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Radioactive Waste Disposal in Thick Unsaturated Zones

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Current Department of Energy plans (*1–3*) for the disposal of both high-level and transuranic (TRU) radioactive wastes (*4, 5*) involve placement of these wastes in underground workings at depths of 600 to 900 meters in geologic media such as bedded salt, basalt, granite, or tuff. Burial at such depths in tectonically stable areas, the concept favored since 1957 (*6*), is generally held to provide assurance against (i) exhumation of the wastes by erosion; (ii) catastrophic release of the wastes following meteorite impact; and (iii) future human intrusion, provided, of course, that economic mineral deposits are not associated with the host media. In addition, and to varying degrees—dependent principally on the waste form and on the hydrogeologic and geochemical setting of the repository—deep burial retards transport of radionuclides to the biosphere by ground water.

Summary. Portions of the Great Basin are undergoing crustal extension and have unsaturated zones as much as 600 meters thick. These areas contain multiple natural barriers capable of isolating solidified toxic wastes from the biosphere for tens of thousands to perhaps hundreds of thousands of years. An example of the potential utilization of such arid zone environments for toxic waste isolation is the burial of transuranic radioactive wastes at relatively shallow depths (15 to 100 meters) in Sedan Crater, Yucca Flat, Nevada. The volume of this man-made crater is several times that of the projected volume of such wastes to the year 2000. Disposal in Sedan Crater could be accomplished at a savings on the order of $0.5 billion, in comparison with current schemes for burial of such wastes in mined repositories at depths of 600 to 900 meters, and with an apparently equal likelihood of waste isolation from the biosphere.

I suggest in this article that there are thick and relatively dry environments in the Great Basin where relatively shallow burial (within 15 to 100 m of the surface) of TRU wastes in tectonically active environments appears to offer as complete isolation of such wastes from the biosphere as deep burial in bedded salt, basalt, tuff, or granite. Moreover, such relatively shallow disposal can be implemented at a fraction of the cost of schemes for deep geologic disposal (*7*). This article was prompted by former President Carter's Interagency Review Group report (*3*) on high-level radioactive waste (HLW) disposal, which strongly endorsed evaluation of multiple geologic media in different hydrogeologic environments before selection of a repository for either HLW or TRU wastes. The major findings of the interagency report were endorsed by Carter in a special message to Congress on 12 February 1980.

It has been recognized for nearly two decades that the thick (as much as 600 m) unsaturated zones of the southwestern states are potentially suitable environments for the disposal of solidified radioactive wastes (*8–10*). The perceived assets of waste burial at relatively shallow depths, hundreds of meters above rather than in deep mines hundreds of meters below the water table, include: (i) extremely low flux of water in the unsaturated zone under present arid and semiarid climatic conditions; (ii) high sorptive capacity for radionuclides of valley-fill sediments, which commonly occur in the unsaturated zone; (iii) ability to bury the wastes in man-made stratigraphic configurations that can significantly inhibit vertical movement of water; (iv) absence of water-related problems during construction and after sealing of a shallow repository; and (v) accessibility of the wastes for monitoring or for removal if a superior disposal scheme is developed. The perceived principal concerns about shallow burial include the possibilities of (i) exhumation by erosion, tectonism, or meteorite impact prior to decay of the actinide elements to acceptable levels of radioactivity; (ii) possible flooding or flushing of the disposal site by a major rise of the water table or by increased deep percolation of precipitation during future pluvial—that is, glacial age–related wetter—climates in the Southwest; and (iii) exhumation by our uninformed descendants.

The past proposals (*8–10*) for utilization of the thick unsaturated zones of the Southwest to isolate solidified radioactive wastes from the biosphere have included placement of the wastes in trenches, tunnels, mines, and drill holes, but at depths of hundreds of meters above the water table. Because of the paucity of hydrogeologic, soil physics, geochemical, tectonic, and other data for the unsaturated zone, these proposals have, at best, been conceptual in nature. As result, the idea has received only peripheral attention to date. In this article I discuss a specific intermountain basin, Yucca Flat, Nevada, for which there are sufficient data to estimate, to a first approximation, the ability of such zones to isolate solidified radioactive wastes for tens of thousands to perhaps hundreds of thousands of years. Al-

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Fig. 1. Sedan Crater, Yucca Flat, Nevada Test Site, Nye County, Nevada (view is to the north-northeast). Crater diameter is 370 m, depth 98 m, and volume 5.0×10^6 m^3. Crater formed in 1962 by a 100 ± 15 kiloton nuclear device detonated at a depth of 190 m in valley fill. Water table is about 580 m below land surface. Vehicles, left side of photo, provide scale. [Photo from W. D. Richards (*11*)]

though I focus on the potential emplacement of TRU wastes (*5*) in a man-made crater, Sedan Crater, the conclusions reached apply equally to emplacement of other solidified radioactive and chemical toxic wastes in trenches, drill holes, or shallow mines in Yucca Flat. The conclusions are also generally applicable to other valleys in the Great Basin having hydrogeologic, tectonic, and geochemical characteristics similar to those of Yucca Flat.

Transuranic Radioactive Waste Disposal in Sedan Crater

Sedan Crater (Fig. 1), the product of a 100 ± 15 kiloton nuclear cratering experiment conducted in Yucca Flat (Figs. 1 and 2) by the Atomic Energy Commission (AEC) in 1962, has an average diameter of 370 m, a depth of 98 m, and a volume of 5.0×10^6 m^3 (*11*). The detonation, one of several in the AEC's Plowshare Program, occurred at a depth of about 190 m in Quaternary-Tertiary valley-fill deposits (*12*) that underlie the site to a depth of approximately 250 m (Fig. 3). The water table occurs in Paleozoic carbonate rocks at a depth of about 580 m. The climate of the Sedan site is arid (*13*). Annual precipitation at the site is about 120 millimeters (4.7 inches); the mesas and ridges flanking northern Yucca Flat receive as much as 254 mm (10 inches).

The volume of Sedan Crater is about 12 times the total volume of TRU wastes of military origin (0.4×10^6 m^3) projected to be at Department of Energy sites by the year 1986 (*3*) and proposed (*1*) for burial at the Waste Isolation Pilot Plant (WIPP) site near Carlsbad, New Mexico. The crater volume is roughly 25 times the volume of military and commercial TRU wastes (0.2×10^6 m^3) projected to be generated between 1980 and 2000 (*3*). The volume of Sedan Crater is adequate to receive several times the existing and projected volumes of TRU wastes to the year 2000 even if burial occurs only in about the lower 85 m of the crater, which would provide a 13-m buffer against exhumation by erosion or man and space for placement of a capillary barrier above the wastes.

One of several possible modes of emplacement of TRU wastes in Sedan Crater is shown diagrammatically in Fig. 4. The lower ~ 85 m of the crater would contain TRU wastes in a matrix of valley fill previously washed and sieved to remove fragments smaller than coarse sand. The coarse-grained valley fill and its contained waste would be covered by an 8-m-thick layer of clay-sized to silt-sized valley fill. The remaining 5 m of crater would be filled with unsorted valley fill, that is, fill containing all natural size fractions. The topmost fill would be landscaped to conform to precratering topography and vegetation. The physical, chemical sorptive, and hydrogeologic properties of the valley fill and its prominent zeolitized tuff component have been described (*14–17*). Reasons for covering the coarse valley fill by a layer of fine-grained fill are discussed later.

