewall samples from 295.7 m (273.6 m). Recovered three sidewall samples from 287.7 m (266.0 m)

Went to within 10.7 m of bottom and hit fill. Circulated and cleaned out to total depth. On the basis of information from the subsequent casing tally and a Birdwell collar locater, it appears that the total depth was increased from 381 m to 381.9 m in the process of this cleanout.

Pulled out of hole. Started running 6.4-m lengths of 14-cm, 7.7-kg, P110 buttress-thread casing with three Lynes external casing packers. Rigged up to circulate casing into place after running casing joint #41. Ran 59 joints of 14 cm casing. Casing and associated equipment ultimately landed in the hole as follows:

Hole total depth	381.9 m
Bottom of 14-cm casing	381.6 m
Top of upper casing float collar	367.6 m
Top of bottom Lynes packer	320.7 m
Top of middle Lynes packer	305.4 m
Top of top Lynes packer	290.2 m

Ran 6-cm Hydril tubing equipped with a "stab-in" assembly on the bottom to seat in the top of the upper casing float collar. Latched into bowl of the casing float collar. Filled the 14-cm x 6-cm annulus with about 3.6 m^3 of untagged water.

Pumped 4.0 m^3 of water (not tagged with LiCl) down the 6-cm tubing ahead of 2.1 m^3 of cement slurry (with 3% $CaCl_2$). Ran two wiper plugs down the tubing on top of the cement. Indication was that both wiper plugs went through the seal plug. There was no overflow from the 14-cm x 6-cm annulus during the cement job. Waiting on cement.

5/8/74 Ran Birdwell temperature log inside the 6-cm Hydril tubing. Log indicated tubing fluid level at 239.0 m. Ran Birdwell density log inside the 6-cm tubing. Log showed tubing fluid level at 239.6 m.

Ran Birdwell neutron-neutron log inside the 6-cm tubing in an effort to determine where the cement went. Cement determination was indefinite.

Latched onto the 6-cm tubing and pulled easily out of the seal assembly. Obviously there was no cement in the 14-cm x 6-cm annulus. Removed all 6-cm tubing.

Reran Birdwell neutron-neutron log inside the 14-cm casing. Considered in conjunction with the temperature log, the neutron-neutron log indicated a possible cement top at 323.1 m. There was some question about the presence of competent cement behind the 14-cm casing in the interval from 354.2 m to 367.3 m.

Ran Birdwell Nuclear Annulus Investigation Log inside 14-cm casing. This log was encouraging but not definite about the presence of good cement behind the 14-cm casing in the interval from 354.2 m to 367.3 m.

5/9/74 Attempted to fill 14-cm casing with LiCl-tagged water. 2.9 m^3 should have filled casing. Pumped in 5.1 m^3 of water with no sign of liquid level rise in casing. Apparently there was no cement between the upper float collar and the casing shoe or the cement was channeled. It was decided to attempt to recement around the casing shoe prior to drilling out of the casing.

It was calculated that a total of 715.4 m^3 of LiCl-tagged mud was left in the hole as a result of drilling operations.

Ran back inside the 14-cm casing with the 6-cm Hydril tubing. Stabbed into the receptacle in the casing float collar. Recemented the 14-cm casing through the 6-cm tubing with 2.1 m^3 of cement slurry (neat cement plus 3% $CaCl_2$). Used no wiper plugs but displaced cement with water. Pulled tubing out of casing. Loaded 14-cm casing to the surface with water.

Started in hole with 12-cm bit. Tagged top of cement inside 14-cm casing at 310.9 m. Rigged up to drill out cement and deepened hole below the casing using air and foam.

5/10/74 Drilled out cement inside 14-cm casing. Drilled 12-cm hole to total depth of 396.9 m. Cut foam pump off and blew hole for about 1 hour. Obtained eight 1/2-liter samples of the produced water. Pulled drill pipe out of well.

Ran Birdwell fluid density log and casing collar log. Fluid level at 239.6 m.

Ran pressurized water sampler on wireline. Obtained two water samples at 385.6 m (359.3 m) depth.

Welder tacked plate on top of the 14-cm casing.

6/18/74 Assembled Reda submersible pump and started running it into well.

6/20/74 Landed pump at 314.6 m (291.4 m) depth. Ran 15 minute pump test at maximum flow rate of 152.6 m^3/day.

7/10/74 Commenced pumping RNM-1 at rate of 130.8 to 152.6 m^3/day at 0800. Continued pumping from Zone I for about 8 hours. Water samples were taken hourly. A total of about 53 m^3 of water was pumped during this sampling period. (Series A samples.)

7/31/74	Pulled pump from RNM-1.
8/1/74	Birdwell ran natural gamma/collar locater log from 383.4 m to 243.8 m. Ran and set drillable packer at 373.4 m (347.6 m).
8/5/74	Hooked up air compressor and blew water out of casing. Loaded casing with 1.6 m^3 of LiCl-tagged water and blew casing dry. Repeated this operation twice, then loaded casing with 0.79 m^3 of LiCl-tagged water prior to perforating.
8/6/74	Birdwell perforated casing in Zone II from 324.0 m to 327.7 m (300.4 m to 303.9 m) with one shot per 30 cm. Took 2 pressurized water samples, one each from 322.5 m and 325.8 m. (299.0 m and 302.1 m) Started running pump back into well.
8/14/74	Continued running pump into well.
8/15/74	Landed pump at 314.6 m. Started pump and pumped down well in about 10 minutes. Took water samples of pumped discharge. Pumped 3.3 m^3 of untagged water down casing. This volume should have filled casing to overflowing, but didn't. Therefore the perforations are partly open.
9/5/74	Commenced pumping from perforations in Zone II at 0930. Pump minimum capacity was greater than inflow rate through perforations, hence Zone II was pumped and water samples were taken every two hours.
9/6/74	Continued pumping from Zone II every two hours. Water samples were obtained at each pumping period. Suspended operations at 0900 after pumping a total of only 1.86 m^3 of water. (B series samples.)
11/5/74	Commenced pumping from Zone II once, and after 1/14/75, twice per day. Water samples were taken at each pumping. Pumping from Zone II was terminated on 1/31/75 after removal of a total of 21.8 m^3 of water. (C-series samples.)
4/10/75	Pulled pump from RNM-1. Obtained two pressurized water samples from Zone II.
4/11/75	Depressed water level in RNM-1 with air pressure. Released air pressure and measured water-level recovery.
	Reperforated casing in Zone II from 324.0 m to 327.7 m (300.4 m to 303.9 m) with 10 charges.

