Enclosed is CARD's Rebuttal to DOE's Response to CARD's Comments on DOE's Compliance Certification Application (CCA) for the Waste Isolation Pilot Plant (WIPP). CARD's Rebuttal consists of two papers, one by Dr. David T. Snow (18 pages) and one by Dr. Richard H. Phillips (32 pages). Also included are pages 26-46 of DOE's Response; for the convenience of the reader, Dr. Phillips has numbered DOE's arguments and his own responses correspondingly.

It is not clear from EPA criteria 194.63 (CFR 61:28, Feb. 9, 1996, p. 5245) that EPA is required to respond to documents submitted before the Notice of Proposed Rulemaking. Nor is there any confirmation in the docket (A-93-02, Item # III-B-1) that EPA considered any information submitted by the public in arriving at its proposed certification decision. Therefore, CARD is resubmitting the original reports by Drs. Snow and Phillips, first submitted on March 17, 1997, so that there can be no question that, as a matter of law, EPA received them in a timely manner. These include:


CARD reserves the option of submitting further comments before the deadline on February 27, 1998.
January 9, 1998

To: U.S. Environmental Protection Agency  
Office of Radiation and Indoor Air  
401 M Street SW  
Washington, D.C. 20460

From: David T. Snow, Ph.D., P.E.  
Citizens for Alternatives to Radioactive Dumping  
144 Harvard SE  
Albuquerque, NM 87106

Re: Reply to DoE Comment Responses dated July 3, 1997 on the DoE CCA

On July 3, 1997, DoE submitted to EPA a set of responses to CARD’s March, 1997 Comments on the Compliance Certification Application. If DoE had applied normal consideration, copying its submission to CARD at that time, the following reply to those responses could have been prepared in more timely fashion for your consideration. DoE has labeled Card’s comments Nos. 1 to 24, and the below replies follow that organization and pagination.

Comment 1, p. 1

There is no contention with CARD’s item 1, that is, DoE admits to the development of aqueous solutions and suspensions of actinides in the repository. Contention remains over items 2 and 3, and these are still unrefuted by DoE in their responses of July 3, 1997. They have asserted that the salt seals will have consolidated and DRZ fractures will have rehealed before repository fluid pressures act across them. Apparently DoE, its consultants, advisors and reviewers are content to conceptualize the seal system sustaining pressures that are below lithostatic for all levels in shafts and boreholes. At such pressures, CARD agrees that it is possible to defend the discharges (e.g., \(1 m^3/10,000\) years) through intact seals with small, continuous hydraulic conductivities attained in plugs of crushed salt and clay after decades of consolidation by salt creep. But that model is unrealistic of seals that have been subjected to pressures that will hydrofracture the materials, part them at their contacts and erode channels as fluids bypass them.

To ignore the eventuality of failure by hydrofracture is to ignore geological analogues as well as theory. Hydrothermal alteration and epigenetic mineralization occurs when an aqueous solution separates from a magmatic silicate melt undergoing crystallization and differentiation. The volatile solutions rise from the melt where their pressures are equal and lithostatic, hydrofracturing the solid containment because lithostatic pressure decreases with altitude more rapidly than does the hydrostatic pressure. Likewise, in absence of an aqueous phase, magma that is hotter thus lighter than its containing rock fracs its way to the surface of a volcano. Just so will gasses or brine in the upper parts of the repository surpass lithostatic when salt closure ceases at the downdip extremity of the facility. Communicating via anhydrite beds over pillars and panel seals, the gas pressures
will be first to exceed lithostatic. The concrete plug at the shaft bottom is permeable, so its fluids attain pressures at even greater exceedance over lithostatic the higher they penetrate above the repository. Contact hydrofracture and salt hydrofracture past salt and asphalt seals will propagate unstably upwards. Since disposal in salt was first conceptualized, the fundamental mechanics of displacement of a low-density fluid inclusion in a plastic, high-density medium has remained intact.

From the moment it became evident that the repository would collect appreciable brine during closure, the concept of nuclear waste disposal in plastic salt has remained indefensible. The NSF did not envision liquids when it recommended salt as a geologic medium for permanent containment of dry waste. Gaseous hydrofracture and discharge is not a fatal flaw, but escape of brine solutions in excess of what can be sequestered by engineered barriers in the repository cannot be prevented.

Comment 2, DoE response, 1st line, p. 5

If the proposed seals represent an established design, then DoE should present precedents for them, with details of emplacement and performance, preferably during centuries of closure of salt, documenting containment of fluids under high pressures. More accurately, it should be said that the proposed seals have been established only in the minds of the designers, neither fixed in concept nor detailed in design. An engineer should affix his seal to DoE’s shaft sealing plans only if he believes that structural failure after his life-span is not his responsibility.

Comment 2, p. 6

There is no certainty that the tentative seal design will be successful in preventing entry of water from the Rustler to the repository. Since the shafts are eccentric to the paneled repository area, subsidence during the decades after sealing will exert shears along any rigid shaft contacts, such as concrete linings. Mine flooding has occurred by reason of dissolution along such contacts. But as the closure rate diminishes when repository pressures approach lithostatic at those depths, neither the salt seals nor the natural ground can be certified to prevent escape of fluids upwards along hydrofractures. In short, the containment of fluids in a large salt cavern is impossible, and has always been so. The concept of nuclear waste disposal in salt was compromised fatally upon discovery of brine seeps into the trial repository rooms at WIPP. DoE has persistently ignored the inevitable need to abandon the project because such containment is required. Succeeding research expenditures have made it no more acceptable because the liquids that can convey radionuclides have not been wholly eliminated.

Comment 3, 3rd para., p. 11

DoE has attempted to use PA as a crutch for ignorance, and few realize the lies engendered: Monte Carlo sampling is a powerful, accurate means of combining terms of a function, each of which is uncertain in magnitude because it ranges over a definable PDF. However, DoE has employed Monte Carlo sampling to also include uncertain alternative magnitudes and competing concepts, both illegitimate applications.
For example, matrix diffusion, as opposed to other mechanisms of species retardation, has been deduced from tracer testing in fractured Culebra dolomite. The range of retardation factors from such local tests cannot be uniformly applicable to other areas, particularly where dissolution channeling minimizes diffusive interchange with wallrock pore spaces. Likewise, sorption derived from tests on crushed rock samples of dolomite cannot be uniformly applied (in absence of field tests) to transport paths of far smaller specific surface area, such as dissolution-enhanced fractured media, or karst channels in salt, anhydrite or siltstone.

Suppose one concept never leads to failure (i.e., to an unacceptable CCDF), while another concept or process, deemed less likely, would, if true, so greatly influence flow that it would inevitably lead to failure. By allowing, say, 10% of the PA runs to follow the adverse concept, averaging its influence with other distributions, the CCDF remains favorable. By sampling distributions independently, the correlations between functions such as diffusive and sorptive retardation with conduit size distribution have been neglected by PA. The process hides the fact that there would be a 10% chance of failure. There is no substitute for the correct concept; each must be judged correctly to be right and admitted, or wrong and rejected. Correct assumptions and concepts are required if PA is to be valid. It cannot ameliorate an unlikely but fatal process or concept by biasing results towards favorable concepts through an averaging process like Monte Carlo sampling.

Comment 3, 1st subpara., p. 12

Insignificant Salado interbed flows have been computed on the basis of flow-tests conducted at low pressures in the anhydrite marker beds adjacent to the test rooms. The equivalent porous-media conductivities are low because they were conducted in an environment already depressurized by drainage to the rooms. BRAGFLO has incorporated fracture conductivity as a function of effective stress, but far greater fluxes would occur as hydrofracture exceeds elastic limits and opens clay partings at salt/anhydrite contacts and within the salt beds, or as existing anhydrite fractures open upon reaching fluid pressures at or above lithostatic. Furthermore, creep closure will stretch the anhydrite beds above and below the rooms, panels and the repository, opening steep fractures appreciably, and enhancing continuity.

Comment 3, 2nd subpara., p. 12

The DoE response suggests that the waste will have the strength to support the weight of the overburden rock. It can be argued that it will first compact (expel air), then saturate and consolidate (expel brine and dissolved waste). Because salt is plastic, when forces transmitted through waste drums attain local loads in excess of lithostatic when calculated over the contact areas, there will be continuing creep of salt towards the spaces where only fluid pressure opposes the motion. Only when the fluids attain lithostatic does creep cease. As stated by DoE in the next subparagraph, closure ceases when the voids are completely saturated with brine. To this must be added, "at lithostatic pressure".

In that sense, not all rooms will act alike. Abrupt roof falls and floor heaves will connect all spaces
to the marker beds above and below the repository rooms, which will provide continuity to panel and repository scale subsidence fractures and thus throughout the repository plan. Brine accumulating on the floor of all rooms may largely drain to the downdip rooms, which will saturate soonest, while updip rooms may attain lithostatic gas pressures in absence of collected brine, venting first by fracturing the highest, weakest parting, propagating the fracture updip and up-section.

Comment 3, last full para., p. 12

It is understood that BRAGFLO computes two-phase displacement along marker beds, incorporating smoothly increasing conductivity as effective stress across fractures decreases. But it does not anticipate a sudden opening and a dramatic increase of flow as a parting opens. The model idealization is believed adequate until lithostatic pressure is approached, whereupon experience such as the Hartman case suggests an abrupt escape of fluids via a single fracture that will curve upwards or jump step-wise upwards to the Rustler. Containment of fluids within anhydrite beds is not to be expected, nor can “isolation” be relied upon.

Comment 3, last subpara., p. 13

It is stated that for error (in BRAGFLO discharges) to be significant, brine inflow (during closure) would have to be large in comparison with the mild seepage data. In the undisturbed repository, gravity drainage of brine to the lowest rooms should influence modeling, progressive but incomplete saturation from down-dip to up-dip rooms occurring, coupled with gas generation until brine discharge along upper level hydrofractures permits further closure.

Comment 4, last para., p. 14, 1st para., p. 15

DoE claims that shaft performance calculations indicate that releases from cuttings, cavings spallings of an intrusion borehole are the greatest contributors to the CCDF, a prediction based on the assumed integrity of the seals. Conversely, the attainment of lithostatic pressures at the bottom of shaft seals will test the contact weaknesses of fully consolidated shaft or borehole seals, or hydrofractures along marker beds may open to the Rustler or to boreholes open to the Rustler. Thus the seal system is implicated in undisturbed release scenarios as well as disturbed cases involving Castile and Bell Canyon fluids.

Under normal circumstances, concrete placed against the walls of a hole drilled through salt, or concrete forming the bottom plug of the shaft seal system will attain radial lithostatic pressure a few years after plugging, and the contact may be envisioned to be as tight as the undisturbed salt. But air propagating (fingering) slowly updip at about repository pressure will be opposed by decreasing rock pressure. If air can open a parting at the repository, it can prize a fracture at any contact, such as salt against concrete, opening first elastically, then increasing by plastic creep. No borehole seal design is leak-proof against a rising column of gas, nor of brine, which is even more unstable because of dissolving power. The claims of negligible seal leakage (2nd subpara., p. 15) assume vanishing permeability of consolidated salt, unrealistic of behavior in the presence of fluids
exceeding lithostatic pressures.

Comment 4, p. 16

DoE's consultants at Sandia National Laboratories and scientists of the Peer Review Panel and National Academy of Sciences have evaluated seal design as though they have had experience to support their judgement of its adequacy. They seem to be of accord in the belief that an impermeable fill of consolidated salt in impermeable wall rocks of annealed salt in the DRZ, all at an isotropic pressure equal to the overburden cannot be breached by air at higher pressures. Apparently such proponents of DoE's proposed seals, or of the typical oil-field abandonment seals, have bought the claim that such materials will not hydrofracture to the surface.

Conversely, this reviewer expects failure by hydrofracture, and has experience to support it. In 1977, experiments in piezometer seal performance were conducted under the writer's direction at Lawrence Berkeley Laboratory, preparatory to application at Stripa, Sweden. The annulus between concentric steel pipes was filled with "Piezoseal", a Portland cement, 20% bentonite mixture, then cured. When one end was connected to a tank of nitrogen at 50 psi, it developed an audible leak and a gradient to the atmospheric end, as recorded at piezometers placed in intermediate sand intervals. Since leakage could not be through the steel nor the bentonite-doped cement, it was concluded that gas pressure had invaded the contact, elastically deforming the steel pipes and or fillings to open a fracture. It seemed such an obvious consequence as to deserve no publication.

The analogy to the salt-filled WIPP shafts is close enough to cast doubt upon seal integrity as gas pressures from below approach lithostatic. Salt has a lower elastic modulus than either materials in the above-described experiment. All rock materials have heterogeneities facilitating air penetration, including a change of granularity at the contact, or a film of dust on the original wall. After air invasion, the salt can deform plastically, enhancing the aperture. Because seal designs such as that proposed for WIPP are wholly untried, it must be assumed that they will behave adversely at such pressures.

Comment 5, p. 19

DoE's response to comments about hydrofracture through the Salado reflects a view on pore-pressure in such evaporite rocks that differs in a significant way from that of the writer. The belief is expressed (1st para.) that the native pore pressure in salt is less than lithostatic because "the rocks themselves support some portion of the overburden pressure". While the statement is true for rocks that exhibit strength, if rock salt is a true plastic, incapable of sustaining shear without eventual strain, then any fluid-filled cavity must attain lithostatic pressure equal to the isotropic pressure in the adjoining salt. Laboratory observations that salt creep is not initiated until some threshold deviatoric stress is imposed are mainly attributable to observational periods too brief to observe the deformation. The size of natural fluid inclusions, on the scale of a millimeter, is a measure of the long-term threshold stress difference salt can sustain.
When the Salado anhydrite beds were formed, erosional channels interrupted them, then infilled with salt. In the subsurface, the anhydrite beds are therefore inclusions in the salt, suggesting that anhydrite may deviate little from the all-around lithostatic stresses of adjoining salt beds. After disturbance, such as the deformations due to current mining activities, stresses deviate from lithostatic, especially as closure of rooms develops extensional roof and floor strains. Fractures in brittle anhydrite are stiff, capable of sustaining normal loads with lesser fluid pressures in the fractures, at least until minute flows from salt to anhydrite equilibrate pressures. Intimate contact of fluids in anhydrite fractures with bounding plastic clay lamina and salt suggest that pore pressures must also approach lithostatic.

Fracture porosity in anhydrite beds is probably small, likely < 10⁻³, so a borehole interception readily diminishes the pore pressures. If the hole were subsequently resealed with an impermeable material other than concrete, pore pressure would slowly recover if it is possible to drain the adjacent clay and salt. In the undisturbed state, if any anhydrite beds have pore pressure less than lithostatic, fluids from the salt would eventually flow to the anhydrite fractures. Though the steep fractures in anhydrite beds probably contain and convey most of the brines in the Salado, they are so short and in such intimate contact with salt that their pressures must have had abundant time to have equilibrated with the salt. The clay laminae bounding anhydrite beds may be residual, not depositional, reflecting the dynamics of changing fracture porosity with tectonics and salt deformation. Brine migration and salt regellation may produce fracture fillings of pure salt and corresponding residual clay along the adjoining impure halite beds. So native fluid pressures in anhydrite should be assumed essentially lithostatic, not the 12.5 Mpa adopted by DoE for use in BRAGFLO. The impermeable salt-filled channels limit repository-related flows to the far-field. Potential outflows are extremely limited until hydrofracture pressure is attained. That is a direct consequence of the interpretation that observed pressures are always sub-lithostatic because of sampling disturbance.

DoE’s position reflects a trust in the observations of Salado fluid pressures that are always at least 2 MPa below lithostatic. Given that condition, it would seem demonstrable that pneumatic pressure in the repository would approach but not exceed lithostatic because it would bleed off through the slightly-pervious anhydrite beds. The next logical deduction is that hydrofracture will not occur. The writer disagrees with that line of reasoning, because of the afore-mentioned native lithostatic pressures.

There are compelling reasons for a more prudent approach to the risk of hydrofracture, reasons that are both economic and safety-related. Failure of containment and a breach to the environment may perhaps not occur for hundreds of years. Radiation health damage may then occur suddenly and without warning. Thereafter, re-entry and remedial removal of the crushed drums of waste would be exorbitant. Prudence is required also because the complexity of repository design considerations in an earth environment of ill-defined properties supports the contention that failure by hydrofracture is likely. Though DoE claims conservatism, it is certainly unconservative to assume that Salado pore pressure is below lithostatic, since the converse would have dictated project abandonment years ago. Project continuance and DoE management goals since inception
have swayed the judgements of innumerable success-oriented persons, and dissenters have disappeared for lack of financial support for the scientific efforts that prove to the contrary demands.

Comment 5, para. 3, p. 19

DoE claims the integrity of seals between panels and of pillars between rooms. As indicated, the DRZ around rigid seals will heal promptly, and stress above lithostatic in pillar regions will locally inhibit hydrofracture. The writer's comment (1st para., p. 17 of DoE response) that coalescence of the DRZ can occur by hydrofracture across pillars should be amended accordingly. However, because slab failures in the roof and floor of rooms will access the interbeds, continuity from room to room and panel to panel will follow the naturally-fractured anhydrite beds, since they extend across panel seal regions and stressed pillars. Along anhydrite beds below the repository strata, brines will drain to down-dip rooms. Air and generated gasses will migrate along roof anhydrites to up-dip rooms at pressures that will increase towards lithostatic as creep closes the deepest, partially-filled rooms. The considerable closure energy of the entire repository volume that is filled with compressed air and gas is available to drive a single pneumatic fracture. Thus failure of the sealed undisturbed repository will be by sudden rupture and discharge to the atmosphere. It will not be, as envisioned by DoE and modeled by BRAGFLO, a gradual bleed-off to the far-field via the marker beds. Whether the pneumatic venting will follow weak partings up-dip (N) and up-structure to the Rustler, or alternatively, along more steeply oriented subsidence-induced fractures is conjectural, and probably moot. Either would compromise geologic containment.

Comment 5, p. 21

As measured at some boreholes, the Rustler/Salado contact zone is tight, compared to the Culebra dolomite. Elsewhere, it is an aquifer of importance. The contact zone is an interval of accumulated clay, evidently residual after dissolution of salt. The presence of clay breccia could reflect either depositional or residual formation. The stratum of residuum varies from inches to a few feet in thickness within the I.WA, but increases to about 20 feet at the Culebra Bluffs outcrop, where the Salado salt is missing. Gypsum underlies the residual clay at that exposure, whereas there is no gypsum within the residual clay. Apparently the dissolution has removed not only the salt, but also the anhydrite interbeds, after their hydration to gypsum. One cannot argue that the underlying gypsum represents the thin Salado anhydrites pancaked together, because residual clays after salt beds cannot have migrated to the thick clay accumulation. The 20+ feet of residual clay without included gypsum could not have accumulated unless the gypsum interbeds had been dissolved. Proceeding eastward from the outcrop area, one must be able to find, in less advanced states of dissolution, the gypsum interbeds lying within the residual clay. Dissolution does not occur uniformly over the area. Not only is it more complete as one traverses westward, but its distribution must be irregular. Patches of salt, patches of gypsum or unaltered anhydrite should remain in areas otherwise altered to the terminal clay residuum. The variable removal of strata gives rise to differential displacements of the overburden, producing by their irregular recurrence a pattern of randomly-oriented steep-dipping subsidence fractures superimposed upon the tectonic pattern, northeast and northwest oriented.
Nor does dissolution occur uniformly at the top of a salt formation. At any time, it is concentrated at local channels of ribbon-like shape, with residual products deposited in, and briefly arched over them. Upon collapse, flow in such channels shifts laterally to attack areas formerly protected. Anhydrite grains and chips and grains of clay particles are transported by the conduit channel flows and redeposited. These processes have been observed by the writer at various stages of development, during studies of the flooded K2 Mine in Saskatchewan. Because the processes have reached conclusion at Culebra Bluffs, with no more salt to be removed, there must be, in the transition zones extending eastward across Nash Draw and the LWA towards the line of no salt dissolution, a region of active channels that typifies an evaporite karst. Though undetected east of the WIPP-33 chain of sinkholes, open channels probably extend east from the discharge area in Nash Draw, across Livingston Ridge and into the LWA, as surface morphology suggests (Phillips, 1987 and March, 1997). They may be oriented preferentially parallel to the northwesterly and southwesterly fractures, with dissolution controlled by the paleo-gradient and its variations over the span of time of formation. Their traces as conduits could be intersected by a gently-dipping hydrofracture propagating upwards from the repository through the remaining thickness of Salado salt.

Comment 6, last para., pp. 24-25

If EPA has concluded that the potash above the repository would not be mined under current economic conditions, that judgement should be reviewed. As recently as 1990, the AMAX Mine was operated by Horizon Corp. by opening an apparently sub-economic 4-ft bed of the McNutt after the original 10-ft bed was exhausted. Because its location uniquely serves all agriculture surrounding the Gulf of Mexico, the potash resource over WIPP should be assumed to be exploited as soon as institutional controls cease to prevent mining.

Because mining subsidence produces steeply oriented fractures across the overlying interbedded salt, anhydrite and clastic sediments, it is folly to rely upon an EPA ruling that only the 7m thick Culebra dolomite will be changed in the process of fracturing. Mining subsidence within or adjacent to the LWA will breach a significant interval of the confining beds to aquifers within the environmental boundary. Consider the conceptual error introduced by EPA's criterion. They have given substance only to enhanced transmissibility of the Culebra dolomite, assumed to be confined, that it may randomly increase as much as 1000-fold. That produced little change in PA, because spatial elements of the Culebra were modeled with random increases of the transmissibility, by factors of 1. to 1000, whose geometric mean 100. most closely indexes the velocity change attributed to mining. Combined with other non-conservative transport functions, such as sorptive and diffusive retardation inapplicable to concentrated flow in channels, the CCDF remained within EPA limits. No consideration has been given to the certain effect of a few subsidence fractures, typically dipping 60 to 75 degrees, open passages that would concentrate conduction across the upper Salado interval, except for the 75m lying between the repository and McNutt horizons. The EPA's concept still requires an intrusion borehole to connect the repository to the Culebra, whereas the occasion of mining would develop widespread vertical connections above the mine, even into the LWA from mines outside its boundary. The 40CFR154 conditions are minimum considerations, not conservative at all.
Due to displacements induced by mining subsidence, steep fractures may not readily reheat in the anhydritic salt formation. Furthermore, there would be no control over the technology of shaft and borehole sealing above a future mine, so containment would be breached thereafter from the mine to the Culebra and to the surface. But to breach from the repository to the mine horizon would require either hydrofracture (undisturbed conditions) or a borehole intrusion. Thus, mining as a certainty outside the LWA and as a probability inside has not strongly modified the CCDF, and would not do so unless a more certain, calculable time of hydrofracture is included in PA. Mining could provide brine storage during venting if hydrofracture from the repository occurs before creep closure of the mine. The presence of a nearby or overlying mine, does, however, shorten a hydrofracture-established path, connecting the repository more immediately to the surface. Given a mechanism of hydrofracture, by attainment of lithostatic pressure in the repository or more readily at the top of a permeable concrete plug at the shaft bottoms, the conditions to breach 50 m of salt would readily breach the rest of the cover. A nearby or overlying mine augments the hazard, therefore.

Comments 7 to 22. Synopsis, p. 27, 4th bullet:

It is noteworthy that DoE has chosen not to respond in detail to comments concerning the Rustler hydrology, including implications of the fracture system in the Culebra, nor to the karst features of the Rustler and Dewey Lake Red Beds. Because the conduit system geometries along various parts of the path are undefined, the transport computations based upon continuous-media properties and generalized gradients suffer from the age-old problem of unknown effective porosities. Consequently, contaminant travel-times may err by orders of magnitude. In fractured and karstic formations, there is great likelihood that transmissibility tests, few in number and limited in dimensions and coverage, have missed the occasional, steep planar fracture conduits and sub-linear solution conduits. Concentrated flow along such features may shorten mean travel times from, say, 10,000 years to as little as 100 years. With rare exceptions such as WIPP-33, test wells and observation wells, being vertical, generally miss the major conduits. Since there was no hydrologic testing done in WIPP-33, the data-base does not reflect the presence nor character of channels. Tests conducted in wells accidentally near a channel may weakly reflect its presence. All of the tests miss the region of most likely solution features extending east of Livingston Ridge into the region of the western half of the LWA.

A scattering of head data-points in either continuous or discontinuous media can always be contoured because values decrease monotonously towards discharge regions. But that doesn't prove the existence of a smooth distribution. Measures in fractured formations often appear capricious rather than smoothly consistent, actually reflecting transients of very different response times in open faults to tight intervening blocks with only fine fractures. The ages of such waters may vary also. A karst channel imbedded in a formation may lie stagnant at different heads than its wall-rocks until suddenly recharged via a swallow hole. As pointed out in comments (Snow, March, 1997, p. 12) on karst hydrology, the technique of T-field modeling relied upon to fill the spaces of missing field data is invalid for discontinuous media. The conduit-size heterogeneity that invalidates T-field modeling increases from east to west due to increasing fracturization and dissolution of fillings and channels, thus the most important segments of potential flow paths from
the repository towards the discharge area in Nash Draw are ill-defined for modeling.

It was pointed out that explorations have not been conducted so as to define the variations of conduit type and their frequencies. Thus, even if T-field interpolation were valid, contaminant velocities would not be determinate because the variations of effective porosities are unknown. If DoE was aware of a line of sinkholes at the surface, including WIPP-33 (Response to Comments, p. 31), why was it not tested, and why was the obvious potential of more such features in or within the LWA not fully explored? Had the model of a simple confined porous aquifer been questioned objectively in response to observations of dissolution features, the truth would have emerged.

Because of its importance to transport, the description of conduit system geometry has received much attention by the community of hydrologists working elsewhere on nuclear waste repositories. Instead of seeking the appropriate geotechnical expertise to characterize conduit geometries, or developing their own innovative means of aquifer investigations for the purpose, DoE’s consultants have discounted, denied and avoided the issues. Instead, they have adopted the classical porous-media approach, treating the Culebra and other Rustler units as though they were sands instead of fractured, dissolved rocks. Likewise, lacking corresponding means of modeling transport through highly heterogeneous fractured media and karstic formations, DoE has made the damaging simplification that equivalent continuous media properties can be estimated, extended stochastically and modeled in conventional, 2-D, layer-cake stratigraphic style. Sensitivity studies of variable parameters and rudimentary 3-D infiltration effects (1 to 2 mm/yr) on regional flows fail to incorporate the range of properties relevant to karst terrain. DoE’s model work does not approximate reality. Suppose that contaminated brine were to be displaced up-dip from the repository to the Rustler along hydrofractures. Might it not rest there in karst channels for a long period while the gradient remains flat? Then, when a 4 or 5-inch rainstorm suddenly recharges the karst via sinkholes, can it not respond to the transient gradient by transporting the waste across the environmental compliance boundary and to Nash Draw in a matter of weeks? Admitting observations of karstification, such as the sinkholes of WIPP-33, it is incumbent upon the applicant to prove that transport will not be rapid nor episodic, that larger effective porosities exist, as the tracer tests (in the wrong areas) suggest, not small effective porosities that would imply CCDF results exceeding EPA limits.

Comments 7-22. p. 28. 1st bullet

The notion of 1 to 2 mm recharge is intuitively questionable to anyone who has visited the Mescalero Plain, a channel-less surface pitted with depressions partially filled with eolian sand. Because sinkholes are known, and observations have been made at WIPP-33 of storm water infiltrating at high rates, it is deduced that many of the sand-filled depressions conceal sinkholes or dolines, conduits for rapid recharge that must aggregate inches over some areas, not millimeters. Such surface morphology and its hydrologic implications, as can be drawn from the Phillips thesis (1987) should merit intense study by DoE. The proponent’s consultants should pursue ground penetrating radar, backhoe excavations, shallow piezometry, surface flow gaging, and other techniques. The Peer Review Panel must not have been shown the field conditions, thus preventing development of their independent opinions.
Comments 7-22, p. 28, 2nd bullet

The CCA uses the assumption that climate change may raise the water table to the surface, a condition impossible in karst terrain. A rise in the water table can multiply karst system discharges many-fold, because small rises saturate larger channel cross-sections and increase low gradients several-fold. The Mescalero Caliche implies a persistent water table below the caliche, even during glacial maxima. That horizon would be a good candidate for modeling the highest water table. Even for modern conditions of precipitation, the water table has remained undefined for lack of diligent field measurement.

Comment 20, last para., p. 30

DoE responded to CARD's concerns about potential cavernous zones in the Rustler. DoE counts upon the interpretation that soft sediments logged in boreholes across the WIPP site are not dissolution residues. That is based on Holt and Powers' investigation of exposures in shafts, where they noted intraformational conglomerates and graded bedding in fillings of erosion-bounded channels. Since these are features of open channels, they convinced everyone that they formed subareally, not in the subsurface as halite was eroded. They expressed the interpretation that a Rustler-age salt pan existed east of WIPP, that mudflats existed to the west and transitional regimes between. Conversely, Holt and Powers' description of features now obscured by shaft linings do not establish their subareal origin. The writer has had uniquely applicable experience in an environment of underground salt dissolution: In company of other geologists, he inspected, recorded, studied and interpreted processes of dissolution and sedimentation that occurred repeatedly in salt beds above a flooding potash mine. From 1988 to 1993, he made monthly inspections at the K2 Mine at Esterhazy, Saskatchewan, where successive inflows (up to 8000 gpm) from an overlying dolomite aquifer followed subsidence fractures that crossed a 30-ft redbed and downwards across 100 ft of bedded roof salt. In the course of weeks, a new leak would carve an elongate solution channel at the top of salt and along several bedding horizons in the salt. The channels were studied on hands and knees as successive new ones were formed and older ones closed by creep. Some were as much as 1000 ft long, downcut towards the mine in stair-step profile. Rounded cobbles were seen, transported from cave-ins of the overlying fractured dolomite, while eroded redbeds produced silt-chip conglomerates, sand, silt and clay which formed bedded deposits along the subterranean stream channels that meandered along the floors of sinuous solution passages walked by intact rock salt. Point bar deposits of the transported elastics contained imbricated cobbles recording flow direction. Graded bedding recorded the progressive diminution of rates as aquifer grouting stanched the flow. If one could revisit the closed passages, such cut-and-fill sedimentary features would be preserved. They would closely resemble those described by Holt and Powers at the WIPP shafts, yet the Saskatchewan channels formed not at the surface but at 3100 feet in depth. It is by no means evident that all Rustler conduits were initiated along fractures formed in response to Salado salt dissolution. Dissolution channels may also have been directly caused by dissolution of salt beds in the Rustler, or by fractures developed as a result of differential subsidence as Rustler or Salado salt was removed. The clay horizons in the Rustler were probably residuals from dissolution of those Rustler salt beds. The solution channels may extend eastward into the WIPP site, because they are related to Rustler, not
larger fraction discharges there than would be allocated by DoE on the basis of its isotropic, non-
channelized model. The important consideration is that brine from the repository, conveyed either
along breached well or shaft seals or along hydrofractures, would arrive at the Rustler aquifer in a
region tributary to Nash Draw, not Malaga Bend. In that region of prevalent solution channels, the
velocity of westerly travel to a discharge area in Nash Draw is likely to be far greater, and travel
times to the compliance boundary will be correspondingly shorter. In terms of fundamental
properties that invalidate the CCA, it is the effective porosity and anisotropy that are different from
those assumed by DoE, thus producing failing CCDF curves. Both properties are strongly
influenced by the presence of preferentially-oriented solution channels, either at salt contacts or in
fractures. Sorptive and diffusive retardation also deteriorate. Failure to seek knowledge of
dissolution by appropriate explorations is the reason for serious doubt of the idealized model
results presented in the CCA.

P. 39, 3rd. para.

As discussed above, the failure to characterize solution channels in and west of the LWA has led
DoE to ascribe to those areas transmissibilities unconservatively minimized. It claims to have
modified measures to account for pore and fracture dissolution features, but it is not evident that
those modifications have been sufficient. Since data on hand were used to adjust recharge to the
level of 0.2 mm/yr for replication of model head distribution, then T-field manipulations consistent
with those magnitudes would not change values appreciably. As gradients decrease too much
while maintaining uniform recharge. Better models can be developed that incorporate more
realistic geology than DoE has offered.

Let us suppose that one gives credence to the observations of Phillips (1987), that surface
manifestations of karstic drainage persist east of WIPP-33 and northeast of the Nash Draw
embayment, both penetrating the LWA. The system of dissolution channels must pervade the
saturated interval to at least the depth of the Culebra where fracture fillings have been dissolved.
The evaporation estimated for the area of Laguna Grande de Sal (Phillips, 1987) suggests greater
effective recharge in that karstic area, since flows from occasional storms drain efficiently via
swallow holes into the aquifer. Extending eastward from the eastern extremity of evident Culebra
leaching, salt beds may remain in the Rustler, preventing all recharge through the unit. Recharge
rate, variable over the region, should correlate best to vertical hydraulic conductivity. While rates
on the order of 1 mm/year may correspond to the low values of laboratory conductivity associated
with intact siltstones, anhydrites and salt, there is no ready method of measuring average
conductivity of ground perforated by a few, widely-spaced swallow holes. The only evident means
would entail opportunistic surface flow measurements at sinkholes on the rare occasions of storms
during years of patient observation. For example, five feet of ponded water in the WIPP-33
sinkhole represents at least a minimum recharge rate over its watershed during some interval
between storms. A rough correlation between vertical and horizontal conductivities also prevails in
such a karst region, since the Salado limits the depth of flow and directs it laterally to the discharge
area. Both vertical and horizontal conductivities far exceed values derived from a steady state
model scaled to the evaporation-controlled discharge, because karst systems operate by transient
events. Quantitative hydrology in karst terrains has evolved slowly, due to measurement
constraints, but has progressed by application of dye-tracing and surface flux measurements, tools neglected by DoE for comprehension of the WIPP site hydrology.

The importance of the admissibility of such alternative models, embodying non-uniform transient recharge, anisotropy and higher-than-measured $T$ values in and west of the LWA, is that transient transport models so constructed would yield far shorter travel times to the environmental compliance boundary. The gradation of solution features, fewer but larger as one moves westward, connote westward decreasing effective porosities and consequently faster transport rates at the same gradient and conductivity. The field observations and demands of conservatism justify and necessitate such interpretative modeling, rather than acceptance of homogeneous-isotropic steady models with uniform recharge that happen to support licensing with acceptable CCDF distributions.

DoE has responded (p. 40) to the noted difficulties of representing local-scale transmissivity, espousing the stochastic tools of de Marsily and others. Such methods fail in karst terrain because their fundamental premise is that conductivity varies continuously. Fractured formations also are discontinuous. From matrix to fracture, conductivity jumps orders of magnitude: from unaltered to solution-channeled evaporites, conductivity jumps orders of magnitude. Measurements in wallrocks bear no relationship to the properties of the conductors. The spatially-variable $T$-fields DoE has applied cannot be defended if solution conduits prevail in the Rustler. The presence or absence of them is the first and foremost characterization required, an activity DoE has neglected.

The connectedness of transmissibilities noted in the first bullet (bottom p. 40) is particularly inappropriate for karstic aquifers. An equidimensional grid can represent intergranular porous media adequately (e.g., a sand), but not a solution-channeled carbonate or evaporite. If one were successful in finding and measuring $T$ for a cell traversed by a channel, then cells upstream and downstream of it (wherever they are), are perfectly connected and highly correlated, while other cells nearby are uncorrelated to it. Such is the nature of the region, roughly west of the middle of the LWA, that remains ill-defined in properties attributable to dissolution. If the Rustler flow field from repository to Nash Draw were characterized as spatially linked in the direction of flow, the transport model for PA calculations would have produced adverse results.

In the last bullet (p. 41), DoE discounts the significance of all $T$-fields, on the grounds that retardation of radionuclides in transport through the Culebra is such as to ensure that no releases occur at the accessible environment. That transport model employs a single horizontal fracture in the Culebra, with matrix diffusion and sorption providing the retardation. In a karst conduit model (the same discharge concentrated at a one-dimensional conduit of tubular cross-section), specific surface would be so small that matrix diffusion and sorption would be negligible. Retardation has been demonstrated at tracer test pads south and southeast of the repository, data consistent with media dominated by a network of fine fractures, but not solution openings. Matrix diffusion is assumed, not proven, since a convective dispersion model can also explain the tracer breakthrough behavior from these tests. Whether retardation of conservative tracers is attributable to matrix diffusion or aperture distribution, or both, it is a property strongly dependent upon conduit-system geometry, whose variations along the flow path remain obscure for lack of exploration efforts by
DoE. Because karst channels exist within the compliance boundary, retardation properties deduced from ill-placed tracer tests cannot be applied in those regions. Hydrofracture from a pressurized repository, following partings in the Salado updip to the west that break to shallower strata and the Rustler would probably connect to dissolution channels of vanishing retardation capacity. It is the mis-representation of effective porosity and retardation that invalidates the DoE transport modeling, both arising from neglect of the true nature and implications of the fractured and dissolved conduit system.

Comment 8. p. 43

DoE responded to some aspects of the alleged inadequacy of fracture characterization. By neglecting work on the Culebra that is within the realm of currently available technology (e.g., slant-hole or horizontal-hole drilling and coring), it has shut off the possibilities of gaining insights into other features that consequently remain wholly obscure. What, for instance, is the nature of fracture system geometry and conductivity for other saturated rock units, such as the thick Rustler anhydrites? And what is the role of fracture-system dissolution, of vugular permeability, and most significantly, of dissolution channels in or on salt beds? What are the hydrological implications of the distribution of massive gypsum bodies, altered from anhydrite beds? There are too many loose ends to the evaluation of transport in this complex medium, too much uncertainty to warrant a licence for radioactive waste disposal at WIPP.

While the fractured Culebra is the most persistent transmissive unit tested, it is only 6-7m thick. If the fracture conduit systems in the very thick anhydrites had been examined and were better understood, might not the site hydrology be found to be dominated by them? DoE assumes that anhydrite fractures are the result of the dissolution of Salado salt, not the dissolution of Rustler salt. Conversely, CARD cited evidence to the effect that abundant Rustler salt dissolution has thinned the unit over the east-west extent of the site. Thus, anhydrite fracturization is consistent with other dissolution features within site boundaries, and thus co-existent with them. Anhydrite fractures need not be numerous to be significant, especially for transport. Given that subsidence develops a certain magnitude of rock mass strain, producing apertures, the fracture conductivity increases with the square of spacing, as does contaminant velocity. So, if a thick monolith of anhydrite tends to have widely-spaced, obscure subsidence fractures, it may provide very short travel times in such units as the Tamarisk or Forty-Niner, even in absence of dissolution conduits. Such undetermined property variations in the aquifer leave corresponding uncertainties in the CCDF.

Whereas DoE claims to have acted conservatively in the PA modeling, to treat the Culebra as confined is obviously incorrect for transport. All Rustler strata participate in the flow field, since they are interconnected by steep fractures, faults and dissolution chimneys. Future mine subsidence will produce cross-cutting features, as may repository driven hydrofractures. One revealing long-term test has been the water level recovery after the Air Intake Shaft was lined and sealed. From 1989 to 1994, monitoring wells on and off the site registered water level rises defining a consistently-varying cone centered on H-16 (with 71 ft of recovery), while sufficient contour control defined a figure elongate in plan, NW-SE. The direction of elongation coincides
with one of the known regional tectonic fracture orientations. The recovery cone reflects the whole saturated, fractured Rustler formation, not just the Culebra, though all monitoring wells are completed in that thin dolomite.

Comment 10, p. 43

With respect to the use of Darcy’s Law, CARD agrees with the assumption of linear friction for the sake of conservatism, even if turbulence may act briefly in transient channel flows following recharge events.

Comment 11, p. 44

It appears to be necessary to reiterate CARD’s objection to the WIPP site T-field construction technique, which is based on an assumed continuity of values. The mathematics is without merit because there are sharp discontinuities between conduit sizes of matrix, fractures and solution channels. Let us suppose that well tests have characterized the Culebra transmissibility at two points in the region separated by a mile, and it is desired to establish a rational value of T at a mid-point between them. In a fracture-dominated medium, it is correct to treat the nodal value to represent some volume around it, i.e., to assign an equivalent continuous-medium conductivity to the thickness and breadth of a defined volume circumscribing the node. The intermediate, undefined node lies within a similar volume. Field experience in karst terrain indicates that adjacent nodal values may bear no relationship to each other. Sudden inflows occur to tunnels in fractured igneous rocks when faults are intercepted, or in carbonate rocks when solution channels are intercepted. Likewise, when salt or potash mining intercepts trapped or connected brine-filled conduits, sudden inflows are experienced. At the WIPP site, the transition from a fully-cemented domain east of the LWA to a maturely-developed karst conduit domain astride Livingston Ridge, there are sub-domains at all scales that are so wildly capricious that a hydrologic test in one gives no clue to its neighbors, each sub-domain differing by several orders of magnitude in transmissibility. The interference testing that has been done supports the contention of structural control. Certain well pairs are apparently connected efficiently, while most pairs are not. DoE has over-worked the data set, never questioning the validity of conclusions based upon smooth contouring or stochastic manipulation.

Comment 12, p. 44

DoE has failed to adopt vastly-improved technology of core recovery available for at least 20 years, or of directional drilling technology available for at least 10 years. Inspection of WIPP Project cores pre-dating 1995 (i.e., most of the data-base) reveals so much rubble and so many missing core intervals as to guarantee that fractured and dissolved features, if present, could not be described. Even the superior, latest cores from the vertical H-19 pad holes are incapable of disclosing the predominant near-vertical fractures of the Culebra. DoE has spent far more to justify poor simplifications of the conduit system than it would have cost to seek contemporaneous skills in the geotechnical and petroleum disciplines that could have, and still could rectify the lack of knowledge. Without such data, the underlying causes and variations of effective porosity and
retardation are unknown. Fracture data are needed to determine if other features, such as dissolution of fractures and development of channels plays a part at the pad scale. Without such explorations targeting fracture systems, there is little hope of discovering dissolution conduits.

As expressed before, the stochastic model is unconservative in the presence of dissolution features that occur in parts of the flow field. DoE’s approach is not robust.

Comment 13, p. 44

In the domain of Rustler dissolution that extends eastward an uncertain distance from WIPP-33 and Nash Draw, the relevance and legitimacy of hydrostratigraphic units is lost due to cross-cutting fractures and solution openings. The assumption of confinement is inconsistent with the presence of such openings, whose distribution can be determined using improved field observations.

Comment 15, p. 45

CARD has reiterated concern for mis-representation of the current Rustler hydrology by models that discount the current effects of widely-separated solution channels in the carbonates and soft, erodible elastic sediments, as well as partial fracture fillings residual after evaporite dissolution. Insofar as the solubility of halite and gypsum facilitates rapid conduit enlargement, minor changes in velocity and chemistry due to increased recharge during the span of 10,000 years can speed the propagation of a dissolution front and enhance the hydraulic conductivity throughout the karst terrain.

While fractures that are short, arcuate and slickensided are typical of those that develop by shrink-and-swell processes in the near-surface, it is not credible to claim that no other types of fractures are present. An orthogonal pattern of regional tectonic fractures is evident elsewhere in the Delaware Basin. They can be observed at outcrops such as Culebra Bluffs, the Capitan Reef and in Carlsbad Caverns. These and any subsidence fractures tend to be missed by drill holes because they are steep and widely separated, especially in poorly-cemented units that deform somewhat plastically.

The argument that fluids apparently saturated in halite or gypsum cannot further dissolve the conduits that convey them is incorrect. The slightest shift towards dis-equilibrium, either by meteoric water dilution or temperature change can facilitate renewed dissolution of either species. The observed coexistence of open fractures and gypsum-filled fractures, open vugs and carbonate-filled vugs reflects the current geochemistry and active dissolution, thus supports current development and thus regional variations in degree. CARD warns against underestimation of the role of undisclosed solution features in controlling transport, especially in the western parts of the IWA.
Abstract of

Comments on doe’s Compliance Certification Application, 1996
For the Waste Isolation Pilot Plant, New Mexico

David T. Snow, Ph.D., P.E.

The complex but untested design of a proposed permanent underground storage facility for the nation’s low-to-intermediate military nuclear waste deserves, but is not getting, the highly conservative treatment the public should expect. Flawed from the outset by brine in the salt beds and by the mechanical squeeze the plastic salt will inevitably impose on the waste drums, it is a certainty that any mobile radioactivity, such as brine may obtain by dissolving some of the plutonium, will ultimately be extruded upwards into shallow aquifers or to the surface. No conceivable seal design can withstand the extrusion, since fluid at pressures equal or more than the pressure of the rocks will fracture upwards along the boundaries of the seals, or along abandoned boreholes to the repository level. Otherwise, if defects in the salt strata prove weaker, fractures will break upwards to the aquifers. Similarly, hydraulic fracturing could occur to and drive brine through the repository in the event that oil-field pressure stimulation is continued in the vicinity, or if our progeny inadvertently sink exploration drill holes through the repository, intercepting highly-pressured brines that predictably underlie the repository.

Doe has relied upon the apparent properties of the Culebra dolomite, a likely path for travel from the repository site to the accessible environment (distant about 5 km) in calculating total radionuclide releases that do not exceed the limits of 40CFR191 in the first 10,000 years. While tests in 30-odd boreholes span four orders of magnitude of hydraulic conductivity (on which speed of travel depends), none of the tests reveal the worst that is likely to exist. Evidence gathered at the surface (such as sinkholes into which storm-waters disappear, and more), as well as subsurface drill data largely obscured by low-technology coring techniques used in the past 30 years, support conservative opinions shared by many geologists that large solution conduits exist at shallow depths. Unlike the slow paths envisioned by DoE, the evident dissolution pathways typical of cavernous regions imply rapid groundwater movements from the region of the WIPP site to nearby Nash Draw. Consequently, the Culebra is not reliably characterized as a barrier to rapid flow or excessive radionuclide releases.

Failing to demonstrate in its application either that the underground repository can retain the radwaste by effective sealing, or by reason of the integrity of overlying strata to contain or delay it, DoE must rely wholly upon engineered barriers in the repository. While one chemical component has been proposed (MgO) as a partial backfill that will minimize plutonium solubility, DoE has not proposed other barriers that could absorb the brines to immobilize the potential effluent. In view of the above, the application should be rejected.
Comments on DoE’s Compliance Certification Application, 1996
For the Waste Isolation Pilot Plant, New Mexico

David T. Snow, Ph.D., P.E.

