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WIPP-RELATED GEOLOGICAL ISSUES

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Abstract—The Waste Isolation Pilot Plant (WIPP) is a proposed repository for disposal of defense transuranic (TRU) radioactive waste. Located in southeastern New Mexico, 25 mi (40 km) east of Carlsbad, the repository has been excavated in the Salado Formation bedded salt at a depth of 2150 ft (655 m) below the surface. The concept of geologic isolation of radioactive waste, with the half-life of the radionuclides measured in tens of thousands of years, is to primarily rely on the geologic barriers to keep the radionuclides from leaking to the biosphere. Several geologic features and processes have been identified during the site characterization of the WIPP site that could impact the performance of the repository for the 10,000 year regulatory period. These include salt dissolution, breccia chimneys, brine reservoirs, Salado Formation hydrology, hydrology of the overlying Rustler Formation water-bearing units, disturbed rock behavior and natural resources. These geologic factors are being considered in the analysis of breach scenarios from the WIPP repository for the next 10,000-year period.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is being excavated and constructed to be a geologic repository for permanent disposal of defense transuranic (TRU) waste. It is located 25 mi (40 km) east of Carlsbad, New Mexico. In addition to support facilities on the surface to provide office space to workers and to receive and handle radioactive waste (Fig. 1), there are four shafts (waste handling, construction and salt loading, air intake and air exhaust shafts) that connect the surface to the underground facilities. The project is being administered by the U.S. Department of Energy (DOE), with Sandia National Laboratories

FIGURE 1. An aerial view of the WIPP (courtesy U.S. Department of Energy).

in charge of site characterization and most of the experiments and Westinghouse Electric Corporation as the managing contractors.

The repository is excavated at a depth of 2150 ft (655 m) below the surface and consists of an experimental area to the north and the main repository to the south of the shafts (Fig. 2). The experiments carried out in the northern part of the facility include mechanics of closure of excavations; effect of heat on closure and brine migration; development of plugs and seals to be used to plug the excavations, shafts and boreholes; and the effect of salt creep on the waste drums. The repository itself will consist of 56 "rooms," each 300 ft long, 33 ft wide and 13 ft high (91.5 m x 10 m x 4 m), divided in eight panels of seven rooms each. The seven rooms of the first panel were excavated between 1986 and 1988, since the DOE had planned to start shipping radioactive waste to WIPP in 1988 for an "operational demonstration." Excavation for the other seven panels of the repository has not yet begun.

Transuranic waste consists of various kinds of trash including paper, rubber, wood, metals and sludges, contaminated with radionuclides heavier than uranium with half-lives greater than 20 years and a level of contamination exceeding 100 nanocuries per gram. The waste has resulted as a by-product of nuclear weapons production in the United States during the past 50 years. Only waste retrievably stored since 1970 is presently planned to be shipped to WIPP. Two-thirds of the planned capacity of waste for WIPP is yet to be produced. Two categories of the TRU waste are currently stored at DOE-managed national laboratories and will be disposed at WIPP. The contact-handled (CH-TRU) waste is contained in 55 gallon (0.21 m') mild carbon-steel drums that have a maximum surface-dose rate of 200 millirem per hour. The remote-handled (RH-TRU) waste will be disposed of in 0.85 nf capacity cylindrical canisters with unshielded surface dose rate higher than 200 millirem per hour and up to a maximum of 1000 rem per hour. The 50 hectare WIPP repository has been designed to hold 850,000 drums (176,000 m') of CH-TRU waste containing 9 million curies of radioactivity and 7,500 canisters (7100 m') of RH-TRU waste containing 5

