UCRL-52073

FIRST OBSERVATIONS OF TRITIUM IN GROUND WATER OUTSIDE CHIMNEYS OF UNDERGROUND NUCLEAR EXPLOSIONS, YUCCA FLAT, NEVADA TEST SITE

Neil B. Crow

MASTER

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Contents

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Abstract

Abnormal levels of radionuclides had not been detected in ground water at the Nevada Test Site beyond the immediate vicinity of underground nuclear explosions until April 1974, when above-background tritium activity levels were detected in ground-water inflows from the tuff beneath Yucca Flat to an emplacement chamber being mined in hole U2aw in the east-central part of Area 2. No other radionuclides were detected in a sample of water from the chamber. In comparison with the amount of tritium estimated to be present in the ground water in nearby nuclear chimneys, the activity level at U2aw is very low. To put the tritium activity levels at U2aw into proper perspective, the maximum tritium activity level observed was significantly less than the maximum permissible concentration (MPC) for a restricted area, though from mid-April 1974 until the emplacement chamber was expended in September 1974, the tritium activity exceeded the MPC for the general public. Above-background tritium activity was also detected in ground water from the adjacent exploratory hole, Ue2aw. The nearest underground nuclear explosion detonated beneath the water table, believed to be the source of the tritium observed, is Commodore (U2am), located 465 m southeast of the emplacement chamber in U2aw. Commodore was detonated in May 1967. In May 1975, tritium activity significantly higher than regional background was detected in ground water from hole Ue2ar, 980 m south of the emplacement chamber in U2aw and 361 m from a second underground nuclear explosion, Agile (U2v), also detonated below the water table, in February 1967. This paper describes these occurrences of tritium in the ground water. A mechanism to account for the movement of tritium is postulated. It is believed that the tritiated water passed through a network of induced and natural fractures in the tuff beneath Yucca Flat which formed a pathway from the sources of tritium to the sites where it was detected, and that hydraulic pressures induced by forces related to the explosions significantly augmented the natural hydraulic gradient in moving the tritiated water outward from the

explosion sites. The implications of induced fractures, which might create a pathway for the leakage of tritiated water downward from the tuff of Yucca Flat into the underlying regional aquifer in the *Paleozoic carbonate rocks*, are discussed.

Introduction

Knowledge that radionuclides have migrated in ground water from sources of radioactivity, at locations such as the Hanford facility[1] and the Idaho National Engineering Laboratory,[2] has created scientific interest in the potential for movement of radionuclides in ground water at the Nevada Test Site, where large quantities of radioactive fission and fusion products have been deposited by underground nuclear explosions in the saturated zone beneath the water table. The contrast between the relatively low permeability of near-surface rocks at the Nevada Test Site and the higher permeability of rocks at sites where radionuclide migration in ground water has been observed suggests that movement of radionuclides would be less extensive at the Nevada Test Site than at the other locations. The presence of radionuclides in ground water at the Nevada Test Site beyond the boundaries of underground nuclear-explosion chimneys* had not been observed until 1974, when above-background activity levels of tritium were measured in ground-water inflow to an emplacement chamber in hole U2aw, in the east-central part of Area 2 in Yucca Flat (Fig. 1). The tritium encountered in hole U2aw apparently was not accompanied by other radioactive elements. The nearest nuclear explosion detonated beneath the water table is 465 m southeast of the centerline of the U2aw hole.

Description of Radionuclide Occurrences

The region in which tritium occurrences were observed has been used very extensively for the underground testing of nuclear explosives. Most of these explosions were detonated

*A nuclear-explosion chimney is a cylindrical zone, around and above the cavity formed by the explosion about its working point, in which the rocks have been fractured into rubble and have collapsed into the cavity.

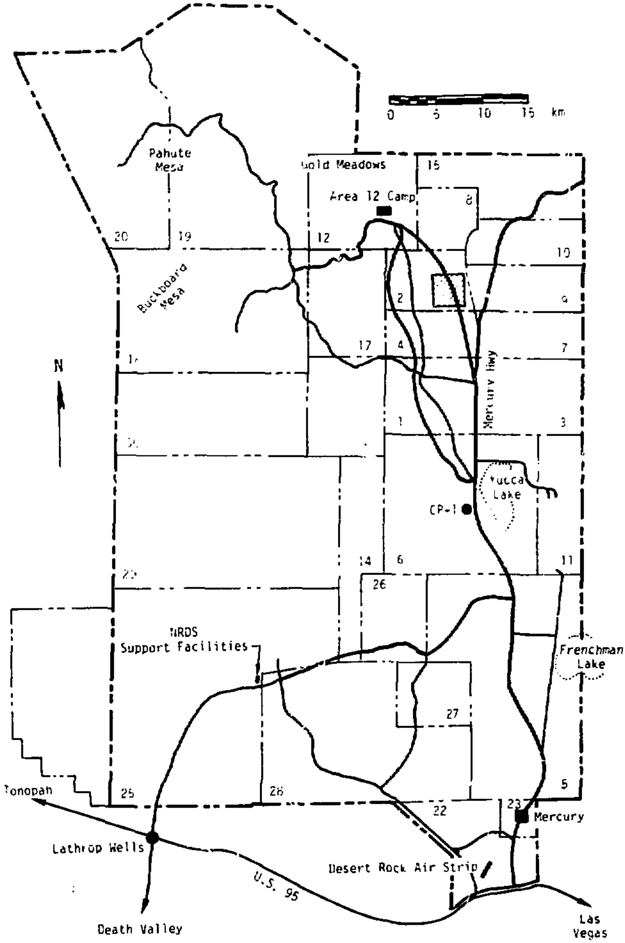

Fig. 1. Index map, Nevada Test Site.

above the water table in the unsaturated zone of the alluvium of Yucca Flat. For reasons discussed later in the paper, it is believed that radionuclides from these shallow explosions have not reached the saturated zone. Other nuclear explosions in this part of Area 2 have been detonated beneath the water table in the water-saturated volcanic rock of Yucca Flat; it is probable that the detected tritium originated from two of these explosions. Figure 2 shows the situation that existed at the time that the tritium was detected; nuclear explosions detonated beneath the water table and holes which have penetrated to the saturated zone are identified by boxes around the hole numbers.

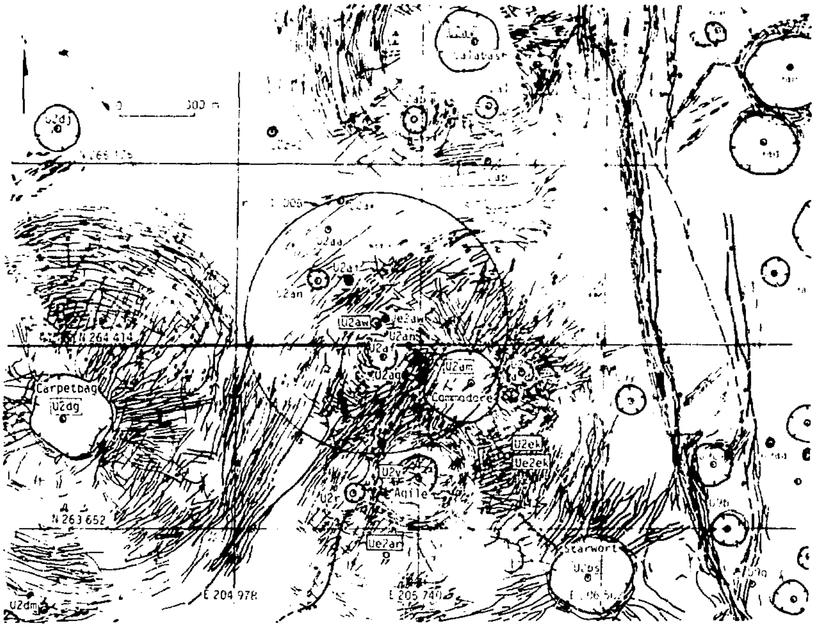

Fig. 2. Map of a portion of Area 2, Yucca Flat, showing surface effects (compiled by U.S. Geological Survey, 1974). Holes Ue2ek and U2ek had not been drilled at the time this map was compiled, but have been added to the map. Boxed hole numbers indicate explosions detonated beneath the water table or holes that have penetrated to the saturated zone.