Introduction

Disposal of radioactive waste is a virgin industry, the product of 50 years’ labor to conceive safe resting places for the legacy of bombs and power plants. Not one prototype has been built anywhere on earth to test the many solutions proposed by the thousands of involved technologists of many persuasions and countries. The nuclear waste disposal industry is in about the same state that dam-building occupied when (in the 1930’s) we suffered in America the failures of the St. Francis Dam, the Fort Peck Dam, the Hales Bar Dam and others. Failures are predictable for prototypes dependent upon geology, an inexact science replete with surprises, usually because exploration provides only a fraction of the necessary data. Since WIPP is the guinea pig, we must treat the ground with the respect experience should have taught us. The wishful thinking, the false confidence detectable in a thousand topics the DoE proposal entails is cause for uncommon conservatism, remembering that the proponent, all its contractors and even reviewers have a positive bias. There is a comfortable interdependency among a diversity of “experts”, none of whom have built a successful repository, nor put their names to their findings. Who are the professional engineers the public has licenced, who can be trusted with this complex paper edifice?

I wish to express a healthy skepticism about some untested expectations of repository containment, and upon the best-case assumptions used to predict transport in groundwater. I submit my qualifications (see website www.mallmerchant.com/dr-snow) to express views drawn from abundant hydro-geotechnical experience, much of it with repository siting.

Apropos of responsibility, the EPA has imposed the common-sense restriction, based on RCRA prohibitions on land disposal of toxic waste (present in some TRU containers) that the waste must be retrievable. EPA only requires that the retrieval be possible, not that it be easy or economic (CCA 7.6.1). It is clear that future generations will find it infeasible, practically precluding retrieval from this site. That effectively leaves no slack for inevitable mistakes in concept, data validity or interpretation, or the design of the many vital parts such as those intended to minimize the mobility of dissolvable actinides, to isolate the repository contents from shallow strata or to limit radionuclide transport in aquifers carrying water to the accessible environment. DoE claims (CCA 7.6) that waste retrieval is possible and it has been demonstrated. Were the simulated waste containers in place in time to be crushed by a roof collapse, then retrieved? Assuming that actual retrieval would be attempted after repository performance proves unsatisfactory, the real conditions would entail crushed drums and wooden boxes under tons of fallen salt, part of whose radioactivity has escaped in liquid form and dispersed throughout cracks of the disturbed rock zone (DRZ) beneath the heaved floor, or as salt backfill impregnations. The total contaminated volume might be five to ten times the original volume, a mechanically-heterogeneous mix of salt, metal and
plastic, poorly suited for machine excavation, diluted but radiologically as variable as its source. The problems of safe handling, as well as of packaging, transport and of disposal would be more monumental and uncertain than the present, near-impossible task of safe siting. The economic burdens would be so great that stop-gap options of surface protection or land abandonment would be far more feasible and likely. A present mistaken decision to store the waste is not permissible because creep closure and its consequences make waste retrieval impractical. If any miner says it can be done, it is because he expects never to be so required.

DoE has been eager to solve the national problem of too many inadequate TRU waste storage facilities around the country, by concentrating it all at WIPP. It has lead to a premature solution. The proposal is elaborate and seemingly conceived carefully, yet it retains unsolved some fundamental problems. Neglect of these has produced a project the public should view as irresponsible, thus not allowable.

At the outset, there were established some wise geological criteria for site selection (CCA 2.1, p.2-6). Some of these have not been satisfied for the WIPP site. Contrary to DoE's claims, 1) the plastic nature of the salt host-rock does not have the ability to encapsulate the waste under all conditions, since fractures of the DRZ around the rooms developed in the stiff anhydrite interbeds provide egress of fluid waste components and collected brines through hydrofractures, and 2) the consequences of karstic dissolution of the Rustler and Dewey Lake Red Beds are unknown in character, though some features of karst exist at and near the site. 5) future exploitation of known resources is neither predictable nor necessarily minimal.

Containment

It is clear that radionuclide releases from WIPP to the accessible environment in excess of the limitations of 40 CFR 191 can occur only if three factors are met:
1. A sufficient fraction of the actinide inventory must be mobilized in dissolved or colloidal form.
2. The engineered containment within and adjacent to the repository must be breached and capable of discharging brine, and
3. The intervening geologic environment and man-made features within it facilitate effective transport to the compliance boundary.
As long as poor definition characterizes the nature of the waste (such as the amount, size distribution and solubility of plutonium particles) and other parameters are ill-defined, such as the amount of reacting brine and numerous other components still being investigated in the actinide source term (AST) project, DoE cannot eliminate the first factor unequivocally. The CCA relies heavily on elimination of factors 2. and 3. Among the various claims being disputed by interveners to this application, the writer addresses some limited but vital subjects related to failure of seals and engineered barriers, discharge from the undisturbed and disturbed repository via paths to the surface or to Rustler aquifers caused by hydrofracturing around borehole seals or shafts or through the overburden strata. Secondly, groundwater flow and transport incident to concentrated discharge in fractures and dissolution conduits of the Rustler and younger formations is discussed, suggesting that those barriers are compromised.
Shaft Seals

The intended hydraulic function of shaft seals (CCA 3.3.1.2) is to “restrict groundwater flow” and “limit radionuclides”, not to eliminate them. There is neither a proven, field-tested technology of sealing (especially in salt), nor an irrefutable conceptual design to assure us that those objectives will be met. Shaft seals in mining applications have histories of such frequent failures as to make a prudent engineer treat the proposed seals with cautious skepticism, even if their design is apparently good, innovative, well-studied and reviewed.

I examine, first, the mechanical behavior of some seal components in relation to each other, during the period of shaft closure before significant repository air pressures are imposed. I examine, second, the propensity for seal failure by pneumatic hydrofracture, a potential mechanism for development of a conduit for concentrated, rapid egress of air and brine, contaminated or otherwise, from the repository to the Rustler aquifers or the surface. It is evident that the seal designers may have given insufficient credence to the hydrofracture mechanism along the seals, or into the strata above the repository, competing avenues for release of the pressures that will build upon compression of the air and gasses that will develop in the repository.

Concrete plugs with asphalt water-stops have recently been redesigned. Such “chemical” seals in mine-shaft use have a checkered history of failure by displacement. Asphalt is a viscous liquid, so when subjected to shear, it is more readily deformed than is salt. The intended function of the asphalt, filling not only a shaft segment, but also filling a tapered kerf (slot) excavated all-around one radius into the shaft wall, is to intercept the DRZ, believed to be the most likely path for fluid bypassing the impermeable seal materials that will fill the shaft. The radial extension of the DRZ around the tip of the kerf has been modeled (CCA 7.6.1) to conceptualize its development and subsequent crack closure when the asphalt and adjoining concrete plugs take on load from the convergence of salt. One cannot tell from the text whether or not the modeling is realistic in conceptualizing the closure consequences.

The asphalt will shrink slightly during cooling (days), after the upper concrete plug has set (hours). Presumably, the concrete plug will support itself in shear without salt damage as the concrete gains strength (months). Ensuing creep deformation of the walls (years) will load the asphalt and concrete. According to reported structural calculations (SEAL 7.4.4.2), the radial stresses for upper, middle and lower seals in asphalt will be only 1.8, 2.5 and 3.2 MPa at 100 years, and in concrete (SEAL 7.4.1.2), only 2.5, 4.5 and 5.5 MPa at 50 years. They claim that such modest backpressures will heal the DRZ, even while creep continues to close the shaft. The geometry of the kerf will speed its closure, relative to the radial closure around cylindrical concrete elements, thus modeling should show vertical components of salt movement towards the kerf. As stated (CCA 7.6.1, Para 2), after 20 years the DRZ is localized, 2 m deep, at the asphalt/concrete contact, where such shear of salt against concrete must be maximum.

The designer’s concern should be that more rapid closure of the kerf will raise the asphalt pressure more rapidly than the salt/concrete contact pressure, so that asphalt may prise and penetrate upwards along that contact. Whenever a fluid of density less than the surrounding rock rises to higher levels, the propagation of the hydrofracture is unstable. There is nothing to prevent
the extrusion of the asphalt until the water-stop is replaced (centuries) by salt, and the asphalt is displaced along the contact of the overlying clay seal segment. Apparently we cannot count on the interception of potential seepage paths along the shaft DRZ by placement of asphalt water-stops, because they may not be permanent.

The asphalt column at the top of the Salado (element 6 of Fig. 3-4) is to be composed of asphaltic aggregate. It will be lightly loaded and will have some shear strength, so will have limited or no mobility past its upper plug of concrete placed against anhydrite of the Unnamed member of the Rustler.

Other parts of the seal system should compact without discharge or distortion.

Repository Pressure and Discharge

Waste emplacement design includes a backfill of sacks of MgO placed to buffer acidity as CO₂ evolves from decomposing organics in the waste. Hydration to Mg(OH)₂ will sequester water beneficially, but release it as CO₂ combines with the hydroxide. Besides maintaining low actinide solubility, it is evident that the MgO will reduce the rate of gas pressure build-up and diminish the liquid filling repository voids.

Castile brine occurrences pressurized by biogenic H₂S (such as ERDA-6, 1981) are analogues for the evolution of repository contents, wherein decomposition of cellulose, plastics, rubber and steel will generate CO₂ and H₂. DoE's concepts of the nature of these Castile brine reservoirs is found in CCA 6.4.8, but there is no recognition that primitive pressures must be lithostatic as a limit, that the extent, interconnectedness and discharge processes must be tied to the stress state of salt. The Castile fluids are stored in rather stiff fractures in the anhydrite. The pressure has developed by microbial reduction made possible by methane or petroleum in the presence of anhydrite. Its threshold for dissipation by hydrofracture along weak contact partings is the lithostatic pressure of salt adjoining such fractures, not the steep fractures interior to the anhydrite beds. Upon tapping such a reservoir with a drill hole, its head is initially thousands of feet above land surface, but as it flows, friction drops the pressure rapidly. It would flow freely until anhydrite fracture closure attains hydrostatic pressure for the brine.

How much of the H₂S is dissolved or gaseous in the Castile is unknown, but it is probably dissolved because none of the drill intersections have produced gas only, followed by brine. In addition to elastic closure of fractures and expansion of brine, evolving gas in the column drives the well discharge. Remote parts of a reservoir become isolated as diminishing pressure causes closure of hydraulic fractures at salt contacts.

In the repository, compaction begins with air only, and ends with air, decomposition gasses and brine from inflows, all at lithostatic pressure. The greatest factor of uncertainty is the amount of brine that will enter during the long room closure period while pressure is below lithostatic. The National Academy review (NAS, 1996, App. C) summarized the competing theories, indicating cumulative inflows in the range of 500 to 800 l/m of drift. It appears that none of those computations were coupled to backpressure computations. Like the Castile anhydrite beds, some
areas of which contain abundant brine, there is probably a variation of brine content in fractures of Salado interbeds, and variations in size and continuity between reservoir areas. Hydrofractures may or may not join various steep-fracture reservoirs, depending upon their pressure histories. So the calculated cumulative brine flows may err by large amounts, and a conservative inflow may total more than 1000 l/m.

The choice of backfilling materials in the rooms provides the only control over final void volumes, since the waste can sustain only so much residual void space when compacted to lithostatic total stress. Ideally, since waste voids will probably become saturated, residual porosity should be maximized, to limit the amount that can otherwise be expelled from the repository after the gas has escaped. The MgO backfill will absorb water into the hydroxide, then yield it as the carbonate is formed. The amount of MgO is said to exceed the gas expected to evolve, so a net water absorption will function to inhibit corrosion, just as will pH control. But unlike salt backfill, MgO will not sequester air; the Mg(OH)\textsubscript{2} will saturate and consolidate as it continues to take load. Compressed air in fractures and contacts and within the collapsed drums will all communicate to hydrofractures that can form as pressure attains lithostatic in the repository. It doesn't seem conservative to assume that the backfill and residual voids will retain all the remaining brine, since gas will continue to evolve. I am unaware of any DoE claim that brine will be unavailable for transport of radionuclide contaminants away from the repository, nor would it be prudent to so assume.

A possible safety measure rejected by DoE is the option of completing the backfilling around the waste and MgO packages with dry compressed or adobe bricks of clay. It is well-known that clays of the montmorillonite family have extremely high cation exchange capacities and can exert high swelling pressures. Reduction of the initial air volume and prompt backpressure would shorten the time to cessation of closure. Diminished inflow and enhanced absorption of brine would ameliorate corrosion. Perhaps an absence of free brine could be guaranteed, limiting the actinide source to the fluids already in the waste, less the actinides which can be absorbed by the clay. In absence of incontrovertible geologic containment and retardation, such engineered barriers may be the only way to get certified.

It is safe to say that a diminished rate of decomposition of the waste does not eliminate the prospect of continued pressure build-up to hydrostatic. As proposed, the large initial voids ratio of the repository (as seen in Fig. 3-8) probably implies that the air cannot be contained at less than lithostatic pressure in the residual voids of the waste containers, some of which will be brine-filled. Continued gas generation, at any rate, will ultimately raise pneumatic pressure to lithostatic in spaces communicating with the DRZ in the marker beds. The compressed air and gasses are available to form and drive hydrofracture either along the seals or through the overburden rocks. The energy available for propagation and friction is in excess of 2.5 X 10\textsuperscript{12} joules, if the original void volume of about 460,000 m\textsuperscript{3} (SEAL 8.3.2), plus any generated gas is compressed to about 1/146 th of that volume.

Seal Failure. In shafts and boreholes, the pre-existing contacts between wall rocks and seal materials are likely paths of hydrofracture, and the vertical aspect enhances instability (runaway propagation to up-hole regions of decreasing rock stress). There is nothing to stop it except
whatever tensile strength may exist in the least-healed discontinuity, such as dust coatings on original walls. It may propagate readily between air-filled voids of the compacted salt fill, and certainly along fluid films in the clay seals. Asphalt deforms to pass air at contacts, and salt will yield to form a parting against concrete. Likewise, boreholes sealed with concrete will not sustain much beyond lithostatic fluid pressures before parting at contacts. The DRZ fractures, even healed ones in salt, are candidates for hydrofracture. One might design end-constraints for a salt column to exceed lithostatic radial pressure, but it would not be permanent. It is easy enough to design effective seals for fluid pressures below lithostatic, but not above.

The computations in SEAL 8., the hydrologic evaluation of seal performance, are perhaps valid, but the assumptions of homogeneous, intergranular or continuous fractured-media properties do not apply under all conditions, such as at high pressures. Seals and DRZ rocks behave as continuous media during early phases of repository closure, but under lithostatic or higher pressures, fluids will travel along singular pathways not envisioned by the modelers. During compaction of clay and perhaps of salt, air can be expelled along contacts of the seals. During any subsequent consolidation phase, water can be expelled along those same pathways. Either fluid will take the path of least resistance, usually by forming a conduit at the rock/seal contact, persistently maintaining that opening as flow occurs or preserving a path susceptible to re-opening and concentrated flow when pressure is raised. Seals can be breached to the Rustler aquifers or to the surface via the unsaturated zone. If engineered barriers in the repository preclude free brine, it would be harmless air and gas discharge. Otherwise, the undisturbed scenario has a potential for radionuclide releases to Rustler aquifers by way of shafts or boreholes.

Hydrofracture through the Salado. If the shaft seals are as good as they can be made, then hydrofracture will occur elsewhere instead. In essence, no fluid phase can be long contained by seals or geologic media when the fluids exceed lithostatic pressure; the best that can be done is to assess the relative weaknesses of competing paths of egress. Mindful that roof slabbings (even presently occurring in the experimental rooms) exposes one or more weak partings, at anhydrites "a", "b" or the clay at the base of MB 138, subsequent closure will cause those members to bend and decline towards the center of the room. Air will remain in the anhydrite fractures even as rock stress attains lithostatic over rooms as well as pillars (the unmined salt between rooms). During roof deformation, shear displacements produce microscopic openings along several such stacked partings that extend towards the centerline of the pillar. Coalescence of the DRZ from room to room can occur by hydrofracture across the pillar regions, completing the continuity of the entire repository, even if there are room or panel seals in place. DoE has chosen to neglect the NAS recommendation (1996, p. 145) for generous, long room entry seals, that would diminish the continuity of the repository. All rooms should dead-end in salt for isolation. Canadian potash mines safely excavate 2000 ft rooms with only one entry. The concrete seals to be emplaced for RCRA compliance (CCA 3.3.2) are not being relied upon for compartmentation to isolate nuclear waste products. Therefore, the energy of air compression and gas generation stored in the entire repository is available to drive a single hydrofracture to great distances.
I anticipate a counter-argument that lithostatic pressure cannot build because the slightly-permeable anhydrite beds would continually bleed air from the repository, especially from the up-dip extremities, while brine continues to drain into the down-dip extremities. The fallacy of that argument is the erroneous belief that brine in the marker beds is at no more than 12.5 MPa (Beauheim, et.al., 1993), when measurement itself disturbs the pressure. Virgin pressure must be lithostatic to prevent salt closure of the fractures. Therefore, it is doubtful that appreciable air losses can occur through the marker beds until that formation pore pressure is exceeded at the repository end, even if it takes centuries to attain it.

In the far-field, remote from any stress perturbations the excavations may impose, it is safe to assume that creep of salt maintains lithostatic, all-around rock pressure equal to the overburden load. In such circumstances, the presence of structural weaknesses will govern the nature of a hydrofracture in response to fluids exceeding lithostatic. Clay partings along contacts between salt and marker beds, and some clay lamina within salt beds are candidate horizons. These may be interrupted at infrequent local breaks in stratigraphy formed during Permian deposition by channels that crossed the shallow salt-flats. They have been observed in the experimental area of the repository (D. Borns and R. Patchett, personal communication, 1995). The effect of such an interruption of a bedding-plane hydrofracture is to force the opening to propagate elsewhere. It is known also that hydrofractures tend to jump up to higher levels in the strata, where load is less. In homogeneous rock, hydrofractures become dish-shaped. Such behavior in the Delaware Basin has been demonstrated. In 1991, the Bates #2 Well encountered brine with 1000 psi shut-in pressure while drilling at 2240 feet. It flowed about 840 gpm for 5.5 days. Responsible for the brine was a Texaco Co. well injecting (oil-field waterflood operations) at 3000 ft depth, about 760 ft lower than the Bates well intersection and about two miles away. It is consistent with that incident to predict that when pneumatic pressure in the repository approaches the fracture gradient of 0.966 psi/ft depth, it will either hydrofrac a seal or produce a single, elongated hydrofracture along a succession of overlying partings of the Salado, ultimately breaching the Rustler aquifers. As EEG (1996, p. 2-4) point out, the Rustler/Salado contact is also a potential pathway. Alternatively, an extensive hydrofracture may intersect a borehole inadequately sealed to sustain the pressures from deeper horizons.

The importance of borehole sealing, at sites both on and off the land withdrawal area, is evident from the Bates #2 Well experience, and from other water-flood hydrofractures encountered in recent years. DoE has chosen to accept the condition of numerous abandoned wells in the region, presuming them to be well sealed in accordance with state regulations. But the imperfection of casing cement jobs and the corrosion that destroys casings in evaporite environments point to predictable vertical paths open to the surface now or in the foreseeable future via the many abandoned and active oil wells. The possibility that waterflood operations in the neighborhood may propagate hydrofracture to the repository, saturate and pressurize it, then hydrofrac an outlet to the surface is very real.

Discharge of air and gasses is innocuous, insofar as TRU waste is not expected to generate appreciable radioactive gas to contaminate the repository air. The significance of pneumatic hydrofracture is that it prepares and maintains an open path for escape of liquids to follow after the available vapor-phase has discharged from the repository. The energy of any remaining room
closure is available to expel fluids of density below that of salt. Only if engineered barriers have been emplaced in the rooms can sufficient brine sequestration be envisioned to preclude eventual brine discharge along hydrofracture conduits, and DoE has not maximized use of such barriers.

Disturbed-case scenarios. Whereas the above considerations leading to pneumatic hydrofracture apply to the undisturbed repository, they should also be applied to the single borehole E1 or E2 case or the E1E2 case that would, at least, discharge accumulated gasses and air from the repository. After hydrofracture, repository pressure may not normally attain lithostatic again without a connection to the Castile brines or waterflood brines. If the drilling occurs subsequent to undisturbed hydrofracturing, pressures may become elevated when a Castile brine reservoir is intercepted, the E1 scenario (CCA, 6.3.2.2.2).

In the event of potash mining in the McNutt member of the Solado overlying the repository, the consequences would be far more extensive than merely the enhancement of Culebra transmissibility (Corbet and Knupp, 1996). In addition to shaft penetrations, the overburden between the mine and the surface would be disrupted by numerous steep subsidence fractures. Many traversing salt may reheal while mining proceeds, but typically, potash mines flood via fractures carrying water from overlying aquifers, as occur in the Rustler. Thus, a mine overlying the WIPP repository can provide different connections to the accessible environment, depending upon the time of repository breaching relative to the time of mining. The mining level, about 75m above the repository, would retain lateral continuity for centuries before it seals itself. Thus, it would provide continuity from the repository to the surface, via the shafts, boreholes old and new, and especially via hydrofractures, the mine and Rustler aquifers. Several of these are potentially more likely than the simple M scenario envisioned by DoE.

The E2 scenario (CCA 6.3.2.2.1), a drill hole inadvertently penetrating the repository would discharge any accumulated air and gas, but if it occurs after venting by undisturbed hydrofracture, the rooms may have closed to a state of near-saturation, facilitating brine discharge to the borehole, driven by expansion of the remaining gas and elastic expansions. The repercussions would depend upon the state of the repository, thus the timing of events. Diversion to the Culebra aquifer would result from successful blowout prevention at the collar of the hole.

A drill hole through a partially vented repository room, a closed access drift or the DRZ of any part of the system could conceivably be drilled deeper for resource exploration, whereupon a pressurized brine reservoir in the Castile could be encountered (E1 scenario, CCA 6.3.2.2.2), producing brine flow. Because no mechanically effective backfill or room seals are to be employed, direct circulation to a point of hydrofracture egress is likely to sweep any mobile contents out of a panel or perhaps two panels, but the panel closures would protect other panels from direct flushing. However, any blowout preventer restraining direct brine discharge up the hole would result in hydrofracture from room to room, to any shaft, borehole or hydrofracture to the Rustler, since the Castile brine is generally at lithostatic pressure for its deep level, thus much higher than lithostatic for shallower levels. The path depicted in Fig. 6-11 represents only one of those possible, and probably not the worst.
Many potential paths are possible with the E1E2 scenario, as described in CCA 6.3.2.2.3, conceivably sweeping as many as two panels of their mobile wastes. It seems unlikely that the DRZ would have greater conductivity than would paths through rooms, but in the event that panel closures function effectively, brine flowing through any salt-bounded fracture could readily enlarge it to concentrate flow, bypassing much of the waste. It is not convincing to say that the E1E2 scenario is the worst case, that it is to be minimized because the compound probability of two such penetrations is low. The E1 drill hole in combination with prior breaching paths seems more likely and dangerous. The event of exploration well penetration of the repository seems unlikely to contaminate the Culebra because such wells would be new and cased through the Culebra. Thus the claimed retardation due to Culebra transport processes might not provide a barrier when needed most.

**Rustler Hydrology**

It has long been DoE’s position that flow through the Culebra dolomite provides a final barrier to excessive releases to the accessible environment. While shorter, more concentrated discharges, in place and time, to the immediate surface are likely to result from exploration boreholes or sealed boreholes, shafts, subsidence fractures or hydrofractures, it is worthwhile to evaluate the conceptual hydrogeology of the Culebra, implemented in so many studies contributing to Performance Assessment (PA).

The case for obtaining a comprehensive set of data to characterize the structure of the Culebra has been made before (Ferrall and Gibbons, 1978; Snow, 1995; NAS, 1996 and others), so that modeling for transport calculations can more correctly represent the true conditions. The reasons have to be reiterated here.

Fractures and stratigraphic features would become secondary in importance if it were realized that the Rustler contains significant solution conduits within the WIPP site and within the range of potential hydrofractures and boreholes that may communicate with the repository. Then, fractures would no longer be the key elements in governing transport. Upon demonstrating karst features within the model domain, it may be so evident that travel times are brief (say, 5 to 250 years) that the Rustler must be discounted as a barrier to transport to the accessible environment.

**Fracture System in the Culebra**

DoE’s hydrologists are among the world’s foremost modelers, but the data DoE has collected to facilitate appropriate conceptual aspects and the details of the models themselves do not reflect the state of the art of geotechnical engineering, in view of the hydrostratigraphy, the fracture system geometry or the suspect dissolution features of the rocks overlying the Salado. Consider, first, the lack of fracture data and its adverse influences.

It was one of the Carlsbad area potash mining companies that convinced ERDA to examine that area; to store TRU waste seemed a great end-use for a spent mine, and when that was rejected, the government got some help in drilling to prove the resource of space could be found beneath the mining horizon. The coring of drill holes has been with the same equipment and of the quality
appropriate to the potash industry, probably by the same "experienced" drillers. For potash exploration, only the chemistry of the ore matters; the quality of core recovery is unimportant. Consequently, any attempt to learn much from the cores in storage, such as structural details, is a frustrating exercise because the core looks like crushed road aggregate, for the most part. Frequently, recoveries are less than 50% of the length of hole, and the weakest parts, such as seams, solution zones and fractured intervals are missing from the hundreds of boxes representing millions of dollars worth of drilling. One hole of the H-11 pad site reflects superior care in obtaining good recovery, though it would still be considered abysmal by engineering geologists trained for damsite exploration work. Instead of the traditional single-tube core barrel used in potash programs, it is reported that the H-19 pad holes of 1995 were drilled, at last, with a triple-tube core barrel, obtaining about 98% recovery. In my view, 30 years of exploration effort before 1995 were squandered in inept technology. Even the 1995 core misses the objective of fracture system characterization because DoE has continued to refuse (DoE letter to EEG, August 17, 1995) to execute slant-hole coring, without which near-vertical fractures cannot be intercepted with sufficient frequency. Outcrop evidence and common knowledge would tell them that flat-lying sediments abound in vertical fractures, as must be the case in the Culebra. A reasonably-representative data-set can and still must be obtained at WIPP by applying well-established directional drilling technology perfected in the last decade by oil companies for the task of intercepting steep producing fractures. It is reported that directional drilling costs about 15% more than vertical drilling, so economics are no impediment.

The need for fracture system data to model the flow and transport of contaminants in the Culebra has been detailed recently (Snow, 1995) and reinforced by reviewers (NAS, 1995), such as Dr. Konikow. The role of matrix diffusion, hydrodynamic dispersion and sorption depend upon parameters that can only be estimated crudely by in-situ tracer tests. The interpretation of tests depends upon models that cannot be well-conceived in absence of data on the fracture system geometry and stratigraphic details.

Indirect inferences of fracture system geometry at the site have to depend upon remote observations, such as the outcrops at Culebra Bluffs along the Pecos River, SW of Nash Draw. According to personal observations preserved in photographs, there are two steep orthogonal sets of fractures, NE and NW in strike, with long traces seen on bedding surfaces and spacings about 1-2m. These are consistent with regionally-pervasive tectonic patterns visible in the Capitan Reef and elsewhere in the Basin (Swift, 1992). Superimposed on the orthogonal tectonic joint pattern are more numerous, randomly-oriented fractures, sometimes abutting in polygons.

Judging by a similar distinction between joints above versus below a dissolved evaporite sequence in Manitoba, I believe that the random set at Culebra Bluffs results from dissolution of underlying evaporites, which occurs differentially over space and time to impose strains in various directions. Horizontal partings at clay lamina in the Culebra probably shear and open by the same differential subsidence mechanism.

At the WIPP site, there has been variable removal of salt from the uppermost Salado rocks and theUnnamed Anhydrite unit of the Rustler, perhaps increasing in magnitude of removal from east to west across the site. Since the demarcation is not abrupt, neither is the distribution of Culebra
fracture types predictable. Only a well-conceived and executed slant-hole drill-coring program could resolve the changes of pattern to be expected across the site. The nature, apertures and spacings of each type are needed, augmented by length parameters from outcrop studies. Core data should facilitate interpretation of fracture system anisotropy and the effective porosity, all in the interests of better PA modeling than is possible with currently oversimplified geometry (such as horizontal fractures only) and the absence of data.

Further objectives should be to include fracture system distinctions across the dissolution-transition zone coincident with the WIPP site, and especially to characterize dissolution channeling effects evident by erosion of fracture fillings and the opening of vugular strata. Fracture conduits traversing the Dewey Lake Red Beds and the several Rustler members are needed, since the assumption made by DoE that the Culebra is confined by impermeable beds is clearly unjustified (see below).

It is appropriate to caution against exploration expenditures for fracture system characterization to the exclusion of dissolution-feature characterization.

Karst Hydrology

If DoE cannot be induced by the reasoning of many to evaluate and employ knowledge of fracture hydrology, preferring to labor handicapped without such knowledge, then what is the efficacy of recommending explorations to obtain knowledge of karst hydrology at WIPP, data even more vital to establishment of transport properties of the Rustler? Fear of failure, having spent $2 billion on studies already seems to have driven completion-oriented managers to deny the existence of karst features (CCA 2.1.3.5.2). Ultimate failure, still a very real possibility, would be to have a repository filled with TRU waste that has to be retrieved later at astronomical costs when our progeny, perhaps ten generations from now, discover shafts, drill holes or springs discharging radioactive brine to the Pecos River. It has been an unspoken hope that slant-hole coring for fractures could accidentally disclose solution cavities in the Dewey Lake and Rustler formations, features already obvious to a field-oriented geologist, reiterated as evidence of karst by a procession of competent but largely discounted scientists (Olive, 1957; Vine, 1963; Bachman, 1974; Anderson, 1978 and 1994; Barrows, 1982; Chaturvedi and Channel, 1985; Phillips, 1987; Snow, 1995; EEG, 1996).

Claiming reliance on retardation during actinide transport through the idealized Culebra towards the accessible environment (5 km distant), the E1E2 scenario is by no means the worst case, but even it cannot approach 40 CFR 191 standards if short travel times implied by karst hydrology are correct in magnitude. The field evidence presented in Phillips' (1987) dissertation on WIPP site geomorphology is so potentially damaging to the project that DoE has suppressed it, not even listing it in the CCA bibliography. That is inexcusable, when the work constitutes the most exhaustive exploration of surface features, including 1000 auger holes and many backhoe trenches investigating sinkholes and solution trenches on the Mescalero Plain. His evidence is clear that there are local windows through the Mescalero caliche horizon and that there are many aligned sinkholes with alluvial infillings. These are evident, even though dune sands mantle much of the plain, free of surface drainage channels. He recorded observations of storm runoff disappearing
down one such sinkhole, the WIPP-33 drill site where five nested caverns were drilled to the depth of the Culebra. Water-balance methods, based on reasonable evaporation rates from Laguna Grande de la Sal, versus stream-gaging data from Malaga Bend seem to indicate that Nash Draw is the discharge point for nine-tenths of the recharge. This implies shorter paths from WIPP via cavernous channel features reasonably deduced from the geomorphology and geochemistry.

In current comments to the CCA, Phillips (1997) has summarized surface and near-surface hydrological evidence to conclude that the karst solution features on and near the WIPP site are subject to modern infiltration events. The Dewey Lake Red Beds have several regions of sufficient transmissibility and potable water that it constitutes a subsurface drinking water supply. He further documents the occurrence of karst features in the Rustler units: the Forty-Niner, Magenta, Tamarisk and Culebra, including sites within the WIPP boundaries. There are places of apparently continuous dissolution extending from Dewey Lake downwards to the Culebra. Salinities in Culebra water samples decrease along the preferred path, to Malaga Bend, according to DoE, as well as along other potential paths to Nash Draw. Their finding is inconsistent with confined flow in the Culebra, but is consistent with fresh-water recharge through sinks, especially west and southwest of WIPP. Portions of the Culebra carry potable water, making it a candidate for drinking water supplies, rather than a “brine unsuitable even for stock-watering”.

The importance of these findings is that the WIPP site is established as a recharge area for a dissolution-enhanced aquifer on and west of WIPP that spans the Dewey Lake and most of the Rustler to at least the Culebra. That is contrary to DoE’s modeling of the thin dolomite as a confined aquifer. DoE has modeled the Culebra with transmissibilities computed on the faulty assumption of continuously-varying values. The T-field computations are invalid for fractured media, much less for karstic channels traversing tighter rocks. Typically, exploration drilling on a random pattern cannot be expected to intercept nor measure the high-conductivity solution channels as must exist to carry storm runoff such as flowed into the WIPP-33 sinkhole on September 18-19, 1985, or as observed in other karst regions of the world. Travel time from the site to Nash Draw is speculative, but if it accords with experience in other karst regions, it may be less than 100 years.

The current regional groundwater model (MASS 14.2) errs significantly by neglect of concentrated, intermittent recharge across strata via sinkholes, at least in large parts of the domain. The continuity of Darcy’s Law models with properties averaged over large regions cannot represent the transient, channelized flows that occur rarely in karst, giving the medium effective porosities that are orders of magnitude smaller than intergranular media would suggest. Recharge estimates of 0.2 to 2.0mm per year were based on small transmissibilities (seemingly neglecting some of the extreme-valued tests) in the Culebra, none that represent vertical flows. This range is at odds with Phillips’ estimated recharge of 0.75 inch/year (1987, p. 224), a more reasonable figure for 15 inches of rainfall that form no surface drainage channels. Phillips’ estimate was based on evaporation from the original surface area of Laguna de la Sal before mine process water was ever discharged there. Sinkholes must connect to highly-conductive channels in the subsurface, features that are believed to develop by headward extension, probably from the discharge points in Nash Draw. The surface morphology suggests that channels must extend onto the WIPP site itself, since sinkholes are present there. As reason to believe that Nash Draw is the terminus of the
shortest, fastest paths from WIPP via the Rustler, there is the significant excess of computed net evaporation at Laguna Grande over the gain of streamflow at Malaga Bend. Flow paths to Nash Draw are shorter than DoE's expected paths to Malaga Bend. Whereas pluvial-period groundwater flow may have been most responsible for karst development, the established paths during today's dry climatic conditions are probably also southwestward into Nash Draw.

Average transport properties would be very different for a Rustler aquifer dominated by even occasional periods of rapid, karstic channel flow. The speed with which organic contamination shows up in karst terrain is suggestive of the behavior to expect of actinide transport. Little specific surface can be active for sorption or matrix diffusion. If efforts to characterize the formations are to continue, then testing of rare solution conduits has to be done. Usually, dye-tracing is employed to establish travel times. The location of drill holes seeking direct evidence of conduits can be guided by the negative gravity anomalies (Barrows, et.al, 1983), by surface morphology, by the distribution of salinities and fracture fillings in the Culebra (Beauheim and Holt, 1990), and by following apparent trends of high transmissibilities deduced from interference testing.

It should be as transparent as the emperor's new clothes that the Culebra and overlying strata are inadequate to the belabored task of providing a barrier to excessive cumulative releases at the compliance boundaries. But if proof must be obtained that transport would be swift and conservative in the Rustler, then perhaps explorations must proceed step-wise, in order to be wholly convincing. Regulatory agencies should require completion of a geophysical and subsurface drilling program to obtain statistically relevant data characterizing fracture system geometry and karst-conduit geometry. Regional efforts in the realm of conventional surface hydrology are needed to confirm suspected partitioning of the recharge between the Malaga bend and Nash Draw discharge areas.

**Summary Statement**

Two of the three major barriers have been shown to be unreliable: neither repository containment nor transport processes guarantee satisfaction of the cumulative release limits of 40 CFR 191. DoE should rely solely on a favorable actinide source term that is brought about by incorporating optimum engineered barriers within the repository (but not in transport) to show compliance. Furthermore, retrieval of the waste after decades of loading is infeasible. Establishment of an alternative site and method of disposal may be necessary. The expense and delay, though burdensome, would serve the public interests better than failed emplacement at WIPP. A monitored retrievable storage facility, safely above the water table in stable rock openings is suggested. There are well-drained candidate sites in fractured tuffs or carbonates in other desert mountain ranges within government nuclear reservations.
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Conceptual Errors in the DOE Model of Groundwater Flow in the Rustler Formation

Richard Hayes Phillips, Ph.D.

The DOE model of groundwater flow in the Rustler Formation is a misrepresentation of reality. The Rustler is a fractured, karstic, anisotropic, artesian aquifer with three-dimensional flow. It should not be modeled as a porous, homogeneous, isotropic, confined aquifer with horizontal flow. The processes of matrix diffusion and clay sorption have not been demonstrated in the field; the values assumed for rock hydraulic properties are at variance with observed lithology and measured transmissivity; and the values assumed for rainwater recharge are unreasonable.

Cavernous Zones at the WIPP Site

Richard Hayes Phillips, Ph.D.

Evidence of karst at the WIPP site is gathered and presented. Zones of unconsolidated or cavernous rock in Rustler mudstone, in both the Forty-Niner and the lower unnamed members, are correlated stratigraphically across the WIPP site; a zone of dissolution in Tamarisk gypsum is identified; encounters of caverns in the Dewey Lake Redbeds are reported; and karst sinkholes at H-7, WIPP-33 and WIPP-14 are described in detail.

Rainwater Recharge at the WIPP Site

Richard Hayes Phillips, Ph.D.

Evidence of rainwater recharge at the WIPP site is gathered and presented. Mescalero caliche, Gatunia sandstone, and the Dewey Lake Redbeds are shown to be transmissive to rainwater recharge. Water in the Dewey Lake Redbeds is commonplace and potable; recharge tends to occur where the Santa Rosa Sandstone is not present. Groundwater and karst features are found in all members of the Rustler Formation. Water in the Culebra Dolomite is everywhere unsaturated, in places potable, and freshest where recharge is greatest.

Potential Flow Paths From the WIPP Site to the Accessible Environment

Richard H. Phillips, Ph.D.
and David T. Snow, Ph.D.

Flow paths from the WIPP site are primarily directed along karst channels and fracture system enlargements, allowing rapid transport to the accessible environment. Potential flow paths from the WIPP site to Nash Draw are identified, consistent with geophysical logs, lithologic descriptions, washouts during drilling, loss of core, loss of circulation of drilling fluid, caverns identified by drilling, multi-well pump tests, high transmissivity, hydraulic heads, groundwater geochemistry, dissolution of halite, distribution of salinity, karst geomorphology, air photo interpretation, sinkholes identified by augering, field observations of rainwater recharge at WIPP-33, field observations of groundwater discharge at Laguna Grande de la Sal, and the regional water balance.
CAVERNOUS ZONES AT THE WIPP SITE

by Richard Hayes Phillips, Ph.D.

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is intended for the permanent disposal of radioactive waste from nuclear weapons production. The project is the brainchild of the United States Department of Energy (DOE). The waste is to be buried in steel drums and plywood boxes in direct contact with salt beds of the Salado Formation. The project lacks engineered barriers; it is the rocks themselves -- the Salado Formation and the aquifers of the overlying Rustler Formation and Dewey Lake Redbeds (shown in cross-section in Figure 1) -- which are intended to be the effective barriers to radionuclide migration.

The Culebra dolomite member of the Rustler Formation has long been recognized as the most likely pathway for contaminated water to travel from the WIPP site to the accessible environment. The Culebra dolomite is not a porous, homogeneous medium; groundwater does not move uniformly and predictably through interconnected pore spaces in the rocks. The Culebra, in most places, is highly fractured, and the effective groundwater flow paths are through the largest fractures, the paths of least resistance.

Dolomite is a soluble rock; it slowly dissolves when exposed to fresh water. As fractures become enlarged by solution, they become even more effective groundwater flow paths. Over time, more and more groundwater flows through fewer and fewer solution-enlarged fractures. Ultimately, these solution conduits become underground caverns, capable of carrying groundwater quite rapidly with little resistance. This type of groundwater hydrology is known by geologists, world-wide, as karst.

The problem with karst as a waste-disposal environment is that some radionuclides may travel unretarded, at the speed of water. The larger the aperture, or diameter, of the solution conduits, the less contact the radionuclides will have with the surrounding rock, and the less the amount of radionuclide retardation. The ability of the Rustler Formation to retard significantly the migration of radionuclides depends upon the absence of karst conditions, of channelized flow, at the WIPP site.

Recent pumping tests at hydrologic test wells in Culebra dolomite at the WIPP site (Beauheim, 1986; Beauheim, 1989) have resulted in unexpectedly short response times between certain test wells. For example, when water was pumped from test well DOE-2, there was a drop in water level within two hours at test well WIPP-13, which is 4835 feet from DOE-2. Test well H-6, which is 10,150 feet from DOE-2, responded within one day. Other test wells, no farther away (e.g. WIPP-12, WIPP-18 and H-5), showed no response at all. This indicates that DOE-2, WIPP-13 and H-6, in the
DEWEY LAKE RED BEDS

SALADO SALT FORMATION

FIGURE 1: GEOLOGIC CROSS-SECTION THROUGH THE WIPP SITE
northern part of the WIPP site, are hydraulically connected by channelized flow in the Culebra dolomite. Similar results indicate a hydraulic connection between test wells H-3, DOE-1 and H-11 in the southeastern part of the WIPP site, with measurable response at test wells H-15, H-17, P-17 and Cabin Baby, and little or no response at test wells H-4, H-12, H-14, P-15 and P-18 [Figure 2]. These hydraulic connections are not necessarily fracture networks, as interpreted by Beauheim (1986, 1989); the response was so rapid that they could be karst channels.

Hydraulic conductivity is the velocity at which water moves through an aquifer. Transmissivity is the rate at which water is transmitted by the aquifer; it is equal to hydraulic conductivity times the thickness of the aquifer. The highest measured values for transmissivity and hydraulic conductivity in the Culebra dolomite aquifer at WIPP test wells are given in Table 1.

It has long been recognized that, in the Culebra dolomite, transmissivity varies by five orders of magnitude in the vicinity of the WIPP site, from 0.002 ft²/day at test well P-18, located 4547.3 feet east of the WIPP site, to 233.0 ft²/day at test well P-14, located 4664.2 feet west of the WIPP site (Haug et al., 1987). It is often represented that transmissivity in the Culebra dolomite increases steadily from east to west, but this is not the case. When measurements of transmissivity in the Culebra dolomite are plotted on a map [Figure 3], contour lines cannot be drawn, not even on a logarithmic scale. Rather, it becomes apparent that, among test wells within one mile of the WIPP site, seven test wells show anomalously high transmissivity in the Culebra dolomite, one to three orders of magnitude higher than in any others. These test wells include, besides P-14, the very six test wells shown by pumping tests to be hydraulically connected (DOE-2, WIPP-13, H-6; H-3, DOE-1 and H-11).

Anomalously high transmissivity in some boreholes is exactly what one would expect in a karstland. A borehole which misses one of the active solution conduits should show values which are much less than the average. This applies to almost all boreholes in a karstland because the area of active solution conduits is only a small part of the total area. It is possible, indeed likely, that none of the measured transmissivities within one mile of the WIPP site are representative of karst conditions in the Culebra dolomite, because none of these test wells were reported to have encountered cavernous zones in the Culebra.

However, cavernous zones were encountered at WIPP-33, a borehole located 2753.4 feet west of the WIPP site. There were five caverns in all: four in the Rustler Formation (two in Magenta dolomite, two in Forty-Niner gypsum), and one in the Dewey Lake Redbeds. The caverns were inferred by: (1) a precipitous drop of the drilling equipment (zero minutes per vertical foot); (2) a loss of circulation of drilling fluid; and (3) no core recovery.
FIGURE 2: RESULTS OF MULTI-WELL PUMP TESTS

- RAPID RESPONSE
- MEASURABLE RESPONSE
- NO RESPONSE
- NOT MONITORED
- NO TEST WELL
<table>
<thead>
<tr>
<th>test well</th>
<th>transmissivity</th>
<th>hydraulic conductivity</th>
<th>source of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>* H-1</td>
<td>0.87</td>
<td>0.038</td>
<td>LaVenue et al. (1989)</td>
</tr>
<tr>
<td>* H-2</td>
<td>0.70</td>
<td>0.032</td>
<td>Beauheim (1989)</td>
</tr>
<tr>
<td>* H-3</td>
<td>19.0</td>
<td>0.86</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>* H-4</td>
<td>1.1</td>
<td>0.046</td>
<td>Haug et al. (1987)</td>
</tr>
<tr>
<td>* H-5</td>
<td>0.2</td>
<td>0.009</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>* H-6</td>
<td>74.0</td>
<td>3.2</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>H-7</td>
<td>1430.0</td>
<td>31.0</td>
<td>LaVenue et al. (1989)</td>
</tr>
<tr>
<td>H-8</td>
<td>16.0</td>
<td>0.59</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>H-9</td>
<td>231.0</td>
<td>7.7</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>H-10</td>
<td>0.07</td>
<td>0.002</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>* H-11</td>
<td>43.0</td>
<td>1.7</td>
<td>Beauheim (1989)</td>
</tr>
<tr>
<td>H-12</td>
<td>0.18</td>
<td>0.007</td>
<td>LaVenue et al. (1989)</td>
</tr>
<tr>
<td>* H-14</td>
<td>0.31</td>
<td>0.013</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* H-15</td>
<td>0.13</td>
<td>0.005</td>
<td>Beauheim (1987)</td>
</tr>
<tr>
<td>* H-16</td>
<td>0.80</td>
<td>0.037</td>
<td>Beauheim (1987)</td>
</tr>
<tr>
<td>H-17</td>
<td>0.22</td>
<td>0.009</td>
<td>Beauheim (1987)</td>
</tr>
<tr>
<td>* H-18</td>
<td>2.0</td>
<td>0.08</td>
<td>Beauheim (1987)</td>
</tr>
<tr>
<td>* P-14</td>
<td>233.0</td>
<td>10.6</td>
<td>Haug et al. (1987)</td>
</tr>
<tr>
<td>* P-15</td>
<td>0.09</td>
<td>0.004</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* P-17</td>
<td>1.7</td>
<td>0.074</td>
<td>Haug et al. (1987)</td>
</tr>
<tr>
<td>* P-18</td>
<td>0.002</td>
<td>0.00007</td>
<td>Haug et al. (1987)</td>
</tr>
<tr>
<td>* WIPP-12</td>
<td>0.10</td>
<td>0.004</td>
<td>Beauheim (1987)</td>
</tr>
<tr>
<td>* WIPP-13</td>
<td>69.0</td>
<td>3.1</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* WIPP-18</td>
<td>0.3</td>
<td>0.014</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* WIPP-19</td>
<td>0.6</td>
<td>0.026</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* WIPP-21</td>
<td>0.25</td>
<td>0.010</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* WIPP-22</td>
<td>0.37</td>
<td>0.017</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>WIPP-25</td>
<td>270.0</td>
<td>11.0</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>WIPP-26</td>
<td>1250.0</td>
<td>54.3</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>WIPP-27</td>
<td>650.0</td>
<td>25.0</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>WIPP-28</td>
<td>18.0</td>
<td>0.69</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>WIPP-29</td>
<td>1000.0</td>
<td>33.3</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>WIPP-30</td>
<td>0.3</td>
<td>0.013</td>
<td>Mercer (1983)</td>
</tr>
<tr>
<td>AEC-7</td>
<td>0.26</td>
<td>0.010</td>
<td>LaVenue et al. (1989)</td>
</tr>
<tr>
<td>* DOE-1</td>
<td>33.0</td>
<td>1.5</td>
<td>Haug et al. (1987)</td>
</tr>
<tr>
<td>* DOE-2</td>
<td>89.0</td>
<td>4.0</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* ERDA-9</td>
<td>0.47</td>
<td>0.020</td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>D-268</td>
<td>1.9</td>
<td></td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>* Cabin Baby</td>
<td>0.28</td>
<td></td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>Engle</td>
<td>43.0</td>
<td></td>
<td>LaVenue et al. (1988)</td>
</tr>
<tr>
<td>USGS-1</td>
<td>515.0</td>
<td></td>
<td>LaVenue et al. (1988)</td>
</tr>
</tbody>
</table>

* Test wells located at or within one mile of the WIPP site.
FIGURE 3: CULEBRA TRANSMISSIVITY, ft²/day

○ ANOMALOUS BOREHOLES
○ KARST SINK HOLES

WIPP SITE BOUNDARY

MILES

O 270
O WIPP-33
O 233
O 1250
O 1.9
O 1430

O 74.0
O 69.0
O 0.10
O 0.25
O 0.47
O 0.13
O 0.31
O 0.33
O 0.16
O 0.002
O 0.019

O 0.022
A camera was then lowered into the borehole, which confirmed the presence of underground caverns. If cavernous zones are present in other WIPP boreholes, the same three criteria should apply. Unfortunately, an examination of the geophysical logs and lithologic descriptions for other WIPP boreholes reveals that the first two criteria -- drilling time and lost circulation -- are rarely noted. Nor can cavernous zones in the Culebra and Magenta dolomite members of the Rustler Formation be detected by a lack of core recovery alone, because the Culebra and Magenta are typically fractured, which makes core recovery difficult. However, a correlation of geophysical logs and lithologic descriptions does reveal a consistent lack of core recovery at two other stratigraphic horizons in the Rustler Formation:

(1) A zone of solution residue characterized by soft reddish-brown siltstone or mudstone with gypsum-filled voids and clasts of brecciated gypsum and anhydrite. This zone grades downward into a greenish claystone separated from the Magenta dolomite by 13.9 to 18.7 feet of anhydrite or gypsum. In the WIPP ventilation shaft this zone is 6.7 feet thick; it washed out 2.5 feet deep into the shaft wall; water seeps into the shaft at this level; and a ten-foot steel liner plate was installed to prevent further caving of the shaft wall.