Can such a simplistic scheme isolate TRU wastes from the biosphere over periods of geologic time—say for at least tens of thousands and preferably hundreds of thousands of years? Specifically, how does such a waste disposal scheme compare with "conventional" deep-mined geologic repositories? In the remainder of this article I address these questions. Although the computations and arguments I present suggest a favorable prognosis, detailed studies of several years' duration will certainly be required for a thorough analysis of the proposed scheme.

Assets and Concerns

The perceived assets of, and concerns about, use of the unsaturated zone as a disposal environment for solidified radioactive waste have been discussed in detail by Winograd (*9*) and outlined above. These matters are discussed below with special reference to a hypothetical repository for TRU wastes in Sedan Crater.

Exhumation is an obvious major concern, because the wastes could be buried within as little as 15 m of the surface. Accordingly, I will first address the likelihood of exhumation of the wastes by tectonism, by normal erosion processes, by meteorite impact, by direct intrusion of volcanic rocks, and by man.

Yucca Flat is within a portion of the Great Basin undergoing crustal extension (*18, 19*) in a northwest-southeast direction. Parts of Yucca Flat have been sinking relative to its margins for at least the last 3 million to 4 million years (*18*); that is, the floor of Yucca Flat is an active and tectonically induced aggradational (depositional) environment. Sedan Crater is 1200 m east of Yucca fault, a major fault trending north-south across most of the length of Yucca Flat (see cover photo and Fig. 2). The latest surface displacement on Yucca fault probably took place between 1,000 and 10,000 years ago. The east side of the fault is downthrown and, along most of its length, separates areas with relatively thick valley-fill deposits east of the fault from relatively thin deposits west of the fault. The valley fill immediately east of the fault is 75 to 380 m thicker than the fill west of the fault (*20*). At the latitude of Sedan Crater, this difference amounts to about 200 m (Fig. 3). Carr (*18*), using gravity surveys by D. L. Healey, showed that Yucca fault is also an important factor in the depth of burial of the

Paleozoic strata underlying Yucca Flat. Evidently, Yucca fault has been an active and major structural element in the tectonic development of Yucca Flat during at least the Quaternary Period (*21*). Thus TRU wastes buried in Sedan Crater would—to the degree that the recent geologic past is an indicator of the future—not be exhumed as a result of tectonism; on the contrary, they would tend to be buried to still greater depths as rock debris is shed from ridges and mesas flanking the valley and as the valley floor east of Yucca fault subsides. Even should crustal extension cease, aggradational conditions would persist in Yucca Flat because the surrounding uplands are hundreds of meters to more than 1000 m higher than the floor of this topographically closed basin (*22*).

Possible exhumation of the wastes due to a future climate-induced integration of the drainage of Yucca Flat and Frenchman Flat appears unlikely. Frenchman Flat (Fig. 2), like Yucca Flat, is a topographically closed basin, but its playa (Frenchman Lake) level is 256 m lower than the playa at the south end of Yucca Flat. Sedan Crater is about 30 kilometers north of and 120 m higher than the surface of Yucca playa. Could pluvially induced headward erosion from Frenchman Flat, and ensuing capture of the Yucca Flat drainage, result in waste exhumation at Sedan Crater? The work of Leopold and Bull (*23*) suggests otherwise. A change in local base level of a major drainage is normally not propagated far upstream. That is, the longitudinal profile of a stream is controlled more by aggradation and degradation in closely adjoining reaches than it is by a distant base level. Moreover, relatively resistant welded tuffs underlie the drainage divide between Yucca and Frenchman flats. The presence of these rocks would retard vertical changes in profile even at the divide. A future event more likely than headward erosion from Frenchman Flat to Yucca Flat is the filling of Yucca playa (altitude, 1195 m) (Fig. 2) to the altitude of the present low divide (about 1210 m) that separates these valleys, followed by transport of sediments across Yucca Flat into Frenchman Flat. Sediments entering Frenchman Flat would be retained by an 180-m topographic closure.

Are the consequences of meteorite impact considerably more severe for shallow than for deep burial of TRU or other toxic wastes? The probability of an impact capable of causing atmospheric release of wastes buried at 600 m in a repository mined in salt has been estimated (*24*) as about 10^{-14} per square kilometer per year. The probability of a meteorite impact resulting in catastrophic exhumation of TRU wastes buried up to 100 m beneath the surface, as in Sedan Crater, is on the order of 10^{-12} per square kilometer per year (*25*). These low probabilities indicate that meteorite impact is not a serious liability to TRU waste disposal in Sedan Crater (*25*).

Breaching of radioactive waste in Sedan Crater by future volcanism also appears extremely unlikely. Explosive silicic volcanism terminated in the Nevada Test Site region 6 million to 7 million years ago (*26*); moreover, no vents for such volcanism occurred in Yucca Flat. The youngest basaltic lavas known in the region are about 300,000 years old and occur about 65 km southwest and 55 km west of Sedan. Basaltic lavas thought to be between 2 million and 7 million years old are buried in alluvium or crop out 12 to 20 km southwest of Sedan Crater (*26*). The joint probability of volcanism occurring and of exhumation of the wastes, by intrusion of basaltic dikes or by an explosive volcanic eruption beneath Sedan Crater, is very small; probabilities of volcanic disruption on the order of 10^{-9} per year have been computed for a potential repository site in the southwestern portion of the Nevada Test Site (*26*).

The concept of burial of TRU wastes within shallow underground workings in valley fill in eastern Yucca Flat, and specifically in Sedan Crater, appears satisfactory with respect to the unlikelihood of exhumation by natural forces such as tectonism, erosion, meteorite impact, and volcanism over hundreds of thousands of years. Exhumation by man is another matter and is one of the most difficult problems for any proposed repository of any depth in any geologic terrane. The absence of known mineral deposits beneath Yucca Flat, coupled with the aridity of the region and the water-table depth of about 580 m at the latitude of Sedan Crater (Fig. 2), might tend to discourage future human intru-