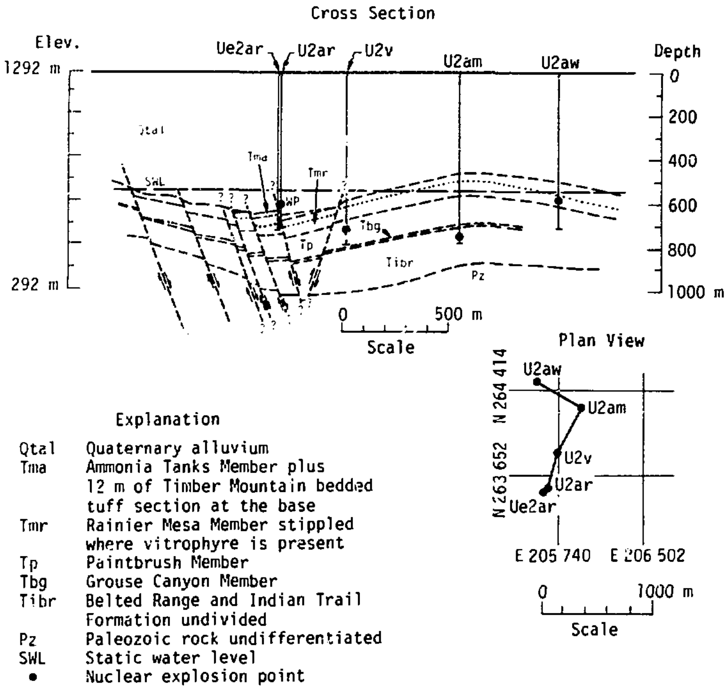

Fig. 3. Geological cross section of Area 2, Yucca Flat (J. Tewhey, LLL, 1976).

Holes Ue2ek and U2ek, which were drilled after the detection of tritium at U2aw and Ue2aw, have been added. Figure 3 is a geologic cross-section, prepared by J. Tewhey of LLL, through the area of interest, showing the relationship of the emplacement and test holes to subdivisions of the tuff beneath Yucca Flat.

TRITIUM ACTIVITY LEVELS

The background level of tritium activity in the ground water in the volcanic rock beneath Yucca Flat may be defined by the tritium activity levels reported from a water supply well which was completed in these saturated volcanic rocks.[3]

The tritium activity levels in ground water sampled from this well vary from 4.0 to 26.0 disintegrations per second per liter (d/s/ℓ).

Above-background levels of tritium activity have been measured in holes U2aw, Ue2aw, and Ue2ar. After detection of these occurrences, samples of water were taken from holes Ue2ek and U2ek; no significant tritium activity was detected. Details of all these measurements are given in the following paragraphs.

U2aw

An abnormally high tritium level was first observed in ground water pumped from emplacement hole U2aw (264505.4 m N, 205557.2 m E, NTS grid) on April 8, 1974; the tritium activity level was 8.78 × 10^4 d/s/ℓ. This measurement and subsequent measurements were made in the course of radiological safety monitoring of a relatively large ground-water inflow encountered during mining of an emplacement chamber in the hole.

The emplacement chamber was mined to an approximate diameter of 5.5 m between the depths of 570 and 576 m below ground level, in the welded tuff beneath Yucca Flat.[4] The inflow of ground water was creating operational problems in the mined chamber, and periodically it was necessary to pump out the sump — the portion of the hole below the emplacement chamber — to control the water level. Figure 4, compiled from data furnished by Fenix and Scisson,[5] shows the cumulative amount of water pumped from U2aw between May 7 and September 16, 1974. In the early part of May, the rate of inflow was approximately 0.33 ℓ/s (28.6 m^3/day). In order to reduce this flow, the chamber was pressure-grouted with cement on May 15 and again on June 16; the grouting was successful in reducing the flow to an average rate of 0.06 ℓ/s (5.5 m^3/day) during the remainder of emplacement operations. This rate of inflow was successfully controlled by regular pump-outs; it caused no operational problems, and the Stanyan event was detonated in the emplacement chamber on September 26, 1974. In all, 1033.2 m^3 (272,950 gallons) of water were pumped from the U2aw hole during metered pumpouts. Unfortunately, the amount of water pumped from the hole before metered pumpouts were begun on May 7 is not known.

R. McArthur mapped the mined chamber in U2aw during May 1974.[4] His map, presented here as Fig. 5, shows that much of the ground-water inflow was entering the chamber from the more southerly of two closely spaced faults striking N 55°E across the southeastern part of the chamber. These faults had a northwest dip of 83°. There were gouge zones 5–10 mm wide at the fault contacts. The amount of

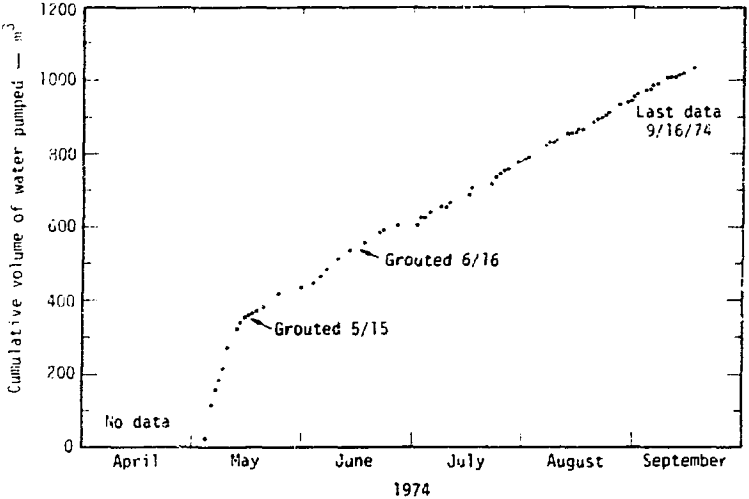

Fig. 4. Cumulative amounts of ground water pumped from hole U2aw, 1974 (Ref. 5).

movement on the faults was not measured, because of limited exposure, but was estimated to be less than 3 m.

The first tritium measurement, made April 8, 1974, indicated a level of tritium activity in the water of 8.88×10^4 d/s/ℓ.[6] In comparison with the estimated concentration of tritium in the water in nearby nuclear chimneys, this level is very small. The water produced during the emplacement operations was handled in accordance with radiation safety regulations. Since completion of emplacement operations, there has been no risk of personnel exposure, because the water occurs some 570 m beneath the ground surface, is not produced for use, and is not near a point at which ground water is produced for use.

To put these measured tritium concentrations in perspective, it should be noted that the level measured is below the maximum permissible concentration (MPC) but is much higher than the background activity level of 4 to 26 d/s/ℓ. The maximum permissible concentration (MPC) of tritium in drinking water is set by the Nuclear Regulatory Commission (10 CFR 20, App. B)

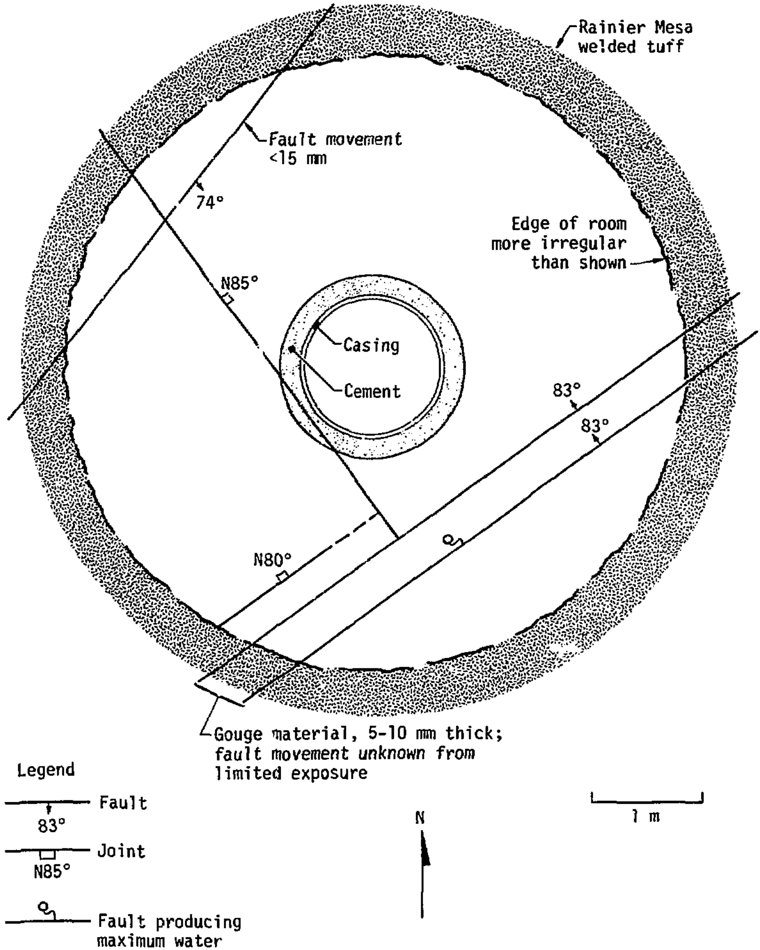

Fig. 5. Map of emplacement chamber in hole U2aw (McArthur, Ref. 4).