(2) A zone of solution residue consisting of claystone or mudstone, gray to dark reddish-brown, with brecciated anhydrite clasts, gypsum crystals, and gypsum-filled fractures; poorly consolidated, and readily crumbled. The claystone grades upward into a layer of soft shale, black to dark gray, immediately beneath the Culebra dolomite. In the WIPP ventilation shaft this zone is 7.1 feet thick; it washed out into the shaft wall; water seeps into the shaft at this level; and a ten-foot steel liner plate was installed to prevent further caving of the shaft wall.

Note that the first zone is in the Forty-Niner member of the Rustler Formation; the second zone is in the lower unnamed member of the Rustler Formation; and both zones produce water, at least in the WIPP ventilation shaft. This is direct evidence that no member of the Rustler Formation is impermeable, that the Magenta dolomite and Culebra dolomite are not confined aquifers. This substantiates the findings of Ferrall and Gibbons (1980), who examined available cores of the Rustler Formation and observed high-angle to near-vertical fractures in each member.

If these zones appeared only in the WIPP ventilation shaft, or elsewhere but rarely, it might be reasonable to regard them as "washed out zones" attributable to drilling fluid. However, both of these zones can be correlated across the WIPP site, with a consistent lack of core recovery. Both zones are poorly consolidated, probably transmissive, and possibly cavernous.
In the zone above the Magenta dolomite there was loss of core, washout, and/or loss of circulation at H-17, H-11b3, H-3b3, H-1, WIPP-19, WIPP-12, DOE-2, WIPP-34, H-16, H-18, and WIPP-33. In the zone below the Culebra dolomite there was loss of core or cuttings at H-11b3, H-3b3, P-1, H-14, H-15, H-18, P-12, WIPP-13, WIPP-11, DOE-2, WIPP-34, and WIPP-14. Detailed summaries of these cavernous encounters, compiled almost entirely from geophysical logs and lithologic descriptions, with occasional reliance on Chaturvedi and Channell (EEG-32, 1985), are given in Tables 2 and 3. The boreholes are mapped in Figure 4.

Dissolution residue was reported in the Forty-Niner member, within 15 to 18 feet of the Magenta, but with no loss of core, at ERDA-9, WIPP-18, WIPP-19, WIPP-21, WIPP-22, and WIPP-13. Dissolution residue was reported in the lower unnamed member, within 2 to 4 feet of the Culebra, but with no loss of core, at ERDA-9, WIPP-18, WIPP-21, WIPP-22, H-6, and WIPP-33.

All the boreholes listed above are located at the WIPP site or within one mile of the WIPP site. In addition, at borehole H-7c, located 2.9 miles southwest of the WIPP site in Nash Draw, there was loss of core at 273.5 to 280.0 feet below the land surface, immediately below the Culebra dolomite. At borehole WIPP-25, located 2.5 miles west of the WIPP site in Nash Draw, there was lost circulation of drilling fluid at 522 to 526 feet below the land surface, within a 20.6-foot section of mud in the lower unnamed member of the Rustler Formation.

There is another dissolution zone in the Tamarisk member of the Rustler Formation. Four boreholes clustered near the center of the WIPP site have encountered washouts or loss of core in Tamarisk anhydrite: at H-1 (650.0-653.5 feet below land surface, 22.5 feet above Culebra); at H-2a (593.0-606.0 feet below land surface, 17.0 feet above Culebra); at H-3b3 (645.5-652.5 feet below land surface, 19.5 feet above Culebra); and at ERDA-9 (690.0-698.0 feet below land surface, 6.0 feet above Culebra). At the same horizon in the Tamarisk member, dissolution residue was encountered in the WIPP ventilation shaft and along two paths leading away from ERDA-9: northward at WIPP-21, WIPP-22, WIPP-19 and WIPP-18, and northwestward at H-18, WIPP-13 and H-6.

Caverns are known to occur in the Dewey Lake Redbeds as well. The lithologic log for borehole H-7c reports "boulders caving in" at 59 feet below the land surface. Lost circulation of drilling fluid in the Dewey Lake Redbeds has been reported at H-7c (24 feet above the Rustler), at WIPP-33 (37 feet above the Rustler), at WIPP-25 (124 to 154 feet above the Rustler), at P-1 (180 feet above the Rustler), and at DOE-2 (400 feet above the Rustler).

This correlation of cavernous zones raises two questions: (1) are karst conditions expressed at the land surface; and (2) if so, is WIPP hydrologic data representative of karst conditions?
### TABLE 2: CORRELATED EVIDENCE OF CAVERNOUS ZONE, FORTY-NINER MEMBER, RUSTLER FORMATION

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Depth (ft)</th>
<th>Above Magenta (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-17</td>
<td>&quot;no recovery,&quot; 7.2 ft, claystone,</td>
<td>542.9-550.1</td>
<td>13.9</td>
</tr>
<tr>
<td>H-11b3</td>
<td>&quot;no recovery,&quot; 6.2 ft, claystone,</td>
<td>595.7-601.9</td>
<td>21.0</td>
</tr>
<tr>
<td>H-3b3</td>
<td>&quot;washed out zone,&quot; 2.5 ft, mudstone,</td>
<td>536.5-539.0</td>
<td>20.0</td>
</tr>
<tr>
<td>H-1</td>
<td>&quot;washed out zone,&quot; 8.5 ft, mudstone,</td>
<td>538.5-547.0</td>
<td>16.0</td>
</tr>
<tr>
<td>VENTILATION SHAFT</td>
<td>&quot;deep washout,&quot; 6.7 ft, mudstone, first liner plate,</td>
<td>569.2-575.9</td>
<td>20.2</td>
</tr>
<tr>
<td>WIPP-19</td>
<td>&quot;no core,&quot; 2.1 ft, mudstone,</td>
<td>620.2-622.3</td>
<td>25.5</td>
</tr>
<tr>
<td>WIPP-12</td>
<td>&quot;no core,&quot; 6.0 ft, clay,</td>
<td>678.7-684.7</td>
<td>19.2</td>
</tr>
<tr>
<td>DOE-2</td>
<td>&quot;no core,&quot; 2.5 ft of 10.2 ft interval,</td>
<td>669.8-680.0</td>
<td>18.6</td>
</tr>
<tr>
<td>WIPP-34</td>
<td>&quot;no core,&quot; 2.7 ft, mudstone,</td>
<td>691.0-693.7</td>
<td>22.1</td>
</tr>
<tr>
<td>H-16</td>
<td>&quot;no recovery,&quot; 2.5 ft, clay,</td>
<td>566.8-569.3</td>
<td>20.9</td>
</tr>
<tr>
<td>H-18</td>
<td>&quot;no recovery,&quot; 7.1 ft, clay,</td>
<td>542.2-549.3</td>
<td>21.9</td>
</tr>
<tr>
<td>WIPP-33</td>
<td>&quot;cavity; determined by drop of drill string during drilling and through interpretation of caliper log,&quot; 9.5 ft, gypsum,</td>
<td>416.5-426.0</td>
<td>23.0</td>
</tr>
<tr>
<td>ALLO AT WIPP-33</td>
<td>&quot;cavity; no core (drill string dropped), possible cavernous formation,&quot; 6.0 ft, gypsum,</td>
<td>430.0-436.0</td>
<td>13.0</td>
</tr>
<tr>
<td>WIPP-19</td>
<td>&quot;no core,&quot; 2.1 ft, mudstone,</td>
<td>620.2-622.3</td>
<td>25.5</td>
</tr>
<tr>
<td>WIPP-12</td>
<td>&quot;no core,&quot; 6.0 ft, clay,</td>
<td>678.7-684.7</td>
<td>19.2</td>
</tr>
<tr>
<td>DOE-2</td>
<td>&quot;no core,&quot; 2.5 ft of 10.2 ft interval,</td>
<td>669.8-680.0</td>
<td>18.6</td>
</tr>
<tr>
<td>DOE-2</td>
<td>&quot;cavity (drill string dropped)&quot;</td>
<td>5.0 ft,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>in Magenta dolomite, no circulation for 24 hour period,</td>
<td>462.0-467.0</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3: CORRELATED EVIDENCE OF CAVERNOUS ZONE, LOWER UNNAMED MEMBER, RUSTLER FORMATION

H-17:
"some rock washed away," core recovered, 0.8 ft, claystone
733.2-734.0 ft below surface, 1.8 ft below Culebra

H-11b3:
"no recovery (estimated zone of core loss)," 2.6 ft, clay,
765.9-768.3 ft below surface, 0.4 ft below Culebra

H-3b3:
"only 20% of the core was recovered," 5.5 ft, black shale and siltstone,
appears on caliper log,
691.5-697.0 ft below surface, directly below Culebra

P-1:
"friable" (brittle, readily crumbled), 10.0 ft, mudstone,
580.0-590.0 ft below surface, 1.0 ft below Culebra

H-14:
"no recovery," 4.6 ft, claystone (?),
569.4-574.0 ft below surface, directly below Culebra

H-15:
"no recovery," 9.2 ft, mudstone,
890.8-900.0 ft below surface, 5.1 ft below Culebra

VENTILATION SHAFT:
"washed out zone," 7.1 ft, mudstone/claystone,
third liner plate,
727.2-734.3 ft below surface, 0.3 ft below Culebra

H-16:
"washed out core," 4.0 ft, claystone,
725.1-729.1 ft below surface, 0.7 ft below Culebra

H-18:
"no recovery," 3.6 ft, clay and claystone,
713.8-717.4 ft below surface, 1.9 ft below Culebra

P-12:
"no sample," 5.0 ft, siltstone,
660.0-665.0 ft below surface, 4.0 ft below Culebra

WIPP-13:
"no core," 2.0 ft, mudstone,
727.0-729.0 ft below surface, 0.1 ft below Culebra

WIPP-11:
"no core," 4.5 ft, mudstone,
888.0-892.5 ft below surface, 8.0 ft below Culebra

DOE-2:
"no core," 1.4 ft, mudstone,
847.6-849.0 ft below surface, 1.6 ft below Culebra

WIPP-34:
"no core," 3.5 ft, mudstone,
860.8-864.3 ft below surface, directly below Culebra

WIPP-14:
"no core," 81.4 ft, mud with gypsum and anhydrite fragments
(upper 71.4 ft), mud and siltstone (lower 10.0 ft),
836.2-917.6 ft below surface, directly below Culebra

ALSO AT WIPP-14:
"no core," 159.9 ft: siltstone and mudstone (10.7 ft) and gypsum (19.5 ft), lower 30.2 ft
of Forty-Niner Member; entire 23.5 ft of Magenta dolomite; entire 87.2 ft of Tamarisk
Member, siltstone, sandstone, anhydrite, clay, gypsum; entire 19.0 ft of Culebra dolomite;
676.3-836.2 ft below surface
Figure 4: Washouts and Loss of Core in Rustler
Every karstland has sinkholes in the land surface. Two types of sinkholes are recognized: (1) collapse sinks, formed when surface rocks collapse abruptly into underground caverns, allowing surface runoff to be swallowed rapidly; and (2) alluvial dolines, or solution-subsidence dolines, formed when surface rocks subside slowly due to solution of underlying rocks; these are flooded after major rainstorms and become filled with alluvial sediments. Collapse sinks are more common where soluble rocks are exposed at the land surface; alluvial dolines are more common where soluble rocks are overlain by sandstones, as at the WIPP site.

West of the WIPP site is Nash Draw, one of the largest karst features with surface expression in the world. Nash Draw is a huge depression, 18 miles long and 10 miles wide, formed by the coalescence of thousands of sink holes. The H-7 test wells were drilled into one of the sinks in Nash Draw; it is located near the western end of an obvious karst valley, walled on both sides by high dunes, and plainly visible in the WIPP site air photos. There are ephemeral watercourses draining into the valley from the sides, but upon entering the valley these watercourses disappear underground. At borehole H-7c a cavern was encountered in the Dewey Lake Redbeds, with lost circulation of drilling fluid and "boulders caving in." The Culebra dolomite was broken into six sections totalling 24.3 feet, separated by five cavities totalling 21.7 feet; this was underlain by 6.2 feet of mud, beneath which there was no core for 80.8 feet. Transmissivity in the Culebra dolomite is 1430 ft$^2$/day, the highest measurement at any of the forty-one WIPP test wells.

The most obvious sinkhole in the WIPP site vicinity is WIPP-33, located in sec 13, T 22 S, R 30 E. It is a closed topographic depression about 700 feet in diameter and 30 feet deep. It is prominent on the WIPP site air photos, and is shown on the USGS topographic maps. One of the few small arroyos in the WIPP site vicinity drains into this depression. It is floored with matted leaves, organic matter and desiccated clay, indicating occasional flooding of the depression. Evidence of surface collapse can be seen in the caliche escarpment at its southeastern rim. Evidence of subsurface collapse was seen in backhoe trenches, where caliche breaks off abruptly, with near-vertical drops of four feet to the sandstone bedrock surface. Joint-controlled solution features were found in carbonate-cemented sandstone beneath the caliche. In the WIPP site gravity survey, a negative gravity anomaly of high amplitude was measured, originating no deeper than the Magenta dolomite. Borehole WIPP-33, drilled into this depression, encountered 44 feet of alluvial fill, and five underground caverns filled with water -- one in Dewey Lake siltstone, two in Forty-Niner gypsum, two in Magenta dolomite. In the Rustler Formation, all anhydrite has been converted to gypsum, and all halite has been dissolved and removed; salt dissolution has also affected the top of the Salado Formation.
Three other sinkholes form a chain trending west-southwestward, directly to WIPP-33, implying an underground flow path beneath them. All are visible in the WIPP site air photos, and all are underlain by structural depressions in the caliche surface. The westernmost sinkhole is 400 feet long, 200 feet wide, 2 to 4 feet deep, is floored by organic debris and desiccated clay, is saturated after rainstorms, contains at least 24 feet of alluvial fill, and swallows some of the water from the WIPP-33 arroyo. The second sinkhole is 300 feet long, 200 feet wide, 8 to 10 feet deep, and is not as well developed, being floored by sand with a weak clay pan and only partly filled with alluvial sediments, although non-incised watercourses are present on its slopes. The easternmost sinkhole is 300 feet long, 150 feet wide, 2 feet deep, is floored by organic debris and desiccated clay, is saturated after rainstorms, contains up to 20 feet of alluvial fill, and has an arroyo disappearing into it. This arroyo formed suddenly during the heavy rains of September 18-19, 1985, only to be swallowed by the sinkhole; this is direct evidence of active karst processes. This same rainstorm filled the WIPP-33 sinkhole with 5.0 feet of standing water, which infiltrated within days.

Another sinkhole in the WIPP site vicinity is WIPP-14, located in sec 9, T 22 S, R 31 E. It is 600 to 700 feet in diameter, 9 feet deep, and is shown on the USGS topographic maps. Draining into the WIPP-14 depression from the east are at least five ephemeral water courses. It is floored by windblown sand, organic debris, and desiccated clay. No collapse is evident at the surface, but such evidence could be obscured by 8 to 15 feet of dune sands that have accumulated on the crests of the depression. It is underlain by a structural depression in the caliche surface, 400 to 650 feet in diameter and 6 feet deep. Gleyed sediments were observed in trench exposures, indicating past ponding, when perched water accumulated in the depression and caliche became extremely leached and degraded, leaving only remnants pockmarked with solution features. Carbonate-filled fractures in Santa Rosa sandstone beneath the caliche are direct evidence of rainwater infiltration. The depression is underlain by a high-amplitude negative gravity anomaly. Borehole WIPP-14, drilled into this depression, encountered 15.4 feet of alluvial fill; there was 243.1 feet of lost core, including 71.4 feet of mud with gypsum and anhydrite fragments directly below the Culebra; halitic mudstone was found in the lower 3.7 feet of the Rustler Formation; all other halite has been dissolved and removed.

There are now 27 hydrologic test wells within one mile of the WIPP site. Six of them (DOE-2, WIPP-13, H-6, H-3, DOE-1, H-11) may be representative of fracture flow in the Culebra, but none are known to be representative of karst conditions. WIPP-33 is located one-half mile from the WIPP site, and WIPP-14 is located within 100 feet of the WIPP site. There is no excuse for not converting these existing boreholes into hydrologic test wells. The simplest explanation is that DOE is not interested in karst.
RAINWATER RECHARGE AT THE WIPP SITE

by Richard Hayes Phillips, Ph.D.

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is intended for the permanent disposal of radioactive waste from nuclear weapons production. The WIPP site was selected in 1974. It is now 1997, and the Department of Energy (DOE) still does not know where the groundwater aquifers are recharged. This, at a minimum, must be understood, or DOE's site characterization has no credibility (EEG-32, 1985; Anderson, 1994; Konikow, 1995; EEG-61, 1996; SEIS, 1996, Appendix H).

DOE's failure to grasp the fundamentals of WIPP site hydrology stems not from a lack of evidence, but from an unwillingness to face the truth: (1) the WIPP site is in karst; (2) the Dewey Lake Redbeds and the Rustler Formation are recharged by rainwater; and (3) groundwater flow at WIPP is three-dimensional.

The controversy over karst at the WIPP site dates to a paper by Larry Barrows entitled: "WIPP Geohydrology -- The Implications of Karst" (Barrows, 1982; reprinted in EEG-32, 1985, Appendix A). Barrows cites as evidence of karst geomorphology: (1) ample precipitation; (2) lack of surface runoff; (3) disappearing arroyos; (4) sink holes; and (5) underground caverns.

The WIPP site is located in one of the largest karstlands in the world. The Pecos River valley is famous for Santa Rosa Sinks, Bottomless Lakes, and Carlsbad Caverns. Within one mile of the northwest corner of the WIPP site is Nash Draw, a huge depression in the land surface, up to 18 miles long and 10 miles wide. Nash Draw was formed by the coalescence of thousands of sink holes caused by the abrupt collapse or gradual subsidence of overlying rocks into underground caverns beneath them.

Nash Draw is bounded on the east by Livingston Ridge, which is actually a rim, a 100-foot escarpment capped by Mescalero caliche. Livingston Ridge is not a geomorphic divide; it does not represent the eastern extent of karst conditions. It is the eastern extent of widespread collapse of surficial rocks into the voids caused by dissolution of evaporite rocks in the subsurface. Karst exists east of Livingston Ridge, but the karst landforms are not as widespread or as well developed as in Nash Draw.

The WIPP site has almost no surface runoff. This is not due to inadequate precipitation. Rainfall averages 14 inches per year, and 20 inches per year is not uncommon. Rather, the WIPP site is covered with windblown sand in the form of deflation basins and partially stabilized dunes. These sands are transmissive enough to allow infiltration of even the largest storms. "Instead of
running off, the precipitation collects in the small topographic depressions and rapidly soaks into the ground. The absence of surface runoff is characteristic of a karstland." (Barrows, 1982)

Most of the depressions are windblown. But some of the larger ones are sink holes, exemplified by WIPP-33 and WIPP-14, located 1.1 mile and 3.4 miles east of Nash Draw, respectively. WIPP-33 is a collapse sink with a disappearing arroyo, underlain by five caverns: one in Dewey Lake siltstone, two in Forty-Niner gypsum, and two in Magenta dolomite. WIPP-14 is a solution-subsidence doline which has held water in the geologic past; now the Culebra dolomite is underlain by 70 feet of mud with gypsum and anhydrite fragments, here interpreted as cave sediments. The cavernous zones at WIPP-33 and WIPP-14 are direct evidence of karst. These zones can be correlated stratigraphically with washouts and loss of core in seventeen other WIPP boreholes and in the WIPP ventilation shaft. The question is not whether karst exists at the WIPP site, but whether karst hydrology is active today.

The Rustler Formation is the most transmissive aquifer and the principal karst horizon at the WIPP site. If karst hydrology is active today, then the Rustler Formation must be recharged by rainwater. A likely process, according to Barrows (1982), is downward infiltration of fresh water through feeders in the overlying Dewey Lake Redbeds to karst channels in the Rustler Formation. Conversely, if karst hydrology is not active today, then the Rustler Formation must not be recharged by rainwater. This would require a continuous impermeable layer, acting as a barrier to rainwater infiltration, somewhere in the stratigraphic column above the Rustler Formation. Bachman (1985) argued that Mescalero caliche forms such a barrier, preventing infiltration and recharge of the Dewey Lake Redbeds and the Rustler Formation.

Caliche is a layer of calcium carbonate that forms in desert soils at the depth of soil water penetration. Where soil cover is thin, the caliche horizon may become plugged and indurated, forming a "hardpan" resistant to erosion and impervious to rainwater. But where soil cover is thick, infiltrating soil water may migrate along the caliche surface until it finds a fracture that allows downward drainage, or a hole where a plant root has penetrated the caliche; or it may collect in a small depression in the caliche surface and begin to dissolve a new hole in the caliche. In the southwestern part of the WIPP site (SW/4 sec 30, T 22 S, R 31 E), where Mescalero caliche is in direct contact with the Dewey Lake Redbeds, trench exposures revealed fifteen solution pipes, 1 to 14 feet in diameter, right through the caliche. Here the Dewey Lake Redbeds are recharged directly by rainwater. These trenches were located in a karst valley, a broad swale one mile long, ten feet deep, trending east-west, and narrowing from 900 feet in the east to 200 feet in the west, where thick groves of mesquite bushes are impenetrable.
Other smaller topographic depressions, visible in the WIPP site air photos, shown on USGS topographic maps, lead directly to the deepest fluvial incisions in Livingston Ridge. The air photos reveal ephemeral or near-surface drainage courses expressed at the land surface as vegetation in dendritic patterns.

The Gatuna Formation, consisting of light reddish-brown, poorly consolidated sandstone, is alluvial fill material deposited in ancient sinks and topographic lows by westward-flowing streams. It was exposed in trenches on the slopes of WIPP-33, below the caliche escarpment. The Gatuna sandstone is commonly fractured, jointed, and broken into blocks. As soil water dissolves the carbonate cement, these openings become enlarged by solution, forming solution pans or tinajitas, and solution grooves or slots. The Gatuna is not a barrier to rainwater infiltration.

The Santa Rosa Formation consists of pale orange, coarse-grained sandstone, cemented by dolomite, interbedded with conglomerate lenses containing dolomite, chert, and quartz pebbles. The Santa Rosa has been eroded from the western part of the WIPP site; to the east, where it remains, it protects the underlying Dewey Lake Redbeds from erosion. At WIPP-14, the Santa Rosa was exposed in trenches beneath a leached and degraded caliche profile. The Santa Rosa exhibited carbonate-filled fractures, direct evidence of rainwater infiltration. The Santa Rosa retards, but does not prevent, rainwater recharge to the underlying Dewey Lake Redbeds.

Water has been encountered in the Dewey Lake Redbeds in eleven test wells within one mile of the WIPP site. All are listed in Table 1. According to the neutron log for H3-b4, a down-hole camera recorded "water streaming from fracture." The water level was 466.85 feet below the surface. Water was also observed in the Dewey Lake Redbeds in the air intake shaft near the center of the WIPP site (EEG-61, 1996, p. 2-6), at WIPP-33 (SAND 80-2011, p. 11), and in three private wells within 2.5 miles of the WIPP site (Ranch, Barn, and Unger). All are shown in Figure 1.

Table 1 reveals a strong correlation between encounters of water in the Dewey Lake Redbeds and absence of the overlying Santa Rosa sandstone. At least nine of the thirteen test wells where the Santa Rosa is not present produced water in the Dewey Lake Redbeds. It is not certain that the other four (H-6, P-14, WQSP-5, and Cabin Baby) did not produce water in the Dewey Lake Redbeds, because the actual neutron logs for these test wells are unavailable. However, the "abridged drill-hole histories" for P-13 (located 224 feet from the H-6 hydropad) and P-14 do not report water in the Dewey Lake Redbeds. Only two of the twenty test wells where the Santa Rosa is present produced water in the Dewey Lake Redbeds. At these test wells (H-11 and H-16) the Santa Rosa is only 54 feet and 15 feet thick, respectively. This is further evidence that the Santa Rosa retards, but does not prevent, rainwater recharge to the underlying Dewey Lake Redbeds.
FIGURE 1: TOTAL DISSOLVED SOLIDS
mg/l, CULEBRA DOLOMITE

CONTOUR INTERVAL 50,000 mg/l

© WATER IN DEWEY LAKE REDBEDS
TABLE 1: THICKNESS OF SANTA ROSA SANDSTONE, MEASURED IN FEET, CORRELATED WITH ENCOUNTERS OF WATER IN DEWEY LAKE REDBEDS, AT WIPP TEST WELLS

<table>
<thead>
<tr>
<th>test well</th>
<th>Santa Rosa water in Dewey Lake</th>
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</thead>
<tbody>
<tr>
<td>H-1</td>
<td>N.P. *</td>
</tr>
<tr>
<td>H-2</td>
<td>N.P. *</td>
</tr>
<tr>
<td>H-3</td>
<td>N.P. *</td>
</tr>
<tr>
<td>H-4</td>
<td>N.P. *</td>
</tr>
<tr>
<td>H-5</td>
<td>217</td>
</tr>
<tr>
<td>H-6</td>
<td>N.P. ?</td>
</tr>
<tr>
<td>H-11</td>
<td>54 *</td>
</tr>
<tr>
<td>H-14</td>
<td>N.P. *</td>
</tr>
<tr>
<td>H-15</td>
<td>126</td>
</tr>
<tr>
<td>H-16</td>
<td>15 *</td>
</tr>
<tr>
<td>H-17</td>
<td>34</td>
</tr>
<tr>
<td>H-18</td>
<td>12</td>
</tr>
<tr>
<td>P-14</td>
<td>N.P. ?</td>
</tr>
<tr>
<td>P-15</td>
<td>N.P. *</td>
</tr>
<tr>
<td>P-17</td>
<td>N.P. *</td>
</tr>
<tr>
<td>P-18</td>
<td>78</td>
</tr>
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<td>ERDA-9</td>
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<tr>
<td>Cabin Baby</td>
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</tr>
<tr>
<td>WQSP-2</td>
<td></td>
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<td>WQSP-3</td>
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</tr>
<tr>
<td>WQSP-4</td>
<td></td>
</tr>
<tr>
<td>WQSP-5</td>
<td>N.P. ?</td>
</tr>
<tr>
<td>WQSP-6</td>
<td>N.P. *</td>
</tr>
<tr>
<td>WQSP-6a</td>
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</tr>
</tbody>
</table>

Note: WQSP-6 and WQSP-6a are shown as one well in Figures 5 and 6.

Sources: DOE/CAO 1996-2184, pp. 2-131, USDW-25; SAND 88-0157, p. 81; SAND 80-2011, pp. 8, 11, 15, C-3; and EEG-61, p. 2-6.
Figure 2 graphically displays the relationship between the western edge of the Santa Rosa sandstone and the locations of wells that produce water in the Dewey Lake Redbeds. Simply stated, the recharge area for the Dewey Lake Redbeds is everywhere that the Santa Rosa Formation is not present.

The water in the Dewey Lake Redbeds is potable. Environmental Protection Agency (EPA) criteria for drinking water are twofold: (1) less than 10,000 milligrams per liter (mg/l) total dissolved solids (TDS); and (2) more than 5 gallons per minute (gpm) of water produced by the well. Water quality data for the Dewey Lake Redbeds are given in Table 2. Five private wells within eight miles of the WIPP site produce water of potable quality in the Dewey Lake Redbeds, but the quantity has never been measured. Three WIPP test wells produce water in sufficient quantity from the Dewey Lake Redbeds, but the quality has never been tested. At seven WIPP test wells, (and also at WIPP-33), water produced by the Dewey Lake Redbeds has never been tested for quality or quantity. At only one test well, WQSP-6a, has both the quantity and quantity of water from the Dewey Lake Redbeds been tested, and it was found to meet both criteria for drinking water (3,920 to 4,238 mg/l TDS, 12 gpm). DOE claims (DOE/CAO 1996-2184, Appendix USDW, Table USDW-4) that test well WQSP-6a is not subject to EPA standards (40 CFR 191, Subpart C) because WQSP-6a is located on-site -- one mile southwest of the center of the WIPP site, 0.3 miles southwest of the waste emplacement panels (DOE/CAO 1996-2184, Figure 3-9). DOE says it is "possible" that other test wells are subject to EPA standards (DOE/CAO 1996-2184, Appendix USDW, Table USDW-4). DOE does not know because DOE has not done the necessary testing. P-17 is 3908 feet outside the WIPP site. WIPP-33 is 2854 feet outside the WIPP site. H-4c is 446 feet outside the WIPP site. All the private wells are outside the WIPP site. Until these wells are properly tested, it cannot be claimed that the Dewey Lake aquifer does not qualify as an underground source of drinking water under 40 CFR 191, Subpart C. Absence of evidence is not evidence of absence.

Directly underlying the Dewey Lake Redbeds is the Rustler Formation. In WIPP boreholes, outside of Nash Draw, the Rustler ranges in thickness from 276 feet at WIPP-33, a collapse sink, to 462 feet at P-18, considered to be a complete Rustler section. The Rustler is divided into five members, here described in descending order: (1) the Forty-Niner member consists of 48 to 78 feet of broken and slumped gypsum with a bed of massive siltstone near the base; (2) the Magenta dolomite, 19 to 28 feet thick, is a highly fractured aquifer; (3) the Tamarisk member consists of 80 to 179 feet of anhydrite or gypsum with clay seams; (4) the Culebra dolomite, 21 to 31 feet thick, also highly fractured, is the most transmissive of the Rustler aquifers; and (5) the lower unnamed member consists of 72 to 150 feet of siltstone and very fine-grained sandstone, with interbedded gypsum or anhydrite.
FIGURE 2: RECHARGE AREA AT WIPP SITE
TABLE 3: LOWEST RELIABLE MEASUREMENTS, TOTAL DISSOLVED SOLIDS, CULEBRA DOLOMITE

<table>
<thead>
<tr>
<th>Well</th>
<th>TDS (mg/l)</th>
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</thead>
<tbody>
<tr>
<td>H-1</td>
<td>30,000</td>
</tr>
<tr>
<td>H-2</td>
<td>8,890</td>
</tr>
<tr>
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<td>H-5</td>
<td>135,000</td>
</tr>
<tr>
<td>H-6</td>
<td>52,000</td>
</tr>
<tr>
<td>H-7</td>
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</tr>
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<td>H-8</td>
<td>2,710</td>
</tr>
<tr>
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<td>WQSP-6</td>
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</tr>
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</table>

Sources: Mercer, 1983 (USGS-WRI 83-4016, Table 8); Ramey, 1985 (EEG-31); Chapman, 1988 (EEG-39); Lappin et al., 1989 (SAND 89-0462, Table 3-12); DOE/CAO 1996-2184, Appendix USDW, Table USDW-2; Annual Site Environmental Reports, 1992-1995.
sandstone is present, with TDS steadily decreasing to the southwest, where the Santa Rosa is absent. This is consistent with the interpretation that Culebra groundwater becomes mixed with increasing amounts of fresh water as it approaches Nash Draw, because the hydrologic regime is increasingly karstic.

A similar observation was made by Chapman (EEG-39, 1988). She concluded (p. 35) that "the only plausible mechanism" for an order of magnitude decrease in TDS as Culebra groundwater moves along its flow path "is the influx of a large quantity of low TDS water. As no fresh-water aquifers are located in the WIPP area, the source of the fresh water must be surface water recharge."

Test wells known to have produced water in the Dewey Lake Redbeds are depicted as bull's eyes in Figure 1. At ten of these wells, TDS in the Culebra dolomite were measured; and in seven of these, the lowest measurement was 36,000 mg/l or less (H-16 was measured only once). According to Ramey (EEG-31, 1985): "Waters with greater than 35,000 mg/l of total dissolved solids are classified as brines." Thus, Culebra water in the recharge area, where the Santa Rosa is absent, is fresh enough not to be classified as brine. In fact, Culebra water at H-2b is potable (8,890 mg/l TDS). H-2b is on-site. DOE has tested the quality, but not the quantity, of Culebra water at H-2b. Five private wells within ten miles of the WIPP site produce water of potable quality in the Culebra dolomite, but the quantity has never been measured. Three test wells outside the WIPP site -- H-7bl, H-8b and H-9b -- produce water of sufficient quality and quantity (less than 10,000 mg/l TDS and more than 5 gpm) to meet EPA criteria and establish the Culebra as an underground source of drinking water under 40 CFR 191, Subpart C. Test well H-7bl is located only 2.9 miles from the WIPP site, in Nash Draw, along a potential groundwater flow path from WIPP to the accessible environment. Water quality data for the Culebra dolomite are given in Table 4. Thirteen wells which produced potable water are shown in Figure 1.

Conclusions: (1) karst landforms exist at the WIPP site, and karst hydrology is active at the WIPP site today; (2) rainwater infiltrates through solution pipes in Mescalero caliche, solution features in Gatuna sandstone, and fractures in the Dewey Lake Redbeds; (3) cavernous zones have been found, in WIPP boreholes, in Dewey Lake siltstone and in every member of the Rustler Formation -- in Forty-Niner gypsum, Magenta dolomite, Tamarisk anhydrite, Culebra dolomite, and mudstone of the lower unnamed member; (4) water has been found at the WIPP site in the Dewey Lake Redbeds and in every member of the Rustler Formation; (5) the Dewey Lake Redbeds and the Culebra dolomite contain potable water at and near the WIPP site, which can only be explained by rainwater recharge; (6) the recharge area for the Dewey Lake Redbeds and the Rustler Formation is at and near the WIPP site, everywhere that the Santa Rosa sandstone is not present; and (7) groundwater flow in the Rustler Formation is three-dimensional.
### TABLE 4: POTABLE WATER IN CULEBRA DOLOMITE

<table>
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<th>well</th>
<th>TDS (mg/l)</th>
<th>date</th>
<th>gpm</th>
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</thead>
<tbody>
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<td>not tested</td>
</tr>
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<td>H-7b1</td>
<td>3,400</td>
<td>03/27/86</td>
<td>5-6</td>
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</tr>
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<td>04/25/88</td>
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<td>11/09/90</td>
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</tr>
<tr>
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<td></td>
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<tr>
<td>H-9b</td>
<td>3,300</td>
<td>11/14/85</td>
<td>9.6-10.5</td>
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<tr>
<td></td>
<td>3,300</td>
<td>01/28/87</td>
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<td></td>
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<td>06/21/88</td>
<td></td>
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<tr>
<td></td>
<td>3,300</td>
<td>01/19/90</td>
<td></td>
</tr>
<tr>
<td>Engle</td>
<td>3,450</td>
<td>03/04/85</td>
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</tr>
<tr>
<td></td>
<td>4,000</td>
<td>12/08/87</td>
<td></td>
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<tr>
<td></td>
<td>3,600</td>
<td>01/31/90</td>
<td></td>
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<td>Poker Trap</td>
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<td>not tested</td>
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<td>04/12/88</td>
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</tr>
<tr>
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<td>4,000</td>
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<tr>
<td>James Brothers</td>
<td>3,940</td>
<td>04/30/50</td>
<td>not tested</td>
</tr>
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</table>

Criteria for drinking water: < 10,000 mg/l TDS and > 5 gpm.  
FIGURE 3: POTABLE WATER NEAR WIPP SITE
(less than 10,000 mg/L TDS)
POTENTIAL FLOW PATHS FROM THE WIPP SITE TO THE ACCESSIBLE ENVIRONMENT

by Richard H. Phillips, Ph.D.
and David T. Snow, Ph.D.

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is intended for the permanent disposal of radioactive waste from nuclear weapons production. The WIPP site was selected in 1974. It is now 1997, and the Department of Energy (DOE) still does not know the position of the water table, the flow paths of Rustler groundwater, or where the Rustler groundwater discharges. Without an understanding of such basic hydrologic parameters, "knowledge about the site is incomplete." (EEG-61, 1996). If completed early in the WIPP investigations, a study of near-surface hydrology would have revealed vital information.

The water table represents the top of the saturated zone. At the WIPP site, the water table "is believed to be in the Dewey Lake Redbeds" (EEG-61, 1996, p. 2-6). DOE has collected data on the hydraulic heads of Culebra groundwater from 35 test wells at the WIPP site and vicinity. According to DOE, contour maps of these water levels "suggest" that Culebra groundwater at WIPP flows to the south (SEIS, 1996, p. 4-20). DOE concludes that groundwater flow in Nash Draw "is unrelated to groundwater at WIPP," (SEIS, 1996, p. 4-18), and "that the Culebra probably discharges into the Pecos River" at Malaga Bend (EEG-61, 1996, p. 2-7). If the position of the water table is "believed," and the groundwater flow path is "suggested," and the groundwater discharge point is "probable," then little is known for certain, and all the risk assessments based upon modeling of radionuclide migration through an assumed groundwater flow path are without foundation.

Groundwater flows occur in a conduit, such as an aquifer, according to its hydraulic conductivity and the gradient of hydraulic potential (heads) acting in that conduit. Since heads in an aquifer can be measured readily by measuring the water surface in cased wells penetrating an aquifer, the gradient is commonly determined from the spacing of contours drawn to describe the potentiometric surface from a number of such piezometers. Such has been the work done for 30 years, in attempts to understand flow in the Culebra dolomite.

If the Culebra aquifer were isolated, above and below, by impervious aquicludes, and the water were supplied and discharged at its edges, the piezometric work might have been adequate for predicting flow paths. It has been recognized (Corbet and Knupp, 1996) that recharge occurs by infiltration through overlying strata, but flow models have assumed uniform areal recharge and smoothly-varying hydraulic conductivity for lateral flow in the aquifer. Had some work been done to assess local variation of
such recharge, more effective understanding of localized flow controls in the Culebra, as well as the Dewey Lake Redbeds, would have ensued. DOE chose to neglect warnings that the system does not vary smoothly. Because the Rustler and Dewey Lake are karstic, the flows are probably dominated by a small number of very conductive horizontal and vertical conduits.

One type of piezometric surface is the water table, depicted as the surface of uppermost saturated rock, having atmospheric pressure. If the piezometric surface for a buried aquifer, like the Culebra, lies below the water table for rocks above it, such as the Dewey Lake, a gradient exists across the strata tending to develop recharge. If they coincide, there is either no recharge since there is no gradient, or there may be great recharge if the interval has such high hydraulic conductivity in the vertical direction that vertical flows take place with a minimal vertical gradient. Such distinctions need to be made at the WIPP site, but because the hydrology of units overlying the Culebra has been neglected, there is no detailed knowledge of the shallow water table nor the heterogeneities of the Dewey Lake and other units.

At a sinkhole, such as WIPP-33, the water table (first water encountered in a drill hole) must coincide with the Culebra piezometric surface. At WIPP-33 a nested sequence of five caverns, one in Dewey Lake siltstone, two in Forty-Niner gypsum, and two in Magenta dolomite, was found during drilling. Rapid surface inflow during the rainstorm of September 18-19, 1985 proved the existence of a vertical conduit connecting these caverns, of such dimensions as to provide rapid, concentrated recharge to the Rustler aquifer. If adjacent Dewey Lake rocks are undissolved, a well located there might disclose a water table higher than the Culebra piezometric surface, the difference implying that a gradient is required to produce slow recharge because of low vertical conductivity. It is still important to the WIPP project that a comprehensive program be undertaken to study the shallow water table, the heterogeneities of vertical conductivity, and the implications for Rustler flow.

WIPP is a disturbed site. Previously existing exploratory boreholes for oil, gas and potash, and the WIPP boreholes and test wells themselves, all requiring casings through the Rustler, have affected hydraulic head distribution in the Rustler. WIPP monitoring wells have experienced sharp rises in water levels. Between 1988 and 1993, water levels in the Culebra dolomite generally rose from 4 to 30 feet (EEG-62, 1996). These water level rises were strongly correlated with a nearby salt water disposal well operated by the oil and gas industry. (EEG-61, 1996). Subsequent measurements are unreliable, as graphically illustrated by DOE’s annual mapping of the changing Culebra potentiometric surface (ASER, 1992-1995, Figure 7-3). For purposes of long-term prediction, what is needed is a record of the primitive conditions (Snow, 1994).
The best record we have of the Rustler potentiometric surface prior to disturbance by WIPP shafts and boreholes is given in Mercer and Orr (1977, Figure 23). This map shows a southwesterly gradient from Forty-Niner Ridge to the Salt Lake (Laguna Grande de la Sal) at the lower end of Nash Draw. Hunter (1985) also produced maps of the Rustler potentiometric surface. These maps also show a southwesterly gradient through Nash Draw to Laguna Grande de la Sal (Phillips, 1987, Figure 75).

One of the most compelling arguments for prevalent flow paths to Nash Draw, as opposed to Malaga Bend, is the water balance. The surface area of Laguna Grande de la Sal is so large (2,120 acres, or 9.23 × 10^7 ft^2 in natural extent), and net evaporation rates are so high (6.32 ft/yr), that the Rustler flow discharging to Laguna Grande and evaporated by the lake must be an order of magnitude greater (5.83 × 10^8 ft^3/year) than the incremental flow discharging to the Malaga Bend reach of the Pecos River (6.53 × 10^7 ft^3/yr) (Phillips, 1987, pp. 219-222, 232-235).

Further, the Malaga Bend brine springs have geochemistry more consistent with the "brine aquifer" at the top the Salado, while Laguna Pequena, which flows into Laguna Grande, has geochemistry more consistent with the gypsum and dolomite aquifers of the Rustler (Phillips, 1987, pp. 242-248). Laguna Pequena is the single, most copious discharging point for the Rustler (Phillips, 1987, pp. 227-231), and most flow paths must be directed there from WIPP, as from elsewhere in the watershed.

The DOE assumes a southerly flow path from the WIPP site to the brine springs at Malaga Bend on the Pecos River, bypassing Laguna Grande. This flow path would have obvious advantages for the DOE: it is 20 miles from the WIPP site boundary to Malaga Bend along this path, compared to 12.5 miles as the crow flies; it runs through areas of low Culebra conductivity for up to 7.85 miles from the WIPP site boundary; and it bypasses Nash Draw.

**DATA FOR DOE FLOW PATH FROM WIPP SITE TO MALAGA BEND**

<table>
<thead>
<tr>
<th>test well</th>
<th>dist. (mi)</th>
<th>conduct. (ft/day)</th>
<th>head (ft)</th>
<th>TDS (mg/l)</th>
<th>NaCl (mg/l)</th>
<th>CaSO4 (mg/l)</th>
</tr>
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<tbody>
<tr>
<td>H-11</td>
<td>0.79</td>
<td>0.009</td>
<td>2975</td>
<td>11000</td>
<td>92650</td>
<td>7620</td>
</tr>
<tr>
<td>H-12</td>
<td>7.85</td>
<td>0.59</td>
<td>2975</td>
<td>3040</td>
<td>345</td>
<td>2460</td>
</tr>
<tr>
<td>H-9</td>
<td>12.27</td>
<td>0.59</td>
<td>2991</td>
<td>2710</td>
<td>85</td>
<td>2420</td>
</tr>
</tbody>
</table>

The geochemistry of Culebra water is inconsistent with southerly flow from the WIPP site. Dissolved halite (sodium and chloride) decreases by a factor of 1300 along the assumed flow path, and the principal mineral constituents change to gypsum (calcium and
sulfate). More importantly, the geochemistry is inconsistent with the concept of the Culebra dolomite as a confined aquifer, bounded above and below by impermeable layers, and containing only fossil water left over from the Ice Ages. Siegel and Anderholm (1994) state that "no plausible geochemical process has been identified that would cause this transformation in a hydrologically confined unit." According to Chapman (1989), the only plausible mechanism is rainwater recharge. DOE has yet to present a flow path that is consistent with the geochemistry.