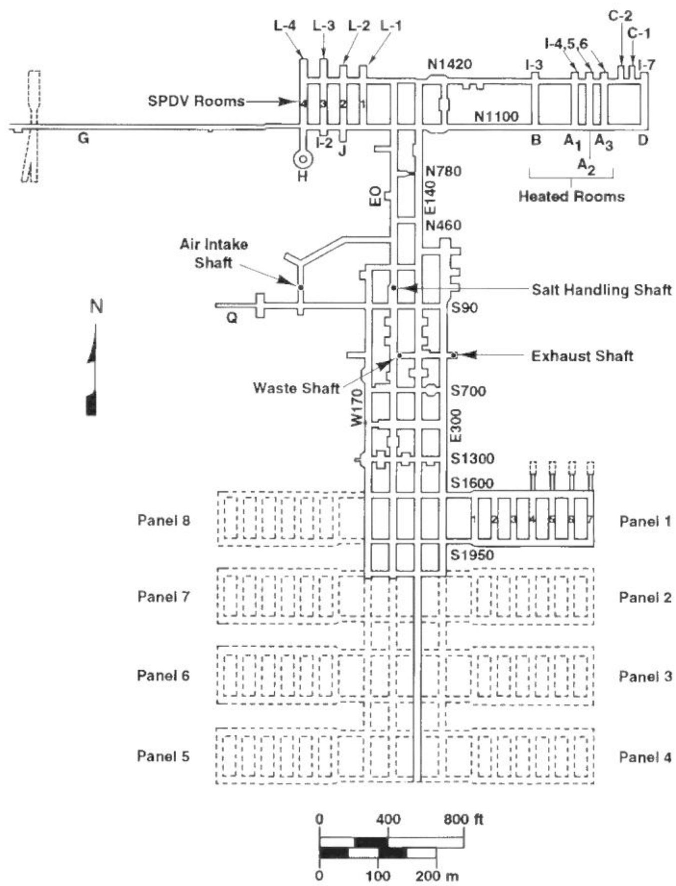

FIGURE 2. Underground layout of the WIPP repository.

million curies. The CH-TRU waste drums will be stacked three high in 56 "rooms" to be excavated in salt. The RH-TRU canisters will be disposed in 36 in. (0.91 m) diameter and 10 ft (3 m) deep horizontal holes.

The TRU waste to be disposed at WIPP consists of both hazardous chemical waste and radionuclides. Its disposal should therefore be according to the requirements of the Environmental Protection Agency (EPA) Standards for the handling and permanent disposal of transuranic radioactive materials (U.S. CFR, 1985), as well as the requirements of the Resource Conservation and Recovery Act (RCRA) (U.S. CFR, 1991). The idea of permanent disposal of the radioactive waste is to isolate it from the environment for a very long period of time. The EPA Standards for radiation protection specify a time of 10,000 years for containment of the waste and require probabilistic risk analyses to assure that potential releases to the environment will have a low probability and not allow more than a specified amount of various radionuclides. The RCRA regulations require assurance of no releases of hazardous materials beyond a specified "unit boundary," which in the case of WIPP has been accepted to be the 2.5 mi by 2.5 mi (4 km x 4 km) WIPP site laterally and up to the top of the Salado Formation vertically.

A geological repository relies primarily on the geology of the site to provide containment of waste for thousands of years. This is especially true for the WIPP project, because there is no commitment to use robust engineered barriers for disposal of the TRU waste. Ninety-seven percent (by volume) of the waste to be disposed at WIPP will be contained in ordinary mild-carbon-steel 55-gallon drums with an expected life of only 20 years, or in Standard Waste Boxes made of plywood or metal. The containers are expected to get crushed and corroded in a few years in the corrosive briny environment of a repository in salt beds and salt creep is expected to close the openings and form a cocoon around the waste. Geologic integrity and the absence of geologic and geohydrologic conditions or processes that may breach the integrity of the repository are, therefore, critical issues in assessing the suitability of the WIPP site for use as a permanent geologic repository for radioactive waste.

The purpose of this paper is to describe and discuss the geological features and processes that potentially may have an impact on the integrity of the WIPP site. Most of the geologic and hydrogeologic investigations pertinent to the WIPP have been performed by the scientists of the U.S. Geological Survey, Sandia National Laboratories, other contractors of the DOE and university researchers. The Environmental Evaluation Group (EEG) has analyzed the importance of various geologic issues and controversies as they have come to light from time to time and has proposed mechanisms and further investigations to resolve them. The EEG is affiliated with the New Mexico Institute of Mining and Technology and has offices in Albuquerque and Carlsbad. It was established in 1978 as an interdisciplinary group of scientists and engineers to provide an independent technical evaluation of various aspects of the WIPP project to protect the health and safety of the people of New Mexico. The group is funded 100% by the DOE.