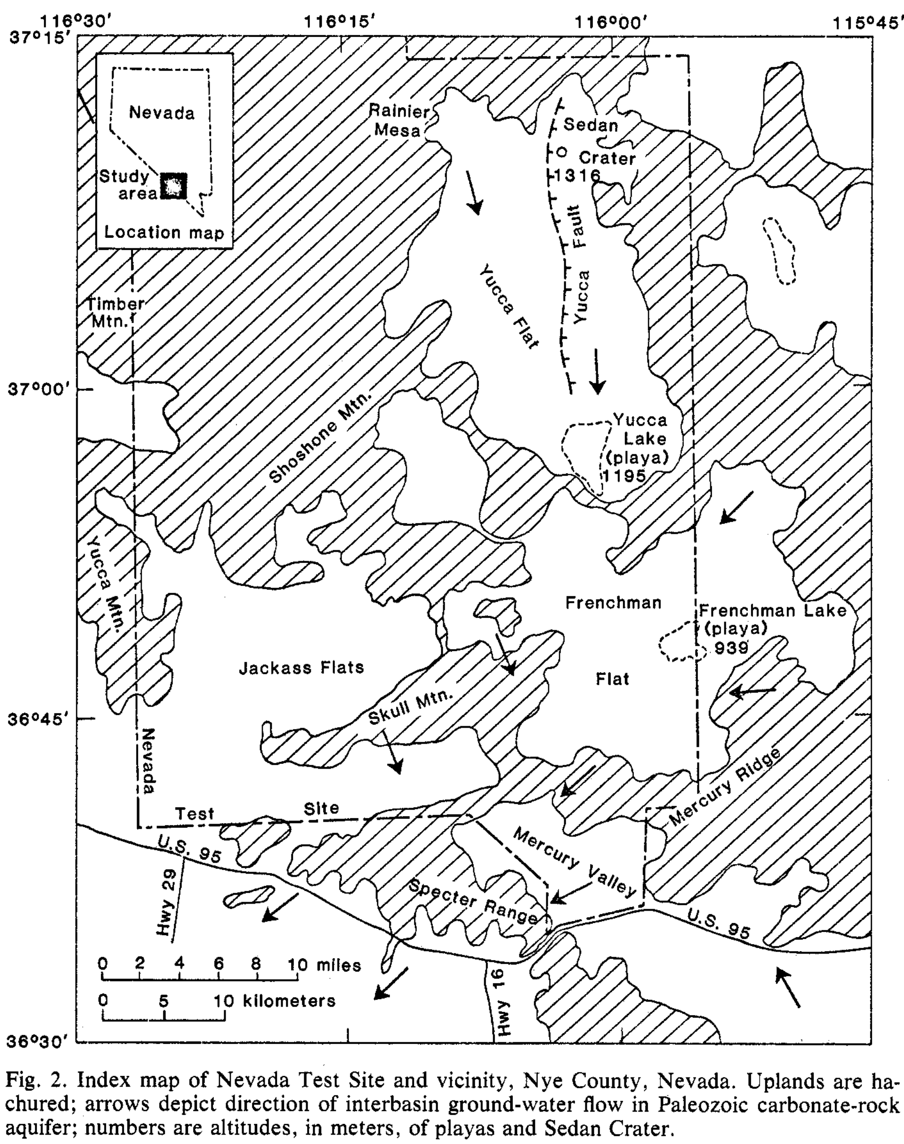

Fig. 2. Index map of Nevada Test Site and vicinity, Nye County, Nevada. Uplands are hachured; arrows depict direction of interbasin ground-water flow in Paleozoic carbonate-rock aquifer; numbers are altitudes, in meters, of playas and Sedan Crater.

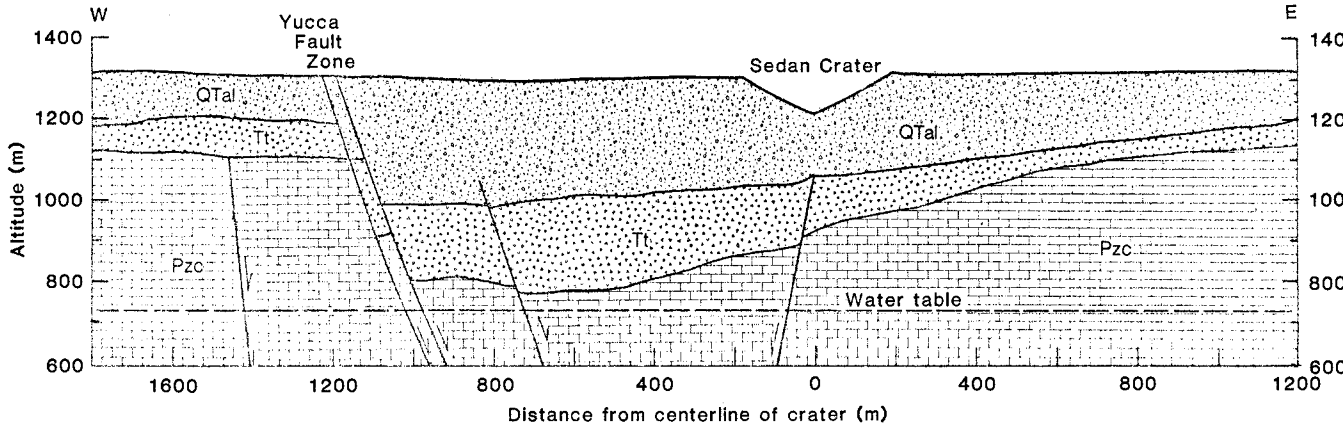

Fig. 3. Diagrammatic geologic section through Sedan Crater (no vertical exaggeration). Abbreviations: *QTal*, Quaternary-Tertiary valley fill; *Tt*, Tertiary ash-flow and ash-fall tuff, massively zeolitized in lower two-thirds; *Pzc*, Paleozoic carbonate rocks. Stratigraphy and inferred buried faults are from isopach maps by A. T. Fernald (1978 and 1979) and D. L. Healey (1977), Geological Survey, Denver, Colorado.

sion. I return to this intractable matter in a concluding paragraph.

Aside from the question of exhumation, the presence of a major young fault, such as Yucca fault, at a similar or even greater distance from a proposed deep (600 to 900 m) geologic repository below the water table might disqualify such a site from serious consideration because of (i) the possibility of earthquake damage during the construction and operational period of the repository, and (ii) the possibility of major shortening of natural ground-water flow paths by earthquake-induced fracturing after sealing of the repository. Such short-circuiting could occur as a result of either fracturing of the seal around the shaft and (or) drill holes, or creation of new and (or) extension of old water-bearing fractures. None of these problems are possible, however, for wastes buried in Sedan Crater, because no underground workings are required and, more importantly, because the wastes at the bottom of the crater would be about 480 m above rather than hundreds of meters below the water table.

I turn next to matters that, in my estimation, are more difficult scientific questions pertinent to the disposal scheme presented for evaluation. What is the flux of water through the unsaturated zone beneath Yucca Flat under present climatic conditions? What fluxes occurred during the wetter (pluvial) climates of the Wisconsin Stage of the Pleistocene and hence, by analogy, might occur during a future ice age? What backup systems exist should the unsaturated zone fail as the primary buffer to percolation of precipitation to the buried wastes, and thence to the water table, during future wetter climates?

Direct measurements of the flux of vadose water (that is, moisture in the unsaturated zone) toward the deep water table beneath Yucca Flat have not been made, and indeed few measurements of such fluxes have ever been attempted, even at depths of a few tens of meters, in similar arid zone environments (*27*). However, indirect estimates of maximum flux and flow velocities are feasible from hydrogeologic data and interpretations presented by Winograd and Thordarson (*13*). Based on their calculations of downward flux of water through saturated Tertiary tuffaceous rocks of central Yucca Flat into underlying Paleozoic carbonate rocks (Fig. 3), and on the physical property data for the overlying unsaturated valley fill presented by Carrol and Muller (*14*), I computed potential downward vadose water velocities on the order of 2×10^{-3} m per year (200 m per 10^5 years) through the unsaturated valley fill. This computation (*28*) is conservative in that steady-state conditions were assumed, that is, that modern recharge is occurring through the valley fill into the tuffaceous rocks and that none of the vertical leakage through the tuff is derived from lateral flow; if either condition does not obtain (*28*), the velocity through the valley fill is less than that cited. The flow rate cited is consistent with conclusions from data in other areas (*27, 28*). Ambient flow of vadose water through thick unsaturated zones beneath interfluvial areas of the southern Great Basin is extremely small; it may not be readily measurable with present instrumentation.