Dissolved sodium and chloride in Culebra groundwater are given in Table 1. When these levels are plotted on a map [Figure 1], and contour lines are drawn, it is shown that the concentration of dissolved halite in Culebra groundwater decreases steadily from east to west across the WIPP site. This should demonstrate that Rustler groundwater is not old, and that fresh water recharge is occurring. Water saturated with halite, incapable of dissolving significantly more halite, contains approximately 318,000 mg/l of dissolved sodium and chloride (EEG-31, 1985). Within one mile of the WIPP site, the highest reliable measurements of dissolved halite in Culebra groundwater, at test well H-5b, range from 124,100 to 139,000 mg/l, well below saturation.

In the Rustler Formation, there has been extensive dissolution of halite across the WIPP site. This interpretation is supported by Powers et al. (1978), Gibbons and Ferrall (1980), Barrows (1982), Borns et al. (1983), Barrows et al. (1983), Mercer (1983), Lambert (1983), Chaturvedi and Rehfeldt (1984), Bachman (1984), Snyder (1985), Chaturvedi and Channell (1985), Lowenstein (1987), Chapman (1988), Brinster (1991), and Anderson (1994). An isopach map of the Rustler Formation (Borns et al., 1983, Figure 2-25) shows a westward thinning of the Rustler from 460 feet at P-18, 0.86 miles east of the WIPP site, to 277 feet at WIPP-33, 0.54 miles west of the WIPP site. Borehole data show a downward and westward drop in the position of uppermost halite remaining in the Rustler Formation. This is attributed to downward and eastward progression of dissolution in the Rustler (Barrows, 1982), first and most extensively from the Forty-Niner member, then from the Tamarisk member, and finally from the lower unnamed member only in the west. The Magenta and Culebra dolomite members are disrupted and fractured as halite is removed from beneath them; as a result they become more transmissive to groundwater, which in turn accelerates the process of dissolution. The process "feeds upon itself." (Snyder, 1985)

When the progression of halite dissolution is plotted on a map, along with the distribution of salinity in Culebra groundwater [Figure 2], it is shown that some test wells contain dissolved halite in Culebra groundwater where there is no halite in the Rustler. These wells (e.g. H-6, P-14, WIPP-25, WIPP-26) are located west of the Rustler "dissolution front." If groundwater is supposed to be flowing from north to south, as DOE contends,
# Table 1: Lowest Reliable Measurements of Mineral Constituents in Culebra Groundwater

<table>
<thead>
<tr>
<th>Well</th>
<th>TDS</th>
<th>NaCl</th>
<th>CaSO4</th>
</tr>
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<td>8,180</td>
</tr>
<tr>
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<td>3,303</td>
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<tr>
<td>H-3</td>
<td>51,700</td>
<td>39,700</td>
<td>5,960</td>
</tr>
<tr>
<td>H-4</td>
<td>18,200</td>
<td>11,860</td>
<td>4,180</td>
</tr>
<tr>
<td>H-5</td>
<td>135,000</td>
<td>124,100</td>
<td>1,170</td>
</tr>
<tr>
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<td>52,000</td>
<td>45,300</td>
<td>4,620</td>
</tr>
<tr>
<td>H-7</td>
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<td>560</td>
<td>2,490</td>
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<tr>
<td>H-8</td>
<td>2,710</td>
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<td>4,680</td>
</tr>
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</tr>
<tr>
<td>P-15</td>
<td>23,700</td>
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<td>3,970</td>
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<tr>
<td>P-17</td>
<td>81,200</td>
<td>71,400</td>
<td>6,700</td>
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<td>P-18</td>
<td>118,000</td>
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<td>6,580</td>
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<tr>
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</tr>
<tr>
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<td>6,210</td>
</tr>
<tr>
<td>Engle</td>
<td>3,000</td>
<td>357</td>
<td>2,450</td>
</tr>
</tbody>
</table>

Sources: Mercer, 1983 (USGS-WRI 83-4016, Table 8); Ramey, 1985 (EEG-31); Chapman, 1988 (EEG-39); Lappin et al., 1989 (SAND 89-0462, Table 3-12); DOE/CAO 1996-2184, Appendix USDW, Table USDW-2; Annual Site Environmental Reports, 1992-1995.
FIGURE 1: DISSOLVED HALITE IN CULEBRA (mg/l)

CONTOUR INTERVAL 20,000 mg/l
Northward from the recharge area there may be a trend of preferential flow that extends through the ventilation shaft, thence to H-16, H-18, and WIPP-13. There were washouts and loss of core at all three test wells; in the ventilation shaft there were five washouts where steel liner plates were installed to prevent further caving of the shaft wall. At H-16, heads in the Culebra (3005 ft) and Magenta (3116 ft) are lower than in the recharge area. At H-18, head measurements are not available. A solution channel must underlie WIPP-13, where the hydraulic head in the Culebra is 3064 feet above sea level and the Culebra is hydraulically connected to the Magenta; (hydraulic heads in the Magenta should confirm this, but the data are not available).

A chain of topographic depressions suggestive of an underlying flow channel can be seen in the WIPP site air photos, snaking through the WIPP-14 sinkhole, where 71.4 feet of mud with gypsum and anhydrite fragments was found below the Culebra. This path may continue westward to WIPP-34 and DOE-2; there was loss of core in the Forty-Niner and lower unnamed members in both boreholes, and loss of circulation of drilling fluid in the Dewey Lake Redbeds at DOE-2. Here, at DOE-2, the path would intercept a network of open fractures which were shown by multi-well pump tests to be hydraulically connected to WIPP-13 and H-6 (Beauheim, 1986). These could be karst channels in the Rustler. This is a zone of high hydraulic conductivity (4.0 ft/day at DOE-2, 3.1 ft/day at WIPP-13, 3.2 ft/day at H-6). Both of these trends which may merge at WIPP-13 pass through areas where there is residual halite in the Rustler Formation; this is consistent with the elevated levels of dissolved halite at WIPP-13.

Multi-well pump testing revealed that WIPP-13 is hydraulically connected to H-6, where the hydraulic heads for the Magenta and the Culebra are equal. Thus, the Rustler aquifer may include both of these dolomites as one. From H-6 at the northwest corner of the WIPP site, it takes little imagination to see a connection to WIPP-33, 0.84 miles to the southwest. The most likely flow path lies beneath an east-west trend of three smaller sinkholes, two of which have swallowed surface water carried by arroyos (Phillips, 1987, pp. 82-86). At WIPP-33, five nested caverns, all filled with water, were found within a 110-foot section of Dewey Lake siltstone, Forty-Niner gypsum, and Magenta dolomite, indicating the thickness of the karst aquifer there. The flow may continue from WIPP-33 to the vicinity of WIPP-25, 2.0 miles west of WIPP-33 in Nash Draw, where gypsum spring deposits at the surface are evidence of groundwater discharge in the geologic past, when the water table was higher (Bachman, 1985). Water in this karst aquifer would continue to Laguna Grande de la Sal.

A flow path from WIPP-13 to WIPP-25 would be consistent with hydraulic heads in the Rustler, which drop steadily from WIPP-13 (3064 ft) to H-6 (3057 ft) to WIPP-25 (3054 ft). No hydrologic
data were taken at WIPP-33. Between WIPP-13 and H-6 the flow path enters the region where no halite remains in the Rustler; this is a possible explanation for the steadily decreasing levels of dissolved salt from WIPP-13 to WIPP-25. The evident recharge of fresh water through sinkholes is also sufficient explanation.

### DATA FOR POSSIBLE GROUNDWATER FLOW PATHS

<table>
<thead>
<tr>
<th>test well</th>
<th>conduct. (ft/day)</th>
<th>head Cul.</th>
<th>head Mag.</th>
<th>TDS (mg/l)</th>
<th>NaCl (mg/l)</th>
<th>CaSO4 (mg/l)</th>
</tr>
</thead>
<tbody>
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<td>6700</td>
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</tr>
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<td>3054</td>
<td>17000</td>
<td>13400</td>
<td>3320</td>
</tr>
</tbody>
</table>

In a semiarid karst such as Los Medanos (where the WIPP site is located), where 14 to 15 inches of annual precipitation may occur during a few large storms separated by many dry months, the groundwater hydraulics may be wildly transient. In Dalmatia, the classic karst region of Yugoslavia, rapid recharge is known to raise the water table as much as 200 feet, and tracer tests reveal velocities of kilometers per week. In New Mexico, lower episodic rainfall may also produce transients, during which most of the discharge occurs. During the longer periods between storm-flows, the gradients vanish in the major channels, while low-permeability rocks outside the channels drain into them. The task of interpretive non-synoptic piezometry from wells tapping domains of different transient behavior, none of which record the behavior of the major channels, may not be very rewarding, nor can it support realistic models of flow or transport.

In every hydrologic system, groundwater moves inexorably toward regional base level, the lowest point in the watershed. In Nash Draw, the lowest point is Salt Lake, or Laguna Grande de la Sal. Salt lakes are in closed drainage basins, with no outlet at the surface or underground. They lose water only by evaporation, which precipitates salt. At Laguna Grande, groundwater seeps upward into the lake (Robinson and Lang, 1938); this is confirmed at test well WIPP-29, near Laguna Grande, where water from the lower unnamed member is able to rise into the Culebra [Table 2]. Laguna Grande has no outlet, at the surface or underground.
A low, but discernible topographic divide exists between Laguna Grande and Malaga Bend of the Pecos River. This topographic divide is now partly breached by an irrigation canal at an elevation of 2960 feet above sea level. The evaporite crust of Laguna Grande has killed all vegetation up to the same elevation, indicating that 2960 feet above sea level is the high-water mark for Laguna Grande. In times of major flooding, Laguna Grande overflows to the Pecos River (Phillips, 1987, pp. 216-217).

The evidence supports a conclusion that flow paths from the WIPP site are predominantly directed to Nash Draw along karst channels or fracture system enlargements. These observations indicate that the Rustler is not a barrier to rapid transport from the WIPP site to the accessible environment.
CONCEPTUAL ERRORS IN THE DOE MODEL OF GROUNDWATER FLOW IN THE RUSTLER FORMATION

by Richard Hayes Phillips, Ph.D.

Konikow (1996) identified the three most common sources of error in modeling of groundwater flow: (1) conceptual errors; (2) uncertainties in the model; and (3) uncertainties in the data.

These are conceptual errors in DOE's model of groundwater flow in the Rustler Formation at the WIPP site and vicinity:

(1) Darcy's Law should not be applied to a karstland, because groundwater velocity is not proportional to the potentiometric gradient (Barrows, 1982).

In permeable rocks other than those giving rise to karst, the water table parallels the land surface, with somewhat less relief. The potentiometric surface is the level to which groundwater will rise in a cased well. These water levels can be mapped, relative to sea level; and contour lines can be drawn, in accordance with the slope of the water table. Groundwater will flow across the contour lines, generally perpendicular to them; and the more closely spaced the contour lines, the faster the groundwater flows. Velocity is proportional to the permeability times the potentiometric gradient. This is expressed as Darcy's Law, the general hydrogeologic equation (Jennings, 1971).

A water table such as occurs in porous rocks like sandstone does not exist in karst. Wells close together often reach water at very different levels (Sweeting, 1973; Jennings, 1971). Trying to map contour lines is futile. Potentiometric contour lines are not a reliable indicator of groundwater velocity or direction.

(2) The Culebra should not be modeled as a porous homogeneous medium with continuously varying properties (Snow, 1995).

Karstified rocks are not porous homogeneous media (Milanovic, 1976). Primary permeability, which depends on the size and degree of interconnection of the original pore spaces in the rock matrix, is uncommon in karst; secondary permeability, consisting of flow through joints, fractures, solution conduits, caverns, and cave sediments, is much more representative (LeGrand, 1983; Milanovic, 1981). DOE admits that "flow velocities are usually orders of magnitude higher in the fractures than in the matrix" (SEIS, 1996, p. H-24). That is precisely the point. According to Rehfeldt (EEG-27, 1984): "The groundwater travel time in open fractures is very short in comparison to travel time in porous media. Open fractures exist in Nash Draw, at H-6, and are likely present elsewhere at and near the WIPP site." Konikow (1995) regards open fractures in the Culebra as "the most likely fatal flaw in site integrity."
The fracture model should not assume "continuous, isotropic, radial flow in cubically fractured medium." (Lovejoy, 1995)

This is an attempt to model a fractured medium as a homogeneous medium. Fractures are an extreme example of heterogeneity. Fractures are preferential flow paths for water (Konikow, 1996).

Flow in the Culebra is highly anisotropic (varies with direction, has preferred orientation). In the northwest corner of the WIPP site is the H-6 hydro pad, which consists of three wells forming an equilateral triangle, 100 feet on a side. The wells are labeled H6a, H6b, and H6c; a line connecting H6a and H6c is oriented east-west. A convergent tracer test was performed in the Culebra by pumping well H6c and simultaneously introducing tracers into wells H6a and H6b. As reported by Rehfeldt (EEG-27, 1984), "the peak concentration of the H6b tracers arrived 30 times faster and at a concentration 10 times greater than the H6a tracers. Flow in the H6b-H6c direction (150° or 330°) is probably through discrete channels whereas flow in the H6a-H6c direction (90° or 270°) was through the dolomite matrix or through a very tortuous system of fractures."

Dissolution of gypsum filling has opened some fractures in the Rustler Formation, creating "anisotropic fracture permeabilities at least an order of magnitude greater than matrix permeability. ... Throughout the site, flows are concentrated in any such fractures ... Large-aperture solution channels may transect regions of fracture-dominated dolomite (and perhaps anhydrite) devoid of mineral fillings." (Snow, 1995).

The Magenta and Culebra dolomites have been fractured since shortly after their deposition. The impact of this fracture pattern on WIPP geohydrology depends upon the size, angle, length, orientation, spacing and extent of the fractures, the degree and type of fracture filling by groundwater, and the amount of fracture enlargement by solution. The most reliable means of evaluating the fracture pattern would be to collect core samples from a slant drilling program. If angled 45° with respect to the horizontal, and oriented perpendicular to the predicted trends of dominant fracture sets, a three-dimensional record could be obtained (Gibbons and Ferrall, 1980).

(4) DOE should not use "a two-dimensional model where significant flow or transport occurs in the third dimension." (Konikow, 1996)

Traditional "layer-cake" hydrogeology represents aquifers as continuous porous media separated by continuous aquitards or aquicludes (Snow, 1995). "There has been too little accounting for the three-dimensional nature of ground-water flow and consequent leakage through confining layers." The Culebra is one part of a three-dimensional flow system (Konikow, 1996). The Rustler is best characterized as one aquifer with five members.
(5) Borehole data should not be assumed to be representative of hydraulic conditions beyond the immediate vicinity.

In karst, the hydraulic conductivity along solution-enlarged fractures may be three orders of magnitude greater than that of the adjacent unaltered rock (Fetter, 1980). Because the active solution conduits comprise a small part of the total area of the watershed, most boreholes will miss them, and will show values for hydraulic conductivity which are not representative of karst conditions (Bloom, 1978; Barrows, 1982). Borehole measurements may reflect aquifer properties only within the immediate vicinity of the borehole (Konikow, 1995). The technique of interpolation between data points, although useful in porous, homogenous media, should not be applied to a karstland (LeGrand, 1973).

(6) Matrix diffusion in the Culebra dolomite is not a reliable mechanism for the retardation of radionuclide migration.

In rocks with dual porosity, groundwater flows mainly through open fractures in the rock, while some groundwater is diffused through smaller fractures into the rock matrix. This process, known as matrix diffusion, is capable of retarding the migration of radionuclides in groundwater (SEIS, 1996). In karst, however, water flowing through fractures in soluble rocks will enlarge the fractures as it does so. The more permeable the groundwater pathways, the more rapidly they will become enlarged (Barrows, 1982). More and more groundwater flows through fewer and fewer solution conduits (Fetter, 1980), with less and less diffusion of groundwater into the rock matrix. The end result is a regional network of primary solution channels and stagnant secondary pathways (Barrows, 1982), with little or no matrix diffusion.

(7) Distribution coefficients used for the Culebra dolomite are not representative of field conditions.

The distribution coefficient (Kd), or sorption coefficient, is a measurement of the proportion of radionuclides that are retarded during migration of groundwater. The magnitude of retardation is proportional to the surface area in the host rock encountered by flowing water and therefore available for sorption. The higher the Kd value, the greater the retardation of radionuclide migration. The Kd values used in WIPP performance assessment were determined in the laboratory from single measurements upon Culebra dolomite samples which were crushed to a powder, thus providing much greater surface area per volume of rock than actually occurs in the field. The results, preferred by DOE, give a Kd value as high as 7300 for Culebra dolomite, compared to a Kd value of 19 for tablets of solid rock, which is more representative of fracture flow in the Culebra dolomite. The greater the aperture (diameter) of the groundwater channels, the lower the Kd value. Under karst conditions, the conservative assumption is that Kd equals zero, that some radionuclides will
travel at the speed of water. The only way to obtain reliable
distribution coefficients is to perform sorbing tracer tests in
the field (GCR, 1978; EEG-61, 1996; SEIS, 1996).

(8) There is no evidence that clay linings on fractures in the
Culebra dolomite will affect radionuclide migration.

The WIPP performance assessment takes credit for radionuclide
retardation due to clay linings on fractures in the Culebra
dolomite. The claim is based on experiments that were performed
not upon fractures in the Culebra, which contain only small
amounts of clay, but upon corrensite clay taken from a black
shale layer in the lower unnamed member of the Rustler. Clay
fillings are most likely to exist in secondary pathways, where
groundwater movement is infrequent enough to allow the clay to
settle out of the water; here the clay could block the movement
of water into the rock matrix, thus preventing matrix diffusion.
The WIPP performance assessment takes "double credit" for a
mechanism that may not exist, by claiming significant
radionuclide retardation in primary pathways in the Culebra,
while denying that clay fillings in secondary pathways would

One of the problems with analyzing DOE's Compliance Certification
Application (DOE/CAO-1996-2184) is its incompleteness. Materials
are continually being added to the docket, and to criticize the
Application now is like shooting at a moving target. By the time
the EPA certifies that the Application is complete, the public
comment period will be over, and DOE will be at liberty to assail
its critics without fear of response, using materials which were
unavailable during the public comment period. Therefore, instead
of analyzing the WIPP performance assessment as it now stands, it
is more reasonable to analyze a completed report, trusting that
the public will be given another chance to analyze the Compliance
Certification Application when EPA deems it complete.

One recent addition to the docket is a Sandia Report by Corbet
and Knupp (SAND 96-2133), received by the New Mexico Attorney
General on January 15, 1997, midway through the public comment
period. The report, which models regional groundwater flow in
the Rustler Formation, is said to have bounded the hydrologic
effects of karst, potash mining, and climatic change, simply by
analyzing the effects of a three order of magnitude increase in
hydraulic conductivity in the Culebra dolomite. Unfortunately,
the report begins with conceptual errors and misrepresentative
data, and the difference is always favorable to DOE.

The use of "geologic data to infer hydraulic conductivity values
for areas in which conductivity measurements were not available"
is inexcusable. DOE has had 20 years to collect the necessary
data. There is no substitute for field work. The interpretation
should be drawn from the data, not the other way around.
These values for rock hydraulic properties, said to be inferred from geologic observations, are not always consistent with borehole data in the vicinity. Examples are given below.

Figure 2-6: The "eastern limit of Salado dissolution" is placed at Livingston Ridge, which is not correct. Seven boreholes east of Livingston Ridge (P-6, P-12, P-13, P-14, H-3, H-6 and WIPP-33) encountered dissolution residue at the top of the Salado.

Figure 2-7: In Zone I, the fracturing and disruption of Rustler strata in Nash Draw is attributed to dissolution of the upper Salado, rather than to karst processes in the Rustler. This zone includes borehole WIPP-25, where the Tamarisk and lower unnamed members consist almost entirely of mudstone breccia and gypsum.

Figure 2-7: In Zone II, Rustler strata is said to be fractured but not disrupted. This zone includes borehole H-7, where 24.3 feet of Culebra dolomite was broken into six sections separated by five cavities totalling 21.7 feet; this was underlain by 6.2 feet of mud, beneath which there was no core for 80.8 feet.

Figure 2-9: The zone assumed to have hydraulic conductivity of $1 \times 10^{-11}$ m/sec ($2.8 \times 10^{-6}$ ft/day) in Rustler anhydrite includes borehole WIPP-33, where all of the anhydrite has been converted to gypsum, some of the gypsum has been removed by dissolution, and two gypsum caves were encountered in the Forty-Niner member.

Figure 2-10: The zone assumed to have hydraulic conductivity of $1 \times 10^{-9}$ m/sec ($2.8 \times 10^{-4}$ ft/day) in Rustler mudstone includes borehole WIPP-14, where 71.4 feet of mud, with anhydrite and gypsum fragments, was encountered beneath the Culebra dolomite.

Figure 2-11: The Dewey Lake Redbeds are assumed to have hydraulic conductivity of $2 \times 10^{-7}$ m/s (0.028 ft/day) everywhere east of Livingston Ridge. This is a wild guess. I am unaware of any measurements of hydraulic conductivity in the Dewey Lake Redbeds. However, at test wells H-11 and WQSP-6, inflow from the Dewey Lake Redbeds was measured at 25 to 30 gallons per minute.

The "assumed values for hydraulic conductivity" in the Culebra dolomite are at variance with measured data. In Figure 2-8, the zone assumed to have hydraulic conductivity of $1 \times 10^{-7.5}$ m/sec ($0.009$ ft/day) includes test wells H-3, DOE-1 and H-11, where hydraulic conductivity is 0.86 ft/day, 1.5 ft/day, and 1.7 ft/day, respectively. The zone assumed to have hydraulic conductivity of $1 \times 10^{-6}$ m/sec (0.28 ft/day) includes test wells DOE-2, WIPP-13, H-6 and P-14, where hydraulic conductivity is 4.0 ft/day, 3.0 ft/day, 3.2 ft/day, and 10.6 ft/day, respectively. The zone assumed to have hydraulic conductivity of $1 \times 10^{-5}$ m/sec (2.8 ft/day) includes test well H-7, where hydraulic conductivity is at least 31.0 ft/day. Hydraulic conductivity (in ft/day) is here calculated as transmissivity (in ft$^2$/day) divided by the
thickness of the aquifer (in feet). It is true that hydraulic conductivity at these eight test wells is anomalously high, but that is exactly the point. To disregard the highest measurements of hydraulic conductivity is to throw out the evidence for karst.

Potential recharge, defined as "the maximum amount of moisture available to recharge the saturated zone," is assumed to be 0.2 to 2.0 mm/yr. These values are claimed by Corbet and Knupp to be "certainly reasonable." In fact, precipitation for the last ten years at the Carlsbad airport has averaged slightly over 15 inches per year, or 40 cm/yr. Corbet and Knupp are saying that annual recharge equals 0.05% to 0.5% of annual precipitation, which is to say that evapotranspiration equals 99.5% to 99.95% of precipitation. From this they conclude that the travel time for vertical leakage to reach the Culebra is "probably thousands or tens of thousands of years." These estimates of recharge are too low. Geohydrology Associates (1978) and Barrows (1982) estimated 96% evapotranspiration and 4% recharge. Phillips (1987) estimated 94% evapotranspiration and 6% recharge.

"Vertical leakage may contribute as little as 5% or more than 50% of the total inflow" to the Culebra at WIPP. This statement is an open admission that DOE does not even know the order of magnitude of rainwater recharge to the Culebra. The truth is that vertical leakage contributes nearly 100% of recharge to the Culebra; the alternative explanation, that the Culebra contains "fossil water" left over from the Ice Ages, is not supported by geochemical data showing Culebra water to be far from saturated.

The conclusion that the Culebra is "poorly connected to the source of recharge" is entirely unsubstantiated. DOE does not even claim to know where the recharge area is located. It is said not to be "feasible" to measure, in the field, the vertical conductivity of the "confining layers" because it would take longer than "several months" to do so. This is a poor excuse. DOE has already had 20 years to study rainwater recharge.

Regarding the hydrologic effects of climatic change, the computer simulations employed by Corbet and Knupp "covered the time period from late in the Pleistocene (14,000 years ago) to 10,000 years in the future." The full-glacial maximum (generally considered to have been 23,000 to 17,000 years ago), and the climate and hydrology associated with it, were not considered. Indeed, Corbet and Knupp assume that the climate over the next 10,000 years will be no different than the last 8,000 years. As for potential recharge, Corbet and Knupp assume that 2.0 mm/yr was realized during the late Pleistocene (14,000 years ago), and that maximum recharge during the Holocene was 0.6 mm/yr. Recharge at 8,000 years ago is assumed to have been zero, although Corbet and Knupp do admit that this value is "somewhat arbitrary."
Glacial advances are cyclical. The Holocene is properly viewed not as an epoch distinct from the Pleistocene, but as the latest interglacial interval. Due primarily to a decrease in obliquity (the tilt of the earth's axis), the amount of incoming solar radiation received during the summer at the Arctic Circle (and throughout most of the northern hemisphere) will decrease during the next 9000 years. The polar ice cap will not be able to melt back during the summer, and a glacial advance is predictable.

During the last full-glacial maximum, summers were at least 10°C (18°F) colder in south-central New Mexico, and the evaporation rate was 40% to 50% of the present rate. The combined amount of precipitation and runoff into the local lake basins of the Texas panhandle was about 50% greater than at present; this would be sufficient to cause Laguna Grande de la Sal (the discharge point for contaminated water from the WIPP site) to overflow into the Pecos River. Climatic transitions can be rapid; temperature drops of up to 5°C (9°F) have been identified. For a fuller discussion of climatic change, see Phillips (1987, Chapter 9).

All the studies cited by Corbet and Knupp relate to groundwater flow through porous, homogeneous media. Not a single report on karst hydrology is referenced. Corbet and Knupp acknowledge that they are using equations for flow in porous media, based on Darcy's law. The idealized cross-sections of groundwater basins (Figure 2-1) are representative of porous, homogeneous media. They bear no resemblance to karst hydrology at the WIPP site.

"Differences in the elevation of the water table" are said to "provide the driving force for groundwater flow." This is not necessarily true. In karst, the driving force for groundwater flow is the flushing of underground caverns by fresh water recharge after major rainstorms. Groundwater will flow through preferential pathways, through channels of high transmissivity, even if the flow path is not directly downgradient.

"All of the outflow" from the Culebra at WIPP is attributed to "lateral flow. Therefore, contaminants introduced into the Culebra will travel toward the accessible environment along the Culebra rather than by migrating upward or downward into other units." This statement is in direct conflict with measured data. DOE's data set for hydraulic heads, incomplete though it is, shows that water in the Culebra can and does flow upward to the Magenta at test wells H-6 and WIPP-25. The Culebra is not a confined aquifer, and DOE's attempt to model it as such is a misrepresentation of reality. If it is simply too difficult, for purposes of performance assessment, to model the Rustler as one complex artesian aquifer with five units, with water flowing up, down, and sideways, as it does in the real world, then the proper response is not to oversimplify the actual conditions of Rustler groundwater flow to the point of science fiction, but to abandon the attempt to obtain EPA certification to open WIPP.
TO: U.S. Environmental Protection Agency (EPA)
Office of Radiation and Indoor Air
401 M Street SW
Washington, DC 20460

FROM: Richard Hayes Phillips, Ph.D.
Citizens for Alternatives to Radioactive Dumping (CARD)
144 Harvard SE
Albuquerque, NM 87106

RE: DOE Response to Comments made to EPA by CARD on the DOE’s CCA

On March 17, 1997, CARD mailed to the EPA, in duplicate, nine scientific papers by five authors, in response to the Compliance Certification Application (CCA) by the Department of Energy (DOE) regarding the Waste Isolation Pilot Plant (WIPP), which DOE seeks permission to open. CARD also resubmitted Richard Hayes Phillips’ doctoral dissertation entitled: “Prospects for Regional Groundwater Contamination due to Karst Landforms in Mescalero Caliche at the WIPP Site near Carlsbad, New Mexico.” On May 16, 1997, without waiting for a response to CARD from DOE, the EPA Administrator informed DOE that EPA had deemed the CCA complete. On July 3, 1997, DOE submitted to EPA an anonymous 75-page response to CARD’s “comments.” Neither DOE nor EPA informed CARD of DOE’s response, and no copy was ever sent to CARD. Nor was CARD informed that the public comment period on the CCA had been extended to August 7, 1997, which could have given CARD an opportunity to rebut the DOE. On September 30, 1997, shortly after receiving a copy of DOE’s response from other sources, Dr. Phillips mailed to EPA a notarized letter stating his intention to write a rebuttal to DOE’s response, and asking for sufficient time to do so. On October 16, 1997, Lawrence G. Weinstock of EPA sent to Dr. Phillips a letter refusing to accept any further submissions until after the issuance of a proposed decision by EPA. On October 27, 1997, EPA published in the Federal Register its proposed decision to open WIPP, denying CARD the opportunity to rebut the DOE.

Five of the scientific papers submitted by CARD on March 17, 1997 concerned karst hydrology in the Rustler Formation. These papers were written by Drs. Richard H. Phillips and David T. Snow. The DOE, in its response, made no reference to Phillips’ doctoral dissertation, and reprinted verbatim some, but not all, of the other works of Phillips and Snow. DOE may not have wanted the EPA to read the parts of CARD’s work that deal with karst hydrology, rainwater recharge, groundwater flow paths, or conceptual errors and misrepresentative data used by DOE. Dr. Phillips, along with his notarized letter of September 30, 1997, resubmitted to EPA the parts of CARD’s work which DOE chose not to reprint, but rather to “summarize.” Phillips wrote: “Our work speaks for itself. We have a right to be judged according to what we actually said, not according to what the DOE says we said.”

The following is CARD’s rebuttal to DOE’s response to “CARD Comments 7 to 22,” the parts which DOE may not have wanted EPA to read. Our rebuttal begins by reexamining CARD’s original reports, identifying the passages which stand uncontested, and restating our original findings together with additional evidence to support them. We then present a point-by-point rebuttal to DOE’s response. As a convenience to the reader, CARD has numbered the arguments made by the DOE, and has numbered the paragraphs of CARD’s rebuttal correspondingly.
CARD urges all readers not to begin with DOE’s response, as EPA appears to have done. A more objective procedure is to begin with the original works submitted by CARD on March 17, 1997, then to read DOE’s response to CARD, and finally to read CARD’s rebuttal to DOE.

CAVERNOUS ZONES AT THE WIPP SITE

Most of CARD’s original paper by the above title stands uncontested. DOE has long held that the Culebra dolomite member of the Rustler Formation is the most likely pathway for contaminated water to travel from the WIPP site to the accessible environment. The Culebra is highly fractured, and the effective groundwater flow paths are through the largest fractures. Dolomite is a soluble rock; it slowly dissolves when exposed to water. As fractures become enlarged by solution, they become even more effective groundwater flow paths. The larger the diameter of the solution conduits, the less contact the radionuclides will have with the surrounding rock and the less the retardation of radionuclides.

Recent pumping tests in the Culebra dolomite have shown certain WIPP test wells to be hydraulically connected. These include DOE-2, WIPP-13 and H-6 in the northwestern part of the WIPP site, and H-3, DOE-1 and H-11 in the southeastern part of the WIPP site. DOE interprets these hydraulic connections as fracture networks, and takes issue with CARD’s contention that they could be karst channels in or near the Culebra. CARD’s original report was based on the multiwell pump tests centered in the Culebra at test wells H-3 and DOE-2. CARD has since become aware of the multiwell pump test centered in the Culebra at test well WIPP-13. Response times were even more rapid; DOE-2, which is 4835 feet (0.92 miles) from WIPP-13, “responded within one hour to the beginning of pumping,” and H-6, which is 7137 feet (1.35 miles) from WIPP-13, “responded within 8 hours.” (CCA, Appendix SUM, p. 110) The delay in maximum drawdown at H-6, relative to the time at which the pump at WIPP-13 was turned off, was only 5 hours (CCA, Appendix SUM, Table 4.7). The apparent transmissivity between WIPP-13 and DOE-2 is 57 ft²/day; between WIPP-13 and H-6 it is 69 ft²/day (CCA, Appendix SUM, p. 114).

The WIPP-13 pump test also showed efficient hydraulic connections to test wells P-14 and WIPP-25. At P-14, which is 13,897 feet (2.63 miles) from WIPP-13, the first drawdown was in 71 hours, and the delay in maximum drawdown was 56 hours (CCA, Appendix SUM, Table 4.7). The apparent transmissivity between WIPP-13 and P-14 is 260 ft²/day (CCA, Appendix SUM, p. 114). P-14, which is located 4664 feet west of the current WIPP site boundary, is the only test well between the WIPP site and Nash Draw; its transmissivity was previously measured (in single-well tests) at 324 ft²/day (LaVenue et al., 1988, SAND 88-7002, Table C.1), the highest measured transmissivity east of Nash Draw. At WIPP-25, which is located in Nash Draw, 20,421 feet (3.87 miles) from WIPP-13, the first drawdown was in 76 hours, and the delay in maximum drawdown was only 26 hours (CCA, Appendix SUM, Table 4.7). The apparent transmissivity between WIPP-13 and WIPP-25 is extremely high, 650 ft²/day (CCA, Appendix SUM, p. 114). Figure 2 of CARD’s original paper should be altered accordingly, with test wells P-14 and WIPP-25 depicted as bull’s eyes.

The demonstrated hydraulic connection between test wells WIPP-13 and WIPP-25 is proof of karst hydrology at the WIPP site. Here is why:
WIPP-13 is located within the WIPP site, 2714.3 feet (0.51 miles) inside the northern boundary, and 7010.6 feet (1.33 miles) inside the western boundary. WIPP-25 is located in Nash Draw, about one-half mile from Livingston Ridge. Located almost exactly midway between WIPP-13 and WIPP-25 is borehole WIPP-33 (1.87 miles west of WIPP-13, and 2.02 miles east of WIPP-25). DOE, in its response to CARD, agrees that “Nash Draw and WIPP-33 are karstic features.” (EPA Docket, A-93-02, Item # II-H-46, p. 27). DOE, in its response to the Peer Review Panel, admits that open fractures have been observed in the Magenta dolomite at WIPP-13 (CCA, p. 9-29). The lithological log for WIPP-13 describes the Magenta dolomite as “broken and shattered by numerous fractures dipping 60°-80° and displacing bedding planes 0.5-1.0 cm;” it describes the Tamarisk member as having a zone of mudstone/gypsum breccia and steeply dipping fractures throughout, one of them filled only with silt; and it describes the Culebra dolomite as being “highly fractured,” with “numerous solution pits,” and underlain by 8 feet of soft, fissile mudstone with poor core recovery. The Culebra and Magenta hydraulic heads are believed to be equal at WIPP-13 and are known to be equal at WIPP-25, where Magenta transmissivity had been measured (in single-well tests) at 375 ft²/day. At WIPP-33 no hydrologic data were taken, but five water-filled caverns were found – two in Magenta dolomite, two in Forty-Niner gypsum, and one in Dewey Lake siltstone. WIPP-33 is the westernmost of a chain of four sinkholes, all of which DOE now concedes to be karst features (EPA Docket, A-93-02, Item # II-H-46, p. 31); they are almost perfectly aligned with WIPP-13. The response time between WIPP-13 and WIPP-25 was extraordinarily rapid – a delay in maximum drawdown of only 26 hours between test wells nearly four miles apart. There was also a measurable response at the WIPP exhaust shaft, 1.50 miles southeast of WIPP-13 (CCA, Appendix SUM, Table 4.7), which suggests an existent flow path from the WIPP repository all the way to Nash Draw. Beaufhein (1987, SAND87-2456, pp. 45, 47) and LaVenue et al. (1988, SAND 88-7002, p. 6-3) state that a higher transmissivity zone between WIPP-13 and the WIPP shafts is necessary to explain the response; this is borne out by a recently reported Culebra transmissivity of 31.0 ft²/day at WQSP-1, located 0.51 miles south of WIPP-13 (CCA, Appendix TFIELD, Table TFIELD-2). DOE still insists that groundwater flow associated with Nash Draw is unrelated to groundwater flow at WIPP (SEIS-II, p. 4-21). This claim has never been substantiated; now it is disproven.

CARD’s original paper correlates and presents borehole data showing washouts and consistent loss of core in two distinct horizons of Rustler mudstone: in the Forty-Niner member about 20 feet above the Magenta, and in the lower unnamed member immediately beneath the Culebra. These are not occasional occurrences. CARD, in Tables 2 and 3, succinctly summarizes 12 such encounters above the Magenta and 14 beneath the Culebra, all of them at or near the WIPP site. CARD describes a similar horizon in the Tamarisk member, with washouts or loss of core in 5 locations and reports of dissolution residue in 7 others. DOE denies that these are evidence for caverns, citing DOE’s own poor coring techniques, and DOE denies that these are dissolution residues, thereby challenging the validity of DOE’s own lithologic logs (EPA Docket, A-93-02, Item # II-H-46, p. 30). CARD has since discovered the caliper log for the WIPP exploratory shaft, which records washouts in nearly the same stratigraphic horizons: in the Forty-Niner member, 574-583 feet below the surface, 18 feet above the Magenta dolomite; in the Tamarisk member, 686-694 feet below the surface, 5 feet above the Culebra dolomite; and in the lower unnamed member, 732-742 feet below the surface, 15 feet below the Culebra dolomite (TME 3178, Figure 3, Sheet 2). The washout in the Tamarisk member would correlate with the dissolution residue of siltstone and gypsum breccia found immediately above the Culebra at WIPP-19, interpreted by some as cave filling (Ferrall and Gibbons, 1980, SAND 79-7110).
CARD's original paper describes in detail six karst sinkholes in the vicinity of WIPP: one at H-7, four at WIPP-33, and one at WIPP-14. DOE concedes that H-7 is a sinkhole, being located in Nash Draw, where the occurrence of karst and collapse features is to be expected (EPA Docket, A-93-02, Item # II-H-46, p. 31). DOE concedes that WIPP-33 is a sinkhole and, for the first time, DOE concedes that three other depressions, east of WIPP-33, closer to the current WIPP site boundary, first identified by Phillips (1987, Chapter IV), are sinkholes as well (EPA Docket A-93-02, Item # II-H-46, p. 31). DOE appears to deny that WIPP-14 is a sinkhole (EPA Docket A-93-02, Item # II-H-46, p. 32), perhaps because this one straddles the current WIPP site boundary; but upon closer examination, what DOE has written is a classic "non-denial denial," reminiscent of Watergate press conferences. CARD never stated that WIPP-14 is a collapse sink; the WIPP-14 depression is an alluvial doline (solution-subsidence doline) 600 feet in diameter, 9 feet deep, with 15 feet of alluvial fill, but there is no evidence of collapse. For this reason DOE can claim that the WIPP-14 borehole exhibited a "normal stratigraphic sequence," even though the Culebra is immediately underlain by 71.4 feet of mud (not mudstone - mud) with gypsum and anhydrite fragments, an occurrence reported nowhere else east of Nash Draw. CARD interprets this material as cave sediments, and DOE has offered no alternative explanation. DOE truncates the words of Barrows et al. (1983, p. 57), who stated that WIPP-14 is an alluvial doline and attributed the high-amplitude negative gravity anomaly measured at WIPP-14 to conversion of anhydrite to gypsum "in the vicinity of karst conduits." The observation by CARD that all halite has been removed from the Rustler at WIPP-14 is indeed "not consistent with the interpretation of Holt and Powers," who claim that there has been no dissolution in the Rustler, that halite was never deposited where today it is absent; however, CARD is unaware of anyone outside of DOE, Sandia Labs and EPA who agrees with Holt and Powers. Not only does DOE fall short of denying that WIPP-14 is a sinkhole; the CCA confirms it. CARD has since discovered this passage in Appendix DEF (p. DEF-30): "Only a few small clusters of shallow dolines on the Mescalero caliche have been identified on the Los Medanos plateau east of Livingstone (sic) Ridge." DOE refers the reader to Figure DEF-7, where the karst features are depicted with three black dots: at WIPP-33, WIPP-13, and WIPP-14.

**RAINWATER RECHARGE AT THE WIPP SITE**

DOE still does not know where the groundwater aquifers are recharged. In the CCA (Appendix HYDRO, p. 51) it is "suggested" that the Rustler Formation is recharged at Bear Grass Draw, some 25 miles north of the WIPP site; this was pure speculation, dating to a report by Robinson and Lang (1938). In the Draft SEIS-II (1996, p. 4-18) it is stated that recharge "probably" occurs 10 to 20 miles northwest of WIPP, where the Rustler Formation reaches the surface; this would be in Clayton Basin, which Hunter (1985) has shown to be hydraulically separated from the WIPP site (Phillips, 1987, Figure 75). In the Final SEIS-II (1997, p. 4-21), DOE changed its mind again and "suggested" that recharge originates "in areas that are north and northeast of the WIPP site." DOE's latest suggestion is not based on field observation or measured data; it is, in the words of EPA, "assumed" and "theorized" by DOE; it is a "new conceptualization" designed to explain the long-standing inconsistency between observed geochemistry and groundwater flow paths (EPA Docket, A-93-02, Item # III-B-3, pp. 77-78).

CARD, in Figures 1 and 2 of its original paper by the above title, has identified and mapped the recharge area for the Dewey Lake Redbeds and the Rustler Formation. Simply stated, the
recharge area is in the south-central and southwestern part of the WIPP site and south of the site, everywhere that the Santa Rosa sandstone is not present. At least 9 of 13 test wells in this area produced water in the Dewey Lake Redbeds. In 7 of 10 Culebra test wells in this area, total dissolved solids (TDS) were measured at 36,000 mg/l or less, fresh enough to be classified as brackish. This is consistent with the interpretation that Culebra groundwater becomes mixed with increasing amounts of fresh water as it approaches Nash Draw, because the regime becomes increasingly karstic, recharged through sinks or swallows.

DOE cannot and does not deny any of this. DOE admits in the CCA and in SEIS-II that the Dewey Lake "contains a productive zone of saturation, probably under water-table conditions, in the southwestern to south-central portion of the WIPP site and south of the site." The saturated zone is typically found in the middle of the Dewey Lake, 180 to 265 feet below the surface, "and appears to derive much of its transmissivity from open fractures." The saturated zone "may be perched or simply underlain by less transmissive rock." Fractures below the saturated zone "tend to be completely filled with gypsum" (CCA, p. 2-131; SEIS-II, 1997, p. 4-29). DOE described the Dewey Lake Redbeds in this area as "relatively transmissive" (SEIS-II, 1997, p. 4-21), but DOE refuses to acknowledge rainwater recharge in the area.

EPA noted that these fracture fillings may be caused by infiltration of rainwater, and that the CCA did not adequately describe the fracture characteristics, the fracture density, the percentage of fractures filled and partially filled, or what caused the fractures in the first place (EPA Docket, A-93-02, Item # III-B-3, pp. 39-40). DOE alleviated EPA's concerns by stating that the Dewey Lake Redbeds have "not produced water within the WIPP shafts, or in boreholes in the immediate vicinity of the waste panels" (EPA Docket, A-93-02, Item # II-B-3, p. 84; see also CCA, pp. 2-98, 2-131), and that the Dewey Lake "exhibits no flow at the WIPP site" (EPA Docket, A-93-02, Item # III-B-3, p.65). These statements are false, for the following reasons: (1) The Dewey Lake Redbeds have produced water in the WIPP exhaust shaft at approximately 100 feet below the surface, which EEG says "can be traced to recharge" (EPA Docket, A-93-02, Item # II-E-36, p. 3). The Dewey Lake produced water in the air intake shaft as well (EEG-61, 1996, p. 2-6). (2) The Dewey Lake Redbeds have produced water in four test wells in the immediate vicinity of the waste panels (H-1, H-2, H-3 and WQSP-6) (EEG-61, 1996, p. 2-6). One of these wells, H-1, is located directly above the waste panels (CCA, Appendix DEF, Figure DEF-8). (3) The Dewey Lake Redbeds do exhibit flow at the WIPP site. Test well P-9 (the H-11 hydropod) produced 25 gallons per minute, and WQSP-6 produced 28 gallons per minute (EEG-61, 1996, p. 2-6). According to the neutron log for H3-b4, a down-hole camera recorded "water streaming from fracture" at 466.85 feet below the surface, 200 feet below the so-called "saturated zone," in a horizon where, according to DOE, "fractures tend to be completely filled with gypsum." (CCA, p. 2-131; SEIS-II, 1997, p. 4-29). This open, water-filled fracture is only 35 feet above the Rustler Formation, which leads to the inescapable conclusion that, in the immediate vicinity of the waste panels, the Dewey Lake Redbeds contain feeder channels which readily transmit water from the surface to the Rustler Formation.

DOE's original fallback position was that the Rustler anhydrites, siltstones and claystones are confining layers (CCA, pp. 2-127, 2-128), barriers to rainwater infiltration. In performance assessment, the Forty-Niner, Tamarisk, and lower unnamed members are assigned a permeability of zero (CCA, pp. 6-123, 6-147, 6-148). This is consistent with testing of unaltered anhydrite core samples in the laboratory. It is not consistent with occasional reports of Rustler claystones producing water at rates equivalent to the Culebra or Magenta (Mercer and Orr, 1979; Mercer, 1983; Chaturvedi and Channell, 1985, pp. 37, 39; Beauheim, 1986; LaVenue et al., 1988, p. 2-5;
Lappin, 1989, Table 4-3, reprinted as CCA, Appendix SUM; Jones et al., 1992, p. 2-12). Clearly, DOE's assumption that rainwater recharge never reaches the Rustler Formation was unwarranted. Under pressure from EPA, "DOE concluded that the presence of anhydrite within Rustler units does not preclude slow downward infiltration, as had been previously argued by DOE." (EPA Docket, A-93-02, Item # III-B-3, p. 78)

Based on an assumption of "extremely slow vertical leakage" (CCA, Appendix MASS, p. MASS-72), DOE concluded that the travel time for infiltrating rainwater to reach the Culebra is "probably thousands or tens of thousands of years." (CCA, Appendix MASS p. MASS-75) According to DOE, this equates to an infiltration rate of 0.2 to 2.0 mm/yr (EPA Docket, A-93-02, Item # II-H-46, p. 37), which amounts to only 0.05% to 0.5% of annual precipitation (40 cm/yr). This would require a continuous, impermeable layer, acting as a barrier to rainwater infiltration, somewhere in the stratigraphic column above the Rustler Formation. If it is not the Dewey Lake Redbeds, then it would have to be the dune sands or the Mescalero caliche, because the Santa Rosa and Gatuna formations are not continuous at the WIPP site.

The lack of surface runoff at the WIPP site indicates that the surface sands are transmissive enough to allow infiltration of even the largest storms. EPA states that about 75% of total annual precipitation results from intense thunderstorms between April and September (EPA Docket, A-93-02, Item # III-B-3, p. 88). Phillips (1987, Chapter IV) stood in one of these thunderstorms and observed one of the few small arroyos at the WIPP site, draining into the WIPP-33 depression; five feet of standing water sank into the sand within days.