Surged the well in three cycles using air pressure. Air pressure was released suddenly following the final surging cycle and water-level recovery was measured. Apparent transmissivity was about twice that prior to reperforation. It was decided to sample water from Zone II no further.

4/12/75 Set wireline drillable packer at 319.4 m (296.0 m). Blew water from casing.

4/25/75 Birdwell tagged water at 318.8 m. Packer appears to have a good seal. Added 1.28 m^3 of LiCl-tagged water to casing. In the process of attempting to blow wash water from casing, the tubing string was dropped and damaged. Packer was not moved, but further casing washing attempts were suspended.

Birdwell ran casing collar locater and perforated Zone III in the interval from 315.4 m to 318.5 m (292.2 m to 295.2 m) with 10 charges. No change in water level after 25 minutes from time of perforating. Perforated Zone III in the interval from 309.3 m to 312.4 m (286.4 m to 289.4 m) with 10 charges. Water level rose 1 m in 50 minutes.

4/26/75 Surged the well in three cycles using air pressure. Air pressure was released suddenly following the final surging cycle and water-level recovery was measured. Analysis of the relatively rapid recovery revealed an apparent transmissivity about three times greater than the largest value measured in Zone II.

Reperforated Zone III in the intervals 309.3 m to 312.4 m (286.4 m to 289.4 m) and 315.4 m to 318.5 m (292.2 m to 295.2 m) with 22 charges. Ran casing collar locator log to confirm perforations. Surged well with air pressure. Released pressure and measured water-level recovery. Reperforation and surging had little effect on apparent transmissivity.

Took one bailer sample of water. Took pressurized water samples. Ran pump and landed it at 307.2 m (284.5 m).

Tested pump and metered 0.17 m^3 of flow at surface.

4/29/75 Pumped intermittently from perforations in Zone III. Water samples representative of a total of 18.9 m^3 were obtained. (D-series samples).

7/29/75 Pulled pump. Obtained two pressurized water samples from 313.9 m (290.8 m). Ran casing collar locator log. Set wireline drillable packer at 304.8 m (282.7 m).

7/30/75 Pressurized casing to test packer. Water loss around packer was the equivalent of 0.09 m^3 per hour.

7/31/75 Rinsed inside of casing twice with LiCl-tagged water. Perforated casing in Zone IV in the intervals 300.5 m to 303.5 m (278.1 m to 280.9 m) and 295.0 m to 298.0 m (272.9 m to 275.7 m) with 44 charges. Obtained one pressurized water sample at 300.5 m. Surged well with air pressure. Very slow water level recovery was measured following pressurization with air.

8/1/75 Reperforated casing in Zone IV in the interval from 300.5 m to 303.5 m (278.1 m to 280.9 m) with 10 charges. A bridge of some kind developed in the well. Reperforation of the interval 295.0 m to 298.0 m was not possible.

8/4/75 Surged well with air pressure to clear perforations. No appreciable water level recovery after surging.

8/5/75 Decided to circulate LiCl-tagged water in casing in order to clear obstructions. Lowered tubing to 291.7 m and circulated down to 293.8 m. Lost circulation at 293.8 m and pumped in about 22.7 m^3 in lowering tubing from 293.8 m to 303.6 m.

8/6/75 Fluid level tagged at 239.6 m. Top of fill at 302.4 m. Ran caliper and casing collar locator logs to ascertain condition of casing. Casing seemed in good condition to 301.8 m.

8/7/75 Lowered pump into well. Pump inlet at 282.9 m (261.4 m). Pumped a total of 45.7 m^3 of water from Zone IV and obtained samples thereof. E-series samples.)

8/8/75 Obtained two pressurized water samples from 299.0 m (276.7 m). Set wireline drillable packer at 289.3 m (267.5 m).

8/11/75 Tested packer with air pressure. Packer found to be sealing well. Rinsed casing twice with LiCl-tagged water.

8/12/75	Perforated casing in Zone V in the intervals 285.9 m to 288.6 m (264.3 m to 266.8 m) and 280.1 m to 282.6 m (258.8 m to 261.1 m) with a total of 38 charges. Surged well with air pressure. Obtained 2 pressurized water samples from 281.3 m.
8/13/75	Lowered pump into well with inlet at 270.7 m. Started pumping water and sampling from Zone V.
8/14/75	Completed pumping and sampling. Removed a total of 18.6 m^3 of water from Zone V. (F-series samples.)
8/15/75	Pulled pump. Obtained two pressurized water samples. Packer at 289.3 m was drilled out and casing cleaned out to 304.8 m.

