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Radioactive Waste Disposal in Thick Unsaturated Zones

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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.

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.

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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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.

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

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

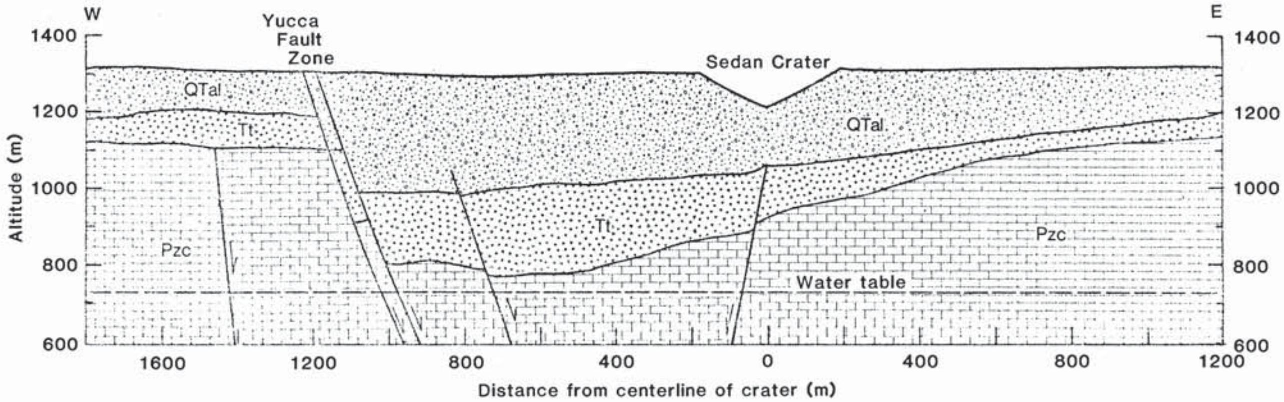

Fig. 3. Diagrammatic geologic section through Sedan Crater (no vertical exaggeration). Abbreviations: *QTal*, Quaternary-Tertiary valley fill; *Tt*, Tertiary ash-flow and ash-fall tuff, massively zeolitized in lower two-thirds; *Pzc*, Paleozoic carbonate rocks. Stratigraphy and inferred buried faults 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 French-