As evidence for a continuous barrier to rainwater recharge and karst hydrology at the WIPP site, EPA cites the Mescalero caliche. "DOE indicated that the Mescalero caliche is typically present beneath the sand." (EPA Docket, A-93-02, Item # III-B-3, pp. 58-59) DOE stated that the Mescalero "covers the WIPP area as a hard, caliche crust," and DOE indicated that the caliche is up to 10 feet thick (EPA Docket, A-93-02, Item # III-B-3, p. 43), which led EPA to conclude that karst development is not a threat to waste containment at WIPP (EPA Docket, A-93-02, Item # III-B-3, p. 52). DOE also said, in the CCA, that the Mescalero caliche "is expected to be continuous over large areas," but that "WIPP data are limited mainly to boreholes." (CCA, p. 2-60). EPA did complain that "a site-specific detailed map of the Mescalero caliche distribution was not provided in the CCA" (EPA Docket, A-93-02, Item # III-B-3, p. 43).

EPA is referred once again to Richard Hayes Phillips' doctoral dissertation, the only extensive work on the surficial geology of the WIPP site and vicinity. EPA has three copies, including one with color photographs submitted at public hearings in Albuquerque in 1990. There is no confirmation that anyone in EPA has read it, or factored into deliberations the relevance of its findings.

Phillips' dissertation contains 16 site-specific detailed maps of the Mescalero caliche surface, based on 1000 augur holes and 10 backhoe trenches, including WIPP-14 and the chain of four sinkholes at WIPP-33. Four of these trenches, described in Chapter V, were located in the eastern end of a karst valley, within the WIPP site (SW ¼ sec 30, T 22 S, R 31 E), within the rainwater recharge area, where Mescalero caliche is in direct contact with the Dewey Lake Redbeds. The karst valley, one mile long, plainly visible in the WIPP site air photos (a valuable tool neglected in DOE geological investigations), is also described in CARD's original paper. DOE, in its response to CARD, does not deny that this is a karst valley.
Trench exposures in the karst valley revealed 15 solution pipes, 1 to 14 feet in diameter, most of them passing entirely through the caliche, the largest of them displaying surface collapse in the Dewey Lake Redbeds. Some of the solution pipes formed where taproots had penetrated the caliche; others formed where rainwater collected in depressions on the caliche surface. Altogether, 15.3% of the caliche surface was absent, with surficial sand in direct contact with Dewey Lake Redbeds. A smooth, continuous caliche surface cannot be expected; the effect is more like Swiss cheese. After heavy rainstorms, water runs along the caliche surface until it disappears into the solution pipes and infiltrates into the Dewey Lake Redbeds.

DOE videotaped the trenches. Larry Barrows, Al Lappin, Steve Lambert and George Bachman all viewed the trenches, as did a number of other scientists affiliated with New Mexico Tech, Texas Tech, EEG, and EPA. The trench exposures were consistent with Mescalero caliche morphology described by Bachman (1973) and Bachman (1974), excerpted in the CCA (Appendix XRE, pp. XRE2-20, XRE2-22). DOE, in its response to CARD, is forced to admit that Mescalero caliche has “some permeability,” and that “recharge to the water table can occur over the entire land surface” (EPA Docket, A-93-02, Item # II-H-46, p. 27). At the WIPP site, there is no barrier to rainwater infiltration at any level above the Culebra.

**POTENTIAL FLOW PATHS FROM THE WIPP SITE TO THE ACCESSIBLE ENVIRONMENT**

Most of CARD’s original paper by the above title stands uncontested. DOE disagrees that: (1) there has been extensive dissolution of halite in the Rustler Formation; (2) the Culebra dolomite is recharged by modern rainwater; (3) DOE’s proposed flow path is inconsistent with groundwater geochemistry; and (4) Laguna Grande de la Sal is the principal discharge point for Rustler groundwater, including the Culebra dolomite. These issues are dealt with in CARD’s point-by-point rebuttal to DOE.

CARD, in its original paper, identified three potential karstic groundwater flow paths from the WIPP site to the accessible environment. Anderson (1996, p. 4) has visualized these flow paths also; he describes them as resembling a “pincer,” leaving the southwestern part of the WIPP site “as an outlier of the main dissolution front.” From the recharge area in the central part of the WIPP site there is a southeasterly flow path to H-3, DOE-1 and H-11, proceeding between H-17 and P-17, thence westward to H-7 in Nash Draw. From the recharge area there is a northwesterly flow path between H-18 and WIPP-18 to WIPP-13 and H-6, thence westerly to the WIPP-33 chain of sinkholes and WIPP-25 in Nash Draw. There is a westerly flow path from the WIPP-14 sinkhole to DOE-2 and WIPP-13, where two flow paths merge and the Rustler becomes one unconfined aquifer with five members. These flow paths remain unchallenged, and CARD has further evidence to support them. They include and extend in a logical way the flow paths recognized by DOE.

Jones et al. (1992, SAND92-1579, p. 2-21) have observed that Culebra fracture fillings are absent or have been dissolved at H-3, DOE-1 and H-11 in the southeastern part of the WIPP site, and at DOE-2, WIPP-13 and H-6 in the northwestern part of the WIPP site. As these six test wells are located within two zones of high transmissivity identified by multi-well pumping tests (Beauheim, 1986; Beauheim, 1989). Jones et al. conclude that open fractures “significantly enhance groundwater flow and solute transport.”
Since the submission of its original paper, CARD has discovered a more complete transmissivity database for the Culebra dolomite (LaVenue et al., 1988, SAND 88-7002, Table C.1; Beauheim, 1989, SAND89-0536, Table 6-1). Accordingly, CARD has updated its own data base, which is given in Table 1 of this paper. Hydraulic conductivity is computed as transmissivity divided by the thickness of the Culebra aquifer, though the transmissive interval is probably thicker.

The rainwater recharge area identified by CARD includes test wells H-1, H-2, H-3, ERDA-9, and all four of the WIPP shafts. Two of the flow paths originate here. When CARD submitted its original paper, the Culebra transmissivity at H-3 (19 ft²/day) was thought to be anomalously high. Now we know that Culebra transmissivities elsewhere in the recharge area are comparable (20.0 ft²/day at H-1; 16.0 ft²/day at H-2; 22.0 ft²/day at ERDA-9; and 28.0 ft²/day at the WIPP exhaust shaft). These transmissivities are more than an order of magnitude (more than ten times) greater than previously believed, implying a faster rate of recharge and lateral flow. Hydraulic continuity throughout the recharge area is indicated by the drawdown at well locations H-1, H-2 and H-3 caused by drainage into the WIPP shafts during the spring of 1983 (LaVenue et al., 1988, SAND88-7002, p. G-6; see also Figures E.1, E.2 and E.3), and by drawdown and recovery at well locations H-1, H-2, H-3, H-16 and ERDA-9 following drilling and grouting of the WIPP air intake shaft between 1988 and 1994 (Silva, EEG-62, 1996, pp. 49-52).

CARD and DOE have identified a zone of high transmissivity through the southeastern part of the WIPP site, indicating a flow path from H-3 to DOE-1 to H-11. CARD noted at the public hearings in February 1997 that lithologic descriptions for H-1, H-2 and H-3 were never published. CARD has since discovered drawings and brief descriptions of Culebra core samples at H-2b, H-2b2, H-3b2 and H-3b3 (Jones et al., 1992, SAND92-1579, Figures 6-2, 6-3, 7-2 and 7-3). At H-2b and H-2b2 the cores were massive or vesicular with some fractures, most of them filled with gypsum. But at H-3b2 the Culebra is “totally fragmented.” Only three core samples totaling 4.0 feet were recovered; 18 feet of Culebra core was lost, and another 5.0 feet of core was lost in black clay (not claystone – clay) immediately beneath the Culebra. At H-3b3 the whole Culebra interval was “broken into pieces” less than 1 foot in length; where pieces were preserved, the core was very porous; some fractures were open, some were filled with gypsum; 14.5 feet of Culebra core was lost, and another 4.0 feet of core was lost in the black clay beneath the Culebra. This is entirely consistent with a cavernous groundwater flow path through the Culebra dolomite and the claystone of the lower unnamed member.

Jones et al. (1992, SAND92-1579) also present drawings and brief descriptions of Culebra core at H-11b1, H-11b2, H-11b3 and H-11b4 (Figures 10-2, 10-3, 10-4 and 10-5). Here the Culebra is sometimes “highly fragmented,” sometimes “massive with subvertical fractures;” core recovery was about 80%. The Culebra is underlain by black clay with subvertical fractures, some of them open, some of them filled with gypsum.

DOE has concluded from tracer-injection testing at H-1, H-2, H-3, P-14, H-14 and H-19 that most or all of the flow in the Culebra dolomite comes from the lower 10 feet (CCA, Appendix MASS, Attachment 15-6, p. 6) to 21 feet (Lappin, 1988, SAND88-0157, p. 77) of the Culebra. This is consistent with the interpretation that fracturing is more extensive in the lower Culebra due to caving in the mudstone and claystone immediately beneath the Culebra. There is direct evidence that the lower unnamed member is involved in groundwater flow along this path; at H-3, the dissolution residue in the lower unnamed member yielded as much water as the Culebra or Magenta (EEG-32, 1985, p. 39).
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<td>USGS-1</td>
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<td>Cooper (1962)</td>
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* Test wells located at or within one mile of the WIPP site.
This southeasterly flow path crosses the WIPP site boundary south of H-11, "where it narrowly lies between the P-17 and H-17 boreholes" (CCA, Appendix TFIELD, p. TFIELD-125). Culebra transmissivities at P-17 and H-17, as measured during the multiwell pump test centered in the Culebra at H-11 (Beauheim, 1989, Table 6-1) are moderately high (21.0 ft²/day and 13.0 ft²/day, respectively), so these test wells probably missed the active solution conduits. LaVenue et al. (1988, SAND88-7002), when attempting a numerical simulation of this flow path, recognized that a "relatively high transmissivity zone between wells H-17 and P-17" is required (p. iii) in order "to reduce the differences between the calculated and observed heads at H-11 and DOE-1" (p. 4-10) to a smaller amount than the margin of error of field measurement. They concluded that the calibrated transmissivities between P-17 and H-17 are approximately $5 \times 10^5$ m²/sec (pp. 4-12, 6-2), or 46 ft²/day.

CARD represents that this flow path then turns westward, following an avenue of low resistance beneath a vast karstic depression with disrupted surface drainage, four miles long and up to 7000 feet wide, extending from the James Ranch dune field to Nash Draw. It then flows beneath a sinuous karst trench walled by high dunes, 2.5 miles long, leading directly to the collapse sink where test well H-7 was drilled. At H-7 a dry cave was found in the Dewey Lake Redbeds, five water-filled caves were found in the Culebra, and transmissivity of 1430 ft³/day was measured in the Culebra. When viewing the WIPP site air photos, the disrupted surface drainage immediately south of the site is indistinguishable in character from Nash Draw. The karst trench, when viewed stereoscopically, is unmistakable. The entire flow path from the WIPP site boundary to Nash Draw demonstrates unconfined flow under water-table conditions. Typical of karst channels, the hydraulic heads in the Culebra are equal at H-11, H-17, P-17 and H-7.

DOE, in its modeling assumptions, recognizes that Culebra flow is "strongly affected by a high-transmissivity zone in the southeastern portion of the WIPP site" (CCA, Appendix MASS, p. MASS-77). DOE prefers a flow path continuing southward from H-17 to H-12 and thence toward Malaga Bend; however, there is no evidence of a hydraulic connection between H-17 and H-12. During the multiwell pump test centered in the Culebra at H-11, there was no response at H-12 for 33 days, and the maximum drawdown was only 6 inches (Beauheim, 1989, Table 5.1), which could not be attributed to the pumping at H-11 (Beauheim, 1989, p. 79). But DOE does allude to H-7 when describing the "high-transmissivity zone" between P-17 and H-17 (CCA, Appendix TFIELD, p. TFIELD-125; see also LaVenue et al., 1988, SAND88-7002, p. 6-1). In SEIS-II (p. 4-25), DOE describes Culebra flow patterns, stating that "flow above the WIPP repository is to the south," "flow south of WIPP is possibly toward the west" (toward Nash Draw), and "flow in Nash Draw is to the southwest" (toward Laguna Grande de la Sal).

It should be noted that H-19, the latest WIPP hydropad, consisting of an array of seven test wells, is located between H-3 and DOE-1, within the zone of high transmissivity. Multi-well pumping tests and tracer tests have been performed at H-19, but the results remain unpublished, tucked away in the Sandia central files, unavailable to the public or even to the Peer Review Panel (CCA, Appendix PEER, pp. 3-60, 3-61). The CCA (Appendix TFIELD, p. TFIELD-126) does allude to the H-19 tracer test of December 1995 through March 1996, and does provide hydrographs (Appendix TFIELD, Figures TFIELD-39 and TFIELD-40) which indicate a rapid response at test wells H-1, H-3, WQSP-4 and WQSP-5 and no response at H-15. EPA should not be content without full disclosure of these most recent drillholes and tracer tests. Reportedly, a triple-tube core barrel produced high-quality core, and hydraulic and tracer testing procedures were superior to the older tests conducted.
CARD, in its original paper, identified a second zone of high transmissivity through the northwestern part of the WIPP site, further described in pages 2 and 3 of this paper. The flow path leads from the WIPP shafts to WIPP-13 through a zone of high transmissivity between H-18 and WIPP-18. The flow path continues from WIPP-13 to H-6 to WIPP-33 to WIPP-25. This flow path ultimately involves all five members of the Rustler Formation. CARD has discovered additional evidence in support of this flow path.

It has been noted that the WIPP exhaust shaft responded to the multi-well pump test at WIPP-13, and that LaVenue et al. (1988, SAND 88-7002, p. 6-3) believe that a high transmissivity zone between WIPP-13 and the WIPP shafts is necessary to explain the response. Lappin (1989, SAND 88-0157, p. 76, reprinted as CCA, Appendix SUM) observes that WIPP-21 “responded strongly and rapidly” to both the multiwell pump test at H-3 and the sinking of the WIPP ventilation and exhaust shafts. “This behavior probably reflects the presence of ... a single fracture or fracture zone connecting the region near WIPP-21 with the two WIPP shafts, but not intersecting WIPP-21 itself.” Lappin notes that even if a given borehole does not indicate local fracturing, there may be fracturing nearby. From these observations, CARD infers that there is a zone of high transmissivity to the west of WIPP-21, from the WIPP shafts to WIPP-13.

CARD stated in its original paper that hydraulic heads in the Culebra and Magenta are equal at WIPP-25 in Nash Draw and at H-6 within the northwestern corner of the WIPP site. Somewhere between the WIPP shafts and H-6 the Culebra and Magenta lose their hydraulic distinction and become a single, unconfined aquifer (see also LaVenue et al., 1988, SAND 88-7002, pp. 2-4, 2-5). CARD also observed that the Culebra head at WIPP-13 (3064 feet) is higher than at H-6 (3057 feet) and concluded that the Culebra and Magenta heads are equal at WIPP-13 as well, stating that hydraulic heads in the Magenta should confirm this, but the data are not available. CARD has since discovered that the Culebra head at H-18 (3059 feet) is also higher than at H-6; again, hydraulic heads in the Culebra and Magenta may be equal, but the data are not available. DOE needs to perform the necessary testing to determine where the Culebra and Magenta lose their hydraulic isolation from each other.

At the public hearings in February 1997, CARD noted that geophysical logs for H-4, H-5 and H-6 were never published; only brief lithologic descriptions were provided (Mercer and Orr, 1979). At H-6 the Culebra was described as “dolomite, light-olive-gray to olive-gray, pitted; some gypsum, light gray; trace mud.” Directly above and below the Culebra are dissolution residues described as “mud matrix with mudstone, clay, and gypsum.” No information was given about the nature and extent of fracturing or the amount of core recovery. CARD has since discovered that only 2.3 feet of core was recovered at H-6b (Jones et al., 1992, SAND92-1579, Figure 9-2). It is described as “dense dolomite with minor vugs and some vertical fractures.” Altogether, 90% of the core was lost, indicative of conditions of dissolution. The release of the geophysical logs for H-4, H-5 and H-6 is required.

In its original paper, CARD observed that hydraulic heads in the Magenta dolomite are higher than hydraulic heads in the Forty-Niner member everywhere that heads have been measured in the Forty-Niner (at H-3, H-14, H-16 and DOE-2). From this DOE concludes that flow between the Magenta and the Forty-Niner at these locations “would be upward.” This, observes DOE, “is not consistent with the results of groundwater modeling, and this inconsistency may be the result of local heterogeneity in rock properties that affect flow on a scale that cannot be duplicated in regional modeling” (SEIS-II, p. 4-27). Upward flow between the Magena and the Forty-Niner is indeed inconsistent with DOE's concept of the Culebra dolomite as a confined aquifer,
sandwiched between two anhydrite beds with zero permeability. These data indicate a discrete flow path which DOE cannot reproduce in its modeling. There is direct evidence that the Forty-Niner member is involved in groundwater flow at these locations. At H-14 and DOE-2 the measured transmissivity of Forty-Niner claystone was more than an order of magnitude (more than ten times) greater than the transmissivity of the Magenta dolomite (Lappin, 1989, SAND88-1057, Table 4.3, reprinted as CCA, Appendix SUM).

Lappin (1989) observes that “there must be a qualitative increase in the transmissivities of the Tamarisk and Forty-Niner anhydrites somewhere between the WIPP site and Nash Draw,” because “evaporite karst in and near Nash Draw involves formation of small caverns and sinkholes within the Tamarisk and Forty-Niner members.” He states that “karstic hydrology might occur within the Rustler Formation at the WIPP site,” which would involve rainwater recharge to the Rustler dolomites and/or anhydrites. In order for this to occur, the Forty-Niner heads would have to be greater than those of the underlying Magenta dolomite, at least in places. The hydraulic heads at H-3, H-14, H-16 and DOE-2 “do not rule out fluid movement from the surface downward” into the Forty-Niner claystones and anhydrites and/or into the Magenta dolomite elsewhere, in areas “where the Dewey Lake is saturated.” Vertical flow from the Magenta to the Culebra would require downward movement through the Tamarisk member; however, “it has not been possible to measure either transmissivities or head potentials within either the claystones or anhydrites in the Tamarisk at or near the WIPP site.” But such measurements may not be necessary; rainwater recharge could happen “near the center of the WIPP site,” where Magenta heads are greater than those of the Culebra, “consistent with downward flow between these two units.” (Lappin, 1989, SAND88-1057, pp. 79, 81, reprinted as CCA, Appendix SUM). This is a fair and honest assessment by Al Lappin, who observed Phillips’ trenches, stood upon the Dewey Lake Redbeds where Mescalero caliche is absent, and evidently understood that rainwater recharge is occurring.

CARD, in its original paper, identified a third groundwater flow path along the northern boundary of the WIPP site, in the Culebra and lower unnamed members of the Rustler, from the WIPP-14 sinkhole to DOE-2 to WIPP-13, where it merges with the flow path from the WIPP shafts. The confluence of two underground flow paths in the Culebra at WIPP-13 is consistent with the interpretation that the Magenta becomes important at WIPP-13, that some Culebra water rises through the interconnected vertical fractures of the Tamarisk member and into the “broken and shattered” Magenta dolomite. When viewed in plan, flow paths converge at WIPP-13. When viewed in cross-section, flow paths diverge at WIPP-13. This illustrates the necessity of modeling the Rustler aquifer in three dimensions.

As the flow path continues toward Nash Draw, the Magenta and higher units become increasingly important. At WIPP-33, five underground caverns, all of them filled with water, were found in a nested sequence: two in Magenta dolomite, two in Forty-Niner gypsum, and one in Dewey Lake siltstone. The four Rustler caverns totaled 22.5 feet within a 50.5-foot stratigraphic section, and the siltstone cavern was 7.0 feet from top to bottom. These are large caverns, connected to extensive conduits carrying water from the WIPP shafts all the way to Nash Draw and thence to Laguna Grande de la Sal and the Pecos River.

The multiwell pump test centered at WIPP-13 has demonstrated a hydraulic connection between the WIPP exhaust shaft and WIPP-25 in Nash Draw. CARD has discovered additional evidence for the tributary flow path from the WIPP-14 sinkhole. In the CCA (Appendix DEF, p. DEF-30), DOE distinguishes between “Nash Draw, where karst features are developed, and a more easterly
region, including the WIPP site," where, according to DOE, "there is no significant shallow dissolution of halite, anhydrite, or dolomite." DOE states that: "These two regions are separated by a transition zone which includes a prong of dissolution extending from Nash Draw towards the site of WIPP-14." The next paragraph refers the reader to Figure DEF-7, which displays a black dot at the location of WIPP-14, together with this description: "Depression Areas North of WIPP Site." It should be noted that although the WIPP-14 borehole is 98 feet north of the current WIPP site boundary, the depression into which it was drilled is 600 feet in diameter, straddling the WIPP site boundary. This is direct evidence of karst geomorphology at the WIPP site.

CONCEPTUAL ERRORS IN THE DOE MODEL OF GROUNDWATER FLOW IN THE RUSTLER FORMATION

DOE must defend its conceptual model of groundwater flow, lest it be shown that the highly dependent performance assessment is fatally flawed. DOE’s charges are dealt with in CARD’s point-by-point rebuttal. However, there is one criticism contained in CARD’s original paper which DOE made no attempt to refute: Borehole data should not be assumed to be representative of hydraulic conditions beyond the immediate vicinity of the borehole.

In karst, hydraulic conductivity along solution-enlarged fractures may be three orders of magnitude greater than that of the adjacent unaltered rock (Fetter, 1980). Because the active solution conduits comprise a small part of the total area of the watershed, most boreholes will miss them, and will show values for hydraulic conductivity which are not representative of karst conditions (Bloom, 1978; Barrows, 1982). Borehole measurements may reflect aquifer properties only within the immediate vicinity of the borehole (Konikow, 1995). The technique of interpolation between data points, although useful in porous, homogeneous media, should not be applied to a karstland (LeGrand, 1973).

DOE’s performance assessment is said to be supported by the work of Corbet and Knupp (SAND96-2133). Their three-dimensional conceptual model of Rustler hydrology is said to justify the two-dimensional mathematical model used in performance assessment (EPA Docket, A-93-02, Item # II-H-46, p. 33). CARD, in its original paper by the above title, assailed the use of geologic data to infer hydraulic conductivity values for areas in which conductivity measurements were not available. CARD, on page 5 of its original paper, presented numerous specific instances of assumed values which were inconsistent with borehole data in the vicinity. The entire page stands unchallenged, and CARD now presents more examples.

Figure 2-7: Zone IV is said to represent “intact strata” in the Rustler. This zone includes the WIPP air intake shaft, where much of the Culebra dolomite exhibits “extensive subvertical to vertical fracturing.” About half of the fractures are filled with gypsum, and the rest are open. Fractures interconnect all vugs, which are as large as 7.6 cm (3 inches) in diameter. The lower 0.15 m (6 inches) consists of brecciated dolomite (Jones, 1992, SAND92-1579, p. 2-19 and Figure 2-10). This description is especially significant in view of the fact that DOE told EPA that "it does not appear that the Culebra is extensively fractured in the vicinity of the WIPP shafts." This led EPA to conclude that DOE’s assumption of dual porosity (fracture flow and matrix diffusion) “may be conservative.” (EPA Docket, A-93-02, Item # III-B-3, p. 38) This zone also includes borehole H-11, where Culebra core is described as “highly fragmented.” (Jones et al., 1992, SAND92-1579, Figures 10-4, 10-5)
Figure 2-9: The zone assumed to have hydraulic conductivity of $1 \times 10^{-12}$ m/sec ($2.8 \times 10^{-7}$ ft/day) in Rustler anhydrite includes borehole WIPP-13 where, according to the lithologic description, 56 feet of Tamarisk anhydrite has been converted to gypsum; 7.1 feet of dissolution residue consisting of mudstone with angular clasts of gypsum breccia was encountered; steeply dipping veins and fractures, one of them filled only with silt, were found throughout the Tamarisk member; the overlying Magenta dolomite is "broken and shattered by numerous fractures dipping 60°-80° and displacing bedding planes 0.5-1.0 cm.;" and the Culebra is believed to be hydraulically connected to the Magenta. This zone also includes borehole WIPP-19, where solution cavities were found in Forty-Niner anhydrite (SAND79-7110, p. 17). This zone also includes the WIPP ventilation shaft, where mudstone in the lower unnamed member of the Rustler contains 24 vertical to subvertical fractures, all but one of them open, most of them interconnected (TME 3177, Figure 5; EEG-32, 1985, Plate 1), and produces water in a dissolution residue immediately beneath the Culebra (EEG-32, 1985, p. 39).

Admittedly, these occurrences may be anomalous, but that is exactly the point. To disregard lithologic descriptions of the most disrupted ground is not a conservative assessment, because groundwater selectively follows the paths of least resistance.

POINT-BY-POINT REBUTTAL TO DOE’S RESPONSE TO CARD’S COMMENTS

1. No one has previously correlated evidence for karst from DOE boreholes and test wells. CARD is first to do so. The mere submission of Basic Data Reports for DOE boreholes as "supporting references" does not mean that the implications of these data have been "considered" by DOE in its performance assessment (PA); indeed, it is CARD’s position that the data were subjectively filtered for EPA examination.

2. If CARD had presented "few arguments" that were not discussed in the Compliance Certification Application (CCA), then DOE should have been able to reprint them, submit them to Larry Weinstock, and respond to them in detail. DOE chooses instead to refer to three of the scientific papers presented by Drs. Richard H. Phillips and David T. Snow as one “comment” each, parts of a “letter,” so that the detail, depth and validity of CARD’s work might go unrecognized by EPA.

3. DOE continues to describe the Culebra dolomite as “fractured,” but not karstic. DOE’s groundwater model may be “consistent with international practice,” but it is not appropriate for karstic media, which are inherently unpredictable. It is not “international practice” to consider disposal of radioactive or toxic waste in karstic regions. Barrows (1982, p. 17) cites 16 papers by 20 authors who have identified karstlands as unacceptable waste disposal environments.

4. CARD does not “confuse” DOE’s “simplifying assumptions” with a “statement of reality.” DOE, specifically Corbet and Knupp, has applied simplifying assumptions, conceptual errors, and misrepresentative data in its modeling of groundwater flow, then called the output “reality.”

5. CARD disagrees that DOE’s Culebra flow model is “consistent with the WIPP borehole data.” In its paper entitled “Conceptual Errors in the DOE Model of Groundwater Flow in the Rustler Formation,” CARD presents numerous examples of boreholes where measured data are inconsistent with DOE’s simplifying assumptions. In each case, CARD has identified the
locations of the boreholes and has contrasted the data measured therein with DOE's misrepresentation. The "detailed localized information" presented by CARD has not been accounted for by DOE, "implicitly" or otherwise.

6 DOE admits that groundwater geochemistry in the Culebra can only be explained by "vertical leakage," synonymous for rainwater recharge. But DOE remains committed to a miniscule rate of rainwater recharge to the Culebra that is unrealistic in view of the geochemistry. Within the WIPP site, total dissolved solids (TDS) vary by a factor of 25 (8,890 mg/l at H-2 to 230,000 mg/l at H-15). Dissolved sodium and chloride (NaCl) also vary by a factor of 25 (4,835 mg/l at H-2 to 124,100 mg/l at H-5), well below saturation (318,000 mg/l NaCl). Such a discrepancy cannot be explained by a recharge rate of 0.2 to 2.0 mm/yr, requiring transit of "several tens of thousands of years," as assumed by DOE. This assumption has no basis in fact, but it would be consistent with an equally slow rate of groundwater flow in the Rustler which, if believed, might support an erroneous finding that the WIPP site is suitable for waste isolation.

7 Regarding climatic change, full-glacial conditions would not "raise the water table to the land surface." Such a concept on the part of DOE reflects a lack of understanding of karst hydrology. An increased amount of groundwater (due to increased precipitation, decreased evaporation, or both) would flow more rapidly than before through existing karst channels, enlarging them through corrosion as it does so. As proof, CARD refers EPA to the Mescalero caliche, which forms in the capillary fringe and dissolves when exposed to standing water. The Mescalero caliche is said to be older than the most recent glacial advances. If the water table had been at the land surface during glacial maxima, the caliche would have been obliterated.

8 It can never be stated categorically that "there are no examples of karstic features" within the WIPP site. A nearly continuous mantle of desert soil and windblown sand up to 13.5 feet thick covers the entire WIPP site and vicinity, obscuring all but the largest and most obvious karst features. One example of a karst feature within the WIPP site is at WIPP-14, where a solution-subsidence doline 600 feet in diameter straddles the current WIPP site boundary.

9 DOE has never considered the human consequences of contamination of the Pecos River (part of the accessible environment) by plutonium from the WIPP site. In restricting its analysis to the WIPP site boundary, and by postulating very long groundwater travel times to that boundary, DOE vouches for the safety of the WIPP site even while claiming not to know the ultimate discharge point for contaminated water.

10 "The DOE has not denied the presence of karst features _____ the WIPP site." This sentence lacks a preposition. What is it - "near," "at," or "within"? There is a space here. A word has been deleted.

11 It is interesting that DOE cites Barrows (1982) without having provided this landmark report to EPA, except as Appendix A to Chaturvedi and Channell (EEG-32, 1985).

12 Harry LeGrand did not carry out an "investigation" of the karst issue. He wrote informal reports, based upon his previous work in other karst regions. To our knowledge, he conducted no field work at the WIPP site other than participating in a one-day field trip led by Larry Barrows. LeGrand's reports were reprinted as appendices to Chaturvedi and Channell (EEG-32, 1985). Nowhere does EEG state that it agrees with LeGrand's conclusions.
13 DOE states that Nash Draw is “some 6 miles (10 kilometers) to the west of the Land Withdrawal Area.” This is an erroneous statement which could have misled EPA into thinking that Nash Draw, one of the largest karst features with surface expression in North America, is “some” safe distance from the WIPP site. DOE personnel drive through Nash Draw every day on their way to the WIPP site. The truth is that the fluvial incisions of Livingston Ridge, which mark the eastern boundary of Nash Draw, reach to within one mile (1.6 kilometers) of the northwest corner of the WIPP site, and to within 1.2 miles (1.9 kilometers) of the southwest corner of the WIPP site, 400 feet from the WIPP site turnoff.

14 DOE states that “there is no evidence from hydraulic conductivities” that the karst development found at WIPP-33 extends into the Land Withdrawal Area (LWA). There are two reasons for this: (1) WIPP-33 is no longer within the LWA, having been gerrymandered out of the WIPP site when its boundaries were reduced. (2) WIPP-33 was never converted to a hydrologic test well, and so there are no multiwell pump tests designed to determine whether or not the five water-filled caverns found at WIPP-33 are hydraulically connected to the zone of anomalously high transmissivity within the northwestern part of the WIPP site (test wells H-6, WIPP-13, and DOE-2). If there is “no evidence,” this is because DOE has not done the necessary testing. WIPP-33 was drilled in 1979. DOE has had 18 years to measure hydraulic conductivity under certifiable karst conditions in the immediate vicinity of the WIPP site. Absence of evidence is not evidence of absence.

15 The “heterogeneous transmissivities” in the Culebra should be cause for grave concern. Within one mile of the WIPP site, measured Culebra transmissivities vary by five orders of magnitude (0.003 ft²/day at P-18 to 324 ft²/day at P-14). DOE interprets these as preferential flow along “fracture networks,” citing Beauheim (1989). EPA should not dismiss CARD’s interpretation that these linear zones of anomalously high transmissivity could be indicative of karstic channels, especially in light of DOE’s own admission that groundwater flow in all members of the Rustler “is primarily controlled by fractures that have been affected by shallow dissolution processes.” (SEIS-II, p. 4-30) In Jones et al., (1992, pp. 3-9, 3-10, 12-19), DOE admits that a variable-aperture channel model, with the bulk of the flow occurring in channels, “could fit the observed data equally as well.” Yet DOE adheres to its “stochastic” model, treating the “heterogeneous transmissivities” in the Culebra as “random variables” without geographic orientation. Given the observed data, the conservative approach would be: (1) to acknowledge that paths of anomalously high transmissivity, being interconnected paths of least resistance, are representative of actual site-scale groundwater flow paths and to assess the suitability of the WIPP site according to these data; and (2) to convert WIPP-33 and WIPP-14 into hydrologic test wells in order to measure Rustler transmissivity under actual karst conditions in the immediate vicinity of the WIPP site. That was done at H-7 in Nash Draw, where Culebra transmissivity is 1430 ft²/day and hydraulic conductivity is at least 31.0 ft/day, or 2.1 miles per year. Figure TFIELD-5 in the CCA does not present “the same data” as Figure 3 in CARD’s paper entitled “Cavernous Zones at the WIPP Site.” CARD presents its data in ft²/day, showing the great range of values. DOE presents its data logarithmically, which obscures the range for most readers. In addition, DOE seldom presents the highest measured transmissivities for a given test well, as CARD does, and as DOE should do if its performance assessment is to be conservative. CARD has subsequently revised its data base with the receipt of reports containing even higher measured transmissivities at twenty-five WIPP test wells (LaVenue et al., 1988; Beauheim, 1989).

16 DOE contends that “the measured head data can be contoured as continuous smooth surfaces and so argue against karstic flow.” This statement is misleading. Any data can be mapped with
EPA should compare Figure 2-31 (CCA, p. 2-125) with Figure TFIELD-7 (CCA, Appendix TFIELD, p. TFIELD-27). On Figure 2.31, thirty test wells are shown, all in their correct geographic locations. The contour lines are on the wrong side of four test wells (H-2, H-3, H-4 and H-15). Six test wells are missing altogether. Four of them (H-8, H-16, WIPP-27 and WIPP-29) do not fit with DOE’s "continuous smooth surfaces," falling on the wrong side of the contour lines; one of them (H-19) is an unknown quantity, the data still unpublished; and one of them (AEC-7) fits perfectly, right on the 932-meter contour line. The most significant problem with Figure 2-31 is that the data are inconsistent, partly confined, partly unconfined, especially in the western half of the field. In places, Culebra water rises through the Tamarisk member and into the Magenta. This is true at WIPP-25 in Nash Draw and at H-6 within the northwestern comer of the WIPP site, where the Culebra and Magenta heads are equal. It is probably true as well at WIPP-13 in the northwestern part of the WIPP site, where the Magenta is broken and shattered by numerous steeply-dipping fractures, the Tamarisk exhibits a zone of mudstone/gypsum breccia (dissolution residue) and steeply-dipping fractures throughout, and the Culebra freshwater head is higher than at H-6. Just northwest of the waste panels is H-16, where the Culebra freshwater head is anomalously low (3005 feet), which is why it does not fit with the contour lines on DOE’s map. CARD believes that some water from the rainwater recharge area in the central part of the WIPP site flows through the Rustler in a northwesterly direction, bypassing H-16 and H-18 on its way to WIPP-13, H-6, WIPP-33 and WIPP-25. No generalized map of the Culebra potentiometric surface, with or without all the data points, can reflect such a discrete channelized flow path. Interpolation between data points is not appropriate for hydraulic heads in unconfined aquifers.

17 DOE proclaims that “head changes in boreholes indicative of rapid recharge at the WIPP site during times of heavy rainfall have not been observed.” There are two reasons for this: (1) boreholes which intercepted karst channels (e.g. WIPP-33 and WIPP-14) were not converted to test wells; and (2) water levels in test wells which did not intercept karst channels cannot be expected to fluctuate with rainfall. Within the WIPP site, the top of the Culebra is 413 ft (at P-15) to 899 ft (at H-5c) below the surface. Rapid infiltration to such depth can only be expected in the sinkholes themselves, as at WIPP-33, where five feet of standing water was observed to sink into the sand in a matter of days (Phillips, 1987, p. 86). However, a steady rise in water levels in the Magenta at test wells H-2 and H-3, and in the Culebra at test wells H-1, H-3 and H-4, all located within the recharge area, were recorded between mid-1977 and mid-1981 (Gonzalez, 1983, SAND83-0210, pp. 22-25). This occurred in undisturbed hydraulic conditions, before the sinking of the first WIPP shaft in July 1981 (CCA, Appendix TFIELD, Table TFIELD-9). DOE says that this rise in hydraulic heads is "unexplained" (CCA, Appendix TFIELD, p. TFIELD-17). CARD offers an explanation. During this four-year period 68.55 inches of rain (17.14 inches per year) was recorded in Carlsbad, compared to an average of 10.85 inches per year during the preceding 25 years. While the rise in Magenta and Culebra water levels cannot be correlated with individual rainstorms, it can be correlated with short-term trends in precipitation.

18 DOE misrepresents CARD’s position regarding the significance of a lack of core recovery. If one omits the word “particularly,” then CARD’s position regarding carbonate rocks is correctly stated. However, evaporite rocks are not typically fractured, so a consistent lack of core recovery in horizons identified by the drill loggers as containing dissolution residues is a clear indication of unconsolidated or cavernous zones capable of transmitting water with little resistance. When these occurrences are correlated and mapped, as CARD has done in its paper entitled “Cavernous Zones at the WIPP Site,” it is shown that these zones snake across the WIPP site, penetrating its heart at the ventilation shaft, extending from the repository to the discharge area in Nash Draw.
On the authority of Powers and Holt, DOE takes the position that these zones are not dissolution residues at all -- that no subsurface dissolution of halite has ever occurred in the Rustler Formation, because no halite was ever deposited where today it is absent. No one besides Powers and Holt and their collaborators subscribe to this. There is “ample published evidence for the real extent of dissolution,” (Anderson, 1996, p. 6). The works of two scientists on the DOE payroll does not “largely rule out this explanation,” as contended by DOE (CCA, p. 2-38). CARD, in its paper entitled “Potential Flow Paths from the WIPP Site to the Accessible Environment” (p. 4), has cited fifteen reports which describe extensive dissolution of halite in the Rustler Formation, and now, in its rebuttal to DOE, cites eight more: Jones et al. (1960), Vine (1963), Cooper and Glanzman (1971), Brokaw et al. (1972), Jones (1978), Ferrall and Gibbons (1979), LaVenue et al. (1988), and Anderson (1996). Many of these authorities are or were consultants to DOE on the WIPP project. DOE, in the CCA, cites Powers and Holt 25 times in 7 pages (beginning at p. 2-38), more often than DOE cites the works of all other scientists combined. Anderson states that “the extensive character of Rustler dissolution at WIPP is recognized by virtually all scientists who have examined this area.” (Anderson, 1996, p.1) “By disregarding the weight of professional opinion regarding the extent and history of dissolution, and by using the Holt and Powers study to claim that dissolution is ‘physically unreasonable,’ when in fact it is real and ongoing,” DOE reveals unacceptable bias. “Climate-related failure of shaft seals has important ramifications for both undisturbed and disturbed containment scenarios, and the DOE application cannot simply eliminate the problem by citing a minority opinion that dissolution is not a significant factor at the WIPP site.” (Anderson, 1996, p. 2) The work of Lowenstein (EEG-36, 1987) should be sufficient to resolve the issue. Lowenstein performed a detailed sedimentological analysis of Rustler cores from four test wells (DOE-2, WIPP-19, H-11 and H-12). This included visual examination of the cores, petrographic analyses of 52 thin sections from selected locations of the cores, and X-ray diffraction analyses of 40 samples from selected locations of the cores. Lowenstein found evidence of late-stage alteration in every member of the Rustler — in gypsum/anhydrite, mudstone, and dolomite. The alteration has involved physical processes such as brecciation, slumping, fracturing and faulting, and chemical processes such as rehydration of anhydrite to gypsum, precipitation of gypsum, and dissolution of halite, anhydrite, and gypsum. The abundance of gypsum-cemented breccias and gypsum-filled fractures that crosscut all other sedimentary features indicate that dissolution in the Rustler is a recent process. Moreover, the zones described by CARD in the Forty-Niner, Tamarisk, and lower unnamed members of the Rustler, are specifically identified as dissolution residues in the Basic Data Reports for at least twelve boreholes (ERDA-6, ERDA-9, H-1, H-6, WIPP-13, WIPP-18, WIPP-19, WIPP-21, WIPP-22, WIPP-25, WIPP-26 and WIPP-33), and for the ventilation shaft. Most of this data is republished in the CCA (Appendix BH). The Peer Review Panel is rightfully concerned that alternative hydrogeologic models which attribute spatially varying porosity and permeability in the Culebra to solution of halite within the Rustler Formation “were considered and discarded.” (CCA, Appendix PEER, p. 3-12)

In order to deny that subsurface dissolution has ever occurred in the Rustler Formation, Powers and Holt attribute all fracturing and brecciation in the Rustler to dissolution at the top of the underlying Salado Formation. Powers and Holt have confused the cause with the effect. Dissolution proceeds from the top down, due to infiltrating rainwater. Dissolution at the top of the Salado cannot occur without dissolution of the Rustler, and the more fractured and brecciated the Rustler, the more likely that dissolution will affect the top of the Salado.

Livingston Ridge does not mark “the eastern limit of significant karst development.” It is not a geomorphic divide. In fact, it is not a ridge at all, but an eastward-retreating escarpment.
marking the eastern edge of Nash Draw. There is significant karst development east of Livingston Ridge, sometimes localized, sometimes extensive, as can be seen by stereoscopic viewing of the WIPP site air photos.

22 DOE admits that WIPP-33 is not the only sinkhole east of Livingston Ridge. Phillips (1987, Chapter IV) demonstrated through structure contour maps based upon 347 auger holes that WIPP-33 is one of a chain of four sinkholes, all of which are evident in the air photos. Phillips also recorded, following a torrential rainstorm, the sudden appearance of a new arroyo which disappeared into the easternmost sinkhole. DOE considers this chain of sinkholes to be a “prong of dissolution” that extends eastward “as far as WIPP-33.” If DOE would examine its own air photos, DOE would discover that the sinkhole drilled as WIPP-33 is the westernmost in this “line of sinkholes described by CARD.” In fact, by confirming that these are sinkholes, DOE inadvertently admits that proven karst features extend 2000 feet east of the WIPP-33 borehole, to within 1000 feet of the current WIPP site boundary. It is exceedingly dangerous for DOE to assume that this is the eastern limit of karst development, that the WIPP site is a karst-free island in the midst of a regional karstland.

23 DOE, citing Powers and Holt (1995), says that “there is no indication that the Salado at the WIPP site has been thinned by dissolution,” and that “evidence for a dissolution residue at the top of the Salado is limited to the west of the WIPP site.” In the CCA (Appendix DEF, p. DEF-30), DOE states that “the edge of halite dissolution at the top of the Salado will not reach the controlled area until well after the period of regulatory concern.” Yet at least seven boreholes east of Livingston Ridge encountered dissolution residue at the top of the Salado. All seven, at the time they were drilled, were located within the WIPP site boundary. Three of them (P-12, P-14 and WIPP-33) are no longer within the WIPP site, having been gerrymandered out of the WIPP site when its boundaries were reduced. Four of them (H-3, H-6, P-6 and P-13) are within the current WIPP site boundary. Dissolution residue at the Rustler/Salado contact was also encountered in the WIPP ventilation shaft, at the heart of the WIPP site. Moreover, this dissolution residue is a water-bearing unit, commonly known as the “brine aquifer,” which is why at least seven hydrologic test wells located within the WIPP site (H-1, H-2, H-3, H-4, H-5, H-6 and H-16) have been completed to this depth. In SEIS-II, after stating that the brine aquifer “is absent under the WIPP site” (SEIS-II, 1997, p. 4-28), DOE observes that, “in Nash Draw,” it “contains the largest concentrations of dissolved solids in the WIPP area,” ranging from 41,500 mg/l in borehole H-1 to 412,000 mg/l in borehole H-5c (SEIS-II, 1997, p. 4-29). These boreholes are not in Nash Draw; they are both within the WIPP site.

**SALADO DISSOLUTION EAST OF NASH DRAW**

<table>
<thead>
<tr>
<th>hole</th>
<th>top of Salado</th>
<th>top of salt</th>
<th>dissolution residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>vent shaft</td>
<td>844.5 ft</td>
<td>845.5 ft</td>
<td>1 ft</td>
</tr>
<tr>
<td>H-3</td>
<td>821 ft</td>
<td>823 ft</td>
<td>2 ft</td>
</tr>
<tr>
<td>H-6</td>
<td>721 ft</td>
<td>723.4 ft</td>
<td>2.4 ft</td>
</tr>
<tr>
<td>P-6</td>
<td>659 ft</td>
<td>661 ft</td>
<td>2 ft</td>
</tr>
<tr>
<td>P-12</td>
<td>749 ft</td>
<td>752 ft</td>
<td>3 ft</td>
</tr>
<tr>
<td>P-13</td>
<td>721 ft</td>
<td>725 ft</td>
<td>4 ft</td>
</tr>
<tr>
<td>P-14</td>
<td>687 ft</td>
<td>695 ft</td>
<td>8 ft</td>
</tr>
<tr>
<td>WIPP-33</td>
<td>675.3 ft</td>
<td>678.0 ft</td>
<td>2.7 ft</td>
</tr>
</tbody>
</table>
DOE has always been reluctant to admit to the extent of shallow dissolution. No later than November 1981 a map was prepared by Richard P. Snyder of USGS, based upon the borehole data cited above, showing the shallow dissolution front extending eastward into the WIPP site itself. This map was stamped “OFFICIAL USE ONLY” and was withheld from the public until March 1983 when it was finally published by Sandia Labs (Borns et al., 1983, Figure A-12). In the meantime, DOE published a map which falsely depicted all of the WIPP site as being free of dissolution in the Salado (WIPP SAR, Figure 2.7-33). And even the map prepared by Snyder does not tell the whole story. Borehole H-3 is anomalous, being located nearly two miles east of the shallow dissolution front. H-3 represents an isolated pocket of Salado dissolution deep within the WIPP site, 400 feet south of the proposed waste disposal area. This implies localized recharge and vertical flow through solution conduits. It is interesting that DOE cites Dennis Powers as its authority for the statement that the Salado at the WIPP site has not been thinned by dissolution. Powers was a co-author of Borns et al. (1983), the very report in which Snyder’s map was first published.

24 It cannot be stated that “there are no examples of karstic solution channels” within the WIPP site unless and until: (1) DOE employs field techniques capable of detecting karstic solution channels up to 1000 feet below the land surface; (2) DOE covers the entire WIPP site with such technology; and (3) DOE turns WIPP-33 and WIPP-14 into hydrologic test wells and conducts multiwell pump tests in them. CARD, in its paper entitled “Cavernous Zones at the WIPP Site,” has shown ample evidence of karstic solution channels that cannot be disproven by DOE.