Granted that present fluxes through the unsaturated zone in Yucca Flat are insignificant, and thereby favorable (*28*) to the disposal of TRU in Sedan Crater, what fluxes are expectable should the climate of the region once again become as moist as it was during the Wisconsin? Also, would the water table rise to inundate the wastes, or a lake form over the waste burial site, following a return to a wetter climate? With regard to the magnitude of water-table rise during past wetter climates, and therefore by analogy during future ones, the recently completed work of Winograd and Doty (*30*) is pertinent. From studies of tufa (or spring) deposits and by consideration of the regional hydrogeology, we concluded that water-table rises of more than 30 m during the Late(?) Pleistocene were unlikely beneath Frenchman Flat; future rises are likely to be less than 30 m. The permeable Paleozoic carbonate-rock aquifer underlying much of the Nevada Test Site, and saturated at about 580 m beneath the Sedan site (Fig. 3), acts as a regional "tile field" controlling the modern deep (as much as 660 m) ground-water levels beneath the valleys of the southern Great Basin (*13, 30*). Deep water tables and long ground-water flow paths characterized the region during Late(?) Pleistocene pluvial climates and are likely to characterize it during similar future conditions.

No geomorphic or stratigraphic evidence suggesting the presence of Pleistocene lakes has yet been found in Yucca Flat, nor is there evidence for such lakes in Frenchman Flat (*31, 32*). Moreover, the data from dozens of drill holes in Yucca Flat and observations made in a 168-m shaft (*13, 33*) penetrating valley fill have not yielded evidence of lake deposits interbedded with the valley fill in northern Yucca Flat. Finally, under tectonic and topographic conditions similar to those that existed in Yucca Flat for the last few million years, a future lake would be located in the south part of Yucca Flat (Fig. 2) and would be of very limited extent. Only 15 m of relief exists between the playa and the drainage divide separating Yucca Flat from Frenchman Flat (Fig. 2). The land surface at Sedan Crater, in contrast, is 120 m higher than Yucca playa.

The magnitude of moisture flux through the thick unsaturated zone beneath Sedan Crater during past and future pluvials is crucial and is not known. That the climate of the Great Basin was wetter during the Pleistocene is well documented by various lines of evidence. At the Nevada Test Site, direct evidence for an increase in effective moisture (due to some combination of reduced temperature and increased rainfall) derives from classical studies of fossil pack rat (*Neotoma* sp.) middens by Wells and Jorgensen (*34*). They showed, as have others (*35*) for adjacent areas, that woodland xerophytic plants (for example, juniper) grew at altitudes as much as 600 m below their present lowest occurrences. Yet desert or semidesert shrubs grew alongside these trees. The work of these paleobotanists, while clearly indicating wetter soil conditions during pluvial times, is also indicative of semiarid conditions on the valley floors of the region. Hydrologists (*32, 36*) have reached similar conclusions regarding the magnitude of climatic change in the Great Basin, particularly the southern Great Basin, during the pluvials of the Wisconsin Stage. Additional evidence for the absence of frequent deep percolation of precipitation through the valley-fill deposits of Yucca Flat during the Pleistocene (and Pliocene?) comes from the valley-fill sediments themselves. Valley fill observed and sampled in a 168-m-deep shaft in northwestern Yucca Flat contained caliche (calcium carbonate) as a cementing material at all depths (*33*). The caliche occurred as thin white stringers, as veinlets, and as coatings on most of the cobbles and boulders. At several depths caliche layers 5 to 15 cm thick were noted (*33*). Such calcareous deposits in the Southwest are believed (*37*) to result from shallow infiltration and subsequent evapotranspiration of soil water in slowly aggrading semiarid aeolian environments. The increased diversity and density of plants growing on the valley floors during wetter climates might have prevented a significant increase in deep percolation compared with that occurring today, despite lower temperatures and (or) increased precipitation.

The cited interdisciplinary evidence for semiarid climates on the valley floors of the region during the Late(?) Pleistocene is strong. Nevertheless, the possibility of volumetrically significant percolation of precipitation to the water table during both past and future pluvial climates must be acknowledged (*38*). Such percolation does not, however, lessen the suitability of Sedan Crater (or the unsaturated zone elsewhere at the Nevada Test Site and adjacent portions of the Great Basin) as a host for TRU wastes. Several additional major backup systems are naturally present or can be constructed to increase the travel time and (or) reduce the concentration of dissolved radionuclides reaching the water table following deep percolation. These backups are (i) the sorptive properties of unsaturated valley fill and underlying zeolitic tuffs; (ii) the probable dilution, by one or more orders of magnitude, of the radionuclide content of vadose water if it were to enter and move through the Paleozoic carbonate-rock aquifer; (iii) the construction of a capillary barrier above the crater backfill; and (iv) the low solubility of the waste form itself. The pertinence of these barriers to Sedan Crater is discussed briefly below.

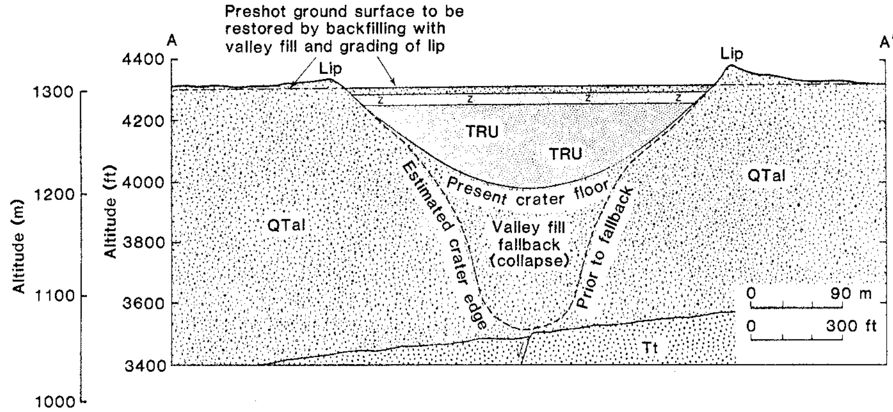

Fig. 4. Diagrammatic section of Sedan Crater showing proposed placement of transuranic radioactive waste (*TRU*) in a matrix of coarse-grained valley fill covered by fine-grained fill (*Z*). Contact of clay-sized to silt-sized valley fill (*Z*) and underlying coarse-sand to granule-sized fill constitutes a proposed capillary barrier to flow in the unsaturated zone. Symbols *QTal* and *Tt* are defined in the legend to Fig. 3. Thickness of valley-fill layers above TRU waste is exaggerated for clarity; otherwise there is no vertical exaggeration. Dimensions of present and prefallback crater are from Richards (*11*); section bearing is N58°W.