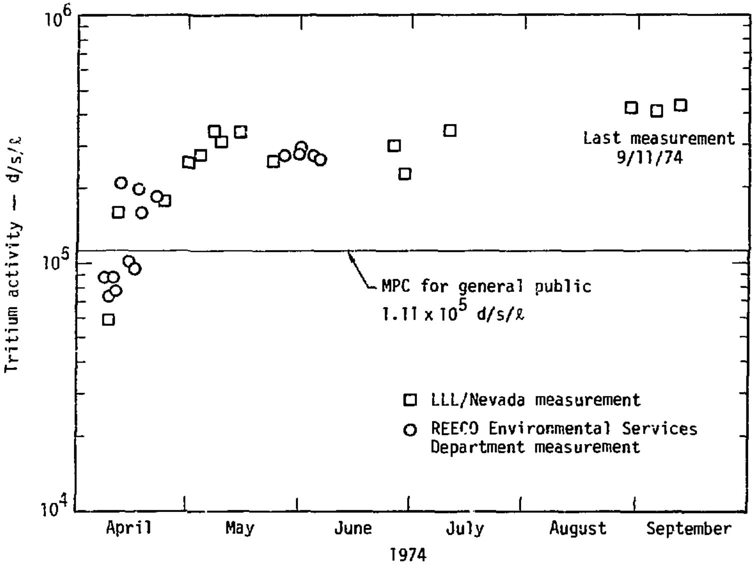

Fig. 6. Tritium activity levels measured in water from hole U2aw, 1974.

at 1×10^{-1} microcuries/mℓ (3.7×10^6 d/s/ℓ) within restricted areas such as the Nevada Test Site, and at 3×10^{-3} μCi/mℓ (1.11×10^5 d/s/ℓ) for short-term exposures of the general public.

During the spring and summer of 1974, while the emplacement hole was being prepared for use, tritium activity levels were measured periodically.[6] The results of these measurements are shown graphically in Fig. 6. A relatively rapid rise in tritium activity level took place in April. Unfortunately, there are no records of the volume of water pumped from the U2aw hole between April 8 and May 7, so it is not possible to correlate activity levels with water volume during this time. Levels were relatively stable between May and mid-July, with tritium activity levels ranging between 2.59×10^5 and 3.44×10^5 d/s/ℓ. No measurements were made after mid-July until late August; by August 28, the tritium activity had risen to 4.18×10^5 d/s/ℓ. During September, very similar tritium activity levels, between 4.07×10^5 d/s/ℓ and 4.44×10^5 d/s/ℓ, were measured in samples of the ground-water inflow. These were four times the MPC for the general public, but did not exceed the standard for a restricted area.

Ue2aw

A ground water sample was taken from this exploratory hole, adjacent to U2aw, on April 14, 1974. The tritium activity level measured in the water sample was 3.92×10^3 d/s/ℓ, well above regional background but below MPC.

Ue2ar

Tritium activity at levels above background was also detected in water sampled from exploratory hole Ue2ar (263527.9 m N, 206166.7 m E, NTS grid), which is located 980.6 m south of U2aw. Four bailed water samples were taken from the hole on May 10, 1975. The hole, which had been drilled some time previously, was filled with cavings nearly to the level of the water in the hole, 544 m below ground level, at the time of sampling. The samples showed tritium activity levels varying between 4.00×10^3 and 1.74×10^4 d/s/ℓ, averaging 1.11×10^4 d/s/ℓ. These levels are well above the regional background.

U2ek

On October 14, 1975, a slightly turbid water sample was bailed from a depth of 564 m below ground level in hole U2ek (263956.8 m N, 206166.7 m E, NTS grid), which is 820 m southeast of U2aw. Tritium activity was measured in the water sample; the level was less than 11 d/s/ℓ.[7] The sample is believed to have consisted largely of ground water; it should be noted, however, that the sample was taken immediately after drilling, and thus the presence of drilling fluid may have modified its composition. Samples taken after proper development of the hole might show different results.

Ue2ek

A water sample was taken from this exploratory hole, adjacent to U2ek, on September 25, 1975. The sample was very turbid and obviously was composed largely of drilling fluid. As in the sample from U2ek, measured tritium activity was less than 11 d/s/ℓ.[7]

OTHER RADIONUCLIDES

Because other radionuclides, such as ^{106}Ru, ^{125}Sb, and ^{137}Cs, have been found in ground water in the chimneys of underground nuclear explosions,[8] it was decided to determine if any gamma-emitting isotopes had been transported to the U2aw hole in the ground water together with the tritium. A ground-water sample taken from the U2aw hole on June 28, 1974, was analyzed in November 1975 by Levy[9] for gamma emissions. Radionuclides whose primary decay mode is gamma emission were not detected in the analysis. We may conclude that gamma-emitting isotopes were not transported as far as the U6aw hole. It is known that ground-water transport of most radionuclides, except tritium, is retarded significantly by sorption on the rock particles through which the water moves, and thus one would not expect to find most radionuclides very far from the place in which they were deposited. Therefore, the absence of gamma-emitting species in the sample was not unexpected.

Source of Tritium

The most probable sources of the tritium encountered in the ground water in the saturated volcanic rock of this part of Yucca Flat are two large underground nuclear explosions which were detonated below the water table near the occurrences. These detonations are the Commodore event, with an announced yield of 250 kt, which was detonated on May 20, 1967, in hole U2am (264261.7 m N, 205953.3 m E, NTS grid); and the Agile event, with a low-intermediate yield, which was detonated on February 27, 1967, in hole U2v (263865.4 m N, 205740.0 m E, NTS grid). Associated with these explosions is a substantial amount of tritium, which is dispersing in the ground water of the saturated zone of the tuff beneath Yucca Flat. The sites of other underground nuclear explosions which might also be sources for tritium are much farther from the locations at which tritium in the ground water was detected.

Many of the underground tests near the sites of the occurrences of abnormal tritium activity levels in ground water were conducted in the unsaturated zone above the water table in the alluvium underlying Yucca Flat. It is believed that the likelihood of any tritiated water associated with these explosions moving downward to the water-saturated zone in the alluvium and tuff beneath Yucca Flat is very small. Very little is known in detail about the movement of interstitial water in the unsaturated zone above water tables in arid regions, but all available data suggest that movement is measured at most in centimeters per year.[10] Moreover, interfacial tension in the pore spaces of the unsaturated granular rocks will exceed gravitational force until the saturation level becomes quite high; because the interfacial forces tend to bind the water to the rock granules, it is likely that little overall motion will occur until sufficient water has moved into the pore space to increase the saturation to the level at which gravitational forces exceed the interfacial tension. Because, in the region of an underground nuclear explosion in the unsaturated zone, little water is available relative to the total volume of unsaturated pore space, it seems unlikely that enough rock would be saturated to permit significant flow of water. Therefore, one would not expect movement of tritiated water in the unsaturated zone much beyond the region in which the forces of the explosion placed it. For these reasons, the shallow explosions detonated above the water table in Area 2 are almost certainly not sources of the tritium found in the saturated zone.

The following analysis of tritium movement is based upon the relationships between the tritium source associated with the Commodore explosion and the emplacement chamber in hole U2aw. It is proposed that tritiated water from the region of the Commodore event moved to the U2aw emplacement chamber through a system of both naturally occurring and explosion-induced fractures, driven by forces associated with both the explosion and the natural hydraulic gradient in the water body in the volcanic tuff of Yucca Flat. It is believed that the principles which describe water movement in the region of U2aw and Commodore are effective elsewhere in the area, so that reasoning based on the relationships of these two locations can be extended to the rest of the area of the tritium occurrence.