25 CARD does indeed conclude that WIPP-14 is a sinkhole, but not because “lost core represents dissolution zones into which there has been collapse.” WIPP-14 is probably not a collapse sink, but is more likely an alluvial doline (solution-subsidence doline), for which the Pecos River valley is well known. CARD specifically differentiates between subsidence and collapse, stating that no collapse is evident at the surface at WIPP-14. Nor is there evidence of collapse beneath the surface, which explains the “normal stratigraphic sequence” claimed by DOE. However, at WIPP-14 the Culebra is directly underlain by 71.4 feet of mud with gypsum and anhydrite fragments, interpreted by CARD as transported cave sediments into which collapse of overlying strata has not yet occurred and through which groundwater can flow almost unimpeded. 71.4 feet of mud (not mudstone -- mud) does not constitute a "normal stratigraphic sequence." Culebra dolomite was not deposited and lithified on top of 71.4 feet of mud; it was formed as a residue of salt dissolution. DOE has not offered an alternative explanation for the presence of mud beneath the Culebra, an occurrence reported nowhere else east of Nash Draw. In the CCA (Appendix DEF, p. DEF-30) DOE states that Nash Draw and the WIPP site “are separated by a transition zone which includes a prong of dissolution extending from Nash Draw towards the site of WIPP-14.” The CCA goes on to say that: “only a few small clusters of shallow dolines on the Mescalero caliche have been identified on the Los Medanos plateau east of Livingstone (sic) Ridge.” The CCA refers the reader to Figure DEF-7, which identifies “Depression Areas North of WIPP Site” at the precise location of WIPP-14. It is important to note that although the WIPP-14 drillhole is located 98 feet north of the current WIPP site boundary, the sinkhole into which WIPP-14 was drilled is 600 feet in diameter and straddles the WIPP site boundary, which constitutes direct evidence of karst at the WIPP site. In 1990, when Phillips led EPA officials on a tour of the WIPP site and vicinity, he found that the road to WIPP-14 had been barricaded.

26 Radiocarbon dates as young as 11,250 years B.P. (before present) have been reported for Mescalero caliche (Phillips, 1987, p. 67). Thus, the conclusion that Livingston Ridge assumed its present position hundreds of thousands of years ago is unsubstantiated. Livingston Ridge is an
eastward-retreating escarpment; its rate of retreat is uncertain, and it could indeed reach the WIPP site within “the regulatory time frame.” The edge of halite dissolution at the top of the Salado will not only “reach the controlled area (WIPP site) during the period of regulatory concern (10,000 years),” it has already reached the WIPP site, as shown above. DOE’s position is more explicitly stated in SEIS-II (1997, p. 4-30), where DOE contends that “dissolution at the top of the Salado at the edge of the WIPP site would not take place for some 225,000 years...” This time frame dates to a paper by Bachman (1973), as quoted in DOE’s response to Anderson (CCA Docket, A-93-02, Item # II-H-23, pp. 5-6). Bachman’s paper was written before the DOE even existed, before any of its test wells were drilled, when it was generally believed that the brine aquifer at the Rustler-Salado contact was confined to Nash Draw. DOE, in its defense of the WIPP site, is compelled to fall back upon an outdated report which preceded most data collection.

27 The issues in dispute are, indeed, the amount of recharge and its infiltration rate to the Culebra. DOE errs by one to two orders of magnitude on both related rates, adopting one which is tantamount to no recharge and infiltration at all. In its performance assessment, DOE relies upon the simplifying assumption that groundwater flow is two-dimensional, confined to the Culebra. DOE assumes that no other subsurface pathway exists above the Salado (CCA, Appendix MASS, pp. 67, 68), contrary to its own admissions that “flow in the Rustler Formation is three-dimensional and occurs to some degree in all Rustler units” (SEIS-II, p. 4-21), and that the two-dimensional model “does not properly account for vertical leakage into the Culebra” (CCA, Appendix MASS, Attachment 15-7, p. 22). DOE admits that the “confined model” is a necessary simplification for performance assessment (CCA, p. 9-18). If the assumption of confined flow was made to avoid the difficulties of three-dimensional modeling, it is a mistake. DOE has speculated about the percentage of rainwater recharge that reaches the Rustler Formation, with guesses ranging from 25% (CCA, p. MASS-69) to 30% (CCA, p. 2-128) to 66% (CCA, Appendix MASS, Attachment 15-7). DOE has never even attempted to measure infiltration rates at the WIPP site. Reliance on a chloride mass balance method is no substitute for measured data. DOE admits that, in its groundwater model, the recharge value was chosen in order to yield the desired result. DOE then claims that the model reveals the locations of the recharge areas, all of which just happen to be distant from the WIPP site. CARD, in its paper entitled “Rainwater Recharge at the WIPP Site,” has already shown that the recharge area for the Dewey Lake Redbeds and the Rustler Formation is at and near the WIPP site, everywhere that the Santa Rosa sandstone is not present. CARD will not restate its supporting evidence here.

28 Since April 1979, when the Draft Environmental Impact Statement (DEIS) was issued, DOE has proceeded on the assumption that Culebra groundwater from the WIPP site would discharge at Malaga Bend on the Pecos River. DOE now concedes that it will not. This admission invalidates the WIPP performance assessment, which charts all flow paths southward toward Malaga Bend only. Phillips (1987, Chapter VIII) showed through geochemical analysis that while groundwater from the Rustler/Salado brine aquifer discharges at Malaga Bend, the dolomite and anhydrite members of the Rustler Formation discharge at Laguna Pequena and Laguna Grande de la Sal in Nash Draw. DOE admits that the Tamarisk discharges at Laguna Grande de la Sal, but denies that the Culebra discharges there (SEIS-II, p. 16-17), seemingly unaware that the Culebra is exposed there (Vine, 1963). Phillips (1987, Chapter VIII) showed through analysis of evaporation rates that Laguna Grande de la Sal may account for ten times as much groundwater flow as do the brine springs at Malaga Bend. DOE denies this (SEIS-II, p. 4-21), citing Hunter (1985, p. 32) who thought the surface of Laguna Grande de la Sal is 660 acres, when in fact it is 2,120 acres (Robinson and Lang, 1934, Plate 4). On one occasion, Phillips (1987, Chapter VIII) measured 394 cubic feet per second (177,000 gallons per minute).
of water flowing from Laguna Pequena into Laguna Grande de la Sal. However, in 1990, when Phillips led EPA officials on a tour of the WIPP site and vicinity and attempted to show them Laguna Pequena, DOE personnel intervened and prevented him from doing so. DOE now recognizes discharge at Laguna Pequena, but still is "not clear" why groundwater from WIPP must discharge at Laguna Grande de la Sal. Such statements reflect a lack of understanding of groundwater hydrology. In Nash Draw, the lowest point of the watershed, both topographically and potentiometrically, is Laguna Grande de la Sal. Such an argument is not "entirely irrelevant with respect to compliance.” Evaporation rates suggest that nearly 600 million cubic feet per year of Rustler groundwater flows into Laguna Grande de la Sal (Phillips, 1987, Chapter VIII). If none of this water comes from the WIPP site, then DOE must propose another discharge point for Rustler groundwater, based upon field observation. In the CCA (Appendix SCR, p. SCR-29), DOE states that: “In the region around WIPP, the principal discharge areas are along Nash Draw and the Pecos River.” If groundwater from WIPP does not discharge to the Pecos River, then it must discharge to Nash Draw. If DOE cannot identify another groundwater discharge point, then EPA certification should be denied because a basic understanding of the regional groundwater hydrology is lacking. DOE must not be allowed to restrict its calculations to the WIPP site boundaries, since that permits DOE to divorce its groundwater model from reality. By ignoring Laguna Grande de la Sal, DOE underestimates by one to two orders of magnitude the amount of rainwater recharge in the Rustler groundwater system.

DOE misrepresents CARD’s presentation of groundwater flow paths. DOE observes that the geochemistry of Culebra groundwater varies markedly across the WIPP site and vicinity. "Zone A," primarily east of the WIPP site, has water with moderately high concentrations of dissolved halite. "Zone B," south of the WIPP site, has water with lower concentrations of dissolved halite than of dissolved gypsum. "Zone C," including most of the WIPP site and immediate vicinity, has water with concentrations of dissolved halite steadily decreasing from east to west. "Zone D" has water contaminated by effluent from potash refineries in Nash Draw. CARD does not believe that Culebra water flows from "Zone C" to "Zone B," as suggested in the CCA. CARD believes that the simplest explanation which accounts for observed groundwater geochemistry is that Culebra water flows from "Zone C" to "Zone D," that is, from the WIPP site to Nash Draw. So does water in the Forty-niner, Magenta, and lower unnamed members of the Rustler. CARD has never “assumed” that groundwater flow is confined to the Culebra; to the contrary, CARD has given evidence that groundwater flow in the Rustler is three-dimensional. DOE admits that Corbet and Knupp (1996) sought a “coherent explanation” of Culebra groundwater geochemistry “consistent with the flow directions presented in the CCA.” Anyone can produce a groundwater model consistent with the desired conclusion. CARD’s interpretation is consistent with field observations and all measured data. In “Zone C,” the steady decrease in concentrations of dissolved halite from east to west, from the WIPP site to Nash Draw, together with the presence of dissolved halite in test wells to the west of the WIPP site (H-6, P-14, WIPP-25 and WIPP-26), where there is no halite in the Rustler, does indeed indicate a westward component to groundwater flow. DOE makes the very same argument for “Zone A” east of WIPP, while insisting that westward flow cannot be happening in “Zone C.” Moreover, the concentrations of dissolved halite in the Culebra at P-14 (18,100 mg/l) are low enough to indicate direct rainwater recharge and a short residence time. Lambert (1983, SAND 82-01, p. 72) made the same observation. DOE generalizes that “the sites of recharge can be found in a groundwater basin model by tracing various flow paths from the WIPP site upstream to the water table.” If the model is wrong, so are the flow paths deduced from it. Such flow paths “were not identified.” (CCA, Appendix MASS, p. MASS-71). DOE cannot rely on speculation that there are three distinct areas of recharge at unknown locations distant from the WIPP site. DOE must either
accept that recharge to the Dewey Lake Redbeds and the Rustler Formation occurs at the WIPP site itself, wherever the Santa Rosa sandstone is not present, or admit that it lacks a rudimentary understanding of the regional groundwater system.

30 DOE claims that Culebra groundwater is more than 12,000 years old. Let us examine DOE’s evidence. (1) According to DOE, no tritium from nuclear testing has been detected in Culebra groundwater. DOE does not reveal which Culebra test wells have been tested for tritium; one would certainly not expect to find it where the Santa Rosa sandstone impedes infiltration. Even if every Culebra test well were tested and found not to contain tritium, this would only mean that Culebra water, at these specific locations, is at least 52 years old, and then only if it could be shown that tritium contamination from nuclear testing had actually occurred in the region. Moreover, tritium was found in WIPP test wells 15 years ago (Barrows, personal communication, May 1983). The data are not revealed by DOE. (2) Stable isotope signatures and radiocarbon dating are not reliable means for determining the age of groundwater; the reader is referred to Chapman (EEG-35, 1986) and Chapman (EEG-39, 1988). (3) DOE says that recharge rates “in excess of 12,000 years are consistent with the flow pattern predicted by the groundwater basin modeling.” A flow pattern, even if correct, reveals nothing about the age of the water. (4) DOE says that “overlying anhydrites are not thought to have been fractured by upper Salado dissolution.” DOE is referring to “Zone C,” where overlying anhydrites are commonly converted to gypsum (e.g. at P-1, P-4, P-12, P-13, P-14, P-15, H-11, H-14, H-16, H-17, H-18, WIPP-11, WIPP-12, WIPP-13, WIPP-14, WIPP-18, WIPP-19, WIPP-33, WIPP-34 and DOE-2) by solution processes due to fresh water recharge proceeding from the top down, regardless of whether dissolution has reached the underlying Salado. (5) The geochemistry in "Zone B" is not relevant. Test wells H-8 and H-9 are far from groundwater flow paths from the WIPP site to the accessible environment in Nash Draw. (6) Not all Culebra water at WIPP is saturated with respect to gypsum. The lowest reported concentrations of dissolved gypsum in the Culebra at test wells within the WIPP site vary by a factor of seven, from 1,170 mg/l at H-5 to 8,180 mg/l at H-1, as compared to 13,180 mg/l at WIPP-29 in Nash Draw. (7) Undersaturation with respect to halite can and should be attributed to short residence times (Ramey, EEG-31, 1985, p. 21). Undersaturation occurs even where halite is present above the Magenta (89,200 mg/l NaCl at P-18), where hydraulic conductivity is said to be very slow (0.0001 ft/day). Under these conditions, a residence time of far less than the 12,000 years postulated by DOE should be sufficient to achieve saturation (318,000 mg/l NaCl).

31 The evidence says that the recharge area for the Dewey Lake Redbeds and the Rustler Formation is at and near the WIPP site, everywhere that the Santa Rosa sandstone is not present. DOE claims that recharge occurs far from the WIPP site precisely because it would “not affect the model results.” The discharge area for groundwater from the WIPP site is at Laguna Pequena and Laguna Grande de la Sal in Nash Draw. It is here that plutonium contamination from WIPP would reach the accessible environment. DOE denies that anything beyond the WIPP site boundary is part of the accessible environment. The argument is that plutonium concentrations in groundwater would be diluted as it travels away from the WIPP site boundary, and therefore would be of less consequence to the victim. The flaws in this argument are: (1) Large amounts of Rustler groundwater, nearly 600 million cubic feet per year, flow into Laguna Grande de la Sal; this is more than ten times as much as DOE has acknowledged (Hunter, 1985, p. 44). DOE argued unsuccessfully for years that Laguna Grande de la Sal is an artificial lake entirely attributable to effluent discharge from potash refineries. (2) The huge volume of Laguna Grande de la Sal does not comport with the very slow recharge rates and groundwater travel times predicted by DOE. (3) Laguna Grande de la Sal has no outlet, either at the surface or
underground, and plutonium entering Laguna Grande de la Sal would concentrate in the lake sediments until (4) Laguna Grande de la Sal overflows into the Pecos River during times of major flooding, at which time actual victims downstream would be affected.

32 DOE has made no “measurements” of rainwater recharge. Campbell et al. (1996) used a chloride mass balance method, which is no substitute for measured data. The derived values (0.2 to 2.0 mm/yr), which Corbet and Knupp (1996) assumed for their equations, are too low. Precipitation at Carlsbad averages nearly 40 cm/yr. Corbet and Knupp are saying that evapotranspiration equals 99.5% to 99.95% per year, that only 0.05% to 0.5% of annual precipitation ever reaches the Rustler Formation. This cannot account for the nearly 600 million cubic feet per year of naturally occurring groundwater flowing into Laguna Grande de la Sal. Hunter (1985) concluded from a literature review that evapotranspiration is 96% in the vicinity of WIPP. Her calculation of 98% to 99.5% (Hunter, 1985, SAND84-2233, p. 44), cited by DOE, was erroneous, based upon a severe underestimate of evaporation from Laguna Grande de la Sal, and an unwarranted assumption that the discharge to the Pecos River at Malaga Bend comes from the Rustler Formation. Phillips (1987, Chapter VIII) calculated an evapotranspiration rate of 95%, based upon water balance equations for which all other variables are well known. A recharge rate of 20 mm/yr is necessary to account for the discharge to Laguna Grande de la Sal.

33 The claim that Corbet and Knupp (1996) have bounded the hydrologic effects of karst, potash mining, and climatic change, simply by analyzing the effects of a three order of magnitude increase in hydraulic conductivity (applied randomly) in the Culebra dolomite was made by an EPA scientist in Albuquerque, New Mexico in January 1997. DOE made a similar claim in SEIS-II (1997, p. H-99). In view of evidence that the Rustler is integrated by dissolution features, this treatment of future effects is unduly restrictive. DOE acknowledges that early interest in the effects of climatic change on the WIPP site “focused on the possibility that wetter climates might increase the rates of salt dissolution. … Questions have also been raised about whether dissolution or precipitation of fracture fillings in the Culebra could occur during climatic changes and alter the rate of radionuclide transport in groundwater.” (CCA, Appendix MASS, pp. 99, 100) In fact, Anderson (1996) and Phillips (1997) are still interested in these points. In DOE’s performance assessment, however, the climate change model is implemented through the use of a single parameter, an increase in hydraulic conductivity in the Culebra dolomite, because EPA criteria erroneously allows DOE to do so.

34 DOE admits that the hydrologic conditions of a full-glacial maximum were not incorporated into its computer simulations. Corbet and Knupp (1996) began their simulations at 14,000 years before present, “when there was a clear decline in the annual precipitation rate.” This is not the same as the full-glacial conditions of 18,000 years before present, when the precipitation rate was higher and the evaporation rate was lower. DOE states that Swift (1992), reproduced as Appendix CLI in the CCA, “forms the basis for the DOE’s present understanding of climatic change.” (CCA, Appendix MASS, p. MASS-100) Swift clearly states that the precipitation rate during the late-Pleistocene full-glacial climate should be the conservative upper limit for DOE’s groundwater model for the next 10,000 years (p. 11, 19), even though he believes a return to full-glacial conditions to be “highly unlikely” (p. 22). DOE states in the CCA (Appendix MASS, pp. 99, 100) that climate change during the next 10,000 years “should be bounded by the extremes of the late Pleistocene glaciation.” It is unfortunate that DOE disregards its own advice. Phillips (1987, Chapter IX), citing future decreases in incoming solar radiation due to predictable changes in the tilt of the earth’s axis, disagrees that a return to full-glacial conditions is highly unlikely, but otherwise agrees with Swift. If such conditions are plausible within the next 10,000 years,
they should be modeled by DOE. Placing the water table at the land surface does not suffice because, as explained above, the water table was not at the land surface during the Pleistocene, as proven by the continued existence of Mescalero caliche.

35 It is not sufficient that Corbet and Knupp (1996) considered the "cyclical nature" of climatic change during the Holocene - that is, since the Ice Age. The issue is that full-glacial conditions, cyclical or otherwise, have never been incorporated into DOE groundwater models.

36 DOE explains that, in its performance assessment (PA), it has "screened out" surface waters, including Laguna Grande de la Sal and the Pecos River, "on the basis of low consequence." DOE cites Appendix SCR, Section SCR.1.5.4., which screens out river flooding and lake formation because the WIPP site itself will not be flooded. That is not the issue. The problem is that Laguna Grande de la Sal, the discharge point for contaminated water from the WIPP site, will overflow into the Pecos River during glacial conditions, as it has during major flooding events of this century. The Pecos River is where the people live. Contaminated surface water is of the highest consequence to them, now and in the foreseeable future.

37 Regarding water quality and quantity in the Dewey Lake Redbeds, it is not true that CARD merely "repeats the documentation given in Appendix USDW of the CCA." Only two WIPP test wells (H-4c and WQSP-6a) are listed by DOE in Table USDW-4. Reports of water in the Dewey Lake Redbeds at eleven other WIPP test wells were collected by CARD from a variety of sources and presented in Table 2 of its paper entitled "Rainwater Recharge at the WIPP Site." DOE's failure to present this data to EPA is an indication that geologic evidence has been used selectively. None of the data on the Dewey Lake Redbeds was included in the Draft CCA. It was at the insistence of the EEG that DOE divulged the information (EEG-61, 1996, p. 2-6). Moreover, the neutron logs and caliper logs for H-1, H-2 and H-3, the hydrologic test wells closest to the center of the WIPP site, have never been published at all; CARD obtained them from the USGS. DOE still claims that the Dewey Lake Redbeds have "not produced water within the WIPP shafts or in boreholes in the immediate vicinity of the panels." (CCA, p. 2-131). To the contrary, EEG has reported that the Dewey Lake Redbeds produce water in the WIPP exhaust shaft at a depth of approximately 100 feet below land surface (CCA Docket, A-93-02, Item # II-E-36). The Dewey Lake produced water in the WIPP air intake shaft as well (EEG-61, 1996, p. 2-6). The Dewey Lake has also produced water in test wells H-1, H-2, H-3 and WQSP-6, all in the immediate vicinity of the waste panels. EEG believes that the CCA should be modified to include the Dewey Lake Redbeds as a potential pathway for release of radionuclides because they contain significant quantities of potable water (CCA Docket, A-93-02, Item # II-E-36). In addition, CARD points out that Culebra water is potable in test well H-2b, located only 0.7 miles west of the center of the WIPP site, within the Land Withdrawal Area (LWA), 0.25 miles from the proposed waste disposal area. Perhaps DOE should calculate the dose to a victim drinking water from this well after institutional control of the WIPP site is lost.

38 When analyzing groundwater flow in a karst terrain, using the highest measured values of transmissivity is both realistic and conservative. It is realistic because the highest measured values are real; they represent the ability of the rocks to transmit water along discrete, localized flow paths at a rate which is orders of magnitude higher than elsewhere in the drainage basin. It is conservative because these are the paths of least resistance, the actual effective groundwater flow paths: to be sure, groundwater flow through karstic solution channels is the worst-case scenario, but this is inevitable, and it is precisely what a conservative person must analyze. Within one mile of the WIPP site, Culebra transmissivities vary by five orders of magnitude.
Corbet and Knupp (1996), by “using the geometric mean of measured values,” have averaged the test values and eliminated karst conditions from consideration.

39 In order to discount the existence of karst conditions at the WIPP site, DOE attributes “fracturing and disruption of Rustler strata” to dissolution of underlying Salado salt. No such correlation has been demonstrated. Each foot of dissolution residue at the top of the Salado represents perhaps 10 to 20 feet of missing salt. At P-14 there is 8.0 feet of dissolution residue at the top of the Salado, and no cavernous zones were reported in the Rustler. At WIPP-33 there is only 2.7 feet of dissolution residue at the top of the Salado, and there are four nested caverns totaling 22.5 feet within a 50.5-foot section of the Rustler. Two of these caverns are in the Magenta, totaling 7.0 feet within a 19.0-foot section of dolomite. Elsewhere the Magenta ranges in thickness from 19 ft (at H-6) to 28 ft (at H-2), but at WIPP-33 only 12.0 feet of Magenta dolomite remains. The missing dolomite is due to dissolution and removal by groundwater; it cannot be attributed to dissolution of Salado salt 209 feet below the Magenta. Within the WIPP site are four drillholes (H-3, H-6, P-6 and P-13) where 2 to 4 feet of dissolution residue was found at the top of the Salado. DOE’s response is to deny its own Basic Data Reports by insisting that there has been no dissolution of Salado salt at the WIPP site. Corbet and Knupp (1996) may have “clearly described” their “mapping of the boundaries marking the extent of these processes,” but their "boundaries" are wrong.

40 DOE concedes that its technique of dividing the WIPP site into model “cells” of four square kilometers (1000 acres each) means that “local-scale variations” are not “represented.” These would include zones of high transmissivity attributable to karst conduits. This “limitation” cannot be “offset” by emphasizing “larger-scale features,” which only compounds the distortion caused by ignoring smaller-scale, but dominant, dissolution features. Nor can this “limitation” be “offset” by emphasizing aspects of groundwater systems that are “less sensitive” to “local-scale variations;” this completely ignores the transport implications of karst.

41 CARD must reiterate its statement that Corbet and Knupp’s assumed value of 0.28 ft/day for hydraulic conductivity in the Dewey Lake Redbeds is pure speculation. It is not based on measured data. DOE admits that it is “based on literature data for similar rock types.” DOE claims that “use of the highest measured conductivities” would be “unrealistic.” To disregard the highest measurements of hydraulic conductivity is to throw out the evidence for karst, and to ignore the significance of maximum values observed in channel flow.

42 CARD did not say that the Santa Rosa sandstone has sufficiently small conductivity to “block” recharge. CARD stated, based on the mapping of actual measured data, that (where it is present) “the Santa Rosa sandstone retards, but does not prevent, rainwater recharge to the underlying Dewey Lake Redbeds.”

43 DOE characterizes Culebra transmissivity as varying “significantly” across the WIPP site. More precisely, it varies by nearly three orders of magnitude, from 0.1 ft²/day at P-15 to 88.0 ft²/day at H-6. Within one mile of the WIPP site, Culebra transmissivity varies by more than five orders of magnitude, from 0.003 ft²/day at P-18 to 324 ft²/day at P-14. DOE claims to “capture the uncertainty associated with the spatial variability of the available data” through the use of a “stochastic model.” The word “stochastic” is defined as “involving or containing a random variable.” Indeed, DOE’s model assumes “that the spatial variation is random.” It is not random. It is spatially dependent. The anomalously high measured transmissivities have distinct directional orientation in the northwestern and southeastern portions of the WIPP site; these
represent preferential flow paths for groundwater and should be treated as such. They are linked, highly correlated. The Peer Review Panel made the same objection, noting that “some localities have implied high permeabilities over distances of several kilometers.” These are hypothesized to be “interconnected fracture zones.” They are “too large in magnitude to be explained by variation in sample interval” in the Culebra; they have distinct spatial orientation; and they “have not been clearly associated with a conceptual model of the geology of the dolomite or of the Rustler Formation as a whole.” (CCA, Appendix PEER, p. 3-8) “All hypotheses failed to correlate the detailed hydrogeology of the Culebra with its tested hydrologic character.” (CCA, Appendix PEER, p. 3-12). The DOE “agrees with this assessment.” (CCA, p. 9-18) The Peer Review Panel concluded that DOE’s “single and multiwell and tracer testing in the Culebra are an attempt to characterize the hydrology of the Culebra ... by numerical modeling alone.” (CCA, Appendix PEER, p. 3-11). Having failed to propose a conceptual model that accounts for all the observed data and satisfies the Peer Review Panel, DOE relies instead upon a method more applicable to a sand and gravel aquifer, treating the data as random variables. It is interesting to note the other definitions of the word “stochastic.” The word also means “characterized by conjecture,” or “involving chance or probability.” It is derived from the Greek word stokhazesthai, meaning “to guess at.”

44 DOE takes the position is that it does not matter how transmissive the Culebra is to groundwater, because any radionuclides in Culebra groundwater would be sufficiently retarded that there would be “no releases to the accessible environment.” Unless and until the DOE demonstrates matrix diffusion, and performs sorbing tracer tests in the field within solution-enhanced conduits, this statement is without foundation.

45 CARD, in its paper entitled “Potential Flow Paths from the WIPP Site to the Accessible Environment,” presents Table 2, “Comparison of Fresh Water Hydraulic Heads,” for the benefit of the reader. To our knowledge, DOE has never compiled all of it in one table. The “point” that CARD makes with this table is that the data set is incomplete.

46 The groundwater flow directions modeled by DOE are not consistent with the observed Culebra heads. The DOE deduces a southerly flow path from the WIPP site, bypassing Nash Draw altogether. This is impossible, for it would require that Culebra groundwater flow up the hydraulic gradient from H-17 to H-12, (2995 ft to 2998 ft), and from H-9 to H-8 (2975 ft to 2991 ft). Moreover, the multiwell pump test centered in the Culebra at H-11 revealed no hydraulic connection between H-17 and H-12 (Beauheim, 1989, p. 79).

47 Both CARD and EEG have observed that hydraulic heads for the Culebra and Magenta are equal at H-6 and WIPP-25. At these locations the Culebra and Magenta are not hydrologically isolated from each other, and the Rustler is one complex aquifer with five members. Whether this is also true at WIPP-13 is not known for certain because of insufficient data. However, the Culebra head at WIPP-13 (3064 ft) is higher than at H-6 (3057 ft) and WIPP-25 (3054 ft), and it is predicted that if the DOE would conduct the necessary testing at WIPP-13, it would be found that the Culebra and Magenta heads are equal there as well.

48 We have already noted that potential victims beyond the WIPP site boundary have been discounted by DOE. As for the two-dimensional model of the Culebra, the equal heads for the Culebra and Magenta at H-6, located within the WIPP site boundary, disprove “the validity of the assumptions.” Demonstrably, the Culebra is not a confined aquifer at H-6.
DOE's failure to characterize fractures in the Culebra through slant-coring or any other method enables DOE to attribute fracturing in the Culebra to dissolution in the underlying Salado, which is inconsistent with the claim that no dissolution has ever occurred at the WIPP site. The Peer Review Panel stated that fracture distribution, aperture, and orientation have not been sufficiently characterized to make possible any correlation between hydraulic properties and geologic features. Such characterization would require slant-coring and three-dimensional modeling (CCA, Appendix PEER, p. 3-9). To be sure, slant coring would be expensive, but not compared to the $2 billion which DOE has spent already. This is not a new suggestion. Gibbons and Ferrall, then under contract to Sandia Labs, proposed a slant-coring program in 1980; DOE declined to publish their proposal.

DOE does not address the issue. The Culebra should not be modeled as a porous, homogeneous medium. Karstic rocks have dual porosity, and groundwater flow in karst cannot be approximated by modeling flow through a single-porosity medium. Moreover, it is disingenuous for DOE to deny that there are "significant (i.e., large-scale)" features with higher transmissivities than those measured in boreholes. The problem is that there are small-scale features with higher transmissivities. They are called "sinkholes" and "solution channels," none of which have been tested.

DOE does not address the issue. The fracture model, of very limited use without fracture data, should not assume isotropic flow. DOE concedes that "Culebra transmissivity is controlled by the abundance of open fractures," but does not take into account that some of these open fractures have been enlarged by solution and are now karst conduits. DOE confuses the issue by presenting the false choice of modeling the Culebra as having randomly-variable transmissivity or randomly-oriented fractures. Neither one is random. The zones of anomalously high transmissivity have preferred direction according to the orientation of solution-enlarged fractures, and they provide linked pathways for groundwater flow, bypassing the rock matrix.

DOE relies on a two-dimensional model which treats the Culebra as a confined aquifer and completely ignores the other four members of the Rustler -- even the Magenta dolomite, long recognized as an important water-bearing unit. DOE claims that "all of the outward flow" from the WIPP site is "by lateral flow along the Culebra." The hydraulic heads at H-6, where the Culebra and Magenta heads are equal, and the water-filled caverns at nearby WIPP-33, two of which were found in the Magenta, are sufficient evidence to negate DOE's model. DOE's neglect of the Magenta dolomite as a potential pathway is based on a number of claims, all of which are erroneous or unsubstantiated. DOE did claim that the Magenta "is unfractured at WIPP" (CCA, p. 2-98). This claim was later modified to read that "the Magenta is a porous medium with no hydraulically significant fractures" at the WIPP site (CCA, p. 6-147). The Peer Review Panel was unconvinced, and stated that: "The principal hydrogeologic difference between the Culebra and Magenta is purported to be the absence of hydrologically active fractures in the Magenta. This assertion is based on two slug tests and very limited field observation in shaft excavations." DOE, in response, stated that: "The only location on the WIPP site at which open fractures have been observed in the Magenta is WIPP-13." (CCA, p. 9-29) We draw attention to WIPP-19, where open high-angle fractures were found in Magenta core (SAND 79-7110, p. 15), and to the WIPP ventilation shaft, where eleven fractures in the Magenta, all of them vertical to subvertical, all of them open, were observed and mapped (TME 3177, Figure 2). Groundwater seepage from the Magenta was reported to produce enough water to wet the shaft wall for about 20 feet below the Magenta (TME 3177, pp. 1-2, 4-4, 5-3). DOE correctly stated that the highest Magenta transmissivity measured at the WIPP site was 0.3 ft²/day (at H-6) (CCA, p. 9-29).
However, Magenta transmissivities were derived from single-well tests rather than multiwell pump tests which, in the Culebra, have found transmissivities in some wells to be an order of magnitude higher than previously thought (LaVenue et al., 1988, Table C.1). DOE also stated that there are no regions of high transmissivity due to fractures and that all flow in the Magenta is matrix flow. The Peer Review Panel called these conclusions "weak," due to "a very limited observational and testing database" (CCA, Appendix PEER, p. 3-55) which does not include, for example, WIPP-13 or WIPP-33. A similar statement was made in SEIS-II, where DOE claimed that: "The Magenta does not have hydraulically significant fractures in the vicinity of WIPP." (SEIS-II, 1997, p. 4-27). However, the Magenta does have two hydraulically significant caverns at WIPP-33, 0.5 miles west of the current WIPP site boundary. DOE twice stated to the Peer Review Panel that at four locations (DOE-2, H-3, H-6 and H-19), "the Culebra has been found to be fractured and have a high transmissibility, whereas the Magenta has not." (CCA, pp. 9-29, 9-30). CARD is unaware of any published lithological descriptions for the Magenta at any of these four test wells, except for one paragraph describing the Magenta at H-6 as: "Dolomite, light-olive gray to olive-gray, silty; some gypsum." (USGS WR 79-98, p. 4). DOE admits that "transmissivities of the Magenta" are "based on sparse data." (SEIS-II, p. 4-27). This is well illustrated by DOE's map of hydraulic heads in the Magenta, which contains almost as many contour lines as data points (CCA, p. 2-129). DOE, in its response to CARD's comments, states that Corbet (1995, Appendix MASS, Attachment 15-7) "carried out an analysis specifically to ensure that the two-dimensional model is adequate" for performance assessment. In this memo, Corbet states that "all of the vertical leakage between the Magenta and the Culebra in the controlled area is directed downward," and that "zero percent of the flow out of the Culebra is by vertical leakage across its upper surface." Corbet further states that: "These results are supported by field observations of fresh-water heads in the Magenta and the Culebra." (CCA, Appendix MASS, Attachment 15-7, p. 21). Corbet overlooks test well H-6, within the controlled area, where the Culebra and Magenta fresh-water heads are equal. In his next sentence Corbet hedges, stating that: "In areas in which the Tamarisk is intact, observed fresh-water heads are higher in the Magenta than in the Culebra." (CCA, Appendix MASS, Attachment 15-7, p. 21) This would seem to exclude WIPP-13 where, according to the published lithologic log, the Magenta dolomite is "broken and shattered by numerous fractures dipping 60°-80° and displacing bedding planes 0.5-1.0 cm," and the Tamarisk member includes gypsum/mudstone breccia and steeply-dipping fractures, one of them filled only with silt. Corbet concedes that "fluid pressures and densities in the strata between the Magenta and Culebra are not known." (CCA, Appendix MASS, Attachment 15-7, p. 21) Yet DOE told the Peer Review Panel that "the Culebra is under pressured with respect to the Magenta and Dewey Lake. Therefore, any cross flow between the units will occur from the Magenta and Dewey Lake to the Culebra." (CCA, p. 9-30) Corbet concludes that "all flow out of the Culebra in the controlled area is by lateral flow," and that "a two-dimensional model is able to represent realistic release paths." This, says Corbet, "is perhaps the most important point to be considered in evaluating the applicability of the two-dimensional model and the strongest argument in its favor." (CCA, Appendix MASS, Attachment 15-7, pp. 21-22). But there are parties within DOE who know that this argument is not true. In SEIS-II, "DOE concluded that flow between the Forty-Niner and Magenta would be upward in H-3, H-14, and H-16, three boreholes which yielded reliable pressure data for the Forty-Niner. This conclusion is not consistent with the results of groundwater modeling, and this inconsistency may be the result of local heterogeneity in rock properties that affect flow on a scale that cannot be duplicated in regional modeling." (SEIS-II, 1997, p. 4-27) On the other hand, this conclusion is consistent with one of the karstic groundwater flow paths described by Phillips and Snow in CARD's paper entitled: "Potential Flow Paths from the WIPP Site to the Accessible Environment." CARD notes that flow between the Forty-Niner and Magenta would also be
upward at DOE-2. In the CCA, the DOE tries to rationalize the Magenta flow path, which is predominantly westward from WIPP-13 to H-6 to WIPP-33 to WIPP-25, by saying that "flow in shallower units (than the Culebra) is expected to be more sensitive to local topography." (CCA, p. 2-128) This argument does not bear scrutiny. At WIPP-13 the Magenta is 564 feet below the surface and only 118 feet above the Culebra. At H-6 the Magenta is 490 feet below the surface and only 90 feet above the Culebra. At WIPP-33 the Magenta, or what is left of the Magenta, is 449 feet below the surface and only 82 feet above the Culebra. The difference in flow directions between the Culebra and Magenta has nothing to do with topography; it has everything to do with karst. The Peer Review Panel concluded that DOE's "assumption" that the Dewey Lake Redbeds and Magenta dolomite" are not flowpaths "is not well supported. ... If the need to assess transport in the Magenta and Dewey Lake were shown to exist, the small hydrologic testing data base and the existing conceptual model would not be adequate to such an assessment." (CCA, Appendix PEER, p. 3-57) CARD contends that the need to model all members of the Rustler as one complex three-dimensional aquifer is shown to exist. DOE has ignored the advice of the Peer Review Panel, as it has with so many others.

53 DOE concedes that "CARD is correct in stating that matrix diffusion becomes less important as fracture apertures widen and groundwater flow rates consequently increase." DOE then claims that "double-porosity groundwater transport models account for this effect." Unfortunately, DOE's model is unrealistic, because its assumed dual porosity involves fracture flow and matrix diffusion, and does not incorporate enhanced conductivity through solution-enlarged channels. More appropriate models do exist. In Jones et al., (1992, SAND 92-1579, pp. 3-9, 3-10, 12-19), there is a discussion, with references to published literature, of a "variable-aperture channel model," where the bulk of groundwater flow occurs in "preferred flow paths" or "channels." It is stated that this model fits the breakthrough curves yielded by the converging-flow tracer tests performed at the H-3, H-6 and H-11 hydropads, but channel-model interpretation approaches were not attempted by DOE. The model preferred by DOE starts with the measured porosities of the Culebra dolomite (which vary by an order of magnitude, from 3% to 30%) (CCA, p. 2-119), and averages this to 16%. Of this "average effective porosity," DOE assumes that fracture flow is represented by 1% porosity and matrix diffusion is represented by 15% porosity (CCA, Appendix PEER, p. 3-59), that matrix diffusion is much more effective than fracture flow. It would follow that retardation of radionuclides by matrix diffusion would be effective. These assumptions are not based upon empirical field data. DOE states that fracture porosity "is thought to be a small percentage of the total volume of the Culebra involved in transport" (CCA, Appendix MASS, p. MASS-80). These values for fracture porosity and matrix porosity are assumed to be constant throughout the WIPP site and vicinity. Never does DOE consider groundwater movement and radionuclide transport through karst channels. Franklin et al. (1981, p. 57), under contract to the NRC, warned against the siting of nuclear facilities in karst terrains. They stated that "flow velocities are often orders of magnitude greater in karst," and that "filtration, which acts in porous media to remove many contaminants from the water, is virtually absent in the karst environment." In the vicinity of WIPP there are large underground caverns, filled with flowing water, at WIPP-33, H-7, and surely elsewhere. Under such conditions, the conservative assumption is that Kd approaches zero, that most radionuclides will travel at the speed of water. Sandia Labs (SEIS-II, Appendix H, p. H-103), the EEG (Chaturvedi and Channell, EEG-32, 1985) and the EPA (SEIS-II, p. H-103) have all calculated that if there is no matrix diffusion, the WIPP will violate EPA standards for groundwater contamination. The Peer Review Panel is concerned that "zones of relatively rapid fracture flow, without significant retardation of radionuclides by physical or geochemical processes, could cause accelerated transport in the Culebra." (CCA,
Appendix PEER, p. 3-13) EEG does not believe that sufficient evidence exists to prove that matrix diffusion will be effective (EEG-61, 1996). Until effective matrix diffusion is demonstrated, and Kd values are measured by the performance of sorbing tracer tests in the field, WIPP should not be licensed.

54 DOE admits that its model for Culebra groundwater transport “does not account for dissolution and consequent widening of fracture apertures” during the next 10,000 years, but this is not CARD’s primary concern. Enlargement of fractures into solution channels at the WIPP site has already occurred. The WIPP site is in karst already, and karst will become more and more developed over time. DOE’s model should account for this not only in the future, but now.

55 It has not been said that “solution collapse” has occurred at the center of the WIPP site. One would expect not to find it in the WIPP exhaust shaft. However, one should not infer from this that there is no relationship between fracturing and dissolution anywhere else within the 10,240-acre WIPP site, especially in areas west of the repository.

56 DOE says that Culebra groundwater is saturated with respect to gypsum. DOE made this statement in response to EPA’s concerns about the potential for dissolution of gypsum fillings in fractures in the Culebra dolomite. DOE convinced EPA that “dissolution processes are not presently occurring the the Rustler” (EPA Docket, A-93-02, Item # III-B-3, p. 38) and that “conditions are not expected to change during the regulatory period,” that is, in the next 10,000 years (EPA Docket, A-93-02, Item # III-B-3, p. 82). DOE’s argument is that infiltrating waters that would cause the dissolution would become saturated with respect to calcium sulfate and therefore would be unable to dissolve anhydrite or gypsum (EPA Docket, A-93-02, Item # III-B-3, pp. 48, 83, 91). As supporting evidence, DOE calculates a gypsum saturation index for Magenta groundwater at test well H-4 (Corbet et al. to Chu, January 16, 1997, p. 10, Attachment to CCA Docket, A-93-02, Item # II-H-23), where measurements of dissolved calcium and sulfate are higher in the Magenta (7210 mg/l to 7760 mg/l) than in the Culebra (4180 mg/l to 7000 mg/l). The truth is that infiltrating rainwater will not be saturated with respect to gypsum until it has dissolved enough gypsum to become saturated. Presently, some Rustler groundwater is saturated with respect to gypsum, and some is not; concentrations of dissolved calcium and sulfate vary not only from well to well, but also from time to time. At test well H-5, measured concentrations of dissolved gypsum in Culebra waters range from 1170 mg/l to 9600 mg/l, varying by a factor of 8.2X. At H-4, the range is 4180 mg/l to 7000 mg/l (1.67X). Along the southeastern flow path, the range is 5800 mg/l to 7200 mg/l (1.24X) at H-3, 7260 mg/l to 9200 mg/l (1.27X) at DOE-1, 7400 mg/l to 8900 mg/l (1.20X) at H-11, and 6520 mg/l to 8900 mg/l (1.37X) at P-17. Along the entire flow path, dissolution of gypsum fillings in Culebra fractures is presently occurring. Anderson (1994, p. 5) has also observed that Culebra groundwater in this area of high transmissivity “is relatively fresh and unsaturated for gypsum,” and that “gypsum cement has been removed by dissolution.” In addition, measured amounts of dissolved calcium and sulfate in Magenta waters ranges from 2700 mg/l to 4600 mg/l (1.70X) at H-3 (Ramey, EEG-31, 1985, pp. 52-60; Chapman, EEG-39, 1988, pp. 50-58; Lappin et al., 1989, SAND89-0462, Table 3.12). Fracture apertures will increase and matrix diffusion will decrease over time, and the rates of these changes will be accelerated during glacial conditions. DOE’s failure to characterize and evaluate the potentially rapid dissolution of gypsum and salt is a flaw in its groundwater model.

57 The examples of Kd values (distribution coefficients) given by CARD are for Pu-239, and are taken from the Geologic Characterization Report (CCA, Appendix GCR), as cited in CARD’s paper. The Kd values clearly demonstrate why DOE prefers measurements made upon crushed
powder (7300) to measurements made upon solid rock (19); there is almost a 40-fold difference between the two values. Moreover, the laboratory experiments were made in water which was not representative of Culebra groundwater geochemistry. CARD did say that the surface area per volume of rock is much greater for crushed powder than for fractured or karstic rocks, and thus the laboratory measurements are not representative of actual conditions. The Peer Review Panel made a similar observation (CCA, Appendix PEER, p. 3-62). CARD did not ask that DOE "attempt to scale the data." The only way to obtain reliable distribution coefficients is to perform sorbing tracer tests in the field. DOE complains that such testing would be costly and difficult, but CARD finds these to be unconvincing excuses, considering the opportunities lost during decades of study of WIPP hydrology. As recently as 1996 the EEG made the same objections to DOE's distribution coefficients (EEG-61, March 1996, pp. 6-8, 6-9; Neill to Salisbury, June 10, 1996). Even if EEG has abandoned this position, CARD has not done so. DOE has recently performed tracer tests at the H-19 hydropad, but the results of these tests are unpublished, unavailable to the public or to the Peer Review Panel (CCA, Appendix PEER, p. 3-60).

CARD is not "mistaken." As recently as November 1996, when the Draft SEIS-II was issued, DOE "anticipated that, in the final compliance certification application, clay fracture linings will be assumed and credit will be taken for some degree of chemical retardation." (Draft SEIS-II, 1996, p. H-86) EEG called this "a mechanism which may not exist." (EEG-61, 1996, pp. 6-12, 6-13) In fact, as CARD stated, DOE's adsorption studies were performed not upon fractures in the Culebra, which contain only small amounts of clay, but upon corrensite clay taken from a black shale layer in the lower unnamed member of the Rustler.

In closing, CARD wishes to pay tribute to Roger Anderson. He is the disinterested patriarch, the man who has investigated the WIPP site and vicinity longer than anyone else, and his words should carry weight:

"A disturbing conclusion is that DOE has selectively presented evidence in support of the application and disregarded evidence which is highly relevant to containment and performance. In so doing, DOE has greatly complicated the task of evaluating the suitability of the site. The non-objective character of the document means that EPA cannot accept even supported conclusions without further investigations." (EPA Docket, A-93-02, Item # II-H-03, p. 6)
Dear Mr. Weinstock,

The Citizens for Alternatives to Radioactive Dumping (CARD) submitted undated comments to the Environmental Protection Agency (EPA) on the Department of Energy (DOE) Compliance Certification Application (CCA). The comments made by CARD consist of nine position papers, and EPA marked these comments as "late" when placing them into the docket. The DOE has elected to respond to the first seven of these position papers (the eighth paper dealt with concerns about waste disposal operations at Los Alamos National Laboratory, and the ninth paper dealt with human errors; both issues unrelated to DOE's CCA).

The DOE believes that the enclosed responses will help EPA as it begins drafting the proposed rule to certify the Waste Isolation Pilot Plant. If you have any questions about these responses, please contact me at (505) 234-7300.

Sincerely,

George E. Dials
Manager

Enclosure

cc: Mary Kruger
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Text of Comment

Containment

It is clear that radionuclide releases from WIPP to the accessible environment in excess of the limitations of 40 CFR 191 can occur only if three factors are met:
1. A sufficient fraction of the actinide inventory must be mobilized in dissolved or colloidal form.
2. The engineered containment within and adjacent to the repository must be breached and capable of discharging brine, and
3. The intervening geologic environment and man-made features within it facilitate effective transport to the compliance boundary.