APPENDIX B

SELECTED CHEMICAL ANALYSES OF WATER SAMPLES FROM RNM-1

(Analyses by USGS)

Volume pumped (m^3)	pH	Cond.[a]	Cations milligrams/liter						Anions milligrams/liter				Milliequivalents per liter	
			Li	Na	K	Mg	Ca	Sr	F	Cl	HCO_3	SO_4	Cations	Anions
						Zone I								
0	8.1	483	0.06	69	8	4	14	0.3	0.6	58	134	36	4.25	4.66
13	8.1	453	0.02	59	7	5	19	0.3	0.6	26	178	29	4.08	4.45
27	8.0	428	0.03	61	7	4	18	0.3	0.6	19	176	33	4.08	4.31
40	8.1	418	0.03	63	8	5	17	0.3	0.6	18	167	32	4.17	4.10
53	8.1	414	0.02	63	8	4	16	0.3	0.6	16	177	32	4.11	4.20
						Zone II								
0.5	9.4	922	--	--	--	--	--	--	--	--	--	--	--	--
1.0	11.2	2,340	--	230	38	1	160	16.	0.9	440	(1)[b]	110	19.88	20.67
1.1	11.5	1,970	--	210	36	0	150	15.	0.9	390	(2)[b]	120	17.56	17.60
1.3	11.4	1,980	--	200	35	0	150	13.	1.0	350	(3)[b]	140	17.10	17.94
1.5	11.0	2,040	--	180	31	--	160	12.	1.0	310	(4)[b]	150	16.65	17.15
7.5	8.9	1,060	--	140	21	6	64	3.5	1.7	150	(5)[b]	160	10.50	10.63
20.9	8.4	960	0.37	126	18	6	50	3.5	2.0	100	(6)[b]	200	8.99	9.16
21.2	8.3	974	0.38	124	19	6	52	4.0	1.9	100	137	200	9.01	9.33
						Zone III								
4.6	7.2	1.080	0.42	128	20	25	72	1.3	0.4	52	463	170	11.76	12.62
8.3	7.2	1,130	0.32	129	21	24	60	1.1	0.4	46	480	130	11.14	11.89
12.0	7.2	1.170	0.28	129	20	24	75	1.2	0.4	43	482	110	11.87	11.42
15.7	7.2	1.100	0.25	125	21	24	72	1.1	0.4	42	476	190	11.32	12.96
18.8	7.2	1,090	0.22	129	19	24	72	1.1	0.4	41	471	110	12.10	11.19
						Zone IV								
0	--	--	11	--	--	--	--	--	--	--	--	--	--	--
12.1	7.0	1.140	3.6	100	19	39	90	0.9	0.3	42	549	120	13.07	12.70
17.1	7.0	1.130	2.8	98	19	40	92	0.9	0.2	29	566	110	13.05	12.40
21.9	7.0	1.100	2.3	97	19	40	92	0.9	0.2	28	545	110	12.94	12.02
27.8	7.0	1.100	2.0	96	19	40	94	0.9	0.2	37	581	120	12.95	13.08
31.2	7.1	1,100	1.9	97	19	40	93	0.9	0.3	31	532	110	12.93	11.90
36.1	7.1	1.100	1.6	94	19	39	93	0.8	0.2	33	582	110	12.67	12.77
41.5	7.0	1.080	1.5	93	19	40	92	0.8	0.2	28	512	110	12.65	11.48
						Zone V								
0	--	--	10	--	--	--	--	--	--	--	--	--	--	--
2.0	7.4	770	0.73	88	12	19	49	0.7	0.3	23	364	86	8.26	8.42
3.8	7.5	730	0.48	76	12	21	50	0.7	0.3	22	359	75	7.92	8.08
7.6	7.3	680	0.44	70	11	20	49	0.6	0.3	20	351	69	7.49	7.77
11.4	7.4	660	0.42	66	12	21	49	0.7	0.3	18	354	66	7.43	7.70
15.2	7.4	689	0.40	65	12	22	50	0.6	0.3	17	352	66	7.51	7.64
18.5	7.4	678	0.39	64	12	20	50	0.6	0.3	16	345	63	7.30	7.43

[a] Specific conductance in µmho/cm.

[b] Concentrations of HCO_3, CO_3, OH, respectively, for Zone II samples are: (1) 0, 52, 71; (2) 0, 47, 42; (3) 0, 59, 53; (4) 0, 54, 58; (5) 167, 7, 0; (6) 124, 1, 0

APPENDIX C
PROCEDURES

I. LASL PROCEDURE FOR REMOVAL OF KR, HT, AND HTO FROM SIDEWALL CORES AND PRESSURIZED WATER SAMPLES

J. W. Barnes, M. A. Ott, D. B. Dunagan, T. P. DeBusk

Gas and water from the sidewall cores which were placed in gas-tight stainless steel containers immediately after retrieval from the drillback hole and the gas and water from the pressurized water samples were processed on the same purification line after the initial removal steps. The core container was attached directly to the evacuated purification line. Measured volumes (1.5 cm^3 at STP) of Xe and Kr carriers were added and allowed to equilibrate with the core for a few minutes. In order to remove the gas and water, the container and core were then heated at 250 to 300°C for several hours, or until the pressure was less than 0.030 torr. The remainder of the procedure is common to both types of samples and is described below.

The pressurized water bottles have a volume of about 2.7 ℓ and a maximum pressure of about 1.4×10^6 Pa. The water was transferred from them by gravity to a 15-ℓ sphere that had been previously evacuated, and Xe and Kr carriers were bubbled through the water. Gas from the original sample bottle and the 15-ℓ sphere was cryopumped with liquid He into a gas volumetric system for accurate pressure, volume, and temperature measurements. Water vapor accompanying the gas was condensed in a trap at -78°C before it reached the volumetric system. The 15-ℓ sphere, cold trap, and gas volumetric were then attached to the gas purification line.

From this point on, the procedures for the gas and water from the cores or the pressurized water samples were the same and are described below:

1. The sample was passed through a trap at -78°C to remove the bulk of the HTO, and then through a molecular sieve (5A) at 0°C to adsorb the last traces of HTO.

2. The gas was passed through CuO (wire form) at 450°C to convert HT to HTO which was collected as a mist at -78°C in a small trap. The mist was removed for scintillation counting of the T by rinsing with 5 ml of inactive water.