Insufficient data are available to allow evaluation of a number of other interesting ideas about behavior of ground water in the region near underground nuclear explosions. Few actual data are available about physical conditions in the rock — precisely to what extent the rock is fractured, changes in permeability and porosity, the distribution of the very large amount of heat deposited in the rock by the explosion and its quantitative effects on the state of water in the rocks, and the sense and magnitude of the forces which the heat might engender. Finally, we need to know more about the way in which these characteristics vary with time after explosion. Clearly, there is serious need of data about these conditions if we are to understand the movement of ground water in the near vicinity of underground nuclear explosions.

FRACTURING INDUCED BY UNDERGROUND NUCLEAR EXPLOSIONS

Summary

Research on the behavior of rocks in the vicinity of underground nuclear explosions has been conducted since such testing commenced. While detailed field studies have been conducted in the vicinity of several underground nuclear explosions,[11,12] there are no experimental data from the area near Commodore. However, a good understanding of the type of rock failure which results from the effects of underground nuclear explosions has been developed from the experimental data and rock mechanical theory,[11] and techniques of estimating explosion effects have been devised which allow prediction of such effects with good confidence. These approximations indicate that it is reasonable to expect pervasive intense fracturing in a cylindrical zone with radius about 2 times the radius of the cavity formed by the explosion (r_c), and pervasive microfracturing in a zone extending out to about 4.2 r_c around the working point; these zones are shown graphically in Figs. 7 and 8. Significant increases in permeability might be expected in the intensely fractured zone, and some enhancement might be anticipated out to the limit of pervasive microfracturing. Beyond the microcracked zone, radial fractures probably extend for a considerable distance; such induced fractures tend to follow preexisting discontinuities in the rocks, such as faults, fractures, and bedding planes.

In the absence of direct experimental evidence at Commodore, these approximations have been used to

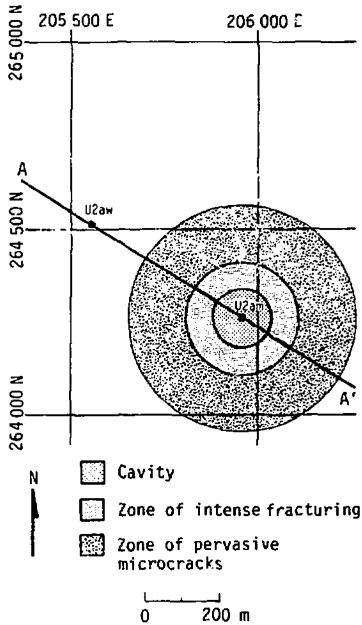

Fig. 7. Plan view showing relationships between Commodore (U2am) and emplacement chamber in U2aw. Section A-A' is shown in Fig. 8.

estimate the dimensions of the zones of different types of rock failure near the working point of the explosion. The cavity radius at Commodore was 73.5 m. It is thus estimated that the zone of intense pervasive fracturing would extend to about 2 r_c, approximately one-third of the distance between the working point of Commodore and the emplacement chamber mined in hole U2aw, and that the zone of pervasive microcracking would extend to 4.2 r_c, approximately two-thirds of the distance between the two points. Induced radial fracturing, tending to follow preexisting discontinuities such as faults and fractures, would be expected to

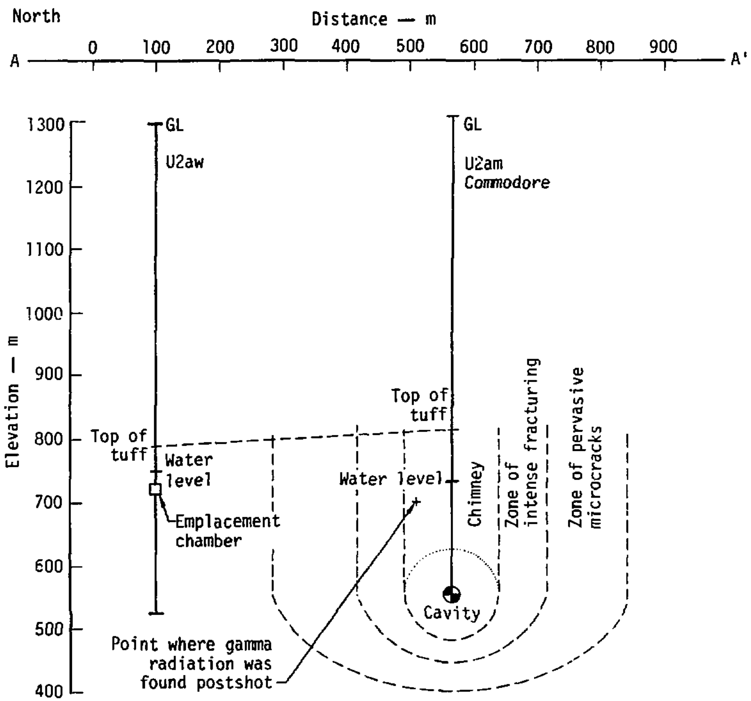

Fig. 8. Cross section showing relationships between Commodore (U2am) and emplacement chamber in U2aw.

extend a considerable distance beyond the microcracked zone, and could easily intersect the emplacement chamber in U2aw. The fact that much of the water entering the emplacement chamber was observed to be coming from a fault zone crossing the chamber (Fig. 5) tends to confirm this hypothesis. Therefore it seems reasonable to conclude that fracturing induced by the Commodore explosion has provided a path for enhanced movement of ground water from the chimney created by the Commodore explosion to the emplacement chamber in hole U2aw.

Discussion

Much of the research on the behavior of rocks near an underground nuclear explosion point has been summarized by Butkovich and Lewis.[11] The paragraphs immediately following are largely excerpted from that report.

When a nuclear explosion is detonated underground, all the energy is released in less than a microsecond. The extreme temperatures and pressures vaporize all of the material immediately surrounding the device, including some surrounding rock, and form a strong shock wave that propagates away from the center of energy. The shock wave attenuates as it moves out until it decays to an elastic wave which travels at the speed of sound in the rock. The shock wave completely vaporizes additional rock, including any water. Beyond the totally vaporized region, sufficient energy is deposited to shock-melt more rock and vaporize the water in the rock. The rock and water that become vaporized expand as a gas and form a growing cavity; growth continues until the cavity pressure is generally between 1.4 and 2 times the overburden pressure. Nuclear explosions in high-water-content rock will form larger cavities than equivalent explosions in dry rock, not only because of the enhancement of pressure due to the expansion of the larger amount of steam but also because wet rock is weak. Cavity growth is usually considered to be spherical; however, this is only generally true, and nearly spherical cavities are formed only when the nuclear detonation occurs at sufficient depths or in strong dry rock. After cavity growth stops, the pressure decays, and the fractured rock above the cavity usually collapses into the void, forming a rubble chimney. The upward growth of the chimney continues until all the fractured rock above the cavity has collapsed, or until it intersects the surface and a collapse crater is formed.

Indirect evidence at the Nevada Test Site indicates that many of the cavities formed in alluvium and tuff are aspherical. Since the confining pressure is least in a vertically upward direction, it is probable that the upper portion of the cavity is larger than the lower hemisphere. Cavity-radius measurements usually define the smaller lower hemisphere of the cavity.

Beyond the cavity, the shock wave generated by the explosion continues to propagate outward, subjecting the rock surrounding the cavity to high levels of stress. The stress causes shear and tension failure in the rock for some distance beyond the cavity, resulting in fracturing. The response of the rock depends upon the intensity of the shock wave, the mechanical properties of the rock, and the effective confining pressure. Because this pressure is greater laterally and downward than upward, the fracturing is more extensive upward than in other directions.

Borg[12] and Butkovich[13] discuss the degree of fracturing in the regions surrounding the cavity and chimney. The zone immediately beyond the original cavity is characterized by intense fracturing; surrounding it is a zone of pervasive microcracks. Beyond the microcracked zone, radial fractures extend for a considerable distance. In another paper, Borg et al.[14] point out that induced fracture systems surrounding cavities are influenced by such preexisting discontinuities in the rock as bedding, jointing, and faults. The shock wave and the elastic wave from the explosion tend to open and enlarge such discontinuities in the rock.