With regard to sorption of dissolved radionuclides by unsaturated valley fill and unsaturated tuff beneath Sedan Crater (Fig. 3), the current work of Wolfsberg and his colleagues (*16*) is especially pertinent. The sorption ratio that they determined, which they label R_d rather than K_d (distribution coefficient) in order to signify the probable absence of exchange equilibrium, ranged from 100 to 8000 milliliters per gram for Pu and 100 to 2000 for Am, dependent on the type of tuff. This preliminary work (done at 22° and 70°C) suggests that the zeolitized tuff beneath the valley fill at Sedan (Fig. 3) and the valley fill itself, because of its significant content of zeolitic, clayey, and other tuffaceous detritus, are sufficiently sorptive to be capable of retarding transport of actinide radionuclides in vadose water by two or more orders of magnitude in comparison to the movement of the water (*39*). Earlier work by Wolfsberg (*15*) had shown R_d's for valley fill on the order of 200 ml/g for ^{85}Sr and 8000 ml/g for ^{137}Cs. Despite several caveats (*40*), all the work to date (*15, 16*) indicates that the zeolitic-rich valley fill and underlying zeolitic tuffs are excellent sorbing media for most fission products as well as for the transuranic elements.

The radionuclide content of vadose water at the Sedan site will be diluted by one to perhaps several orders of magnitude if such water ever reaches the Paleozoic carbonate-rock aquifer, 480 m beneath the crater (Fig. 3), and moves therein toward Frenchman Flat. Assuming steady-state conditions, downward flux of vadose water through a cylinder of valley fill with the radius of Sedan Crater would be on the order of 7×10^{-4} of the previously cited (*13, 28*) downward flux through the tuffaceous rocks in the central part of Yucca Flat, about 1×10^{-4} of the total flux out of the carbonate-rock aquifer at the south end of the flat, and about 1×10^{-7} of the total water stored in the carbonate-rock aquifer beneath the flat (*41*). These volumetric comparisons are particularly meaningful because any downward flow of vadose water reaching the water table beneath Sedan Crater occurs in the upper reach of the flow system in the carbonate-rock aquifer beneath Yucca Flat. That is, the bulk of the south-flowing ground water (Fig. 2) enters the carbonate-rock aquifer south of the latitude of Sedan Crater. Moreover, the aquifer is extremely heterogeneous; dispersivities of hundreds of meters to perhaps kilometers can be expected in this dense but extensively fractured aquifer (*42*). Both factors—volumetric dilution and dilution by dispersion—should greatly reduce the concentration of dissolved or colloidal radionuclides moving through the aquifer to Frenchman Flat; dilution of one to several orders of magnitude does not appear unreasonable to me for dissolved radionuclides reaching the south end of Yucca Flat in the carbonate-rock aquifer (*43*). A further dilution, possibly 50-fold, is likely during flow within the carbonate-rock aquifer between Frenchman Flat (Fig. 2) and the natural discharge area at Ash Meadows, Nevada, about 55 km southwest of central Frenchman Flat. This final dilution represents the ratio of the volumetric flux in the aquifer beneath Frenchman Flat and Mercury Valley (Fig. 2) to that leaving Yucca Flat (*13*).

The barriers to transport of radionuclides from Sedan Crater discussed heretofore rely on natural processes. Two additional major barriers could be "engineered" into the Sedan or other waste repositories built in unsaturated valley fill. The first involves the construction of capillary barriers to vadose water movement. Retardation of downward infiltration of soil moisture at the contact of fine-grained and underlying well-sorted coarse-grained soils or sediments is well documented in the soil physics literature (*44*). This phenomenon, popularly referred to as the wick effect, reflects the difference in matric potential (the suction exerted by a porous medium on its contained moisture) between fine- and coarse-grained porous media. Downward drainage of vadose water from unsaturated fine into unsaturated coarse sediments begins at the saturation level (in the fine material) at which gravitational forces exceed interstitial tensional forces. In very fine grained sediment (for example, clayey silt) that overlies relatively well-sorted coarse sediment, this level may approach complete saturation before vertical drainage occurs. This phenomenon can be utilized as an engineered barrier to keep soil or vadose water away from buried radioactive wastes, as has been recognized for nearly a decade. Several recent studies (*45*, *46*) confirm its efficacy, but the work of Rancon (*46*), at the Centre d'Études Nucléaires de Cadarache, France, is especially pertinent. In a 6-year field experiment in a humid climate, Rancon demonstrated that no infiltration entered an experimental trench filled with gravel and capped with fine soil. Even the application of 40 centimeters of water (about half the annual precipitation) in a several-hour irrigation experiment did not result in water entering the coarse layer. Wick or capillary barriers serve two general purposes. First, they keep infiltration close to the surface, where, particularly in an arid and semiarid climate, soil water can be removed by evaporation and transpiration. Second, they appear to divert percolation laterally away from wastes buried in trenches, even in humid climates.

In Sedan Crater, clay-sized to silt-sized valley fill and coarse-sand to granule-sized fill may be used for construction of a capillary barrier when emplaced as shown in Fig. 4. Such a barrier at Sedan would be two orders of magnitude larger than Rancon's experimental trench and would undoubtedly require extensive engineering pilot studies to determine the degree to which various fine-coarse geometries can retard or divert deep percolation (*47*). On the other hand, annual precipitation at the crater is about one-seventh of that at Rancon's field site. The prognosis appears favorable that the wick effect should work at the Sedan and other arid or semiarid sites to greatly retard or even prevent percolation to the depths of TRU burial during future pluvial climates (*48*).

The second potential man-made barrier to radionuclide transport is the waste form itself. A final decision has not been made on the physical and chemical form(s) into which TRU wastes will be fabricated prior to burial. Tentative plans exist (*1*, pp. 5-1 to 5-10) for converting TRU waste to siliceous slag after incineration. Obviously, an additional major barrier to waste mobilization by vadose water can be achieved by fabrication of the wastes in a form that has relatively low solubility and is also physically and chemically compatible with the valley fill surrounding the waste. Discussion of possible waste forms, their resistances to leaching in an unsaturated environment, and the state [ionic, colloidal(?)] of the leached actinide elements is beyond the scope of this article.

Are the natural and man-made barriers to radionuclide transport, discussed above, reasonably independent, or will one or two fail on failure of a third? This question deserves detailed thought prior to a commitment to TRU waste disposal in Sedan Crater or other sites in thick unsaturated zones of the region. If one accepts the likelihood that, due to tectonic subsidence, the wastes will not be exhumed by erosion in the next 10^4 to 10^6 years, then the remaining barriers—slow vadose water flow, sorption, dilution in carbonate aquifer, wick effect, and low solubility of waste form—appear to be largely independent of each other in that time frame. If, after detailed study, the probability of exhumation proves significant, then the attractive hydrogeologic, tectonic, and geochemical features of the very thick unsaturated zone beneath Yucca Flat (and selected adjacent valleys) might still be utilized by burying TRU wastes in shallow (say 100 to 200 m) mines at greater depths than provided by Sedan Crater, but still well above the water table.