3. The N_2, O_2, CO, CO_2, and any other reactive gases present were removed on a Ti (3-mm-diam. metal sponge) getter at 900 to 1000°C.

4. The noble gases were finally collected and held on a molecular sieve trap at liquid nitrogen temperature. (This trap also served as the cryopump for the purification system.)

5. The molecular sieve trap was heated to 450°C to remove the noble gases which were then cryopumped with liquid He into a transfer tube.

The combined noble gases from this initial separation were taken to another line and adsorbed on a charcoal bed at liquid nitrogen temperature. Separation of the noble gases from each other was performed by a stepwise increase in the temperature of the charcoal bed while He was passed through at a controlled rate. This constituted a simple gas chromatography system which used a differential thermal capacity head as the detector. Argon was removed at -78°C, Kr at -40°C, and Xe at 25°C. (Radon remains on the molecular sieve under these conditions.) Helium was removed from the separated Kr by pumping while the sample was frozen. The separated Kr and Xe were finally purified by another passage through 900 to 1000°C Ti getter. The chemical yields were determined by measuring the pressures and temperatures in a known volume. The Kr was cryopumped with liquid He into a 4-cm^3 stainless steel counter tube having a 0.025-mm Ti window for β-counting of ^{85}Kr.

Extraction of the mixed noble gases takes about 3 hours for a core sample and about four hours for a pressurized water bottle. Separation of Kr from Xe and transfer to a counter tube takes about two hours more.

II. GAMMA-SPECTRAL ANALYSES OF SIDEWALL-CORE AND WATER SAMPLES

A. LLL M. S. Coops, W. N. Hayes, Jr., H. B. Levy, J. S. Schweiger

For both solid and liquid samples, aliquots were taken of sizes that would be suited to standardized containers for which the counting geometry was known. Samples were counted with Ge-Li detectors and the data collected on 4096-channel analyzers. The resultant data were analyzed using the LLL GAMANAL computer code, which utilized all significant γ-rays of a radionuclide to determine its activity level.

A longitudinal slice was taken from each core to be analyzed. The slice was dried in an oven and then ground in a ball mill. From the ground-up material still containing some small chunks, a "representative" sample (with chunks) was taken for γ-ray analysis.

For the C-series water samples, the bottles were shaken and 25-ml aliquots were taken and put into standard containers for γ-counting.

The D-series water samples had significant amounts of sediment in them, and 3.8-ℓ samples were filtered through a 1-μm Nuclepore filter. The filter containing the sediment was dried and weighed, then subjected to γ-ray analysis. A 25-ml aliquot was taken from the filtrate and also subjected to γ-ray analysis. Because many of these counting rates were so close to background, it was felt that results on these samples were not adequate to characterize the source term properly. However, the results were sufficient to obtain a measure of the trend of the distribution of all activities between the solid and liquid phases. In the early samples, almost all of the ^{106}Ru was in the filtrate while most of the ^{125}Sb and ^{137}Cs were on the residue. By the end of the series essentially all of the ^{106}Ru and ^{125}Sb activities were in the water, while a small but measurable amount of the ^{137}Cs activity still remained on the solid residue. The amount of residue ranged from a high of 2 grams in one of the early samples to less than 0.1 gram in the later ones.

In both the "E" and "F" series water samples, a 200-ml aliquot was taken after thoroughly shaking the entire sample. Ten ml of concentrated HCl was added and the aliquot was evaporated down to a small volume. The aliquot was transferred to a standard counting vial and brought up to 20 ml with 3 N HCl. The aliquot was then submitted for γ-analysis.

B. LASL   A. E. Norris, G. C. Giesler, J. W. Barnes, D. B. Dunagan

After removal of gases and water from the sidewall cores, they were ground in a special ball mill, weighed, and representative 7-gram samples were removed for γ-spectral analysis in a calibrated Ge(Li) spectrometer system.

The pumped water samples were stored in plastic containers which were shaken just before removal of 500-ml aliquots for γ-spectral analysis. Some of the B-series water samples had been acidified and filtered in the field. Many samples had considerable sediment and in order to determine whether an appreciable fraction of the total activity was associated with the sediment, portions of each of the samples from the B series were filtered through Nuclepore 1-μm filters. Five ml of conc. HCl was added to each aliquot which was then evaporated at low heat to a small volume in a 600-ml beaker covered with a Speedyvap. The small volume was then transferred with washing to a 60-mm-diam. Petri dish and evaporated to dryness. The complete procedure took about 48 hours. Blanks and

γ-ray standards were prepared in the same way. The samples were measured with a Ge(Li) spectrometer, and the data were analyzed using the BRUTAL computer code. The results are tabulated in Appendix D-I and show that there is little effect on the activities measured, whether or not the water was filtered or acidified. The measured ^{125}Sb activities varied considerably from sample to sample and the amount in the water seemed to decrease with increasing time elapsed since the sample was pumped, as though the ^{125}Sb were plating out in some way.

III. DECAY DATA USED IN γ-SPECTRAL ANALYSES AT LLL AND LASL

Nuclide	$T_{1/2}$ (days)	E_γ (keV)	γ-Ray Abundance (γ per disintegration)
^{106}Ru	369	662	0.098
^{125}Sb	1012	428	0.304
^{137}Cs	10,960	662	0.850

APPENDIX C

IV. RADIOCHEMICAL PROCEDURE FOR ^{90}Sr (LASL)

R. J. Prestwood

Since the radioactivity in the water samples to be analyzed had been produced some 10 years earlier, the only radioactive yttrium isotope present was 64-h ^{90}Y in equilibrium with 29-year ^{90}Sr, and a simple procedure based on isolation and β-counting of ^{90}Y was used. Due to hydrolysis and absorption of yttrium on container walls in neutral or basic solution, care was taken to acidify the water samples and then allow enough time for re-establishment of equilibrium between ^{90}Sr and ^{90}Y. An outline of the procedure follows.