Empirical relationships consistent with rock mechanical theory have been developed to make quantitative estimates of the dimensions of the zones of pervasive fracturing. Butkovich[13] and Schatz[15] specify a measure of force of the shock wave, the failure-associated distortional stress denoted by ε_f. Schatz has correlated this parameter with observed failure; he shows that the "limit of intense fracturing" is at a radius from the energy source where the calculated $\varepsilon_f = 0.1 = 10\%$. The "limit of microfracturing" is at a radius where the calculated $\varepsilon_f = 0.01 = 1\%$. The measured chimney collapse height extends to a distance about equal to the calculated limit of the failure stress, where $\varepsilon_f = 0$. While no explicit model associates the magnitude of ε_f with permeability enhancement, Butkovich[13] states that significant enhancement of permeability might be expected in the zone of intense fracturing, and some enhancement of permeability is likely out to the limit of microfracturing.

The distortional stress ε_f has been correlated empirically with dimensions of the various zones of fracturing in the rock surrounding a nuclear explosion cavity. The present consensus is that in the tuff of Yucca Flat, the zone of intense fracturing extends about 2 cavity radii (r_c) horizontally from the working point, and the zone of microfractures extends to about 4.2 r_c. The distances are larger vertically upward, and smaller below the cavity.[16]

For this study, it is important also to estimate the dimensions of these zones from the working point of Commodore upward to the level of the water table, a distance of about 178 m. In modeling explosion chimneys, the chimney has been represented successfully by a cylinder, whose radius is that of the cavity, extending upward towards the ground surface and bounded at the bottom by the lower hemisphere of the cavity.[13] Figure 8, a detailed cross section through the test holes in which tritium was encountered, shows this model. For the portions of the fracture zones extending upward approximately from the working point to the vicinity of the water table, it seems reasonable to supplement the chimney model with additional concentric models representing the zones of pervasive fracturing. These models are similar, but not identical; while the upper portion of each zone is represented by a cylinder having the radius of the zone, the lower portions are aspherical. They are represented by the lower halves of oblate spheroids, each having the horizontal radius of the corresponding cylinder and a vertical axis set at 1.5 r_c for the intensely fractured zone and 2.0 r_c for the zone of microcracks. This is the overall model shown in Figs. 7 and 8.

For the Commodore explosion, which created a cavity 73.5 m in radius, these empirical correlations indicate that the zone of intense fracturing extends horizontally approximately to 2 r_c = 147 m, while the zone of microfracturing extends approximately to 4.2 r_c = 308 m, both measured from the working point of the explosion. It seems appropriate to assume, on the basis of the reasoning used to develop the models, that the zones of fracturing are approximately the same size at the level of the water table. The zone of intense fracturing thus can be assumed to extend almost one-third of the horizontal distance from the Commodore working point to the U2aw chamber, and the microcracked zone approximately two-thirds of the horizontal distance between the centerlines. These relationships are shown in Figs. 7 and 8. If, as predicted, these fracture zones enhance permeability, a pathway for fluid movement has been created for a substantial fraction of the distance between the Commodore chimney and the emplacement chamber at U2aw.

As mentioned earlier,[14] radial and tangential cracks induced by the explosion beyond the pervasively fractured zones tend to follow and enlarge existing discontinuities such as faults and fractures. Because such features appear to make up the major part of the effective permeability in the ground-water system in the welded and partly welded tuff of Yucca Flat, any enlargement which would enhance their permeability would be highly significant. If such fractures, enlarged by the explosion, intersect the fracture zones induced by the explosion, a pathway for fluid movement from the edge of the fracture zones to the region of the emplacement chamber at U2aw would be formed.

The map of the emplacement chamber (Fig. 5) shows that much of the water entering the chamber came from the more southerly of two faults crossing the southeastern part of the chamber at a strike of N 55° E. It is believed that these faults are part of the regional system, because their strike corresponds very well with the regional fracture trend of N 50° E described by Barosh.[17] It seems probable also that there has been some enhancement of the permeability of the fault from which much of the water is entering the chamber.

On the basis of the argument developed above, it is concluded that a pathway for fluid movement through induced and natural fractures in the region between the Commodore working point and the U2aw emplacement chamber was probably created by the Commodore underground nuclear explosion.

DISTRIBUTION OF RADIONUCLIDES ASSOCIATED WITH UNDERGROUND NUCLEAR EXPLOSIONS

Numerous studies (e.g., Refs. 18 and 19) provide information about the behavior of radionuclides associated with underground nuclear explosions. All the material in the immediate vicinity of a nuclear explosion is vaporized. Recall from an earlier section of this paper that, in addition to the material that is vaporized, rock in the zone immediately surrounding the expanding vaporized material is melted by the shock wave from the explosion. Within the cavity, there is a mixture of vaporized and melted material; with the decay of the temperature and pressure peaks associated with the explosion, the less-volatile species begin to condense. After cavity growth stops, the vaporized rock condenses and the molten rock begins to cool. As cooling continues, the liquid condenses and melted materials gravitate to the bottom of the cavity. At about this time, the fractured rock above the cavity begins to collapse into the molten rock (or puddle glass) at the bottom of the cavity, hastening the cooling and solidification of the vitreous substance. The remainder of the materials associated with the explosion, including the more-volatile radionuclides, remain as vapor in the chimney. During further cooling, the materials condense on the surface of the rubble composed of shattered rock throughout the chimney. Surface effects, including both surface tension and sorption, immobilize nearly all of the condensed radionuclides at or near their condensation sites. Eventually, when there has been sufficient cooling, the water vaporized by the explosion condenses, ground water flows into the chimney, and some of the soluble radionuclides deposited on the rock rubble will be dissolved in the water. The radionuclides ^{106}Ru, ^{125}Sb, and ^{137}Cs have been found in chimney water at the Nevada Test Site.[8] It is known that transport of most radionuclides through granular rock is retarded significantly by sorption, so that one would not expect to find most radionuclides very far from the site at which they condense. Tritium, however, is not significantly retarded by sorption and moves with the water in which it is incorporated. Measurements of water from U2aw for gamma emissions show that no gamma-emitting nuclides have been transported in the ground water with the tritium as far as that site.

A large amount of tritium is associated with thermonuclear explosions, and it is probably present in the cavity in free-radical form at early times after the explosion. Water originally present in both the zone of vaporization and the zone of melting is also vaporized by the explosion. This includes all interstitial water in both zones, all the bound water in the vaporized zone, and much of the bound water in the melted rock, which is above the temperature at which the hydrated forms of many minerals are stable. All of the minerals in the cavity region are subject to extremely high pressures and temperatures, and there is evidence from petrographic studies[14] that mixing is thorough at early times after the explosion. Thus the tritium free radicals associated with the explosion are mixed intimately with the vaporized water at temperatures sufficiently high to cause dissociation of the water molecules and allow incorporation of the tritium in some of them. The tritiated water remains as a vapor in the chimney and adjacent region until cooling below the boiling point of water results in condensation. At the relatively shallow depth of burial of the Commodore explosion, virtually none of the tritium produced would be incorporated in the melt.[20]

HYDRAULIC FORCES AFFECTING GROUND WATER NEAR COMMODORE AND THE U2aw EMPLACEMENT CHAMBER

Summary

Movement of ground water in the saturated rock beneath the region of the Commodore explosion and the U2aw emplacement chamber is influenced both by forces created by the underground nuclear explosion and by forces associated with the regional hydraulic gradient. There are no experimental data about the characteristics of the ground-water regime in and near the chimney of the Commodore explosion. What follows summarizes an interpretation based on data obtained elsewhere at the Nevada Test Site, the principles of ground-water movement, and available knowledge about the effects of underground nuclear explosions. Details are given in the sections following.

The tritiated water in the explosion cavity is moved radially outward by the pressure pulse associated with the explosion. While this pulse lasts only a relatively short time, it is important because of its large magnitude. Other operative forces include the gas pressure of the explosion and the heat deposited in the rock by the explosion. The total effect of these forces is to move tritiated water vapor from the cavity radially outward into the fractured zones beyond it. It is known that ground water forms a mound above the site of an underground nuclear explosion as a result of such forces. While some of the water in the mound moves inward to the chimney of the nuclear explosion after the initial forces have decayed, there remains an outward hydraulic component from the mound.