As long as poor definition characterizes the nature of the waste (such as the amount, size distribution and solubility of plutonium particles) and other parameters are ill-defined, such as the amount of reacting brine and numerous other components still being investigated in the actinide source term (AST) project, DoE cannot eliminate the first factor unequivocally. The CCA relies heavily on elimination of factors 2. and 3. Among the various claims being disputed by interveners to this application, the writer addresses some limited but vital subjects related to failure of seals and engineered barriers, discharge from the undisturbed and disturbed repository via paths to the surface or to Rustler aquifers caused by hydrofracturing around borehole seals or shafts or through the overburden strata. Secondly, groundwater flow and transport incident to concentrated discharge in fractures and dissolution conduits of the Rustler and younger formations is discussed, suggesting that those barriers are compromised.

DOE Response

Results from the performance assessment modeling shows that the behavior of the undisturbed disposal system will result in extremely effective isolation of the radioactive waste. Concrete, clay, and asphalt components of the shaft seal system will provide an immediate and effective barrier to fluid flow through the shafts, and will isolate the repository until salt creep has consolidated the compacted crushed salt components that will permanently seal the shafts. The disturbed rock zone around both the shafts and the repository excavations will heal over time, and will not provide a ready pathway for fluid flow. Brine flowing out of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species. The quantity of actinides that may reach the accessible environment during undisturbed performance transported through the interbeds is six orders of magnitude
below the EPA limits for compliance demonstration. The performance assessment results show that for undisturbed scenarios no migration of radionuclides occurs vertically to the top of the Salado Formation through the shaft seal system.

The factors controlling the aqueous actinide concentrations discussed in Chapter 6, Section 6.3.4.5 states:

"The solubility of the actinides as a function of equilibrium between anhydrite, halite, MgO, and brine is calculated outside of the performance assessment using FMT, a computer code for calculating actinide concentration limits based on thermodynamic parameters. The parameters for FMT are derived both from experimental investigations specifically designed to provide parameter values for this model and from the published literature. FMT and its application are described in Appendix SOTERM (Section SOTERM.3.5). Table 6-11 presents a summary of solubility parameter values for each actinide oxidation state consistent with the assumptions regarding chemical conditions stated in this section and in Section 6.4.3.4. These values are documented in Table 6-11 and in Appendix PAR (Parameters 36 through 45 and Table PAR-39). Details of the generation of Table 6-11 are given in Appendix SOTERM (Section SOTERM.3).

Actinide concentration may not be equal to the values sampled in LHS. This condition could arise when there are not sufficient actinides in the solid phase in a particular cell, when combined with the dissolved actinides that may have been transported into that cell from an adjacent cell, to achieve the concentration value as determined by LHS sampling. This situation is referred to as inventory limited.

The actinide inventory is depleted on a cell-by-cell basis by the computer code NUTS (NUclide Transport Systems) for the undisturbed, E1, and E2 scenarios. The treatment of the E1E2 scenario is described in Section 6.4.13.5. In a computational cell, the processes affecting actinide dissolved concentration are dissolution of solid actinide compounds, advection of dissolved actinides by brine flow from neighboring cells and interaction with colloidal particles (see Section 6.4.3.6). NUTS dissolves each actinide until the maximum concentration determined by the actinide source term algorithms is obtained or an inventory limit is reached. In the repository, the transfer of actinides between solid phase and solution is tracked to preserve mass balance of the actinide inventory. Outside the repository, the model does not precipitate actinides into the solid phase, thereby giving a conservative measure of mobile actinide quantities (see Appendix SCR, Section SCR.2.5.3.2)."
Performance assessment did not suggest that the barriers of the Rustler and younger formations are compromised by groundwater flow and transport incident to concentrated discharge in fractures and dissolution conduits. The shaft seal system includes engineered materials possessing high density and low permeability. Components of the seal system within the Salado provide the primary barrier by limiting fluid transport along the shaft during the regulatory period. Components of the seal system within the Rustler limit commingling of groundwater between water-bearing members. Components of the seal system overlying the Rustler fill the shaft with common materials of high density, consistent with good engineering practices.
Shaft Seals

The intended hydraulic function of shaft seals (CCA 3.3.1.2) is to "restrict groundwater flow" and "limit radionuclides," not to eliminate them. There is neither a proven, field-tested technology of sealing (especially in salt), nor an irrefutable conceptual design to assure us that those objectives will be met. Shaft seals in mining applications have histories of such frequent failures as to make a prudent engineer treat the proposed seals with cautious skepticism, even if their design is apparently good, innovative, well-studied and reviewed.

I examine, first, the mechanical behavior of some seal components in relation to each other, during the period of shaft closure before significant repository air pressures are imposed. I examine, second, the propensity for seal failure by pneumatic hydrofracture, a potential mechanism for development of a conduit for concentrated, rapid egress of air and brine, contaminated or otherwise, from the repository to the Rustler aquifers or the surface. It is evident that the seal designers may have given insufficient credence to the hydrofracture mechanism along the seals, or into the strata above the repository, competing avenues for release of the pressures that will build upon compression of the air and gasses that will develop in the repository.

Concrete plugs with asphalt water-stops have recently been redesigned. Such "chemical" seals in mine-shaft use have a checkered history of failure by displacement. Asphalt is a viscous liquid, so when subjected to shear, it is more readily deformed than is salt. The intended function of the asphalt, filling not only a shaft segment, but also filling a tapered kerf (slot) excavated all-around one radius into the shaft wall, is to intercept the (disturbed rock zone) DRZ, believed to be the most likely path for fluid bypassing the impermeable seal materials that will fill the shaft. The radial extension of the DRZ around the tip of the kerf has been modeled (CCA 7.6.1) to conceptualize its development and subsequent crack closure when the asphalt and adjoining concrete plugs take on load from the convergence of salt. One cannot tell from the text whether or not the modeling is realistic in conceptualizing the closure consequences.

The asphalt will shrink slightly during cooling (days), after the upper concrete plug has set (hours). Presumably, the concrete plug will support itself in shear without salt damage as the concrete gains strength (months). Ensuing creep deformation of the
walls (years) will load the asphalt and concrete. According to reported structural
calculations (SEAL 7.4.4.2), the radial stresses for upper, middle and lower seals in
asphalt will be only 1.8, 2.5 and 3.2 MPa at 100 years, and in concrete (SEAL
7.4.1.2), only 2.5, 4.5 and 5.5 MPa at 50 years. They claim that such modest
backpressures will heal the DRZ, even while creep continues to close the shaft. The
geometry of the kerf will speed its closure, relative to the radial closure around
cylindrical concrete elements, thus modeling should show vertical components of salt
movement towards the kerf. As stated (CCA 7.6.1, Para 2), after 20 years the DRZ
is localized, 2 m deep, at the asphalt/concrete contact, where such shear of salt
against concrete must be maximum.

The designer’s concern should be that more rapid closure of the kerf will raise the
asphalt pressure more rapidly than the salt/concrete contact pressure, so that asphalt
may prise and penetrate upwards along that contact. Whenever a fluid of density less
than the surrounding rock rises to higher levels, the propagation of the hydrofracture
is unstable. There is nothing to prevent the extrusion of the asphalt until the water-
stop is replaced (centuries) by salt, and the asphalt is displaced along the contact of
the overlying clay seal segment. Apparently we cannot count on the interception of
potential seepage paths along the shaft DRZ by placement of asphalt water-stops,
because they may not be permanent.

The asphalt column at the top of the Salado (element 6 of Fig. 3-4) is to be composed
of asphaltic aggregate. It will be lightly loaded and will have some shear strength, so
will have limited or no mobility past its upper plug of concrete placed against
anhydrite of the Unnamed member of the Rustler.

Other parts of the seal system should compact without discharge or distortion.

DOE Response

The CCA performance assessment is based on an established design, as documented
in CCA Appendix SEAL. Appendix Peer (PEER 1.2 Conceptual Models Peer
Review Report (July 1996), Section 3.20) concludes the current design is readily
achievable and adequate for supporting current compliance performance assessment
calculations. However, as the shaft seal system will not be constructed for several
decades, it is reasonable to assume that construction techniques will improve and that
new or improved material specifications will be available at some point in the future.
As stated in Chapter 3, Section 3.3.1:

"Such a seal system will not be implemented for several decades, but in order
to establish performance requirements now that can be achieved at a later date,
a shaft seal system has been designed possessing excellent durability,
performance, and constructability using existing technology. The design
approach is conservative, with redundant functional elements and various common materials. Because this design is not the only possible combination of materials and construction strategies that would adequately limit fluid flow within the shafts, future developments may change the design."

The intent of the statement that shaft seal design “may change” reflects the expectation that technology improvements will occur. The seal system design presented by the DOE represents a design that will work, and can be built using today’s technology. Appendix SEAL (Appendix A, page A-1) states:

“The shaft seal system will not be constructed for decades; however, if it were to be constructed in the near term, materials specified here could be placed in the shaft and meet performance specifications. A material specification is necessary today to establish a frame of reference for design and analysis activities and to provide a basis for seal material parameters. This document was used by three integrated working groups: (1) the architect/engineer for development of construction methods and supporting infrastructure, (2) fluid flow and structural analysis personnel for evaluation of seal system adequacy, and (3) technical staff to develop probability distribution functions for use in performance assessment.”

The design basis for the current certification performance assessment calculations is known and is documented in detail in Appendix SEAL:

- Design Description - Appendix SEAL (Appendix A) and Chapter 4 of Appendix SEAL and,
- Material Specifications - Appendix SEAL (Appendix D) and Chapter 5 of Appendix SEAL
- Any changes to the seal system design would be incorporated through the recertification process and would require acceptance by the regulator prior to implementation.
Repository Pressure and Discharge

Waste emplacement design includes a backfill of sacks of MgO placed to buffer acidity as CO₂ evolves from decomposing organics in the waste. Hydration to Mg(OH)₂ will sequester water beneficially, but release it as CO₂ combines with the hydroxide. Besides maintaining low actinide solubility, it is evident that the MgO will reduce the rate of gas pressure build-up and diminish the liquid filling repository voids.

Castile brine occurrences pressurized by biogenic H₂S (such as ERDA-6, 1981) are analogues for the evolution of repository contents, wherein decomposition of cellulose, plastics, rubber and steel will generate CO₂ and H₂. DoE's concepts of the nature of these Castile brine reservoirs is found in CCA 6.4.8, but there is no recognition that primitive pressures must be lithostatic as a limit, that the extent, interconnectedness and discharge processes must be tied to the stress state of salt. The Castile fluids are stored in rather stiff fractures in the anhydrite. The pressure has developed by microbial reduction made possible by methane or petroleum in the presence of anhydrite. Its threshold for dissipation by hydrofracture along weak contact partings is the lithostatic pressure of salt adjoining such fractures, not the steep fractures interior to the anhydrite beds. Upon tapping such a reservoir with a drill hole, its head is initially thousands of feet above land surface, but as it flows, friction drops the pressure rapidly. It would flow freely until anhydrite fracture closure attains hydrostatic pressure for the brine.

How much of the H₂S is dissolved or gaseous in the Castile is unknown, but it is probably dissolved because none of the drill intersections have produced gas only, followed by brine. In addition to elastic closure of fractures and expansion of brine, evolving gas in the column drives the well discharge. Remote parts of a reservoir become isolated as diminishing pressure causes closure of hydraulic fractures at salt contacts.

In the repository, compaction begins with air only, and ends with air, decomposition gasses and brine from inflows, all at lithostatic pressure. The greatest factor of uncertainty is the amount of brine that will enter during the long room closure period while pressure is below lithostatic. The National Academy review (NAS, 1996, App.C) summarized the competing theories, indicating cumulative inflows in the
range of 500 to 800 l/m of drift. It appears that none of those computations were
coupled to backpressure computations. Like the Castile anhydrite beds, some areas of
which contain abundant brine, there is probably a variation of brine content in
fractures of Salado interbeds, and variations in size and continuity between reservoir
areas. Hydrofractures may or may not join various steep-fracture reservoirs,
depending upon their pressure histories. So the calculated cumulative brine flows may
err by large amounts, and a conservative inflow may total more than 1000 l/m.

The choice of backfilling materials in the rooms provides the only control over final
void volumes, since the waste can sustain only so much residual void space when
compacted to lithostatic total stress. Ideally, since waste voids will probably become
saturated, residual porosity should be maximized, to limit the amount that can
otherwise be expelled from the repository after the gas has escaped. The MgO
backfill will absorb water into the hydroxide, then yield it as the carbonate is formed.
The amount of MgO is said to exceed the gas expected to evolve, so a net water
absorption will function to inhibit corrosion, just as will pH control. But unlike salt
backfill, MgO will not sequester air; the Mg(OH)₂ will saturate and consolidate as it
continues to take load. Compressed air in fractures and contacts and within the
collapsed drums will all communicate to hydrofractures that can form as pressure
attains lithostatic in the repository. It doesn't seem conservative to assume that the
backfill and residual voids will retain all the remaining brine, since gas will continue
to evolve. I am unaware of any DoE claim that brine will be unavailable for transport
of radionuclide contaminants away from the repository, nor would it be prudent to so
assume.

A possible safety measure rejected by DoE is the option of completing the backfilling
around the waste and MgO packages with dry compressed or adobe bricks of clay. It
is well-known that clays of the montmorillonite family have extremely high cation
exchange capacities and can exert high swelling pressures. Reduction of the initial air
volume and prompt backpressure would shorten the time to cessation of closure.
Diminished inflow and enhanced absorption of brine would ameliorate corrosion.
Perhaps an absence of free brine could be guaranteed, limiting the actinide source to
the fluids already in the waste, less the actinides which can be absorbed by the clay.
In absence of incontrovertible geologic containment and retardation, such engineered
barriers may be the only way to get certified.

It is safe to say that a diminished rate of decomposition of the waste does not
eliminate the prospect of continued pressure build-up to hydrostatic. As proposed, the
large initial voids ratio of the repository (as seen in Fig. 3-8) probably implies that
the air cannot be contained at less than lithostatic pressure in the residual voids of the
waste containers, some of which will be brine-filled. Continued gas generation, at any
rate, will ultimately raise pneumatic pressure to lithostatic in spaces communicating
with the DRZ in the marker beds. The compressed air and gasses are available to
form and drive hydrofracture either along the seals or through the overburden rocks. The energy available for propagation and friction is in excess of \(2.5 \times 10^{12}\) joules, if the original void volume of about 460,000 m\(^3\) (SEAL 8.3.2), plus any generated gas is compressed to about 1/146 th of that volume.

**DOE Response**

The H\(_2\)S encounter by ERDA No. 6 is not considered to be a factor associated with a Castile brine encounter. As stated in Appendix GCR Section 1.6:

"Regional exploration of bedded salt for a radioactive waste repository in the Delaware Basin included boreholes into the evaporites and associated rocks. One such hole, ERDA No. 6, encountered an accumulation of saturated NaCl-Na\(_2\)SO\(_4\) brine accompanied by H\(_2\)S-rich gas. This fluid and fluids from other boreholes elsewhere in the area have been characterized geochemically according to solute content, \(^{18}\)O/\(^{16}\)O and D/H ratios and natural actinide content. Deviations from the equilibrium \(^{234}\)U/\(^{238}\)U activity ratio (a) of 1.0 were found in all water samples. These deviations are used to affirm the isolation of ERDA No. 6 and to establish bounds on the age of the ERDA No. 6 fluid.....

......The geochemistry of the proposed WIPP site shows that the mineralogy of most of the rock salt is relatively simple."

As further stated in Section 8.4.5 of Appendix GCR:

"A significant deposit of native sulfur is being exploited by the Frasch process approximately 50 miles south of the WIPP site in northeastern Culberson County, Texas. The occurrence is associated with brecciated and carbonatized anhydrite beds of the Castile Formation. Considerable exploration has been under way since discovery of the Culberson deposit, but that exploration has been aligned along the southern and western parts of the Delaware Basin where the Castile Formation either lacked halite during deposition or the halite has been removed by dissolution. The genesis of the deposits is believed to depend on a combination of bacterial action, induced fracture permeability and a source of hydrocarbons (presumably from upward escape of natural gas or crude oil along fractures from the Delaware Mountain Group). The closest analogy to such a setting in the northern part of the Delaware Basin and the vicinity of the WIPP site would be either "breccia pipes" or H\(_2\)S-laden brine reservoirs. Careful attention was given in selecting the WIPP site to avoid such structures; further investigation has not revealed any such structures, therefore, no sulfur deposits are expected."
The conceptualization of a Castile brine reservoir and the uncertainty analysis are summarized below in order to assure the reviewer of the comprehensive manner in which this important issue has been addressed by DOE.

Castile brine reservoirs are believed to be fractured systems, with high-angle fractures that are wide spaced. Therefore, a borehole can penetrate through a volume of rock which contains a brine reservoir without intersecting any fractures and thus not produce any brine. They occur in the upper portion of the Castile. Although appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, there is little direct information on the areal extent of these reservoirs or the interconnection between them. The presence of a pressurized brine pocket is treated in the conceptual model of WIPP as discussed in Section 6.4.8. of the CCA.

The Castile brine reservoir conceptualization has been done after careful analysis and evaluation of data from years of research. As mentioned in the CCA, WIPP-12 was deepened in 1981 to test for possible brine and gas in the deformed Castile. The probability of encountering brine and gas was considered low because ERDA-6 and other known brine reservoirs in the Castile occurred in areas with greater deformation. During drilling, fractured anhydrite in the upper Castile (lower A3) began to yield pressurized brine and gas. The borehole was deepened to the basal anhydrite (A1) of the Castile. Subsequent reservoir testing1 was also conducted to estimate reservoir properties (see Section 2.2.1.2.2 and Section 6.4.8 of the CCA).

The results from numerous hydraulic tests performed in the ERDA-6 and WIPP-12 boreholes suggest that the extent of the highly permeable portions of the Castile is limited. As discussed in Section 2.1.3.3 and modeled in Section 6.4.8, the vast majority of brine is thought to be stored in low-permeability microfractures; about 5 percent of the overall brine volume is stored in large open fractures. The CCA model uses parameter values derived from the ERDA-6 and WIPP-12 tests for quantifying some reservoir characteristics.

DOE does recognize that the units intersected by a drill hole may be sources for brine flow to a waste panel either during or after drilling. In fact, the CCA cites an example, where the Castile contains isolated volumes of brine at fluid pressures

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greater than hydrostatic (see discussed in Section 2.2.1.2.2). The WIPP-12 penetration of one of these reservoirs provided data on one brine reservoir within the controlled area. The potential consequences of a drill hole tapping both a waste panel and a brine reservoir is accounted for through uncertainty analysis that has been deemed reasonable and adequate by the Conceptual Model Peer Review Panel. As per the Panel,

"Given that the conceptual model predicts that there will be enough brine to corrode the waste and that other assumptions appear conservative, making other impacts unlikely, the model is adequate for its intended use...The conclusions appear to be valid. Estimates of inflow volumes from the mechanisms proposed in the model appear to be reasonable... The model is adequate for implementation."

Although site characterization, repository design, and waste characterization activities have removed much uncertainty from the analysis, some uncertainties remain. These remaining uncertainties have been incorporated in the performance assessment through the use of reasonable, realistic, and conservative assumptions about models and parameter values. In general, the DOE has not attempted to bias the performance assessment toward a conservative outcome, and therefore the mean CCDF represents a reasonable estimate of the expected performance of the disposal system.

Because of the many associated uncertainties, the DOE has made conservative decisions during the design of the conceptual and computational models, as listed in Table 6-30 of the CCA. For example, within the repository portion of the BRAGFLO model, fluid flow in a single panel is treated as if all rooms were a single void (that is, pillars are omitted). This assumption allows brine flow through an intrusion borehole to contact more waste than it would if it followed a more realistic flow path between rooms. The effect is conservative with respect to brine flow through a plugged and abandoned borehole. Similarly, the DOE has chosen to model fluid flow through plugged and abandoned boreholes as if all intrusions occurred into a down-dip (that is, southern) panel, which is also a conservative assumption. As noted in Section 6.2 and Appendix SCR, in some cases processes have been omitted from the model because the only possible effects of including them would be beneficial to system performance.

Brine will be available for transport of radionuclide contaminants. The discussion in Chapter 6, Section 6.0.2.2 shows no effect on the compliance determination.

"Some quantity of brine is expected to be present in the repository under most conditions and this brine may contain actinides (which dominate the radionuclide inventory and are therefore the elements of primary regulatory interest) mobilized as both dissolved and colloidal species... Brine flowing out
of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species, but the quantity of actinides that may reach the accessible environment boundary during undisturbed performance through the interbeds is insignificant and has no effect on the compliance determination.

Consolidation will continue until it reaches mechanical equilibrium. As stated in Appendix PORSURF, Section PORSURF.2:

"Creep closure of the excavation begins immediately and causes the volume of the cavity to become smaller. If the room were empty, rather than partially filled with waste, closure would proceed to the point where the void volume created by the excavation would be eliminated and the surrounding halite would return to its undisturbed, uniform stress state. In a waste-filled room, the waste will eventually contact the surrounding rock; the rate of closure will decrease and eventually cease as the strength of the waste becomes sufficient to support the rock above the room. Initially, unprocessed waste can support only small loads, but as the room continues to close after contact with the waste, the waste will consolidate and support a greater portion of the weight of the overburden. Consolidation will continue until it reaches mechanical equilibrium.

The presence of either brine or gas retards the closure process. First, if brine is present and immobile in the waste, closure largely ceases when the void volume decreases to the point where the voids are completely filled (saturated) with brine."

Waste degradation processes indicate that the role of the gas phase in fluid flow and the pressure history of the repository will be far more important than would be expected if the initial air were the only gas present. The total volume of gas that may be generated by corrosion and microbial degradation may be sufficient to result in repository pressures that approach lithostatic. Sustained pressures above lithostatic are not physically reasonable within the disposal system, and fracturing of the more brittle anhydrite layers is expected to occur if sufficient gas is present. The conceptual model implemented in the performance assessment causes permeability and porosity of the anhydrite marker beds to increase rapidly as pore pressure approaches and exceeds lithostatic. This conceptual model for pressure-dependent fracturing approximates the hydraulic effect of pressure-induced fracturing and allows gas and brine to move more freely within the marker beds at higher pressures.

These pressures will not exceed lithostatic, because fracturing within the more brittle anhydrite layers will occur and provide a pathway for gas to leave the repository. Fracturing is expected to enhance gas and brine migration from the repository, but
gas transport will not contribute to the release of actinides from the disposal system. Brine flowing out of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species, but the quantity of actinides that may reach the accessible environment boundary during undisturbed performance through the interbeds is insignificant and has no effect on the compliance determination. Overall, the behavior of the undisturbed disposal system will result in extremely effective isolation of the radioactive waste.

The validity and adequacy of the DOE modeling effort in this area has also been confirmed by the Conceptual Model Peer Review Panel. The panel determined the Salado and the impure halite modeling efforts to be adequate. As stated in Chapter 9, Section 9.3.1.1:

"Although differences in the behavior of pure and impure halite, variable degrees of impurity, and complexities of stratigraphic distribution of zones of impurity exist, the modeling of all halite rocks in the Salado as impure halite is an acceptable model simplification. . . The model appears to be adequate for the same reasons that the overall Salado model is adequate. Brine inflow sufficient to corrode the waste and to drive biogenic degradation is assumed. For error to be significant, brine inflow would have to be very large, which is unlikely. . . The conclusions drawn on the basis of the impure halite model are valid for PA purposes."
Text of Comment

Seal Failure. In shafts and boreholes, the pre-existing contacts between wall rocks and seal materials are likely paths of hydrofracture, and the vertical aspect enhances instability (runaway propagation to up-hole regions of decreasing rock stress). There is nothing to stop it except whatever tensile strength may exist in the least-healed discontinuity, such as dust coatings on original walls. It may propagate readily between air-filled voids of the compacted salt fill, and certainly along fluid films in the clay seals. Asphalt deforms to pass air at contacts, and salt will yield to form a parting against concrete. Likewise, boreholes sealed with concrete will not sustain much beyond lithostatic fluid pressures before parting at contacts. The DRZ fractures, even healed ones in salt, are candidates for hydrofracture. One might design end-constraints for a salt column to exceed lithostatic radial pressure, but it would not be permanent. It is easy enough to design effective seals for fluid pressures below lithostatic, but not above.

The computations in SEAL 8., the hydrologic evaluation of seal performance, are perhaps valid, but the assumption of homogeneous, intergranular or continuous fractured-media properties do not apply under all conditions, such as at high pressures. Seals and DRZ rocks behave as continuous media during early phases of repository closure, but under lithostatic or higher pressures, fluids will travel along singular pathways not envisioned by the modelers. During compaction of clay and perhaps of salt, air can be expelled along contacts of the seals. During any subsequent consolidation phase, water can be expelled along those same pathways. Either fluid will take the path of least resistance, usually by forming a conduit at the rock/seal contact, persistently maintaining that opening as flow occurs or preserving a path susceptible to re-opening and concentrated flow when pressure is raised. Seals can be breached to the Rustler aquifers or to the surface via the unsaturated zone. If engineered barriers in the repository preclude free brine, it would be harmless air and gas discharge. Otherwise, the undisturbed scenario has a potential for radionuclide releases to Rustler aquifers by way of shafts or boreholes.

DOE Response

The hydrologic evaluation of seal performance in SEAL 8 are valid. The performance of the shaft seals constitutes only one aspect of the compliance calculations. As demonstrated in Figure 6-41 of the CCA, the releases from cuttings, cavings, and spallings are shown to be the most important contributors to the location
of the mean CCDF. Figure 6-41 provides a display of the relative contribution of each mode to the total release. The mean CCDF for subsurface releases (e.g., through an intrusion borehole and the Rustler as mentioned in the comment) resulting from groundwater transport is not shown because those releases were less than $10^6$ EPA units. No radionuclide transport to the Culebra occurred through the shaft seal system.

The assumption of homogeneous, intergranular or continuous fractured-media properties do apply under conditions such as at high pressures. Repository pressures are not expected to cause seal failure because pressures high enough to cause fracturing of interbeds will not occur until after the long-term components of seals are consolidated. As stated in Chapter 3, Section 3.3.1.6.2 and 3.3.1.6.3:

"In the physical setting, pore fluids can create pore pressure and reduce the rate of the compacted salt column reconsolidation. Calculations demonstrate that repository gas pressure will not impact reconsolidation. The fluid flow analyses conducted to support seal system design efforts can be reviewed in Appendix SEAL (Appendix C). As a result, the salt column achieves its long-term effective permeability at 100 years following seal construction."

"Fluid pressure of the Salado is higher than fluid pressure in the Rustler so that upward migration of brines could occur through an inadequately sealed shaft. Results from modeling (discussed above) demonstrate that the crushed-salt seal will reconsolidate to a very low permeability within 100 years following repository closure (see Appendix SEAL, Appendix C). Structural results reported in Appendix SEAL (Section 7.4) show that the DRZ surrounding the compacted clay and compacted components will completely heal within the first several decades (see Appendix SEAL, Appendix D, Table D-20). As a result, upward brine flux at the Rustler and Salado contact in the sealed AIS is approximately 35 cubic feet (1 cubic meter) over the 10,000-year regulatory period. This brine originates in the marker beds; no brine from the repository migrates up the shaft."

In addition, many of the shaft seal components have been modeled conservatively by the DOE. For example, within the shaft seal system, concrete components are modeled as if they degrade 400 years after emplacement. This underestimates their potential to limit fluid flow over the long-term. These conservative assumptions do not affect the location of the mean CCDF, which, as shown in Section 6.5.3, is dominated by cuttings and cavings releases.

Concrete, clay, and asphalt components of the shaft seal system are expected to provide an immediate and effective barrier to fluid flow through the shafts, isolating the repository until salt creep has consolidated the compacted crushed salt components.
that will permanently seal the shafts. Around the shafts, the DRZ in halite layers are expected to heal rapidly because the presence of the solid material within the shafts will provide rigid resistance to creep. The DRZ around the shaft, therefore, will not provide a continuous pathway for fluid flow.
Hydrofracture through the Salado. If the shaft seals are as good as they can be made, then hydrofracture will occur elsewhere instead. In essence, no fluid phase can be long contained by seals or geologic media when the fluids exceed lithostatic pressure; the best that can be done is to assess the relative weaknesses of competing paths of egress. Mindful that roof slabbing (even presently occurring in the experimental rooms) exposes one or more weak partings, at anhydrites “a”, “b” or the clay at the base of MB 138, subsequent closure will cause those members to bend and decline towards the center of the room. Air will remain in the anhydrite fractures even as rock stress attains lithostatic over rooms as well as pillars (the unmined salt between rooms). During roof deformation, shear displacements produce microscopic openings along several such stacked partings that extend towards the centerline of the pillar. Coalescence of the DRZ from room to room can occur by hydrofracture across the pillar regions, completing the continuity of the entire repository, even if there are room or panel seals in place. DoE has chosen to neglect the NAS recommendation (1996, p. 145) for generous, long room entry seals, that would diminish the continuity of the repository. All rooms should dead-end in salt for isolation. Canadian potash mines safely excavate 2000 ft rooms with only one entry. The concrete seals to be emplaced for RCRA compliance (CCA 3.3.2) are not being relied upon for compartmentalization to isolate nuclear waste products. Therefore, the energy of air compression and gas generation stored in the entire repository is available to drive a single hydrofracture to great distances.

I anticipate a counter-argument that lithostatic pressure cannot build because the slightly-permeable anhydrite beds would continually bleed air from the repository, especially from the up-dip extremities, while brine continues to drain into the down-dip extremities. The fallacy of that argument is the erroneous belief that brine in the marker beds is at no more than 12.5 MPa (Beauheim, et al., 1993), when measurement itself disturbs the pressure. Virgin pressure must be lithostatic to prevent salt closure of the fractures. Therefore, it is doubtful that appreciable air losses can occur through the marker beds until that formation pore pressure is exceeded at the repository end, even if it takes centuries to attain it.

In the far-field, remote from any stress perturbations the excavations may impose, it is safe to assume that creep of salt maintains lithostatic, all-around rock pressure equal to the overburden load. In such circumstances, the presence of structural weaknesses will govern the nature of a hydrofracture forming in response to fluids
exceeding lithostatic. Clay partings along contacts between salt and marker beds, and some clay lamina within salt beds are candidate horizons. These may be interrupted at infrequent local breaks in stratigraphy formed during Permian deposition by channels that crossed the shallow salt-flats. They have been observed in the experimental area of the repository (D. Borns and R. Patchett, personal communication, 1995). The effect of such an interruption of a bedding-plane hydrofracture is to force the opening to propagate elsewhere. It is known also that hydrofractures tend to jump up to higher levels in the strata, where load is less. In homogeneous rock, hydrofractures become dish-shaped. Such behavior in the Delaware Basin has been demonstrated. In 1991, the Bates #2 Well encountered brine with 1000 psi shut-in pressure while drilling at 2240 feet. It flowed about 840 gpm for 5.5 days. Responsible for the brine was a Texaco Co. well injecting (oil-field waterflood operations) at 3000 ft depth, about 760 ft lower than the Bates well intersection and about two miles away. It is consistent with that incident to predict that when pneumatic pressure in the repository approaches the fracture gradient of 0.966 psi/ft depth, it will either hydrofrac a seal or produce a single, elongated hydrofracture along a succession of overlying partings of the Salado, ultimately breaching the Rustler aquifers. As EEG (1996, p. 2-4) point out, the Rustler/Salado contact is also a potential pathway. Alternatively, an extensive hydrofracture may intersect a borehole inadequately sealed to sustain the pressures from deeper horizons.

The importance of borehole sealing, at sites both on and off the land withdrawal area, is evident from the Bates #2 Well experience, and from other water-flood hydrofractures encountered in recent years. DoE has chosen to accept the condition of numerous abandoned wells in the region, presuming them to be well sealed in accordance with state regulations. But the imperfection of casing cement jobs and the corrosion that destroys casings in evaporite environments point to predictable vertical paths open to the surface now or in the foreseeable future via the many abandoned and active oil wells. The possibility that waterflood operations in the neighborhood may propagate hydrofracture to the repository, saturate and pressurize it, then hydrofrac an outlet to the surface is very real.

Discharge of air and gases is innocuous, insofar as TRU waste is not expected to generate appreciable radioactive gas to contaminate the repository air. The significance of pneumatic hydrofracture is that it prepares and maintains an open path for escape of liquids to follow after the available vapor-phase has discharged from the repository. The energy of any remaining room closure is available to expel fluids of density below that of salt. Only if engineered barriers have been emplaced in the rooms can sufficient brine sequestration be envisioned to preclude eventual brine discharge along hydrofracture conduits, and DoE has not maximized use of such barriers.
DOE Response

Hydrofracture through Salado

Lithostatic pressure by definition means the pressure resulting from the weight of the overlying stratigraphic column. So the maximum pressure that could be exerted on resident fluid in the Salado Formation at a particular depth would be linked directly to the weight of the overlying units, including a portion of the Salado Formation when considering the repository. In reality though, the fact that rocks have strength, including bedded salt, means that the rocks themselves support some portion of the overburden pressure, thereby ensuring that true lithostatic pressure is not exerted on fluids within the rocks. In the case of the Salado Formation, the bedded salt has substantially less strength than other units within the stratigraphic column (i.e., the bedded salt deforms as lower differential stress), and as a result, the pressure on fluids within the bedded salt increases above hydrostatic pressure but is not likely to reach lithostatic pressure. This is especially true in the anhydrite interbeds, which have substantially more strength than halite-rich layers, and have pre-existing, partially healed fractures within which fluid resides.

Another process which may affect the pressure within the disposal rooms will be the generation of gases resulting from corrosion of metals and the biodegradation of organic material in the waste itself. Both of these processes require the presence of water in some form, and both processes consume water. For either or both of these processes to continue, additional water must be introduced into the disposal rooms. As the gas pressure in the disposal rooms approaches lithostatic pressure, the repository and the Salado Formation will be in equilibrium, and no pressure gradient exists for water to flow into the disposal rooms.

If lithostatic pressures occur within the disposal rooms, the possibility of hydrofracturing exists. Two locations where fracturing is least likely to occur in the vicinity of the repository are around the panel seals and across the pillars between adjacent disposal rooms. The panel seals, by their very nature and engineering design, will act as rigid bodies shortly after emplacement. The amount of salt creep necessary to compress, and for practical purposes eliminate, the surrounding DRZs is relatively small when compared to the amount of salt creep that must occur in the disposal rooms to compacting both the waste and the backfill in addition to compressing the DRZ. Pillars between the disposal rooms will behave similarly to panel seals. Once disposal operations begin, adjacent disposal rooms will not remain open for long periods of time prior to backfilling and closure. As a result, the DRZ around the disposal rooms will be of limited extent and is unlikely to extend across a pillar. As will be the case for the panel seals, the relatively wide pillars will act as rigid bodies, and relatively little salt creep will be required to compress and virtually eliminate any DRZ.
Salt creep will occur in the disposal rooms, because the waste and backfill must be compressed in addition to the DRZ. From experience in salt mines and in excavations at the WIPP, most of the salt creep in excavated rooms will occur in the vertical direction (i.e., both the roof and floor will creep more than the walls). The expected extent of salt creep of the floor and ceiling is likely to result in displacement of anhydrite marker beds primarily along existing or reopened fractures. These displacements may provide pathways for gases in the disposal rooms to reach the anhydrite marker beds. Based on observations at the WIPP, these marker beds are already fractured, and as a result, the gas pressure exerted on these marker beds is unlikely to create new fractures (other than reopening previously sealed fractures), or a single fracture that would extend a considerable distance from the repository. Stresses applied to fractured rocks tend to be dissipated by movements along existing fractures rather the creation of new fractures.

The DOE’s conceptual model of the disposal system has marker beds in the vicinity of the disposal rooms (MB138, anhydrite layers a and b, and MB139) acting as migration pathways for brine and gas flow (see Section 6.4.5.2 of the CCA). MB139 and anhydrite layers a and b will be within the DRZ that is expected to surround the excavations, and MB138 was included to account for uncertainty in the extent of the DRZ. Clay partings were not included in the model, because the inclusion of additional small-scale fractures will tend to dissipate the gas pressure rather than concentrating the pressure for fluid migration through the marker beds.

The proposed analogy between the Texaco water-flood situation and the WIPP is not valid. The geologic setting at the two locations are distinctly different, and as a result, the response of the WIPP disposal system to injection wells in the vicinity of the repository would not be the same as the response in the Texaco injection area. In addition, the practices associated with the Texaco injection were distinctly different than what is current practice in response to more recent regulations which apply to the completion and operation of injection wells. For performance assessments, the DOE is directed by 40 CFR Part 194.33(c)(1) to assume that "Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared."

To assess the possible effects of a leaky injection well in the vicinity of the WIPP as a separate issue from performance assessment, the DOE analyzed what effect brine disposal in the vicinity of the WIPP might have on the disposal system (please see Phase II FEPs, Summary Memo of Record, FEP NS-7a: The Effects of Salt Water Disposal and Waterflooding on WIPP by D. M. Stoelzel and D. G. O’Brien). The analyses included selecting the maximum injection pressure allowed by regulation and preferentially flawed borehole casing and cement that allowed the pressure to affect preferential anhydrite interbeds that would connect the borehole with the disposal rooms. In addition, assumptions about material properties affecting brine flow were
deliberately selected to overestimate the effects of injection on the disposal system. This analysis demonstrated that hydrofracturing cannot extend from the Withdrawal Area boundary to the repository during the 10,000 year performance period and that the volume of brine located within the interbeds that would be forced into the disposal rooms would be relatively small (Stoelzel and Swift, 1997). Stoelzel and Swift (1997) conducted additional modeling studies that confirmed the CCA screening decision documented in Appendix SCR.3.3.1.3.1.

As for the EEG's suggestion that the Rustler/Salado contact is also a potential pathway for radionuclide migration, the material that composes the Rustler/Salado contact is the insoluble residue remaining after dissolution of bedded salt. This material includes the clay, which results in high radionuclide-sorption values. The DOE believes that considering only flow and transport in the Culebra Dolomite, which has lower retardation values than the Rustler/Salado contact material, conservatively overestimates the lateral extent of radionuclide migration that may result from human intrusion into the repository.

Reference:

Disturbed-case scenarios. Whereas the above considerations leading to pneumatic hydrofracture apply to the undisturbed repository, they should also be applied to the single borehole E1 or E2 case or the E1E2 case that would, at least, discharge accumulated gasses and air from the repository. After hydrofracture, repository pressure may not normally attain lithostatic again without a connection to the Castile brines or waterflood brines. If the drilling occurs subsequent to undisturbed hydrofracturing, pressures may become elevated when a Castile brine reservoir is intercepted, the E1 scenario (CCA, 6.3.2.2.2).

In the event of potash mining in the McNutt member of the Salado overlying the repository, the consequences would be far more extensive than merely the enhancement of Culebra transmissibility (Corbet and Knupp, 1996). In addition to shaft penetrations, the overburden between the mine and the surface would be disrupted by numerous steep subsidence fractures. Many traversing salt may re-heal while mining proceeds, but typically, potash mines flood via fractures carrying water from overlying aquifers, as occur in the Rustler. Thus, a mine overlying the WIPP repository can provide different connections to the accessible environment, depending upon the time of repository breaching relative to the time of mining. The mining level, about 75 m above the repository, would retain lateral continuity for centuries before it seals itself. Thus, it would provide continuity from the repository to the surface, via the shafts, boreholes old and new, and especially via hydrofractures, the mine and Rustler aquifers. Several of these are potentially more likely than the simple M scenario envisioned by DoE.

The E2 scenario (CCA 6.3.2.2.1), a drill hole inadvertently penetrating the repository would discharge any accumulated air and gas, but if it occurs after venting by undisturbed hydrofracture, the rooms may have closed to a state of near-saturation, facilitating brine discharge to the borehole, driven by expansion of the remaining gas and elastic expansions. The repercussions would depend upon the state of the repository, thus the timing of events. Diversion to the Culebra aquifer would result from successful blowout prevention at the collar of the hole.

A drill hole through a partially vented repository room, a closed access drift or the DRZ of any part of the system could conceivably be drilled deeper for resource exploration, whereupon a pressurized brine reservoir in the Castile could be encountered (E1 scenario, CCA 6.3.2.2.2), producing brine flow. Because no
mechanically effective backfill or room seals are to be employed, direct circulation to a point of hydrofracture egress is likely to sweep any mobile contents out of a panel or perhaps two panels, but the panel closures would protect other panels from direct flushing. However, any blowout preventer restraining direct brine discharge up the hole would result in hydrofracture from room to room, to any shaft, borehole or hydrofracture to the Rustler, since the Castile brine is generally at lithostatic pressure for its deep level, thus much higher than lithostatic for shallower levels. The path depicted in Fig. 6-11 represents only one of those possible, and probably not the worst.

Many potential paths are possible with the E1E2 scenario, as described in CCA 6.3.2.2.3, conceivably sweeping as many as two panels of their mobile wastes. It seems unlikely that the DRZ would have greater conductivity than would paths through rooms, but in the event that panel closures function effectively, brine flowing through any salt-bounded fracture could readily enlarge it to concentrate flow, bypassing much of the waste. It is not convincing to say that the E1E2 scenario is the worst case, that it is to be minimized because the compound probability of two such penetrations is low. The E1 drill hole in combination with prior breaching paths seems more likely and dangerous. The event of exploration well penetration of the repository seems unlikely to contaminate the Culebra because such wells would be new and cased through the Culebra. Thus the claimed retardation due to Culebra transport processes might not provide a barrier when needed most.

DOE Response

Drilling occurring subsequent to undisturbed hydrofracturing has been addressed in the compliance calculations. As addressed in 40 CFR § 194.33(b)(2):

"In performance assessments, drilling shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame."

Because inadvertent human intrusions are assumed to occur at anytime between 100 years and 10,000 years after the decommissioning of the facility (AICs are effective for the first 100 years, see details in Section 6.4.12.2) drilling does occur subsequent to undisturbed hydrofracturing. The random sampling of both the time and the interval of intrusion between the 100-10,000 year time-frame ensures that the effect of drilling after undisturbed hydrofracturing is already considered in the compliance calculations.

Subsidence fractures in the event of potash mining is specifically addressed in Chapter 6, Section 6.4.6.2.3. The modeling of the effects of subsidence is consistent with the conceptual model and other guidance presented by the EPA in 40 CFR Part 194. As
stated in Chapter 6, Sections 6.4.6.2.3:

"The EPA clarifies its conceptual model on the effects of mining on hydraulic conductivity of the units of the disposal system in the Preamble to 40 CFR Part 194 (EPA 1996a, 61 FR 5229). The EPA states:

Some natural resources in the vicinity of WIPP can be extracted by mining. These natural resources lie within the geologic formations found at shallower depths than the tunnels and shafts of the repository and do not lie vertically above the repository. Were mining of these resources to occur, this could alter the hydrologic properties of overlying formations—including the most transmissive layer in the disposal system, the Culebra dolomite—so as to either increase or decrease groundwater travel times to the accessible environment. For the purposes of modeling these hydrologic properties, this change can be well represented by making corresponding changes in the values for the hydraulic conductivity. The Agency has conducted a review of the data and scientific literature discussing the effects mining can induce in the hydrologic properties of a formation. Based on its review of available information, the Agency expects that mining can, in some instances, increase the hydraulic conductivity of overlying formations by as much as a factor of 1,000, although smaller and even negligible changes can also be expected to occur. Thus, the final rule requires DOE to consider the effects of mining in performance assessments. In order to consider the effects of mining in performance assessments, the DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining."

Based on its review of available scientific data, the EPA expects that mining can occasionally increase the hydraulic conductivity of overlying formations by as much as a factor of 1,000, although smaller and even negligible changes can also be expected to occur. Thus, the final rule requires DOE to consider the effects of mining in compliance calculations. The EPA has also added four important clarifying concepts. First, they have concluded that there are no minerals vertically above the repository that are similar to those currently being extracted in the Delaware Basin. Second, the EPA has not drawn any conclusions about the effect of mining on groundwater travel times to the accessible environment. Third, it may be assumed that the important effects of change in hydraulic conductivity occur only in the Culebra. Fourth, the hydraulic conductivity data established in the Culebra by the DOE may be multiplied, in case of mining, by a factor from 1 to 1,000. Therefore,
in focusing on the effects of increasing Culebra transmissivity, the DOE has adhered strictly to the guidance from the EPA and thus satisfied all criteria and requirements of the 40 CFR 194.

As explained in Section 6.4.6.2.3, the effects of subsidence caused by potash mining are included in the compliance calculations because of specific criteria in the 40 CFR Part 194 regulations. DOE has incorporated the effects of subsidence caused by mining, by using the conceptual model introduced by the EPA in 40 CFR Part 194.32 (b) and (c), which state what gets mined, when it gets mined, and the effects of mining on the disposal system.

Within the disposal system, mineral resources similar to those currently being mined outside the disposal system may be mined at an uncertain time in the future. Outside the disposal system, mineral resources reasonably expected to be mined in the near future should be assumed to be mined. DOE has included both of these effects in analyses of both disturbed and undisturbed performance. Inside the disposal system, whether and when a mining event occurs after the active institutional control period is determined by a probabilistic model, whereas anything that is reasonably expected to be mined outside the disposal system is assumed to be mined by the end of WIPP disposal operations.

As explained in Section 6.4.12, the sequences of future events that may occur are determined using a random sampling procedure described in detail in Appendix CCDFGF (Section 3.2). Each 10,000-year sequence is generated by randomly sampling six parameters, two of which are the interval of time between drilling intrusions (which yields both the number and time of intrusions) and the occurrence of mining. Probability distribution functions are assigned to each of these six parameters and random sampling from these distributions is used to generate 10,000 equally likely, independent futures for the WIPP for each realization executed and CCDF constructed.

Inadvertent human intrusions are assumed to occur at any time between 100 years and 10,000 years after the decommissioning of the facility. Both the number and time of intrusions are determined sequentially by sampling from a CDF derived from the Poisson model that probabilistically describes the time period that elapses between an intrusion at a fixed time and the next intrusion. The time interval to the next intrusion following an intrusion may vary from 0 years to greater than 9,900 years, with a probability determined by the rate constant \(l\). This ensures that the time of drilling (as modeled in the CCA) may occur either before or after undisturbed hydrofracturing has taken place. Hydrofracturing that might occur after intrusion, as a result of pressure increases from continued gas generation or Castile brine inflow, is included in the analysis.
This group of comments by CARD are written by Dr. R. H. Phillips and Dr. D. T. Snow. They present a wealth of detailed information on the hydrology of the Delaware Basin and, in particular, the Rustler Formation. However, most of this information has already been presented in the CCA and its supporting references. Therefore, it has already been considered by the DOE in the formulation of the WIPP performance assessment (PA) models and supporting databases. In particular, the available geological and hydrological observations are implicitly accounted for by the stochastic model used by the DOE to represent flow in the Culebra. Furthermore, the information presented by CARD is interspersed with a considerable amount of speculation and error, as well as misrepresentation of the DOE position. The DOE's conceptual model is often in agreement with CARD, although the CARD comments claim otherwise. CARD has presented few arguments that have not been discussed in the CCA and that relates to the adequacy of the models used in the CCA.