To a 500-ml aliquot of pumped water, add 5 ml of $HClO_4$ and Y carrier. Allow the solution to evaporate in a hood at room temperature until only the $HClO_4$ remains. Dilute the solution with water and precipitate $Y(OH)_3$ with NaOH. (See Ref. 13 for the standard precipitation methods mentioned here.) Dissolve the precipitate in HCl and filter to remove insoluble material. Reprecipitate with NaOH, dissolve and reprecipitate twice with NH_4OH. (These steps serve to eliminate Al and Ca.) Precipitate YF_3 and metathesize with NaOH. Dissolve in a minimum amount of HCl; precipitate the oxalate (to remove Fe), ignite to the oxide, mount, and β-count. Follow the decay long enough to detect the presence of any long-lived rare earth activities. A least-squares analysis of the data is then performed to determine the amount of 64-hour ^{90}Y in the sample.

APPENDIX D

RESULTS OF γ-SPECTRAL AND RADIOCHEMICAL ANALYSES

I. ACTIVITY RATIOS FOR FILTERED, UNFILTERED, AND ACIDIFIED B-SERIES SAMPLES (LASL)

A. E. Norris

B-Series Sample Number	0.1 N HCl[a]	Ratios: Unfiltered/Filtered ^{106}Ru	^{125}Sb	^{137}Cs
1	X	---	1.36	1.36
2	X	0.58	0.28	0.69
3		1.20	0.18	0.76
4	X	---	---	1.00
5	X	1.17	3.73	1.28
6		1.11	0.53	1.14
7	X	1.00	0.66	1.01
8		1.15	1.84	1.01
9	X	1.20	0.19	1.06
10		1.24	0.34	1.09
11	X	0.98	1.08	0.92
12		1.13	0.65	1.00
13	X	1.10	0.95	1.03
		Average Ratios		
	Acidic	1.00	1.18	1.04
	Non-Acidic	1.17	0.71	1.00
	Overall	1.08	0.98	1.03

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[a] X denotes that the sample was made 0.1 N in HCl.

APPENDIX D

II. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF B-SERIES WATER SAMPLES (LASL)

A. E. Norris, R. J. Prestwood, B. P. Bayhurst

B-Series Sample Number	Total Volume Pumped (m^3)	U = Unfiltered F = Filtered	dpm/ml at t_o[a]			
			^{106}Ru	^{125}Sb	^{137}Cs	^{90}Sr
1[b]	0.503	U	---	5.03	0.76	n.a.[c]
		F	---	3.69	0.56	
2[b]	0.620	U	370	1.35	0.61	
		F	635	4.77	0.88	
3[b]	0.767	U	242	1.10	0.22	
		F	202	6.10	0.29	
4[b]	0.880	U	---	1.69	0.19	
		F	---	----	0.19	
5[b]	0.975	U	658	4.62	0.59	
		F	563	1.24	0.46	
6	1.143	U	4480	19.4	1.37	
		F	4020	36.7	1.20	
7[b]	1.219	U	7360	8.76	2.45	
		F	7330	13.2	2.42	
8	1.319	U	8110	69.8	2.44	
		F	7050	38.0	2.42	
9[b]	1.437	U	7510	16.2	2.69	
		F	6260	85.5	2.54	
10	1.539	U	9420	47.6	2.85	
		F	7580	138.	2.61	
11[b]	1.649	U	7370	45.0	2.54	
		F	7530	41.7	2.76	
12	1.751	U	8760	78.1	2.39	↓
		F	7720	120.	2.40	
13[b]	1.868	U	7890	146.	2.53	11.2
		F	7200	154.	2.46	n.a.

---

[a] Disintegrations per minute per ml (dpm/ml) corrected to detonation time of Cambric.

[b] Sufficient HCl was added to these samples at the time of pumping to make them 0.1 N.

[c] n.a. = not analyzed.

APPENDIX D

III. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF C-SERIES WATER SAMPLES

A. LASL RESULTS

A. E. Norris, R. J. Prestwood

C-Series Sample Number	Total Volume Pumped (m^3)	dpm/ml at t_o			
		^{90}Sr	^{106}Ru	^{125}Sb	^{137}Cs
2	2.905	9.90	8070	67	1.04
7	4.513	9.18	6980	282	2.10
13	5.689	--	6620	238	2.09
19	6.969	9.88	7370	241	2.28
21	7.565	9.99	8860	136	2.25
24	8.233	10.21	10130	91	2.33
27	9.335	9.47	9190	103	2.25
30	10.221	7.41	7480	48	1.93
33	11.452	8.13	10370	56	2.02
35	11.949	7.56	8700	56	2.15
37	12.765	8.16	8260	26	1.83
43	14.997	5.72	6430	164	1.95
46	16.072	5.95	4780	68	1.64
50	17.116	6.39	5750	129	1.88
53	18.130	7.20	6120	126	1.77
57	19.449	--	4880	76	1.81
60	20.858	--	6330	117	2.04
61	21.361	--	6800	113	2.03
62	21.427	--	6640	113	2.07
64	21.555	--	6970	91	1.87
65	21.715	--	6930	94	1.84
66	21.811	7.24	6990	98	2.17

APPENDIX D

III. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF C-SERIES WATER SAMPLES

B. LLL RESULTS

H. B. Levy

C-Series Sample Number	Total Volume Pumped (m^3)	dpm/ml at t_o ^{106}Ru	^{125}Sb	^{137}Cs
15	6.123	4900	237	2.07
17	6.659	4610	199	0.96
22	7.968	9430	171	2.00
28	9.842	5640	65	2.24
34	11.796	10490	71	2.09
38	13.317	7160	40	0.73
44	15.525	3330	87	1.52
47	16.422	4110	55	1.78
51	17.564	7060	96	1.59
54	18.613	6200	72	1.45
58	19.875	4470	62	1.66
61	21.361	4090	91	2.04
66	21.811	5310	91	0.92