The matter of future human intrusion is the crucial unresolved, and perhaps unresolvable, issue. The Interagency Review Group report (*3*) on radioactive waste disposal explicitly acknowledges that we cannot predict the behavior of our descendants, and that therefore disposal site characteristics must not encourage future human intrusion. Obviously, areas containing economic minerals, oil, or gas should be avoided. Potable water supplies are also economic resources to be protected. As mentioned earlier, Yucca Flat is underlain by a carbonate-rock aquifer containing potable water. This aquifer is buried as much as 1200 m beneath the valley floor. Water levels in wells tapping it range from 470 to 660 m beneath the surface, depending on their position in Yucca Flat; beneath the Sedan site the water table is projected to be at depth of about 580 m. This aquifer is capable of yielding 100 to 1000 m^3 per day with drawdown of a few meters to tens of meters. In northern Yucca Flat the carbonate-rock aquifer has a low transmissivity (*49*). Nevertheless, what is the likelihood of humans tapping this aquifer in the future for domestic or municipal water? And what are worst-case scenarios for the radionuclide content of the well water at various distances from Sedan Crater? Answers to such questions will fall in the domain of risk analysts and mass-transport modelers. I point out, however, that contamination of this aquifer, caused by TRU waste burial in Sedan Crater, appears possible only if there is a sequential failure of the several barriers discussed above. Finally, it should be pointed out that federal control of the Nevada Test Site area for military uses appears likely as long as our government survives or until nations beat their swords into plowshares. Are there better places to dispose of nuclear wastes of all kinds—from the standpoint of maintaining institutional control over the wastes—than at a major military nuclear installation that also has hydrogeologic, tectonic, and geochemical conditions highly favorable for waste isolation?

Conclusion

The association together in Yucca Flat of a thick unsaturated zone comprised of rocks with high sorptive capacity for radionuclides, very slow flow of vadose water through this unsaturated zone, and crustal extension provides a series of natural and apparently independent barriers to the exhumation, mobilization, and transport to the hydrosphere of radionuclides buried in Sedan Crater. These primary barriers can be augmented by engineered ones to provide additional safeguards against radionuclide release in the event of return of the somewhat wetter climates which occurred in the Great Basin during the Pleistocene Epoch. The hydrogeologic, geochemical, and tectonic environment of Yucca Flat, and adjacent portions of the Great Basin, appears capable of isolating buried radioactive waste from the hydrosphere for times on the order of tens of thousands to hundreds of thousands of years.

Waste burial at relatively shallow depths (15 to 100 m) hundreds of meters above the water table obviates concern about the durability of shaft and borehold seals—a major unknown in the design and risk analyses of waste repositories mined hundreds of meters below the water table. Relatively shallow waste burial also permits ease of monitoring, waste retrieval if needed, and can be accomplished, in the case of Sedan Crater, at a saving of perhaps \$0.5 billion (*7*) in comparison with presently authorized plans to dispose of transuranic wastes in a deep-mined repository. On the other hand, several potential liabilities, including one specific to Sedan Crater, are evident. First, burial of radioactive waste at shallow-depth in a tectonically active area—both matters at odds with currently favored concepts for waste disposal—may initially face adverse public reaction. Second, waste burial in Sedan Crater might be preempted by joint Department of Defense–Department of Energy defense-related activities. Third, unresolved technical matters—some equally pertinent to migration of radionuclides from deep waste repositories—remain. For example, our knowledge of the physicochemical mechanisms controlling sorption of dissolved (colloidal?) actinide species by common minerals in unsaturated or saturated environments is in its infancy. In addition, direct measurements of the downward(?) flux of water through natural and disturbed (as at Sedan) unsaturated zones, even to depths of only tens of meters, remain sparse, yet such data are needed as a check on the flow rates estimated by indirect methods.

To the degree that detailed geotechnical studies endorse the ideas proposed here for TRU wastes, the thick unsaturated zones beneath Yucca Flat, and adjacent valleys of the Great Basin undergoing crustal extension, also warrant consideration for the disposal of solidified low-level and high-level radioactive wastes and solidified highly toxic chemical wastes (*50*). On the basis of available knowledge, such environments appear capable of isolating solidified toxic wastes from the hydrosphere for perhaps hundreds of thousands of years, barring future human intrusion.