GEOLOGICAL SETTING OF WIPP

The WIPP site is situated in the northern part of the Permian Delaware Basin. The repository is located at a depth of 2150 ft (655 m) from the surface in the Salado Formation of the Permian Ochoan Series. The Salado Formation is about 1975 ft (602 m) thick at the center of the WIPP site and the repository is situated at a depth of 1300 ft (396 m) from the top of the formation (Fig. 3). The Delaware Basin is bounded by the Permian Capitan Reef (Fig. 4). The basin contains about 15,000 ft (4575 m) of Paleozoic sedimentary rocks overlying the Precambrian basement. The formations of interest with respect to the WIPP project, from the oldest to the youngest, are the Bell Canyon Formation of the Delaware Mountain Group, the Castile, Salado, Rustler and Dewey Lake Formations of the Permian Ochoan Series, the Upper Triassic Santa Rosa Sandstone Formation that tapers from the east to the west across the WIPP site and the Pleistocene Gatuňa Formation. A caliche layer known as the Mescalero caliche is consistently encountered underlying the surficial sands at the WIPP site.

The site lies on a generally flat plain covered with sand, caliche and

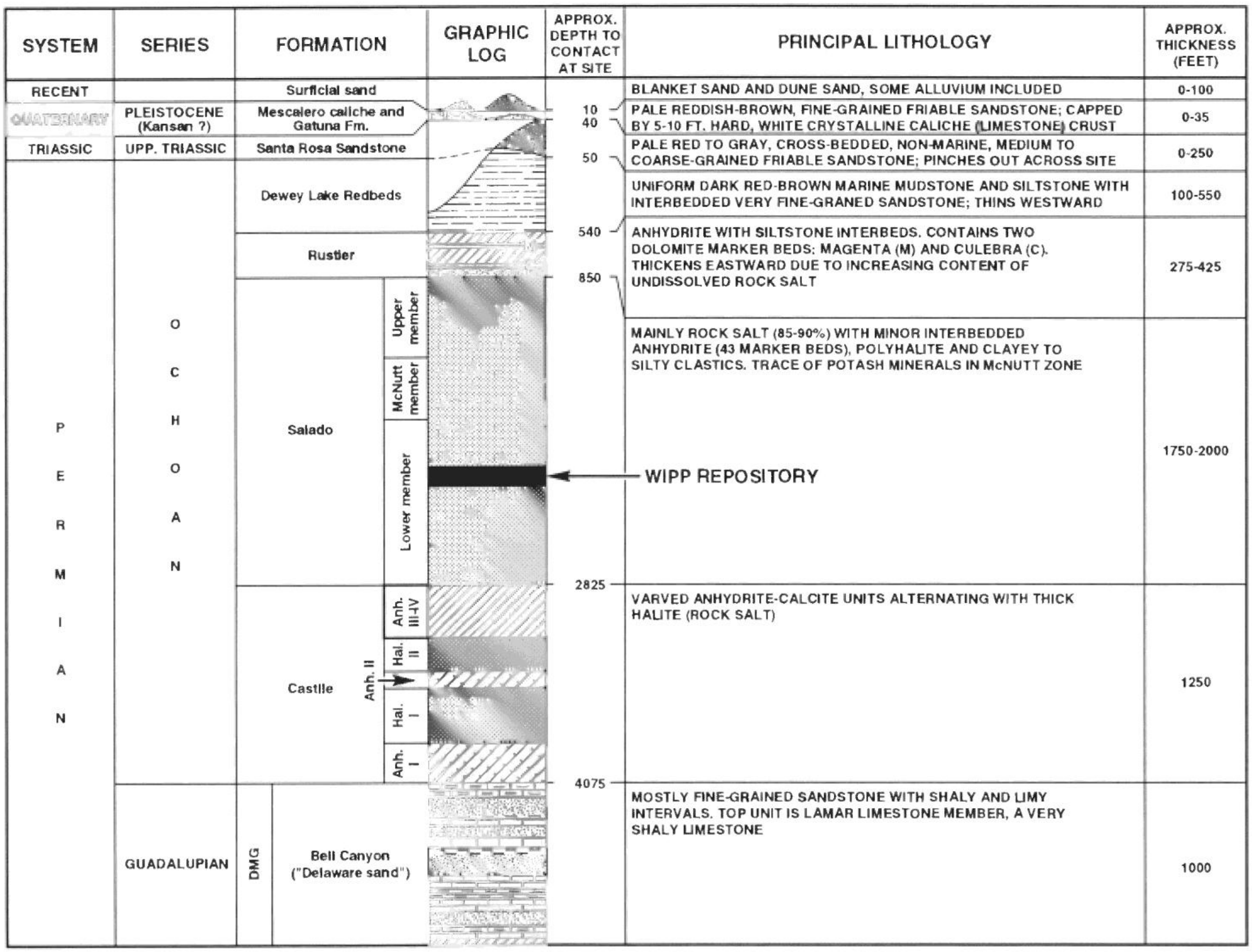

FIGURE 3. Generalized stratigraphy at the WIPP site, including the complete Ochoan section and overlying strata, plus underlying Guadalupian Bell Canyon Formation (adapted from Fig. 4.3-2 of Powers et al., 1978).

desert bushes. It is located in a gypsum-karst region. A subsidence landform feature called Nash Draw lies about 3 mi (5 km) west of the WIPP site. It is 6-7 mi (10-12 km) wide in the east-west direction, about 18 mi (30 km) long in the north-south direction and has resulted from erosion by solution and fill (Lee, 1925) of soluble rocks, a process that has occurred in the past and which is also presently active. The Pecos River flows from northwest to southeast, about 12 mi (20 km) west of the WIPP. Based on the presence of saline seeps along the Malaga Bend of the Pecos River (14 mi southwest of WIPP repository), a marked increase in the salinity of the river south of the bend and the general flow direction of the water-bearing beds of the Rustler Formation, the Malaga Bend has been identified as an area of discharge of the Rustler water from Nash Draw and perhaps even from the WIPP site.