APPENDIX D

IV. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF D SERIES WATER SAMPLES

A. LASL RESULTS

A. E. Norris, R. J. Prestwood

D-Series Sample Number	Total Volume Pumped (m3)	dpm/ml at t_o			
		^{90}Sr	^{106}Ru	^{125}Sb	^{137}Cs
1	0.587	10.60	4770	41	2.74
2	1.136		5130	42	6.75
3	1.635	6.98	5620	19	15.53
(2 wks. later)			(5890)	(22)	(13.55)
4	2.434		5020	20	12.47
5	4.054	6.87	4240	23	3.81
6	5.311		3890	24	2.35
7	6.556	6.78	3740	25	2.56
8	7.798		3670	27	2.07
9	9.036	6.92	3300	28	1.77
10	10.274		3560	29	1.75
11	11.508	7.01	3680	27	1.77
12	12.742		3730	30	1.83
13	13.980	6.79	3560	28	1.72
14	15.210		3470	23	1.64
15	16.444		3950	31	1.73
16	17.674	6.87	3700	28	1.64
17	18.908		3430	27	1.67
3 filter			280[a]	11[a]	10.8[a]
3 filtrate			5620	16	1.7
3 Total Activity			5900	27	12.5

---

[a] Activity on filter was corrected to equivalent dpm/ml to permit comparison with the filtrate.

APPENDIX D

IV. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF D-SERIES WATER SAMPLES

B. LLL RESULTS

H. B. Levy

All of the odd-numbered D-series samples plus numbers four and ten were treated in the following way: The entire water sample was passed through a 1-μm Nuclepore filter. The filter containing the sediment was dried and weighed, then subjected to γ-ray analysis. In many cases, particularly for ^{106}Ru and ^{137}Cs, the activity levels were either below the level of detectability or just barely above. It was felt that the results from these samples were not good enough to properly characterize the source term at this level. However, the γ-spectroscopy results did provide a measure of the trend of the distribution of the different activities between the solid and the liquid phases. The approximate percentage of the ^{106}Ru, ^{125}Sb, and ^{137}Cs that remained in the filtrate is shown below along with the weight of solid material. In the early samples almost all of the ^{106}Ru was in the filtrate, while most of the ^{125}Sb and ^{137}Cs were in the residue. By the end of the D series, essentially all of the ^{106}Ru and ^{125}Sb activities were in the water, while a small but significant amount of the ^{137}Cs activity still remained in the solid residue.

TABLE B-I

DISTRIBUTION OF ACTIVITY BETWEEN LIQUID AND SOLID PHASES

D-Series Sample Number	Weight of Precipitate (grams)	Activity in Filtrate (%)		
		^{106}Ru	^{125}Sb	^{137}Cs
1	0.920	98	45	23
3	1.114	--	28	2
4	2.014	96	81	7
5	1.174	--	86	17
7	0.277	99	93	42
9	0.106	99	94	60
10	0.111	--	94	70
11	0.091	--	94	60
13	0.105	--	--	--
15	0.065	99	96	85
17	0.073	99	96	77

APPENDIX D

IV. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF D-SERIES WATER SAMPLES

TABLE B-II

LLL RESULTS FOR LATER SAMPLES

H. B. Levy

D-Series Sample Number	dpm/ml at t_0		
	^{106}Ru	^{125}Sb	^{137}Cs
12 (Sup)[a]	2080	20.7	0.84
12 (Mix)[a]	------ Sample lost -------		
14 (Sup)	2240	22.2	0.94
14 (Mix)	2130	20.6	0.93
16 (Sup)	2090	21.5	0.98
16 (Mix)	2200	22.8	1.03

---

[a] "Sup" refers to a sample from the supernatant; "Mix" refers to a sample taken after thorough mixing.

APPENDIX D

V. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF E-AND F-SERIES WATER SAMPLES

A. LASL RESULTS

G. C. Giesler, R. J. Prestwood

Sample Number	Total Volume Pumped (m^3)	dpm/ml at t_o	
		^{90}Sr	^{137}Cs
E 1	0.114	0.62	n.a.[a]
E 2	1.514	n.a.	2.99
E 7	11.924	5.40	n.a.
E 12	20.630	n.a.	1.08
E 13	21.766	5.71	n.a.
E 17	26.309	n.a.	0.95
E 18	27.444	5.76	n.a.
E 22	31.986	5.59	1.02
E 26	36.529	5.89	n.a.
E 27	37.665	n.a.	1.07
E 30	41.072	5.93	n.a.
E 32	43.343	n.a.	0.97
E 34	45.614	5.99	n.a.
F 1	0.712	0.21	n.a.
F 3	4.743	n.a.	0.37
F 6	6.299	0.21	n.a.
F 8	8.529	n.a.	0.22
F 11	11.928	0.25	n.a.
F 13	14.271	n.a.	0.15
F 16	17.655	0.25	n.a.
F 17	18.692	n.a.	0.23

---

[a] n.a. = Not analyzed

APPENDIX D

V. RESULTS OF γ-SPECTRAL AND ^{90}Sr ANALYSES OF E-AND F-SERIES WATER SAMPLES

B. LLL RESULTS

H. B. Levy

Sample Number	dpm/ml at t_o ^{137}Cs[a]
E 3	0.66
E 9	0.76
E 16	0.78
E 22	0.77
E 28	0.74
E 34	0.70
F 2	0.78
F 6	0.17
F 10	0.15
F 13	0.12
F 15	0.085
F 17	0.066

---

[a] The only nuclide detected by γ-ray spectroscopy was ^{137}Cs.