The DOE considers it appropriate to provide a general response focused on the relevance to compliance of the issues raised by CARD. Some of the detail in the CARD comments is, therefore, not addressed specifically. However, response to specific points is made within the discussions where it is clear that new information is being presented by CARD or where it is clear that CARD disagrees with the positions provided in the CCA.

The CARD comments essentially concern the adequacy of the hydrological model and data used in the CCA to represent the Culebra and Rustler Formations. This response is split into four general discussion categories covering the main issues raised. The general discussions and the comments covered by each discussion are listed below. Some comments fall into more than one category.

(i) Screening of karst formation and its consequences.

Comments 7, 9, 20, 21, 22

(ii) Treatment of recharge and climate-related variations.

Comments 19, 21

(iii) Use of borehole data to parameterize CCA models.

Comments 14, 18
(iv) Adequacy of the CCA model for Culebra hydrology.

Comments 7, 8, 9, 10, 11, 12, 13, 15, 16, 17, 20, 22

The synopsis of the DOE's response is as follows:

- The DOE recognizes that the Culebra is an extremely heterogeneous, fractured medium. The uncertainties involved in attempting to characterize the hydrogeological character of the Culebra have led to the development of a hydrological model for CCA based on well data. This approach is consistent with international practice.

- The CCA model uses several simplifying assumptions. CARD regularly confuses assumptions as a statement by the DOE of reality. The DOE's conceptual model, as presented in the CCA, is in agreement with the following points raised in the CARD comments:
  - regional groundwater flow is three-dimensional,
  - all rocks above the Salado (including the Mescalero caliche) have some permeability,
  - recharge to the water table can occur over the entire land surface,
  - Nash Draw and WIPP-33 are examples of karstic features.

The DOE disagrees that:

- karst occurs within the WIPP site,
- extensive halite dissolution has occurred in the Rustler within the WIPP site.

- Simplifying assumptions made in developing the CCA models are justified by sensitivity analyses using or considering more detailed representations of the system. In particular, extensive three-dimensional groundwater flow modeling has been undertaken to support the two-dimensional CCA model.

- The Culebra flow model used in the CCA is conditioned using measured transmissivity data and tested for adequacy by comparing observed and calculated steady-state and transient heads. It is, therefore, consistent with the WIPP borehole data and accounts for the observed, heterogeneous fracture flow. Contrary to the assertion by CARD, the head data can be contoured as continuous smooth surfaces and so argue against karstic flow. The amount of borehole data collected is sufficient to adequately parameterize the CCA model.

- The use of probability distribution functions for parameters and the generation of one hundred different spatially-variable transmissivity fields captures the range of
uncertainty in the Culebra flow conditions. Therefore, the detailed localized
information repeated in the CARD comments is implicitly accounted for in the model
results.

- The DOE has demonstrated that the hydrochemistry of the Culebra is consistent with
the groundwater basin model. Past interpretations of inconsistency were made on the
basis of a two-dimensional flow field. Contrary to the contention of CARD, the DOE
does not deny the occurrence of vertical leakage. However, recharge rates are slow.
Groundwater in the Culebra, within the vicinity of the WIPP site, is probably at least
several tens of thousands of years old.

- The CCA uses the assumption that the climate will change and uses conditions that
raise the water table to the land surface in a few hundred years as a conservative
upper limit for precipitation during the next 10,000 years. The DOE assumes that the
recharge rate during the late Pleistocene was sufficient to maintain the water table at
the land surface. The CCA model allows for a factor of up to 2.25 increase in
Culebra flow velocities due to increased precipitation in the future. This method of
accounting for the effects of future climate change was considered adequate by the
Conceptual Model Peer Review Panel.

- The DOE agrees that Nash Draw is a karstic feature. However, there are no
examples of karstic features within the Land Withdrawal Area (LWA). The DOE
has investigated several features in the vicinity of the WIPP site previously thought
most likely to indicate karst. The nearest observed features are at WIPP-33, which
may represent a prong of dissolution extending eastward from a karst transition zone
near Livingston Ridge.

- The CCA uses calculations of radionuclide transport to the accessible environment,
which is conservatively assumed to lie at the ground surface and at the lateral
subsurface limit of the controlled area. Radionuclide transport to points miles beyond
this boundary is not conservative nor informative.

Screening of Karst Formation and its Consequences

The term “karst” refers to a type of surface morphology that results from the
dissolution of rock, largely by percolating groundwaters. Karst topography most
commonly forms in carbonate rocks, although it can also form in other readily soluble
rock types such as evaporites. Associated with karst are hydrological characteristics
related to dissolution features. These include rapid infiltration, fracture flow,
channeling, and irregular groundwater velocities.
CARD states the DOE denies the existence of, or is not interested in karst. The DOE has not denied the presence of karst features at the WIPP site, and its position on the relevance of karst formation to the integrity of the WIPP site is clearly presented in Appendix DEF, Sections DEF.3.3 and DEF.3.4 of the CCA. This position has been corroborated by the EEG in work published by Chaturvedi and Channell (1985) and re-iterated in a recent submission to the EPA (Chaturvedi, 1990; Docket No. II-D-102). This position is again summarized here.

Section 2.1.6.2 and Appendix DEF, Section DEF.3.3, of the CCA summarize the occurrence of karstic features in the vicinity of the WIPP site. Information is also available from Barrows (1982), who initially raised the concerns about the implications of karst formation for the safety of the WIPP, Chaturvedi and Channell (1985), who describe an investigation of the issue carried out by LeGrand in response to Barrows on behalf of the EEG, and Bachman (1985). One of the best examples of karst topography in the vicinity of the WIPP is at Nash Draw, some 6 miles (10 kilometers) to the west of the Land Withdrawal Area (LWA).

As documented in Appendix DEF, Nash Draw contains many karstic features, such as collapse sinks and swallow holes. Both the EEG study and Bachman (1985) consider, however, that east of Nash Draw around Livingstone Ridge there is a transition zone that marks the eastern limit of significant karst development. A prong of dissolution may extend further east from this transition zone, as indicated by dissolution features encountered by WIPP-33. However, there is no evidence from hydraulic conductivities that this prong extends into the LWA.

Comment #20 by CARD documents several observations concerning the possible presence of karst features at the WIPP site including (i) heterogeneous transmissivities, (ii) cavernous zones, and (iii) surface features. These observations are discussed below.

(i) The heterogeneous distribution of transmissivities and the presence of hydraulic connections between some boreholes (see also p.10 of Comment #22). The DOE interprets these as the result of preferential flow along fracture networks (e.g., Beauheim, 1989). CARD contends that they could be karstic channels. Observed karstic features to the west of the WIPP are largely related to dissolution of the Salado and collapse and fracturing of overlying units. Formation of karstic channels in the Culebra are not apparent in areas that have not fractured due to underlying dissolution. However, in terms of the CCA model, the interpretation of the origin of high conductivity zones is not important. The CCA represents all the measured conductivities, including those observed in the pump-tests mentioned by CARD, with spatially-varying transmissivity fields. Attachment A of Appendix TFIELD in the CCA presents the 100 conditionally-simulated calibrated transmissivity fields, all of
which reproduce the observed transmissivities shown in Figure TFIELD-5 (see, for example, Appendix TFIELD, Section TFIELD.4.2.2). Figure TFIELD-5 presents the same data as Figure 3 in Comment #20. Furthermore, contrary to the assertion by CARD in Comment #10, the measured head data can be contoured as continuous smooth surfaces and so argue against karstic flow (see later). Head changes in boreholes indicative of rapid recharge at the WIPP site during times of heavy rainfall have not been observed. Such changes would be expected if recharge was occurring through karstic channels.

(ii) Cavernous zones encountered in WIPP-33. The DOE attributes the karst encountered at WIPP-33 to gypsum dissolution. However, CARD contends that a consistent lack of core recovery at two stratigraphic horizons in other boreholes within the LWA can be used, by analogy to WIPP-33, to infer cavernous zones extending across the site. CARD contends that these two horizons, one above the Magenta in the Forty-niner member and one below the Culebra in the unnamed lower member, are associated with deposits interpreted by CARD as dissolution residues. These horizons have also been well documented by the EEG in Chaturvedi and Channell (1985), along with another postulated dissolution residue in the Tamarisk member. There are two points to make. First, as CARD itself points out, lack of core recovery alone, particularly in the carbonate rocks, cannot be taken as evidence for caverns because of the fractured nature of the rocks and the ineffectiveness of the recovery technique. Second, the horizons identified in the CARD comments and the EEG work have been studied extensively by the DOE and are almost certainly not dissolution residues.

The three horizons (M2/H2, M3/H3, M4/H4) in question were studied extensively by Holt and Powers on behalf of the DOE. As well as performing studies of surface outcrop and extensive analysis of drilling data and geophysical logs, Holt and Powers also studied sedimentary structures in the Rustler Formation in three of the WIPP shafts. These detailed studies are documented in Appendix FAC of the CCA and are summarized by Powers (1997). The DOE studies demonstrate that the spatial changes and structures observed in the Rustler are largely related to depositional facies variation and processes, and not to post-depositional dissolution. In the proposed dissolution residue units, sedimentary structures show features consistent with sub-aerial exposure. Channels filled with intraformational conglomerates, and graded bedding in units bounded by erosional contacts are unequivocal evidence that the beds were not deposited in a salt pan environment. In addition, a 200-foot (61.5 meters) thick halite unit cannot be reduced to a 10-foot (3 meter) thick residue while preserving such bedding and similar sedimentary structures. Soft sediment textures demonstrate that some halite was removed from the beds during exposure, not after the rocks were buried. Holt and Powers...
(1988; Appendix FAC) proposed that the sedimentary features and thickness variations of the Rustler Formation are consistent with a depositional environment that varied laterally from a salt pan east of the WIPP, through intermediate saline environments, to mudflats in the west that were exposed sub-aerially and developed small channels.

Rustler rocks display post-depositional alteration, as do all sedimentary rocks. However, there is no evidence that significant quantities of halite have been removed by post-depositional dissolution. Recent drilling at H-19 on the depositional margin of the halite in the Rustler has documented localized structures that can be attributed to dissolution of halite through water/rock interaction (Holt, 1997). However, these structures are confined to the margin of the halite and, therefore, have only a localized effect on transmissivity and cannot be taken as evidence of karstic activity across the LWA.

In summary, the DOE does not consider that the horizons referred to by CARD are dissolution residues and that there is no evidence for cavernous zones across the WIPP site.

(iii) **Surface features.** The karst features described by CARD (in both Comment #20 and #21) at WIPP-33, east of Nash Draw, have already been well documented (e.g., Sandia, 1981; Bachman, 1981). H-7 is located in Nash Draw, and so the occurrence of karst and collapse features at this borehole is to be expected. Within Nash Draw, collapse of the Rustler beds through dissolution at the top of the underlying Salado has caused extensive fracturing and brecciation of the Rustler and allowed extensive percolation of groundwater. Holt and Powers (1988) demonstrated a general relationship between removal of Salado halite by dissolution and the amount of brecciation of overlying units. East of Livingstone Ridge there is a marked decrease in the extent of Salado dissolution and a consequent decrease in the extent of fracturing of the Rustler (e.g., Powers and Holt, 1995). As mentioned above, this is considered to mark a transition zone that marks the eastern limit of significant karst development. A prong of dissolution seems to extend east from this transition zone as far as WIPP-33. This is evidenced at the surface by the line of sinkholes described by CARD (Comment #20). However, there is no indication that the Salado at the WIPP site has been thinned by dissolution (Powers and Holt, 1995) and there are no examples of karstic solution channels within the LWA.

CARD proposes that a dissolution residue is found at the Rustler-Salado contact in the vicinity of the WIPP site. Holt and Powers (1988) considered this zone to mark a primary erosional contact marking the energetic change from the shallow brine environment of the Salado to the marine lagoonal
environment of the Lower Rustler. Evidence for a dissolution residue at the top of the Salado is limited to the west of the WIPP site and comes from thickness changes in the Upper Salado (Powers and Holt, 1995) and the Salado-like natural gamma signature of the residue (Jones et al., 1960) under Nash Draw.

CARD suggests that WIPP-14 is a sinkhole and that lost core represents dissolution zones into which there has been collapse (Comments #20 and #22). WIPP-14 was one of the boreholes drilled by the DOE specifically to investigate possible karst areas identified by Barrows et al. (1983). The borehole exhibited a normal stratigraphic sequence. The gravity anomaly at WIPP-14 observed by Barrows et al. (1983) has been interpreted to arise from poorly indurated surface material and conversion of anhydrite to gypsum in the Rustler Formation (Barrow in Appendix C of Chaturvedi and Channell, 1985). The observation by CARD that all halite has been removed is based on the assumption that halite was originally present. This is not consistent with the interpretation of Holt and Powers (1988) that the WIPP-14 sediments were deposited on the margins of an evaporitic pan and, therefore, that there was no significant deposition of halite.

Evidence of the timescale for development of Nash Draw comes from radiometric dating of the dissolution residue at the top of the Salado beneath Nash Draw and observations of the youngest sedimentary formations overlying the WIPP site. Within Nash Draw, a U-Th analysis of Upper Salado dissolution residue indicates an age of at least 700,000 years (Szabo et al., 1980). Gatuná Formation sediments were deposited unconformably on older units across the Delaware Basin from at least 13 million years ago to about 500,000 years ago (Powers and Holt, 1993). Thicker deposits of the Gatuná Formation in Nash Draw are evidence that the Draw had already formed a depression in the land surface at the time that the Gatuná was being deposited. The Mescalero caliche overlies the Gatuná, and the upper crust of the Mescalero caliche is interpreted to have formed about 420,000 years ago (Szabo et al., 1980). Along Livingstone Ridge on the eastern margin of Nash Draw, the surface rocks, including the Mescalero caliche, show evidence of deformation. Thus, it has taken at least hundreds of thousands of years or more for the margin of Nash Draw to assume its current form. This timescale, combined with the lack of evidence for any dissolution of the Salado at the WIPP site, means that there is no expectation that the edge of halite dissolution at the top of the Salado will move eastward and reach the controlled area during the period of regulatory concern. Therefore, the DOE does not consider karst formation in the future to pose a threat to the integrity of the disposal system well beyond the regulatory timeframe.
Treatment of Recharge and Climate-related Variations

CARD incorrectly asserts that the DOE fails to recognize the recharge of the Dewey Lake by infiltrating rainwater, leakage to the Rustler, and the three-dimensionality of groundwater flow at the WIPP site. The DOE's conceptual model for the Culebra allows for vertical leakage across the basin. Corbet and Knupp (1996) performed three-dimensional modeling of the groundwater basin to support the simplified two-dimensional approach taken in the CCA PA. In Corbet and Knupp's modeling, a uniform potential recharge across the basin of 0.2 to 2.0 millimeters per year was used, with the range accounting for future climatic variations. This range is also consistent with the findings of Campbell et al. (1996), who used a chloride mass balance method to determine localized infiltration rates at the WIPP site itself. The recharge value was also chosen to yield a modeled water table consistent with that observed. The model results showed that the groundwater in the Culebra within the WIPP site boundary had originated outside the site by a combination of lateral flow of distal leakage along the Culebra and by up to 60% vertical leakage from overlying units nearer the site. Discharge predominantly occurred by lateral flow only. The model also showed that it takes thousands of years for water to reach the Culebra in the WIPP site along both recharge routes. The net effect of this recharge and discharge pattern is captured in the boundary conditions and transmissivities used in SECOFL2D, the two-dimensional groundwater flow code used in the CCA PA. Therefore, contrary to CARD's contention, the DOE does allow for vertical recharge and three-dimensional groundwater flow. The issues in dispute seem to be the amount of recharge and its infiltration rate to the Culebra, both now and in the future. These issues are discussed below in terms of hydrochemical evidence for recharge, hydrochemical evidence for residence time and infiltration rates to the Culebra, the CCA treatment of recharge, and the CCA treatment of climate change.

Hydrochemistry

CARD uses the groundwater geochemistry in the Culebra to infer westward flow directions across the WIPP site (p.4 of Comment #22) and influx of dilute vertical leakage along flowpaths to the south and west of the site (p.11 of Comment #21). A number of points need to be made in response:

(i) The predominant north-south groundwater flow direction across the WIPP site is determined by the measured transmissivities and heads. There is no a priori fixing of the flow direction. Appendix TFIELD of the CCA describes how the measured transmissivities are used to generate spatially-variable transmissivity fields for SECOFL2D. Corbet and Knupp (1996) showed the flow directions in the present-day groundwater system at the basin scale. These flow directions were determined by the distribution of transmissivities used in the
three-dimensional model and, in turn, these transmissivities are related to geological variations.

(ii) The DOE does not believe that groundwater in the Culebra within the LWA will discharge at Malaga Bend. The DOE does not dispute that some parts of the Rustler may discharge to Laguna Pequena and Laguna Grande de la Sal, but it is not clear why CARD insists that groundwater from the LWA must do so. The three-dimensional modeling did not show that Laguna Grande de la Sal will be a discharge area for the WIPP in the next 10,000 years. This argument is, in any case, entirely irrelevant with respect to compliance, since the accessible environment for the CCA calculations is more strictly defined as the lateral subsurface limit of the controlled area.

(iii) CARD contends that westward flow must occur because saline groundwaters with NaCl concentrations in excess of 10,000 milligrams per liter occur in Rustler rocks with no halite. CARD then considers that a large dilution by rainwater recharge is necessary during westward flow, since groundwaters to the east are more saline. However, the groundwater basin model developed by Corbet and Knupp (1996) has recently been utilized to produce a coherent explanation of the hydrochemistry of the Culebra that is consistent with the flow directions presented in the CCA (Corbet, 1997). This explanation is summarized here. Based on major-solute compositions, four hydrochemical facies have been delineated in the Culebra (Ramey, 1985; Siegel et al., 1991):

- Zone A contains saline (~ 2 to 3 molal) NaCl brines with Mg/Ca molar ratios of about 1.2 to 2, and lies in the eastern part of the LWA.

- Zone B contains relatively dilute CaSO₄-rich groundwater (ionic strength < 0.1 molal) and lies west of the eastward extent of dissolution of the Upper Salado.

- Zone C contains waters of variable composition with low to moderate ionic strength (0.3 to 1.6 molal). The most saline (NaCl rich) water is found in the eastern edge of this zone, close to borehole locations where halite is observed in the Tamarisk Member.

- Zone D is defined based on inferred contamination of water from the other facies by potash-refining operations in the area. The Culebra groundwaters in this area have anomalously high salinities (3 to 7 molal) and K/Na weight ratios (0.2) compared to other wells in the study area (salinities < 3 molal; K/Na weight ratios 0.01 to 0.09).
Earlier interpretations of groundwater flow and solute chemistry in the Culebra Member of the Rustler, including that of CARD, have been based on the premise that rock/water interactions along a flow path away from the WIPP site must transform Facies C water into Facies B water. This premise is only valid if flow is assumed to be confined to the Culebra. However, the three-dimensional groundwater basin modeling of Corbet and Knupp (1996) has shown that the Facies C and B waters originate from different recharge areas and travel paths to the Culebra, and that the solute chemistries of these waters are consistent with interactions with the rocks that occur along their respective flow paths to the Culebra. This eliminates the previous concern about the apparent inconsistency between the observed solute chemistry and flow directions in the Culebra.

Corbet (1997) has concluded that Facies A groundwater occurs in a region of unaltered Rustler with a very low hydraulic conductivity and, therefore, moves extremely slowly. This water probably was recharged more than 600,000 years ago. Solutes in the Facies A water are from dissolution of Rustler and/or Salado halite and perhaps from synsedimentary brines. The solute concentration of Facies A water increases toward the east, reflecting a source of solutes east of the WIPP and slow advective/diffusive transport toward the west. Facies B groundwater occurs in a region of relatively rapid vertical leakage into the Culebra. This groundwater entered the Rustler in a region to the southwest of the WIPP site and has reacted mainly with Rustler anhydrite along its path to the Culebra. As Facies B water flows to the southeast it probably mixes with Facies C groundwater. Facies C groundwater was recharged to the north and northeast of the WIPP site. It is mainly meteoric recharge water that has reacted with Rustler anhydrite and halite. As Facies C water flows toward the south across the WIPP site, it is joined by small amounts of Facies A solutes being transported from the east.

The findings of the groundwater basin modeling are consistent with the conclusion of Bodine and Jones (1990) that Culebra groundwaters are mainly recharge waters that have interacted with Rustler anhydrite and halite before reaching the Culebra. The groundwater basin modeling results are also consistent with the recharge of groundwater south of the WIPP site as proposed by Chapman (1988) and Myers et al. (1991). Finally, the groundwater basin modeling results also support the conclusion of Lambert (1991) that extensive dilution of more saline water has not produced the Facies B water.

Residence time

CARD implies that dilution by vertical leakage into the Culebra must be rapid. However, there is no chemical evidence as to why this must be the case. No anthropogenic signatures, e.g. bomb tritium, have been detected in Culebra groundwaters. Stable isotope signatures and radiocarbon ages indicate that the

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dominant component of the Culebra groundwaters is thousands of years old (see Siegel et al., 1991 for summary). Travel times from the atmosphere to the Culebra in excess of 12,000 years are consistent with the flow pattern predicted by the groundwater basin modeling. The DOE finds it difficult to conceptualize Facies C water as having been recharged less than 12,000 years ago because overlying anhydrites are not thought to have been fractured by Upper Salado dissolution, and because lateral flow rates within the Culebra are very slow. Consequently, the DOE considers that Facies C groundwater was recharged more than (and perhaps much more than) 14,000 years ago (Corbet, 1997). It should also be noted that modeled travel times to the Culebra are not very sensitive to assumed recharge rates (Corbet and Knupp, 1996).

Residence times of more than 12,000 years for the Facies B water are also consistent with the groundwater basin model. However, shorter residence times are probably also consistent with this modeling. This is because lateral flow rates in the Culebra are much faster than in the region of Facies C water and the overlying anhydrites are thought to be fractured. One minimum radiocarbon date of 14,900 yr has been obtained from the H-9 well (Lambert, 1987). This well is located in the Facies B zone, near to the eastern extent of Upper Salado dissolution, that is, in the region where mixing of Facies B and C waters is expected.

CARD stated in Comment #19 that the groundwater in the Culebra cannot be "fossil water" because it is undersaturated. The waters are saturated with respect to phases such as gypsum and calcite (Siegel et al., 1991). Undersaturation with respect to halite reflects a combination of availability of halite to react with the water, the large amount of halite dissolution required to achieve saturation, halite dissolution rates, changes in groundwater chemistry through other reactions, and groundwater flow rates. Undersaturation cannot, therefore, be simply attributed to short residence times, particularly when the waters are saturated with respect to other phases.

**Recharge**

CARD criticizes the DOE for not identifying the points of recharge to and discharge from the Rustler Formation. Corbet (1997) identified the likely recharge zones for the hydrochemical facies observed at the WIPP site. Because the flow field used to model the Culebra in the CCA is based on the observed transmissivity distribution and the values of hydraulic head at the boundaries, the points of recharge beyond the model boundaries do not affect the model results. Similarly, the CCA calculations are only concerned with discharge to the accessible environment, a distance of a few kilometers from the repository. The points of discharge to the surface beyond the accessible environment are irrelevant to the compliance calculations.
In the three-dimensional modeling used to support the PA, Corbet and Knupp (1996) used values of recharge thought to be representative of the long-term average over a 4 square kilometer area. These values of 0.2 to 2.0 millimeters per year are consistent with those determined by Campbell et al. (1996), whose measurements were observed to be comparable with those from similar environments elsewhere. Corbet and Knupp (1996) applied the recharge across the entire top surface of their model. The average long-term recharge value used was justified by comparing the calculated hydrological conditions (water table and heads) with those observed. This probably resulted in a better estimate of the value than the disparate and uncertain mass balance approaches quoted by CARD.

In addition, Hunter (1985) estimated evapotranspiration rates of 98% to 99.5% for the region. These are considerably higher than those quoted by CARD (Comment #19) and consistent with a recharge rate of around 2 millimeters per year.

**Climate Change**

CARD misrepresents the treatment of future climate change by Corbet and Knupp (1996) in two ways. First, the claim that Corbet and Knupp “is said to have bounded the hydrologic effects of karst, mining, and climate change, simply by analyzing the effects of an increase in the hydraulic conductivity of the Culebra” is not correct. No such claim for the effects of karst and mining has been made, and the effects of climate change were not analyzed by increasing the hydraulic conductivity of the Culebra. Second, CARD questions why the full-glacial maximum was not considered. The CCA uses the late Pleistocene full-glacial climate as a conservative upper limit for precipitation during the next 10,000 years (Appendix CLI, Section CLI.5 and CLI.6). Corbet and Knupp (1996) clearly stated that the last glacial maximum occurred in the Pleistocene some 22,000 to 18,000 years ago. However, the groundwater flow model requires an estimate of recharge, not precipitation. The DOE assumes, therefore, that the recharge rate during the late Pleistocene was sufficient to maintain the water table at the land surface, and Corbet and Knupp (1996) began their simulations at the end of the Pleistocene at 14,000 years BP, when there was a clear decline in the annual precipitation rate (Appendix CLI). The starting flow field was equilibrated using a recharge rate set to raise the water table to the land surface, i.e., the top model boundary. Therefore, extending the simulations further back into the Pleistocene with the same or higher recharge rate would have no effect on the results.

The DOE agrees with CARD that a glacial advance is predictable, but does not envisage a return to maximum Pleistocene conditions within the next 10,000 years (Appendix CLI, Section CLI.8). The cyclical nature of climate changes was considered in the model of Corbet and Knupp (1996). Three historical wet cycles during the Holocene have been identified and presented in Appendix CLI of the CCA.
Corbet and Knupp (1996) included these cycles in their analysis and used two models for future climate evolution:

(i) An increase in precipitation 500 years into the future, which then remains constant for the next 10,000 years (the "step" pattern).

(ii) Cyclical increases and decreases in precipitation every 2,000 years (the "Holocene" pattern).

The recharge rates used by Corbet and Knupp (1996) for the Holocene were varied for sensitivity analyses, but the range was limited to values that did not result in unrealistically high simulated heads for the present. This modeling was used to parameterize the Climate Index, a multiplication factor for the Culebra flow velocities to account for the effects of future climate change in the CCA (Corbet and Swift, 1996; Appendix PAR. Parameter 48). The CCA allows for a factor of 2.25 increase in Culebra flow velocity due to increased precipitation in the future. This method of accounting for the effects of future climate change was considered adequate by the Conceptual Model Peer Review Panel (Appendix PEER, Section 1, Part 3.18).

The observation by CARD that future runoff and precipitation could cause Laguna Grande de la Sal to overflow into the Pecos River is irrelevant to the performance of the disposal system, because modeled radionuclide releases are summed at the LWA boundary for evaluating regulatory compliance. Such surface phenomena are screened out of the performance assessment on the basis of low consequence (Appendix SCR, Section SCR.1.5.4).

Potable Water

CARD repeats the documentation given in Appendix USDW of the CCA of water quality and quantity as determined from boreholes in the Dewey Lake Redbeds and Rustler Formation. However, no water in the vicinity meet the EPA's definition in the rule of an underground source of drinking water (USDW) so DOE conservatively developed its own criteria for a hypothetical USDW. The DOE indicates in the CCA that potable water (as determined by the DOE criteria of TDS < 10,000 milligrams per liter and production of > 5 gallons per minute) occurs in the Magenta and in the Dewey Lake within the LWA, and are also possible outside the LWA in the Dewey Lake and Santa Rosa Formations. Note that none of the occurrences of potable water meet the EPA definition of a USDW because they do not meet the EPA criteria for a water distribution system, and therefore, no underground waters met the EPA's definition of a USDW in the vicinity of WIPP. CARD criticizes the DOE for not undertaking further investigation of possible USDWs. However, the DOE has taken a bounding approach in demonstrating compliance with the EPA's groundwater protection requirements of 40 CFR § 191.14. The bounding analysis assumed that all
of the radionuclides reaching the accessible environment were available to a hypothetical USDW at the edge of the LWA. Even with such an unrealistic assumption, releases were well below the regulatory standards for drinking water (see Chapter 8 of the CCA). Therefore, further characterization of possible USDWs would be of no consequence to meeting the groundwater protection requirements and would be an inappropriate use of resources.

Use of Borehole Data to Parameterize CCA models

CARD questions some hydraulic properties used by Corbet and Knupp (1996) and inferred from geological observations (Comment #18). CARD also raises the question of how the DOE can be sure that the site characterization boreholes have captured the range of Culebra transmissivities (e.g., last full paragraph on p.3 and last paragraph on p.13 of Comment #20). These questions are addressed below by considering the derivation of both regional- and local-scale hydraulic model parameters.

Regional-scale hydraulic parameter values

The DOE realizes that a limitation of the basin-scale three-dimensional groundwater flow modeling is the necessary coarse discretization of the hydraulic properties. To approximate hydraulic values within a broad area by using the highest measured value, however, would be neither realistic nor conservative. The approach of Corbet and Knupp (1996) is documented in Sandia record package SWCF-A 1.2.07.1:PDD:QA: Non-Salado: Culebra Transmissivity Zone: CLIMTIDX/GLOBAL. As a first approximation, Corbet and Knupp estimated average hydraulic conductivities using the geometric mean of measured values and, where necessary, published values for similar, intact rock-types. They then modified the values where appropriate to account for the effects of post-depositional processes comprising Salado dissolution, dissolution of pore- and fracture-filling minerals, and interaction with halite deposits. As discussed above, the DOE considers that fracturing and disruption of Rustler strata resulted from collapse after dissolution of the Upper Salado and not, as contended by CARD, from extensive dissolution of Rustler evaporitic salt deposits. The mapping of the boundaries marking the extent of these processes is clearly described by Corbet and Knupp (1996) and the supporting record packages. There are two approximations in the boundary mapping that prevented accounting for all local-scale variations: the regional scale of the map, and the discretization of the boundary into 2 kilometer lengths.

The 2 kilometer by 2 kilometer cell dimensions mean that details within the region covered by the site characterization cannot be represented. Corbet and Knupp (1996) acknowledged that local-scale observations, such as some of those made by CARD, are not reproduced. This limitation was offset by placing emphasis on results from...
simulations that reproduced the larger-scale features of the modern-day flow pattern. Because of the heterogeneous hydrological nature of the Rustler Formation, there is considerable uncertainty in deriving large-scale values of hydraulic conductivity and recharge rates from the available observations. Therefore, Corbet and Knupp (1996) examined the sensitivity of model results to the assumed values of conductivity and recharge, and placed more emphasis on observations of the behavior of the system that were less sensitive to changes in these parameters. An example of such an observation is that nearly all outflow from the Culebra beneath the site is by lateral flow.

CARD claims that the hydraulic conductivity value used for the Dewey Lake unit is a wild guess, quoting data from two wells as examples of higher values. In the modeling of Corbet and Knupp (1996) the hydrological unit representing the Dewey Lake also represents the overlying Triassic rocks. The value for this unit used by Corbet and Knupp (1996) was based on literature data for similar rock-types. Attempts to measure the conductivity of the lower Dewey Lake rocks have failed because of its extremely low value. CARD states that the Triassic rocks have a sufficiently small conductivity to "block" recharge. Therefore, use of the highest measured conductivities in the Upper Dewey Lake would have been unrealistic.

**Characterization of local-scale transmissivity**

The DOE recognizes that the transmissivity of the Culebra varies significantly across the WIPP site. It is not, therefore, possible to estimate the transmissivity with certainty at all points of interest from only a limited number of boreholes. One generally accepted method of representing such heterogeneity is through use of a stochastic model (e.g., de Marsily, 1986). Such models assume that the spatial variation is random. However, in using a stochastic model approach, the DOE has ensured that the pattern of transmissivity generated by the model is constrained by actual observations, (i.e., the borehole data). The CCA uses one-hundred generated spatially-variable transmissivity fields to capture the uncertainty associated with the spatial variability of the available data.

As with any modeling, the question arises as to how many data are required to build sufficient confidence that the model is an adequate representation for the purposes of PA? This question can be examined in a number of ways for the stochastic model used by the DOE:

- **Examine the fit of the calculated field to the calibration data.** Section TFIELD.4.2.2 of the CCA compares steady-state heads and transient heads from pumping tests with those calculated using the generated transmissivity fields. The fit is good. An improvement over earlier work was noted and attributed to use of a finer grid in the WIPP site area and to an independent
optimization of the properties for the higher and lower transmissivity portions of the model. These two conditions produced higher transmissivities connected in a more tortuous fashion than in previous WIPP PAs.

- **Examine the changes in the calculated fields caused by the introduction of more calibration points.** The sensitivity of modeling results to the number of transmissivity measurements used to condition the stochastic model was examined within the INTRAVAL program (Andersson et al., 1996). An independent team of modelers from AEA Technology in the UK performed three hundred realizations of their transmissivity field model using 0, 10, 20, and 39 transmissivity measurements for conditioning (Figure 4.13 of Andersson et al., 1996). The reduction in uncertainty for their model was large between the realizations using 0 and 10 measurements, and reduced further between the realizations using 20 and 39 measurements, which indicate appropriate data incorporation to allow reliable estimates of transmissivity variations.

- **Examine the sensitivity of transport calculation results to fields generated with different numbers of calibration points.** Because of the retardation of radionuclides in the Culebra, the final CCDFs calculated by the CCA are, in fact, not sensitive to the Culebra transmissivity and, therefore, are not sensitive to changes in the generated field. No releases to the accessible environment were calculated with any of the one-hundred generated transmissivity fields.

The transmissivity fields are generated from data that cover several orders of magnitude. The DOE has already drilled a number of boreholes and conducted pump-tests to investigate proposed karst features and to ensure that no outlying high transmissivity areas are omitted from the modeling. The method of generating the transmissivity fields, the number of fields generated, and the range and number of observed data used to condition the fields ensure that the behavior of groundwater flow in the Culebra and the associated uncertainty are captured in the PA. The DOE’s modeling approach has been corroborated by the Conceptual Model Peer Review Panel, who state (Appendix PEER, Section 1, Part 3.2.2.4):

> “The existing transmissivity field models seem to cover the regions of greatest concern to site performance with what appears to be an adequate testing data distribution to rule out local variations in flow significant to performance of the site. The density of field testing data seems to be adequate.”

It is not clear what point CARD is trying to make with the documentation of measured heads in Table 2 of Comment #22. The DOE agrees that differences in hydraulic heads between boreholes can be used to constrain groundwater flow directions. This is true for both porous isotropic media and for fractured rocks where
fracture lengths are short compared to the distances between the head measurements. Table TFIELD-3 in Appendix TFIELD of the CCA presents essentially the same Culebra head data as that documented by CARD. However, there are slight differences between the data presented by the DOE and CARD because the DOE has re-analyzed well data and recalculated the steady-state head data to eliminate, to the extent possible, the effects of drilling, construction and well testing (see Section TFIELD.2.2.4). The head data presented by the DOE have been contoured as continuous smooth surfaces, arguing for a continuous flow field. As stated above, a comparison of the observed Culebra heads with those calculated using the conditionally-simulated Culebra transmissivity fields used in the CCA show good agreement. Therefore, the groundwater flow directions calculated by SECOFL2D are consistent with the observed Culebra heads.

The observed Culebra heads are consistent with the assumption that the Culebra is acting as a drain for overlying units. CARD claims that heads at WIPP-25 and H-6 indicate upward flow from the Culebra to the Magenta. Of the sixteen wells for which head data are available for both the Culebra and the Magenta, thirteen wells clearly indicate downward flow, two indicate downward flow within the range of uncertainty (WIPP-25 and WIPP-27), and one shows equal heads in both units and is, therefore, indeterminate (H-6). WIPP-25 and WIPP-27 are in Nash Draw where collapse has disrupted the confining layer between the Magenta and the Culebra. Flow paths in Nash Draw and beyond the accessible environment boundary are of no relevance to the compliance calculations and/or, to the validity of the assumptions made in the two-dimensional CCA model of the Culebra.

Adequacy of the CCA Model for Culebra Hydrology

The conceptual and mathematical models for groundwater flow and transport in the Culebra have developed iteratively over the last decade using input from field tests, preliminary performance assessment analyses, and peer review (e.g. Sandia, 1991, 1992-1993). The Culebra has non-uniform properties, both horizontally and vertically. For CCA purposes, it is necessary to capture the effects of this variability in order to derive robust predictions for radionuclide transport. The term robust is used here to mean as realistic as possible, given the variability and uncertainty associated with the system, but without overpredicting the retardation performance of the system. In some cases, the DOE has chosen to make conservative, simplifying assumptions to capture the effects of variability and to bound uncertainty. The iterative cycles of preliminary performance assessments, field tests, and sensitivity analyses have been aimed at achieving a robust representation of the Culebra in the CCA.

CARD makes several comments concerning the adequacy of the CCA model for Culebra hydrology and radionuclide transport. The majority of points made by CARD...
have been dealt with in the general response above. The remaining points are addressed specifically here.

**Comment#8  Fracture Characterization**

The DOE recognizes that the Culebra has a complex fracture network. There is also the potential for some vertical flow. As CARD notes, the distribution of Culebra fracture types is not predictable. The DOE considers it doubtful that even a very costly slant-hole drill-coring program would allow development of a fracture network model that accurately represented the distribution of fractures in the Culebra. The uncertainties in the hydrogeological character of the Culebra have led to the development of a hydrological model for CCA based on well data. As the Conceptual Model Peer Review Panel noted (Appendix PEER, Section 1, Part 3.2.1), the large number of hydrological tests within the LWA, the variety of types of testing, and the long period of monitoring suggest that the DOE's flow model is sufficient to answer compliance-related questions about the Culebra. The DOE has adopted a simplified and conservative representation of the Culebra flow field. The Culebra is treated as confined in order to maximize lateral flow and minimize travel times to the accessible environment. For the same reasons, the fractures are assumed to be horizontal and continuous (interconnected).

**Comment#10  Use of Darcy's Law**

For a rock system of parallel and continuous fractures with laminar flow, an equivalent hydraulic conductivity can be defined based on the conductivity of the fractures, the conductivity of the matrix, and the fracture apertures and spacing. Applying Darcy's Law, this equivalent hydraulic conductivity can be used to approximate flow in the fractured rock as an equivalent porous medium (e.g., de Marsily, 1986). Such approximations assume that water flow is in steady state. In transient systems, the transmission of pressure variations tends to occur more quickly in the fractures than in the matrix (double porosity), and time-dependent derivations of Darcy's Law are used. Results of hydrological tests on wells completed in the Culebra are consistent with the response of a heterogeneous medium obeying Darcy's Law (Jones et al., 1992). Results of some well tests have indicated double-porosity behavior during the early part of the test (Jones et al., 1992). However, the time of pressure equilibration between the different porosities is short compared to the time considered in the WIPP PA. Therefore, for the purposes of fluid flow calculations in the PA, the DOE models the Culebra as a heterogeneous, single-porosity medium obeying Darcy's Law. This CCA model, together with the generated transmissivity fields, reproduces the observed heads (contoured as a smooth potentiometric surface) in the Culebra (Appendix TFIELD, Section TFIELD.4.2.2). The DOE considers this to be an adequate demonstration of the robust nature of the model, including the appropriateness of assuming Darcian flow.
Comment#11 Treatment of the Culebra as a porous, homogeneous medium with continuously varying properties

It is clearly stated in the CCA (Section 2.2.1.4.1.2) that Culebra transmissivity is controlled by the abundance of open fractures. However, for CCA purposes, the movement of water through both fractures and matrix is approximated by a model of a heterogeneous, single-porosity medium obeying Darcy's Law. The transmissivity fields used in the CCA model are based on the transmissivities measured from field tests. There is no evidence of significant (i.e., large-scale) zones with higher transmissivity than those already observed in the boreholes used to condition the CCA model.

Comment#12 Treatment of the fracture flow as isotropic

As stated above for Comment #8, even an extensive slant-drilling program is unlikely to allow development of a model to predict fracture distributions and orientations. Therefore, the DOE represents the Culebra as a single-porosity medium with a spatially-variable transmissivity in the PA. This stochastic model reproduces the observed transmissivities and heads, and captures the uncertainty due to the heterogeneous nature of the Culebra. The approach taken by the DOE is more robust than it would have been if we had attempted to characterize a randomly-oriented fracture set.

Comment#13 Use of a two-dimensional representation for the Culebra

The use of a two-dimensional horizontal representation of the Culebra in SECOFL2D is a simplified implementation of the actual three-dimensional groundwater flow system. Three-dimensional modeling of the regional groundwater flow in the Rustler Formation has been performed to help understand the system and guide its conceptualization for the purposes of the CCA (e.g., Davies, 1989; Corbet and Wallace, 1993; Corbet and Knupp, 1996). Corbet and Knupp (1996) actually used nine hydrostratigraphic units to model the Rustler, rather than the five suggested by CARD.

Corbet (1995; Appendix MASS, Attachment 15-7) also carried out an analysis specifically to ensure that the two-dimensional model is adequate for estimating actinide transport within the PA. This analysis showed that, although a significant amount of vertical leakage occurs into the Culebra, all of the outward flow from the LWA was by lateral flow along the Culebra. Therefore, the two-dimensional model accounts adequately for the release pathways. The impact of neglecting vertical leakage when calculating transmissivity from transient pumping tests is small because the length of time of the pumping tests is too short for significant leakage to occur. However, accounting for possible changes in boundary conditions with time for the
two-dimensional model must consider the effects of changes in vertical leakage at the basin scale. This has been done using the three-dimensional groundwater basin flow model (Corbet and Swift, 1996; Appendix PAR, Parameter 48).

**Comment #15 Treatment of matrix diffusion**

Attachment 15-6 of Appendix MASS of the CCA documents that tracer tests at the H-11 and H-19 hydropads could not be interpreted by models allowing for heterogeneous hydraulic conductivity alone. These tests corroborate previous evidence for double-porosity effects and matrix diffusion affecting transport in the Culebra (Jones et al., 1992). The Culebra transport model (SECOTP2D) therefore accounts for advection through fractures and other permeable porosity, dispersion during advection due to heterogeneity, and matrix diffusion. The derivation of the parameter values used to characterize these processes is described in Attachments 15-3 and 15-6 of Appendix MASS, and Appendix PAR, Parameters 35, 49, 50, and 51. The advective and diffusive porosities and the half-matrix block length are sampled parameters, the upper and lower range limits for which are based on field and laboratory observation. These parameters, therefore, capture the uncertainty due to the heterogeneous distribution and size of Culebra fractures and porosities.

CARD is correct in stating that matrix diffusion becomes less important as fracture apertures widen and groundwater flow rates consequently increase. Double-porosity groundwater transport models account for this effect. For the purpose of responding, the DOE assumes that CARD is actually concerned that the CCA model for Culebra transport does not account for dissolution and consequent widening of fracture apertures during the 10,000 year simulation.

Section 8.7 of Appendix FAC of the CCA describes fracture styles in the Rustler Formation. Gypsum fracture fillings usually indicate separation along a single fracture. Several episodes of crosscutting relationships show that the fracture style changed through time. At the WIPP exhaust shaft, arcuate gypsum-filled fractures have slickensided surfaces. The slickensides probably developed as the mudstone units deformed due to loading and unloading. The fractures are observed to be dissimilar to fracturing associated with solution collapse (Holt and Powers, 1988). There is no apparent relationship of WIPP fracturing to dissolution at the WIPP site. The DOE considers that differential unloading is responsible for the majority of the Rustler fractures.

Culebra groundwaters are saturated with respect to gypsum and calcite and supersaturated with respect to dolomite. There is, therefore, no possibility that fracture apertures could increase by dissolution at the present time. Furthermore, for any future climate scenario, it is likely that the groundwater will be saturated with respect to gypsum before it enters the Culebra. There is no evidence that matrix diffusion could decrease over the regulatory period.
Comment#16 Representiveness of $K_d$ values

Radioactive waste disposal programs worldwide base the distribution coefficient ($K_d$) data used in their performance assessments on laboratory measurements. Reasons include cost, logistical constraints, and the difficulty of obtaining meaningful field measurements. The cost and difficulty in setting up and interpreting sorbing tracer tests conclude that such tests can be used only to build confidence in limited parts of a $K_d$ database.

The procedure and rationale followed by the DOE in developing $K_d$ values is clearly set out in Appendix MASS, Attachment 15-1, and Appendix PAR of the CCA. The $K_d$ values used in the CCA have been commented on by the EEG, and the DOE has responded to these criticisms (Response to EEG Comment #12, 7 February, 1997). The observation by CARD implies that the laboratory $K_d$ values have been used directly with no scaling considerations which is not the case. The example given by CARD cannot be considered specifically because CARD does not indicate where the figures quoted came from or even to which radionuclide they apply. However, the DOE considers that the batch laboratory results on crushed rock are representative of the field scale tests because grain sizes and available surface areas at the two scales are similar. This consideration was accepted by the EEG in their February 7 comment and by the Conceptual Model Peer Panel in their Supplementary Report of December 1996 (Appendix PEER, Section 1, Part 3.10.2). It is not appropriate to attempt to scale the data by considering the relative surface areas of crushed rock and fractures; the conceptual model used in the CCA for retardation considers only sorption in the matrix of the rock, not the fractures.

The DOE also conducted flow-through tests on intact rock-cores for comparison with the crushed rock experiments. Breakthrough was not observed for Pu, Am, and Th, even after pumping brine through the cores. Therefore, only minimum $K_d$ values could be derived for these radionuclides. The $K_d$ parameter ranges used in the CCA are consistent with these minimum values. Flow-through tests for U and Np generally yielded lower $K_d$ values than the crushed rock experiments because the contact times in the flow tests were not sufficiently long to allow equilibrium to be reached. Therefore, $K_d$ values derived from the crushed rock experiments are more reliable. Despite this, the $K_d$ parameter range for U used in the CCA was extended to encompass the results of the flow-through tests.

Comment#17 Evidence for clay linings retarding radionuclide migration

CARD is mistaken; the DOE takes no credit for radionuclide retardation on clay fracture linings.
References


*DOE's Response to CARD's March 1997 Letter on the on the WIPP Compliance Certification Application*


Corbet, T.F., and Knupp, P.M. 1996. The Role of Regional Groundwater Flow in the Hydrogeology of the Culebra Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico. SAND96-2133, Sandia National Laboratories, Albuquerque, NM.


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