Forces acting in the chimney of the underground nuclear explosion — vapor refluxing and water-phase convection in the permeable chimney rubble — act to mix the tritiated water produced in the explosion cavity with the water in the chimney above the cavity for a substantial distance above the working point of the explosion. Thus for a shot like Commodore, it is probable that all the water in the chimney beneath the water table contains a considerable amount of tritium.

Within a fairly short period after the explosion, the forces due to the explosion decay substantially, and further movement of ground water is due largely to regional hydraulic gradients. The water body in the saturated rock beneath this part of Yucca Flat — virtually all volcanic tuff — is semiperched. This type of water body is characterized by a hydraulic potential which decreases vertically downward. This indicates that, as well as the more usual horizontal hydraulic gradient, there

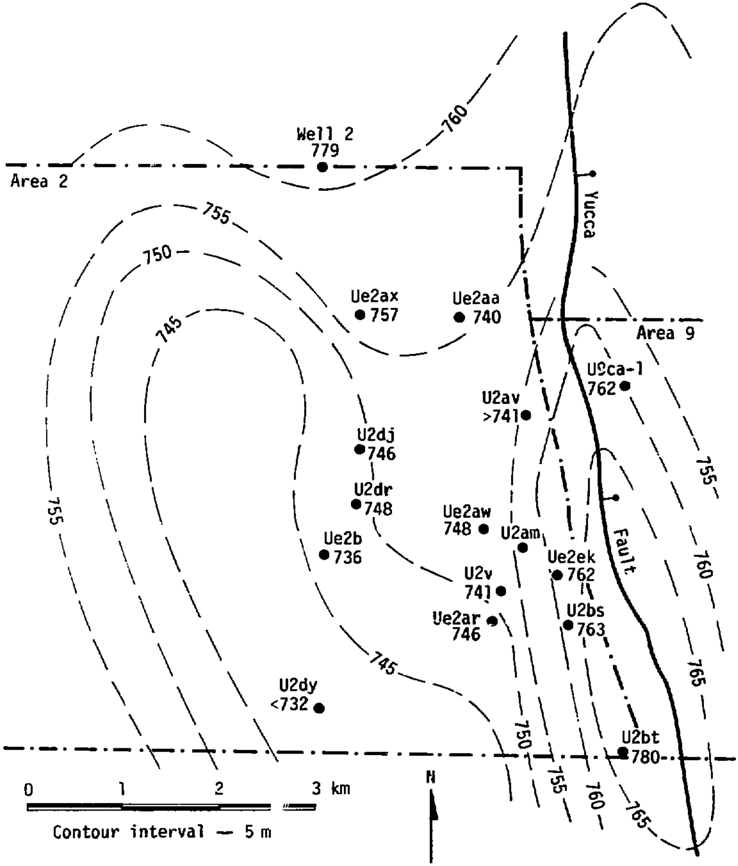

Fig. 9. Map of water table, part of Yucca Flat (modified from Dudley, Ref. 21).

is a vertical hydraulic gradient, which allows leakage downward of the water body to the regional aquifer below. The direction of horizontal flow can be estimated from the hydraulic gradients indicated on the water table map, Fig. 9.[21] The map indicates that the movement of ground water in the vicinity of Commodore is westward, which is generally favorable for ground-water movement from the Commodore working point toward the emplacement chamber in U2aw.

Calculations based on estimated conditions support the hypothesis that the water pumped from the U2aw emplacement chamber is not fully representative of the tritiated water predicted to be in the Commodore chimney, but rather is the dispersed edge of a slug of tritiated water moving outward from the chimney. A transport calculation of the movement and dispersion of a slug of tritiated water from the Commodore chimney toward the U2aw emplacement chamber indicates a calculated tritium activity level in the region of the emplacement chamber that agrees within a factor of 2.5 with the measured activity levels in the chamber. This lends support to the belief that the Commodore explosion was the source of the tritium in the U2aw emplacement chamber.

Hydraulic Forces Induced by Underground Nuclear Explosions

Despite its relatively short duration, the pressure pulse associated with an underground nuclear explosion is important in moving material radially outward from the working point of the explosion. The pressure pulse is due to the sudden expansion of the material vaporized by the explosion; included are both the rock and the water around the detonation point. Because a significant part of the pressure is due to the expansion of superheated water vapor, the pressure is higher and more prolonged[11,22] in the vicinity of nuclear explosions, such as Commodore, detonated in the water-saturated rock below the water table than it is in the case of explosions detonated in the dryer rock above the water table. The pressure pulse decays relatively rapidly; Butkovich and Lewis[11] state that pressures are in the range of 1.4 to 2 times overburden (lithostatic) pressure at the time cavity growth is complete, usually less than a second after the explosion takes place. Soon afterward, pressure is below lithostatic, and by the time the cavity collapses, pressure is essentially hydrostatic. In the case of Commodore, surface collapse occurred 8 minutes and 40 seconds after detonation; clearly, cavity collapse took place some time earlier. Thus it is apparent that the pressure pulse had decayed within a few minutes after detonation.

Other forces tending to move water outward from the detonation point include the gas pressure of the explosion itself, which causes the formation of the cavity and compaction of the rock immediately outside the cavity.

For explosions detonated below the water table in saturated rock, ground water is very probably moved upward above the shot point, and may form a ground-water mound above it.[23] Some of the water in the mound will move back into the permeable chimney rubble. However, water in the outer part of the mound would tend to move radially outward, creating a hydraulic gradient outward from the chimney region.

The net result of these induced forces would be to create significant horizontal forces which would tend to move water through available pathways outward from the chimney.

It is known that a considerable amount of heat is deposited by an underground nuclear explosion in the rock immediately outside the chimney.[11] The effects of this heat on the movement of ground water in the region are not discussed in this paper, because there is not sufficient information available about the precise character of the rock or the state of the water near the Commodore chimney to allow use of appropriate analytical techniques. Thus we cannot give even reasonable approximations of the sense or magnitude of moisture movement which would result from thermal gradients in the saturated zone in this region. If we are to gain a better understanding of the movement of ground water due to thermal effects near nuclear chimneys, it will be necessary to obtain more experimental data.

Because the emplacement chamber in hole U2aw (where tritiated water was first detected) is located between 170 and 176 m higher than the working point of the Commodore explosion, we must consider ways in which the tritiated water might move upward as well as outward. We have already considered two mechanisms, gas pressures and the pressure pulse plus the associated ground-water mound, which would tend to move water upward from the working point. Another mechanism is the hydraulic gradient induced by the pumping at hole U2aw to keep the emplacement chamber clear. The tritium activity levels seen in the water from the hole increased over time (Fig. 6), as water was pumped from the hole. It seems clear that the pumping was bringing in water from zones of higher tritium activity; these undoubtedly were closer to the source, and could have been deeper than the emplacement chamber as well.

Tritiated water may also move from the vicinity of the working point of a nuclear explosion vertically upward in the chimney rubble under the influence of the heat remaining near the shot point. This heat source may be present for a period of a few years; for example, in the nearby Starwort chimney (U2bs), recent measurements of temperature indicate that temperatures of approximately 101°C remained in the rock immediately adjacent to the chimney and in the chimney itself two years after the detonation. There are two mechanisms which would account for vertical movement of water in the chimney region: a natural water-vapor-reflux condenser, and convection of liquid water due to differential heating.

A natural water-vapor-reflux condenser in a nuclear explosion chimney would result from continuing vaporization of water present in the vicinity of the working point by the heat residing in the rocks. As long as these rocks remain above the boiling point of water, vapor will form and will rise in the chimney until the vapor contacts rocks cooler than the boiling point of water. The vapor will condense on these rocks and the resulting water will trickle down into the hotter zone, where it will again vaporize and move upward. Because the temperature distribution in the rocks in the Commodore chimney is unknown, it is not possible to estimate the height to which water from the cavity region would rise as a result of such a reflux system. When the water has returned to the liquid phase, both in the zone at the top of the water reflux system and, later, when the system has cooled below the boiling point of water, the emplaced heat can still induce water movement. The hot rock would heat water by contact, and the hot and less-dense water would move upward through the rather large effective permeability in the chimney rocks, displacing the cooler water above downward. This water in turn would be heated and rise, forming a convection cycle in the chimney which would tend to mix the water. Again, the height to which the water would rise through convection is not known, but presumably it would be a considerable height above the detonation point.