APPENDIX D

VI. RESULTS OF γ-SPECTRAL ANALYSIS OF SIDEWALL CORE SAMPLES

G. C. Giesler (LASL), H. B. Levy (LLL)

The results of γ-spectral analyses at LLL and LASL of sidewall core samples treated as described in Appendix C-II are given below. The ^{137}Cs results are given in Table III, Section V of the text. Cores analyzed at LLL are denoted by the superscript b. The different specific activities observed at LLL and LASL for core material from the same depth probably result from the inhomogeneity of the cores and to a lesser degree from contamination with drilling fluids. However, the same trends are observed, and except for ^{137}Cs, no significant γ-activity over background was detected above 292 m.

Core Number	Vertical Depth (m)	dpm/g at t_0									
		^{60}Co	^{106}Ru	^{125}Sb	^{134}Cs	^{144}Ce	^{152}Eu	^{154}Eu	^{155}Eu	^{239}Pu	^{241}Am
57	292.1	90	---	300	--	---	--	70	120	n.a.[a]	n.a.
58[b]	292.1	200	1.9×10^4	780	7	---	--	6	220	--	270
52[b]	297.9	10900	7.3×10^5	28100	3500	1.3×10^6	650	460	11700	43400	13100
54	297.9	24500	9.0×10^5	58500	5880	2.4×10^6	550	740	27400	n.a.	n.a.
55[b]	297.9	9450	5.4×10^5	21200	3150	1.0×10^6	565	375	9100	49900	11200
49[b]	298.2	13400	1.3×10^6	50300	5750	2.1×10^6	765	580	18300	85500	19200
50	298.2	26200	1.0×10^6	73200	7930	3.6×10^6	820	1008	36200	n.a.	n.a.
45	311.2	---	---	---	--	---	40	--	110	n.a.	n.a.
42	319.9	---	---	---	--	---	--	--	---	n.a.	n.a.
43[b]	319.9	4	---	17	--	---	--	6	---	--	7
40	331.5	---	---	---	--	---	--	--	---	n.a.	n.a.

---

[a] n.a. = not analyzed for that nuclide.

[b] Cores analyzed at LLL; all others at LASL.

VII. T ANALYSES OF PUMPED WATER SAMPLES

A. COMPARISON OF LASL AND LLL RESULTS OF T AND Li ANALYSES OF FILTERED AND UNFILTERED B-SERIES WATER SAMPLES

W. R. Daniels, B. R. Erdal, P. Q. Oliver (LASL),
J. E. Fontanilla, N. W. Howard, J. Rego (LLL)

The average of the ratios of LASL to LLL results for T is 0.998 if samples 3 and 4 are omitted, thus indicating no bias for T analyses between the laboratories. The LASL values for the unfiltered samples are about 3.5% higher than the LLL results, possibly due to the method of analysis. LASL distilled the samples prior to scintillation counting while LLL did not, and the unfiltered samples may have been cloudy enough to slightly reduce the counting efficiency. The LASL results on the average show <2% difference between samples filtered in the field and those which were not, provided samples 1, 2,and 3 are not included. Sample 2 is known to have been contaminated with 7 just prior to filtration, and LASL sample 3 may have been incorrectly designated, since the LLL results look all right. However, there is no ready explanation for the high value observed at both LASL and LLL for unfiltered sample 1.

The agreement between LLL and LASL for Li appears to be satisfactory, and the results for unfiltered and filtered samples are not significantly different. The value of ≈ 3 ppm did indicate the need for further pumping to reduce dilution from drilling fluids.

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VII. T ANALYSES OF PUMPED WATER SAMPLES

A. COMPARISON OF LASL AND LLL T AND Li ANALYSES FOR FILTERED AND UNFILTERED B-SERIES WATER SAMPLES

		Tritium				Li(ppm)		
B-Series Sample Number	Volume Pumped (m^3)	Filtered	Unfiltered Filtered		Unfiltered	Filtered		Unfiltered
		LASL/LLL	LASL	LLL	LASL/LLL	LASL	LLL	LASL
1[a]	0.50	1.012	1.156	1.132	1.039	24.3	25.8	27.5
2[a]	0.63	0.983	0.386	0.364	1.043	8.7	9.8	7.9
3	0.77	1.553	0.601	1.050	0.904	5.2	5.3	4.3
4[a]	0.88	0.875	1.040	0.918	---	4.4	4.8	4.2
5[a]	0.97	0.974	1.026	0.974	1.026	4.3	4.7	4.2
6	1.14	0.996	---	0.964	---	4.8	6.1	5.2
7[a]	1.22	0.974	1.021	0.969	1.028	6.4	6.7	6.2
8	1.32	0.999	---	0.966	---	4.5	5.0	4.4
9[a]	1.44	0.989	1.022	0.990	1.021	4.1	4.2	3.9
10	1.54	0.994	---	0.964	---	3.3	3.9	3.4
11[a]	1.66	1.011	1.010	0.965	1.054	3.4	3.6	3.3
12	1.75	0.998	---	0.976	---	3.1	3.6	3.2
13[a]	1.87	1.042	0.999	1.008	1.032	3.1	3.4	3.0

---

[a] Sufficient HCl was added to make these samples 0.1 M in HCl. The acid was added to the container before the H_2O was pumped in except for B1a and B2a where it was added afterward, but prior to filtration.