References and Notes

1. Department of Energy, *Draft Environmental Impact Statement, Waste Isolation Pilot Plant* (DOE/EIS-0026-D, Washington, D.C., 1979), pp. 1-1 to 1-9 and 2-20 to 2-22.
2. ______, *Draft Environmental Impact Statement, Management of Commercially Generated Radioactive Waste* (DOE/EIS-0046-D, Washington, D.C., 1979), vol. 1, pp. 1.1–1.36.
3. Interagency Review Group on Nuclear Waste Management, *Report to the President* (TID-29442, Washington, D.C., 1979), pp. 35–76 and appendix D (tables 1, 11, 14, and 15).
4. Estimated volumes of TRU waste which I cite below for the period 1980 to 2000 are based on an assumed nuclear capacity of 148 gigawatts electric in 2000.
5. High-level radioactive wastes include intact but spent-fuel rod assemblies and (or) wastes generated during recovery of uranium and plutonium from spent fuel. Because of their radioactivity and heat, these materials require remote handling. Transuranic wastes result from reprocessing of spent fuel and fabrication of plutonium to produce nuclear weapons. These wastes, largely of defense origin, generate little heat, but their actinide-element content is of the same order as that in HLW, necessitating their isolation from the biosphere for equal periods of time. Isolation times of 10^3 to 10^6 years have been suggested by various authors [Office of Science and Technology Policy, *Subgroup Report on Alternative Technology Strategies for Isolation of Nuclear Waste* (TID-28818, Washington, D.C., 1978), appendix A, pp. 8–13].
6. D. S. Metlay, in *Essays on Issues Relevant to the Regulation of Radioactive Waste Management* (NUREG-0412, Nuclear Regulatory Commission, Washington, D.C., 1978), pp. 1–19.
7. Estimated construction, engineering, and technical support costs for placement of TRU wastes at a depth of 640 m in bedded salt at the WIPP site near Carlsbad, New Mexico, are on the order of \$0.5 billion, exclusive of the value of denied potash and oil and gas reserves and resources (*1*, p. 3-7). The Sedan Crater disposal scheme involves no mining, no mineral denials, and should cost significantly less than deep disposal.
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10. National Academy of Sciences, *The Shallow Land Burial of Low-Level Radioactively Contaminated Solid Waste* (Washington, D.C., 1976), pp. 66–71; *Radioactive Wastes at the Hanford Reservation, A Technical Review* (Washington, D.C., 1978).
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12. The valley-fill deposits consist of poorly sorted clay to gravel-sized alluvium derived from Tertiary tuffaceous rocks and Paleozoic carbonate and clastic rocks comprising the hills surrounding northern Yucca Flat.
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16. K. Wolfsberg, E. N. Vine, B. F. Bayhurst, in *Sandia Lab. Rep. SAND 80-1464* (1980), pp. 39–48 and 111–128.
17. I. J. Winograd and W. Thordarson (*13*), pp. C31–C38 and C43–C46; W. Thordarson, *U.S. Geol Surv. Open-File Rep. TEI-862* (1965).
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19. J. H. Stewart, in *Geol. Soc. Am. Mem. 152* (1978), pp. 1–31; M. L. Zoback and M. D. Zobak, *J. Geophys. Res.* **85**, 275 (1980).
20. A. T. Fernald, isopach map of valley-fill deposits, written communication (1978); W. J. Carr (*18*), pp. 22–33, figure 10.
21. The absence of thickening of late Tertiary volcanic rocks in most areas beneath Yucca Flat suggested to Carr (*18*) that the medial depositional troughs in Yucca Flat are relatively young features, less than 3 million to 4 million years old.
22. The time frame over which basin subsidence might lower the wastes to the water table, 580 m below the present surface, might be viewed as the converse of the question of possible exhumation. Using the maximum estimated (7100 m) uplift in the Great Basin given by Stewart (*19*) and the minimum uplift time (say, 7 million years), a maximum uplift rate (or maximum subsidence rate of the basin) of 1 m per 10^3 years is indicated. At this maximum rate, it would take nearly 5×10^5 years for subsidence to carry the TRU wastes 480 m from the bottom of Sedan Crater to the water table. More pertinent subsidence rates, as low as 0.3 m per 10^3 years, are suggested by the subsurface geologic data for Yucca Flat; the maximum rate is cited to demonstrate worst-case conditions. Also, because of the major role of a regional carbonate-rock aquifer in controlling the deep ground-water levels of the southern and eastern Great Basin (see subsequent discussion) and the proximity of the Death Valley topographic-hydrogeologic sump (*13, 30*), it is likely that ground-water levels will become lower with time.
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24. H. C. Claiborne and F. Gera, *Oak Ridge Natl. Lab. Rep. ORNL-TM-4639* (1974), pp. 13–27.
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26. W. J. Carr, oral communication (1980); *U.S. Dep. Energy Rep. NVO-196-12* (1979), p. 19; B. R. Crowe and W. J. Carr, *U.S. Geol. Surv. Open-File Rep. 80-357* (1980).
27. The most comprehensive measurements of deep infiltration within thick unsaturated zones that I am aware of are those made in two 17-m lysimeters placed in Pleistocene sediments at Hanford, Washington, during the period 1972 to 1977. In general, these measurements indicated no fluctuation in moisture content between depths of 12 and 16 m and fluctuations of 1 percent or less between 2 and 12 m. Estimates of steady-state flow—on the order of millimeters per year—for these alluvial sediments were hampered by lack of accurate values for hydraulic conductivity at volumetric moisture contents as low as 6 percent. Upward vapor transport was held to be important at the low moisture levels present. The pertinent reports are L. E. Brownell *et al.*, *Atlantic Richfield Hanford Co. Rep. ARH-ST-123* (1975); G. V. Last, P. G. Easley, D. J. Brown, *ibid.*, *ARH-ST-146* (1976); T. L. Jones, *Rockwell Int. Rockwell Hanford Operations Rep. RHO-ST-15* (1978); R. J. Baca, I. P. King, W. R. Norton, *ibid.*, *RHO-SA-31* (1978). The reader also is referred to T. W. Sammis and L. W. Gay, *J. Arid Environ.* **2**, 313 (1979); U. Kafri and J. Ben-Asher in "Hydrology and water resource in Arizona and the Southwest," *Proc.*

Ariz. Sect. Am. Water Resour. Assoc., Hydrol. Sect. Ariz. Acad. Sci. **6**, 203 (1976). Pre-1974 references on paucity of deep percolation are summarized by Winograd (*9*).

28. The downward flux through the tuffaceous rocks used is the maximum given by Winograd and Thordarson (*13*), namely 65 acre-feet annually (equivalent to 2.8×10^6 ft^3 or 8.0×10^4 m^3) through an area of 18×10^8 ft^2 (1.7×10^8 m^2). To obtain velocity, I used a porosity of 0.20, which represents the average volumetric saturation of valley fill indicated by the geophysical log analysis of drill holes by Carrol and Muller (*14*). However, analyses of samples from the U1-C shaft in valley fill in west-central Yucca Flat suggest a volumetric water saturation of 0.13. Should the shaft data prove more representative than those derived from the geophysical log analysis, the cited velocities would be increased by about 50 percent. If steady-state conditions do not occur, considerably less or even no downward flux may occur through the valley fill, and the drainage through the saturated tuffs cited in (*13*) is a vestige of the Wisconsin pluvial climates. Yet another indication of the paucity of moisture flux in Yucca Flat is available from other data in (*13*); if ground-water flow through all the saturated strata in the flat (tuff and Paleozoic carbonate and clastic rocks) is considered, no more than a few thousandths of present-day annual precipitation infiltrates to the water table. This computation is also highly conservative; it excludes known underflow into Yucca Flat from adjacent areas. Ongoing measurements of matric potential and volumetric water content to a depth of 10 m by D. Nichols [written communication (1980)] in an unsaturated valley fill near Beatty, Nevada (about 75 km southwest of Sedan), suggest—when used in conjunction with unsaturated valley-fill hydraulic conductivity data of Mehuys *et al.* (*29*)—hydraulic conductivities in the range 10^{-6} to 10^{-4} m/year; these unsaturated conductivities yield velocities even smaller than my estimates for Yucca Flat valley fill. Obviously, fluxes beneath major arroyos and beneath areas covered with sand dunes will be higher than those cited here, but such conditions do not pertain to Yucca Flat. I have assumed above that the moisture flux through the disturbed valley fill, underlying and to be emplaced in Sedan Crater, will not be significantly greater than that in undisturbed fill. Should direct measurements of flux not support this assumption, additional capillary barriers (*44–47*) can be constructed to reduce flow to natural amounts.
29. G. R. Mehuys *et al.*, *Soil Sci. Soc. Am. Proc.* **39**, 37 (1975).
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37. L. R. Gardner, *Geol. Soc. Am. Bull.* **83**, 143 (1972); L. L. Lattman, *ibid.* **84**, 3013 (1973); D. M. Stuart and R. M. Dixon, *Soil Sci. Soc. Am. Proc.* **37**, 323 (1973); C. N. Brown, *J. Geol.* **64**, 1 (1956).
38. Unsaturated hydraulic conductivities vary by orders of magnitude in response to small changes in vadose water content as shown most appropriately by the data of Mehuys *et al.* (*29*) for valley-fill deposits. Thus, even if major recharge events were uncommon during pluvial climates, vadose water fluxes between such events may have exceeded modern fluxes due to increased unsaturated hydraulic conductivity of the valley fill.
39. Retardation was estimated by using the cited R_d's and the equation