We have one piece of evidence which allows us to estimate the height to which tritiated water might have risen in the Commodore chimney. In a directionally drilled postshot hole into the Commodore chimney, the first abnormal gamma radiation level was encountered at a point 54.0 m N and 25.0 m W of the working point, and 147.0 m vertically above it.[24] The point is shown on Fig. 8. Probably this is the point at which the drill entered the chimney, and it is likely that gamma radioactivity would be found farther up the chimney. Nonetheless, the point is only 31 m below the measured preshot water level in U2am, and 29 m lower than the elevation of the top of the emplacement chamber in U2aw. Since the gamma-emitting nuclides are far less volatile than the tritiated water in the chimney, it seems probable that the tritiated water would move farther up the chimney than the gamma-emitting species. Data from the Faultless event, at the Central Nevada Supplementary Test Site,[25] indicate that the tritium does move farther up the chimney than gamma-emitting nuclides. Because the indicated water table is not far above the elevation at which gamma-emitting nuclides were encountered in Commodore, it seems reasonable to believe that tritium moved up in the ground water at least to the water table level in that chimney.

Ground-Water Movement in Yucca Flat

Once it is in the regional ground-water system, tritiated water from a nuclear-explosion chimney would move under the influence of the regional hydraulic gradient as well as that of any residual forces caused by the nuclear explosion. Because part of the pathway postulated for water movement between Commodore and the U2aw chamber lies in this system, we must consider the movement of water in it. In the part of Yucca Flat under consideration, the saturated zone lies almost entirely in the tuff beneath the Flat. As this saturated zone has decreasing hydraulic head downward, it is defined as a semi-perched body of ground water. Winograd and Thordarson[26] believe that the water in the saturated tuff of Yucca Flat is leaking slowly downward to the regional aquifer in the Paleozoic rocks which underly this region of southwestern Nevada. The hydraulic head potential in the Paleozoic carbonate aquifer is substantially lower than the head in the tuffaceous volcanic rocks. Because the effective permeability of the tuff of Yucca Flat, and especially the basal tuff, is very low, vertical movement of water in the semiperched zone is very slow; Winograd and Thordarson estimate the rate of vertical downward movement to be from 0.0001 to about 0.06 m/year. The total volume of the downward leakage from Yucca Flat is believed to be on the order of 25,000 to 85,000 m^3/year. Flow rates in fracture zones are high in relation to interstitial flow, but apparently there are few fracture systems which allow drainage of the water downward out of the tuff. An increase in the number of fractures would result in an increase in the downward movement of water from the tuff.

In addition to the vertical component of the hydraulic gradient, semiperched water bodies are subject to horizontal hydraulic gradients. An understanding of horizontal hydraulic gradients can be gained by the construction of a hydraulic-head-potential surface map. A potentiometric surface represents the level to which water will rise in wells completed in a saturated ground water system. While it is not strictly correct to speak of a stable water level in a semiperched water body, the drainage rate at Yucca Flat is so low in proportion to the total volume of water that water levels may be considered to be stable for periods of a few tens of years. Construction of a hydraulic-head-potential map is complicated by the problem of determining the potential in the upper part of the saturated zone, which establishes the water table. Because the hydraulic head is lower in the lower portion of the water body — a characteristic of a semiperched water body — the water level measured in a hole penetrating deep into the water body reflects this lower potential and not the higher potential in the upper part of the saturated zone. Thus, such a measurement gives a water level lower than the water table. Figure 9, compiled by Dudley,[21] is a hydraulic-head-potential surface map showing the configuration of the water table and is based on water levels measured in holes drilled into the saturated zone in north-central Yucca Flat. Slopes indicated on the map are related to areal head differentials in the upper portion of the saturated semiperched ground water system; water moves from areas of higher head to areas of lower head. It is presumed that the gross pattern of areal flow in the upper portion of the semiperched system, which can be inferred from Fig. 9, is essentially the same at greater depth in the system.

Analysis of Ground Water Movement in the Region of Commodore and the U2aw Emplacement Chamber

Study of the hydraulic-head-potential map indicates that, between the Commodore working point and the U2aw chamber, the surface slopes generally westward. Thus one can infer that ground-water flow is to the west in this area. Flow in this direction is generally favorable for movement of water from the region of the Commodore chimney to the region of the U2aw chamber.

It was not possible to estimate the horizontal ground-water flow rate between the Commodore working point and the U2aw chamber from measurement of tritium in inflow to the chamber. Measurements were taken over too short a period of time to define a pulse of tritium activity, and it is not clear whether the level had stabilized or would have risen if measurements had been possible over a longer period of time. The arrival of a discrete pulse of tritium in ground water at U2aw was not seen in the sense of observation of rising and, finally, declining tritium levels. Because the emplacement chamber was used in September

1974 for detonation of the Stanyan device, it was impossible to continue measurements.

Too little is known about the behavior of the tritiated water slug from the Commodore cavity and chimney as it moved through the surrounding rocks to allow convincing quantitative estimates of the tritium activity level one might expect to encounter at a given point beyond the chimney, such as the emplacement chamber in U2aw. For example, the tritiated water mixes with water in the rocks beyond the chimney by dispersion, but in this case we know nothing about the magnitude of this effect. Also, the volume of water in the fracture pathways through which the water moves is unknown.

It does seem reasonable that the tritium activity levels measured in the U2aw chamber are not fully representative of the tritiated water in the Commodore chimney. No measurements were made of tritium activity levels in the Commodore chimney; however, it is possible to estimate the level of tritium activity which might be expected. Because many of the parameters used in making an estimate are known only approximately, such an estimate is very rough. However, because our interest is primarily in the order of magnitude of tritium activity in the chimney water, even an approximate estimate is useful.

We know the dimensions of the chimney reasonably well, there is a measured preshot water level for Commodore, and we can estimate the porosity of the rock in the chimney region. With these data, we can estimate the volume of water in the Commodore chimney. If we assume, for the sake of argument, that the total yield of 250 kt was due entirely to nuclear fusion, we can use the fact that approximately 2 g of tritium is produced by 1 kt of nuclear fusion[27] to calculate that about 500 g of tritium was produced by Commodore. This is equivalent to 5×10^6 Ci of tritium activity. If we assume further that all the tritium was dispersed uniformly in the water in the chimney region, we can calculate a range of tritium activity that might reasonably be expected in the chimney water. If the tritiated water in the chimney is assumed to occupy 20-30% of the total chimney volume below the water table, the calculations predict that tritium activity levels in the range of 1.6×10^8 to 2.4×10^8 d/s/ℓ (4.3-6.5 μCi/mℓ) would be encountered. These estimates represent activity levels which might reasonably be expected in the Commodore chimney water.

The maximum tritium activity level observed in the water produced from the U2aw chimney was 4.4×10^5 d/s/ℓ, almost three orders of magnitude less than the estimated levels calculated above for Commodore chimney water. Radioactive decay and dispersion of tritium in the water presumed to flow from the Commodore chimney to the emplacement chamber at U2aw would undoubtedly serve to attenuate the peak activity level to some degree, but the activity in the chamber water is so much lower than that expected in the chimney water as to suggest that the water pumped from the U2aw chamber is the dispersed vanguard of a slug of tritiated water moving outward from the Commodore chimney, and not the main body.

The concentration of tritium in water at U2aw presumed to have been transported from the Commodore explosion site was estimated by using the solution to a one-dimensional transport model with a pulse tracer input.[28] It was assumed that transport began from the Commodore site at the time of detonation and continued until May 20, 1974, over a period of 7 years. Ground-water flow velocity was assumed to be 30 m/year, which is within the range of estimates given for flow velocity in similar volcanic rocks beneath Pahute Mesa.[29] For dispersivity, a value of 15 m was used, which is near the lower end of the range determined in various field measurements of dispersivity.[14] The initial concentration of tritium in ground water at the Commodore site was assumed to be 1.9×10^8 d/s/ℓ. With these assumptions, the solution of the transport equation yielded an estimate of tritium concentration at U2aw on May 20, 1974, of 1.2×10^5 d/s/ℓ. The observed tritium level there on the same date was about 3×10^5 d/s/ℓ. The correspondence of the estimated and observed tritium concentrations at U2aw to within a factor of 2.5 lends some credence to the presumption that the Commodore event was the source of tritium found at U2aw.