APPENDIX D

VII. T ANALYSES OF PUMPED WATER SAMPLES

B. B-SERIES WATER SAMPLES

B-Series Sample Number	Volume Pumped (m^3)	T at t_o (μCi/ml) LLL
1	0.503	1.001
2	0.626	1.093
3	0.767	1.861
4	0.880	0.175
5	0.975	0.333
6	1.143	2.061
7	1.219	3.348
8	1.319	4.125
9	1.437	4.798
10	1.539	5.195
11	1.649	5.362
12	1.751	5.651
13	1.868	5.727

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VII. T ANALYSES OF PUMPED WATER SAMPLES

C. C-SERIES WATER SAMPLES

W. R. Daniels, P. Q. Oliver (LASL), J. E. Fontanilla, J. Rego (LLL)

C-Series Sample Number	Total Volume Pumped (m3)	T at t_o (μCi/ml)	
		LASL	LLL
1	2.578	---	7.56
2	2.907	8.24	---
3	3.210	---	---
4	3.502	---	7.48
5	3.986	---	---
6	4.209	---	---
7	4.512	7.36	---
8	4.766	---	7.08
9	4.974	---	7.06
10	5.107	---	---
11	5.300	6.98	---
12	5.406	---	6.96
13	5.689	7.75	---
14	6.004	---	9.75
15	6.125	---	9.71
16	6.219	---	9.97
17	6.659	---	10.78
18	6.863	---	10.42
19	6.969	11.55	---
20	7.400	---	12.69
21	7.567	12.10	---
22	7.968	---	13.16
23	8.078	---	---
24	8.233	13.02	---
25	8.752	---	13.00
26	9.206	---	---
27	9.335	11.88	---
28	9.842	---	10.64
29	9.986	---	---
30	10.221	8.47	---
31	10.667	---	8.93
32	11.080	---	---
33	11.451	10.84	---
34	11.795	---	8.86
35	11.951	9.94	---
36	12.272	---	8.53
37	12.764	9.42	---
38	13.317	---	10.78
39	13.643	---	---
40	14.165	---	---
41	14.608	---	---

C-SERIES WATER SAMPLES

C-Series Sample Number	Total Volume Pumped (m^3)	T at t_o (μCi/ml)	
		LASL	LLL
42	14.998	---	---
43	14.998	7.30	---
44	15.524	---	6.82
45	15.948	---	---
46	16.073	6.09	---
47	16.421	---	6.93
48	16.523	---	---
49	16.932	---	---
50	17.118	7.63	---
51	17.564	---	6.70
52	17.754	---	---
53	18.132	8.41	---
54	18.613	---	7.79
55	18.927	---	---
56	18.988	---	---
57	19.449	7.18	---
58	19.877	---	7.89
59	20.320	---	---
60	20.858	8.48	---
61	21.361	8.52	8.26
62	21.425	---	---
63	21.528	---	---
64	21.554	---	---
65	21.713	---	---
66	21.812	8.40	8.39

APPENDIX D

VII. T ANALYSES OF PUMPED WATER SAMPLES

D. D-SERIES WATER SAMPLES

W. R. Daniels, P. Q. Oliver (LASL); J. E. Fontanilla, J. Rego (LLL)

D-Series Sample Number	Total Volume Pumped (m^3)	T at t_0 (μCi/ml) LASL	T at t_0 (μCi/ml) LLL
1	0.587	5.92	6.18
2	1.136	----	6.05
3	1.635	----	6.25
4	2.434	----	6.07
5	4.054	6.36	6.18
6	5.311	----	6.38
7	6.556	----	6.43
8	7.800	----	6.47
9	9.036	6.66	6.63
10	10.274	----	6.49
11	11.508	----	6.53
12	12.742	----	6.57
13	13.980	6.75	6.64
14	15.210	----	6.51
15	16.444	----	6.58
16	17.674	----	6.74
17	18.908	----	6.48

APPENDIX D

VII. T ANALYSES OF PUMPED WATER SAMPLES

E. E-SERIES WATER SAMPLES

W. R. Daniels, P. Q. Oliver (LASL); J. E. Fontanilla, J. Rego (LLL)

E-Series Sample Number	Total Volume Pumped (m3)	T at t_0 (nCi/ml)	
		LASL	LLL
1	0.114	139.6	---
2	1.514	46.4	---
3	4.353	93.2	98.6
4	6.246	112.5	---
5	8.139	118.2	---
6	10.031	---	---
7	11.924	126.9	---
8	13.817	---	---
9	15.709	127.3	134.5
10	17.602	---	---
11	19.495	134.3	---
12	20.630	---	---
13	21.766	136.4	---
14	22.902	---	---
15	24.037	137.8	---
16	25.173	140.0	143.5
17	26.309	142.5	---
18	27.444	143.9	---
19	28.580	139.4	---
20	29.715	---	---
21	30.851	143.2	---
22	31.987	---	147.1
23	33.122	141.9	---
24	34.258	---	---
25	35.394	143.0	---
26	36.529	---	---
27	37.665	145.5	---
28	38.800	---	150.6
29	39.936	146.4	---
30	41.072	---	---
31	42.207	145.1	---
32	43.343	148.9	---
33	44.479	147.3	---
34	45.614	149.3	152.4

APPENDIX D

VII. T ANALYSES OF PUMPED WATER SAMPLES

F. F-SERIES WATER SAMPLES

W. R. Daniels, P. Q. Oliver (LASL); J. E. Fontanilla, J. Rego (LLL)

F-Series Sample Number	Total Volume Pumped (m^3)	T at t_0 (nCi/ml)	
		LASL	LLL
1	0.712	44.9	---
2	1.753	49.6	52.0
3	2.881	49.7	---
4	4.035	49.6	---
5	5.190	49.9	---
6	6.299	49.6	50.2
7	7.404	48.7	---
8	8.529	49.6	---
9	9.638	49.0	---
10	10.785	49.0	52.0
11	11.928	49.0	---
12	13.098	49.4	---
13	14.271	49.4	52.0
14	15.433	49.0	---
15	16.584	49.4	50.2
16	17.655	49.0	---
17	18.692	49.0	50.2

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