$$\frac{\overline{V}}{\overline{V}_c} = 1 + \frac{\rho_b}{n} K_d$$

where $\overline{V}$ is average linear velocity of ground water; $\overline{V}_c$ is average velocity of the retarded species (actually 0.5 point of C/C_0 plot; where C denotes concentration); ρ_b is dry bulk density, taken as 1.7 for alluvium, and n is porosity, taken as 0.2 (upper value of unsaturated volumetric moisture content). Use and limitations of this equation and of K_d's (or R_d's) are discussed by R. A. Freeze and J. Cherry [*Groundwater* (Prentice-Hall, Englewood Cliffs, N.J., 1979), pp. 402–413] and by Wolfsberg *et al.* (*16*). The major role played by even modest sorption (say, K_d of 15 ml/g) in retarding transport of dissolved radionuclides is well illustrated by G. de Marsily, E. Ledoux, A. Barbreau, and J. Margat [*Science* **197**, 519 (1977)]. Their article is also pertinent to a disposal scheme in the unsaturated zone in what they consider a vertical ground-water flow path of only 500 m.
40. Some caveats on all cited R_d values are in order, however. First, although no clear relation of sorption to grain size was apparent in the R_d experiments, the R_d's were nevertheless determined on crushed rather than natural tuff specimens. Second, the experiments were of the batch rather than the column type. Both factors probably favor higher R_d's than those obtained with natural samples. (The cited authors recognized these caveats, and experiments to evaluate them further are under way.) Third, we are not certain how R_d's yet to be measured for unsaturated flow conditions will compare with those reported for saturated flow. Fourth, experiments with unsaturated valley fill from the Sedan site are in order. A potentially detrimental aspect of sorption, namely the general question of whether geochemical retardation of actinides might result in a critical mass in a repository at some future time, has been addressed by E. J. Allen [*Oak Ridge Natl. Lab. Rep. ORNL/TM-6458* (1978)], in the WIPP Environmental Impact Statement [(*1*), pp. 9-144 to 9-146], and by the National Academy of Sciences [*A Review of the Swedish KBS-II Plan for Disposal of Spent Nuclear Fuel* (National Academy of Sciences, Washington, D.C., 1980), pp. 51–52]. The consensus of these studies is that criticality is unlikely, particularly in the absence of ground water.
41. To obtain an estimate of the volume of water in storage in the carbonate-rock aquifer, I assumed a width of 9.6 km, a depth (or thickness) of 1.5 km, a length of 29 km, and an effective fracture porosity of 0.001. The dimensions and porosity were chosen to minimize the estimate of water in storage. See (*28*) for other data pertinent to computation.
42. I. J. Winograd and F. J. Pearson, Jr., *Water Resour. Res.* **12**, 1125 (1976).
43. The dilution estimates cited are pertinent only if the carbonate aquifer is tapped at some distance, say on the order of kilometers from the repository. Water pumped from a deep well tapping the aquifer at or near Sedan could not be diluted to the magnitude cited.
44. D. E. Miller, *U.S. Dep. Agric. Conserv. Res. Rep. 13* (1969); J. R. Eagelman and V. C. Jamison, *Soil Sci. Soc. Am. Proc.* **26**, 519 (1962); W. N. Palmquist, Jr., and A. I. Johnson, *U.S. Geol. Surv. Prof. Pap. 450-C* (1962), p. C142.
45. J. C. Corey and J. H. Horton, *Dupont Corp. Savannah River Lab. Rep. DP-1160* (1969); R. Rancon (*46*); E. O. Frind, R. W. Gillham, J. F. Pickens, in *Proceedings of the First International Conference on Finite Elements in Water Resources*, W. G. Gray, G. F. Pinder, C. A. Brebbia, Eds. (Pentech, London, 1976), p. 3.133.
46. D. Rancon, in *Underground Disposal of Radioactive Wastes* (International Atomic Energy Agency, Vienna, 1980), vol. 1, pp. 241–265.
47. Geometric arrangements of fine-grained over coarse-grained layers other than that shown in Fig. 4 are feasible. For example, the wastes could be emplaced in a silt-sized zeolitic tuff matrix (to further enhance radionuclide immobilization), which would be covered in turn by layers of well-sorted (coarse-grained) and poorly sorted valley fill.
48. Over a period of 10^2 to 10^4 years I would expect that some fractures might develop across the capillary barrier due to the relatively active tectonism of the region. In general, however, the friable nature of the valley fill containing and overlying the TRU wastes should tend to prevent formation of open fissures. Similarly, the ~ 150 m of fallback material (*11*) underlying Sedan Crater is likely to be much more friable than undisturbed calcium carbonate cemented valley fill and therefore less likely to propagate upward fissues initiated by "deep-seated" tectonism. If open fissures should extend to the surface, they would be potential avenues for intermittent surface water runoff until they filled with sediment. It is hoped that fissures opening during the period of institutional control of the site would be filled by our descendants.
49. The transmissivity of 265 m of carbonate-rock aquifer at Department of Energy well 2, about 4 km west of Sedan, in only 16 m^2/day (1300 gallons per day per foot) (*13*).
50. In earlier papers (*9*), I analyzed the assets and liabilities of disposal of high-level radioactive wastes (other than spent fuel) in unsaturated valley fill. I acknowledged that the low thermal conductivity of relatively dry valley fill would necessitate either disposal of aged HLW, "fresh" waste with a lower curie content, or waste emplacement at low densities. The HLW might be buried as solids either in shallow (100 to 200 m) mines, shallow (30 to 100 m) drill holes, or deep (20 to 30 m) trenches. Mining in the unsaturated valley fill at the Nevada Test Site has posed no particular problems to date [P. D. Pack and E. H. Skinner, in *Site Characterization, 17th U.S. Symposium on Rock Mechanics*, W. S. Brown, S. J. Green, W. A. Hustrulid, Eds. (Utah Engineering Experiment Station, Univ. of Utah, Salt Lake City, 1976), p. 5A3-1]. A preliminary appraisal [J. R. Smyth *et al.*, *Los Alamos Sci. Lab. Informal Rep. LA-7962-MS* (1979)] of the thermal aspects of an HLW repository in valley fill concluded that such disposal was feasible provided the heat production of the waste is tailored to the thermal conductivity of the valley fill. Placement of spent fuel in the unsaturated zone would necessitate careful study of the diffusion of gaseous products to, and their concentration at, the surface. A variety of rocks occur in unsaturated-zone environments of the Great Basin, although only valley fill has been discussed. I have focused on these unconsolidated sediments primarily because of their excellent sorptive properties for radionuclides and their ability to act as a buffer to deep percolation. However, toxic waste disposal is also feasible in other rocks found in unsaturated-zone environments—for example, welded tuff, zeolitized tuff, sandstone, and basalt—particularly where such media are overlain by valley fill; the alluvium would serve as a buffer to store precipitation near the surface and to return it to the atmosphere via evapotranspiration. Utilization of unsaturated basalt, even in the absence of an alluvial cover, was suggested by the National Academy of Sciences (*10*) for HLW disposal at Hanford.
51. I thank M. S. Bedinger, W. J. Carr, G. P. Eaton, W. E. Hale, W. D. Nichols, E. F. Rush, W. S. Twenhofel, D. B. Stewart, E. P. Weeks, and W. E. Wilson for thoughtful review comments. This article is an expansion of a talk presented before the Nevada Operations Office of the Department of Energy in Las Vegas on 10 March 1977.