Other Tritium Occurrences in Area 2

Tritium was also detected in ground-water samples from exploratory hole Ue2ar, south of the Commodore and Agile chimneys (Fig. 2). The average tritium activity level measured was 1.1×10^4 d/s/ℓ. This is of the same order of magnitude as the tritium activity seen in hole Ue2aw, adjacent to U2aw, which is believed to represent reasonably well the tritium activity level of that region before pumping of ground water from hole U2aw disturbed the existing conditions. The ground-water hydraulic gradient, indicated on Fig. 9, is favorable for movement of water toward

Ue2ar from the site of Agile, the nearest nuclear explosion detonated beneath the water table. For these reasons, it is believed that the source of the tritium found in the ground water from the Ue2ar exploratory hole in the Agile chimney.

It is very interesting to note that no tritium activity has been detected in U2ek and Ue2ek. It is believed that the direction of the hydraulic gradient has not allowed flow of the tritiated water from the two nuclear chimneys eastward to the vicinity of these holes. On September 25, 1975, the water table in Ue2ek was estimated by Stone[30] to be 533 m below ground level. This level was determined at a time when the hole penetrated only a limited distance into the saturated zone in the volcanic rocks, and thus it may be presumed to represent the hydraulic head near the top of the zone. Using an estimated ground level of 1295 m, the elevation of the water table at Ue2ek is 762 m above sea level, 21 m higher than its elevation at Agile, which is 741 m (Fig. 9). Assuming the absence of a permeability barrier — and there is no evidence for one — the difference in hydraulic head between the two holes apparently precludes movement of the tritium front from Agile to Ue2ek and U2ek. This evidence confirms Dudley's interpretation (Fig. 9), which shows a pronounced mound in the water table to the east of Commodore and Agile in the vicinity of U2ek.

Possible Effects of Nuclear Explosions on the Regional Paleozoic Carbonate Aquifer

If an underground nuclear explosion in this part of Yucca Flat is emplaced near the base of the tuff, conceivably fractures could be induced through the lower part of the tuff and into the top of the Paleozoic carbonate rocks containing the regional aquifer. If this were to happen, local vertical downward movement of the water from the explosion, most probably tritiated, could be accelerated appreciably.

The aquifer in the Paleozoic carbonate rocks is characterized by considerably higher flow rates than those observed in the volcanic tuff of Yucca Flat. Winograd and Thordarson[25] have estimated flow rates in the regional aquifer in the carbonate rocks beneath Yucca Flat; assuming a range of values of effective porosity from 0.01 to 1%, horizontal flow rates were calculated to be between 1.8 and 180 m/year. Borg et al.[14] are of the opinion that the average effective porosity may be near the upper end of this range, or have even greater values. They comment further that these estimates are not based on quantitative hydraulic measurements; the estimates should be regarded as nothing more than considered guesses. There is a need for field hydraulic tests to determine values of effective porosity for this lower aquifer; such tests would allow more accurate estimates of flow rates.

Once in the Paleozoic carbonate aquifer, tritiated water from the vicinity of a nuclear-explosion chimney thus has the capability of relatively rapid movement; in 10 years, it could move as much as 1800 m. While this rate of movement presents no danger of contamination of water supplies off the Test Site, since the boundary is approximately 50 km south in the direction of flow in the regional aquifer, it does suggest that a considerably larger region of contamination could result than if the tritiated water was contained in the tuff aquitard under Yucca Flat.

At the Commodore site, near-surface particle-motion measurements made at the time of the detonation were analyzed by Preston.[31] He indicates that the stress wave reflected from the Paleozoic carbonate rocks arrived relatively early and was very strong. The record from the deepest gage (152 m below the surface) indicates that the reflected wave arrived about 100 ms or less after the direct wave. Preston interprets this to indicate that the Paleozoics may lie from 91 to 122 m below the working point. This record and other strong-motion data indicate that the presence of a strongly reflecting surface close beneath the working point of an underground nuclear explosion leads to stronger surface motions from the explosion. Since the radius of the Commodore cavity is 73.5 m, the top of the Paleozoic rocks estimated by Preston is within a range of 1.25 r_c to 1.67 r_c.

In a more recent study by the U.S. Geological Survey,[32] the position of the top of the Paleozoic rocks was estimated to be 911 m (plus or minus 10%) above sea level. Assuming the 10% uncertainty, the distance of the top of the Paleozoics below the working point would be within a range of 2.05 r_c to 2.45 r_c.

It is concluded that the top of the Paleozoic rocks is within the zones of pervasive fracturing, and that some enhanced permeability might be expected. There is additional evidence for this: Because unusually strong reflections of stress waves from the Commodore event were measured, clearly the basal tuff and the uppermost Paleozoic rocks were subjected to very strong stresses. It is therefore quite probable that pervasive fracturing was induced in the basal tuff aquitard and also in the topmost part of the Paleozoic rocks. Such fractures would provide a pathway for vertical drainage of the tritiated water from the Commodore chimney into the carbonate rocks below, and probably into the fracture system that makes up the regional aquifer. If this is the case, somewhat wider spreading of the tritium might result than would have occurred if the tritiated water were confined to the basal tuff aquitard.

Conclusions

Ground water in a region in Area 2 at the Nevada Test Site is contaminated with tritium which is believed to originate in the chimneys of two large underground nuclear explosions detonated in the region, Commodore (U2am) and Agile (U2v). The activity levels of tritium encountered are small relative to levels known to be present in nuclear explosion chimneys, of which there are many in the region, and no gamma-emitting radionuclides have been encountered in the ground water. No risk of personnel exposure exists, because the ground water is not produced. The rate of horizontal movement of ground water is not known with certainty but is believed to be in the range of 30 m/year. Because the nearest water well in the direction of flow is more than 15 km distant, tritium activity would have decreased virtually to zero due to radioactive decay by the time the front reached the region of the water well. Further, because the boundary of the Test Site is more than 50 km distant in the same direction, it is also clear that no significant tritium activity from this source would cross the boundary. For purposes of comparison, it is noted that tritium activity levels in the ground-water inflow to the U2aw emplacement chamber did not exceed the MPC for a restricted area, though MPC for the general public was exceeded for a period of time in the summer of 1974.

In exploratory hole Ue2aw — adjacent to U2aw — and in Ue2ar to the south of Agile, tritium at levels below MPC for the general public but well above regional background were detected. It is believed that an adverse hydraulic gradient in the saturated zone of the tuff of Yucca Flat has prevented or retarded movement of the tritium front eastward to the region of Ue2ek and U2ek, where above-background levels of tritium have not been detected.

The spread of tritiated water radially outward from a nuclear explosion chimney in Yucca Flat is believed to be due to movement of the water through explosion-induced fractures that intersect the preexisting fractures in the regional system, in which virtually all the ground-water flow takes place. It is also believed that the transmissivity of these preexisting fractures near the explosion sites is increased by mechanical forces associated with the explosion. Hydraulic gradients generated by the explosion are believed to be sufficient to add significant impetus to the flow of ground water radially from the chimney into the regional system.

It is apparent that the tritium activity levels seen in the ground-water inflow to the U2aw emplacement chamber during mining and emplacement operations do not represent the maximum concentration of tritium activity which would be expected in the tritiated water originating in the Commodore explosion chimney. It is believed that this chimney water is dispersing into uncontaminated water.

The distance of the working point of an underground nuclear-explosive test from the interface of the tuff and Paleozoic carbonate rocks underlying it should be given consideration in siting such tests in this part of Yucca Flat, to avoid intensive fracturing in the basal tuff and uppermost carbonate rocks. Such fracturing would allow greater leakage of radionuclides, especially tritium, downward into the regional aquifer in the Paleozoic rocks. The higher permeability characteristic of these rocks would allow wider dispersion of the radionuclides than if they were contained in the tuff. While it is virtually certain that there would be no contamination of ground water beyond the boundary of the Nevada Test Site as the result of such fracturing, there would most probably be a significantly larger contaminated region than if the radionuclides remained in the tuff.

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