All the formations shown on Fig. 3 are geohydrologically significant. Ground water occurs in the upper part of the Bell Canyon Formation in poorly cemented sandstone stringers (Hiss, 1976). The Castile Formation is about 1500 ft (470 m) thick at the WIPP site and overlies the Bell Canyon. It consists of alternating layers of anhydrite and halite, with four anhydrite and three halite members. The uppermost anhydrite member contains pressurized brine reservoirs that have been encountered by two of the boreholes drilled for the WIPP project and by several oil and gas exploratory wells. The Salado Formation overlies the Castile Formation and the repository is located in its lower part (Fig. 3). The Salado consists primarily of halite with a zone of potassium- and magnesium-bearing minerals (sylvite, langbeinite) and thin (<3 ft) seams of clay, anhydrite and polyhalite. Before 1986, thick salt beds, as in the Salado Formation, were considered essentially dry and impermeable. Observations from the WIPP excavations, however, indicate that the salt beds may be saturated with brine and the salt may exhibit Darcian flow, albeit at very low permeability.

The Rustler Formation overlies the Salado and contains the most important geohydrologic units in the region. The thickness of the Rustler varies between 275 ft to 425 ft (84 m to 130 m) in the northern Delaware Basin and is approximately 310 ft (95 m) at the WIPP site. Sedimentology of the Rustler Formation was described by Lowenstein (1987) and Powers and Holt (1990). The formation contains three recognized fluid-bearing zones; in ascending order the Rustler-Salado contact residuum, the Culebra dolomite and the Magenta dolomite. The transmissivity of the Culebra is the highest, followed by the Magenta and the Rustler-Salado contact. The water quality is highly variable within each unit. The total dissolved solids concentration is lowest in the Magenta and highest in the Rustler-Salado contact zone. Nearly all the water in the Rustler Formation at the WIPP site has total dissolved solid (TDS) concentrations greater than 10,000 mg/l.

All three Rustler hydrologic units probably discharge into the Pecos River, 14 mi (22 km) to the southwest near the Malaga Bend. The recharge areas are identified rather imprecisely as being upgradient of

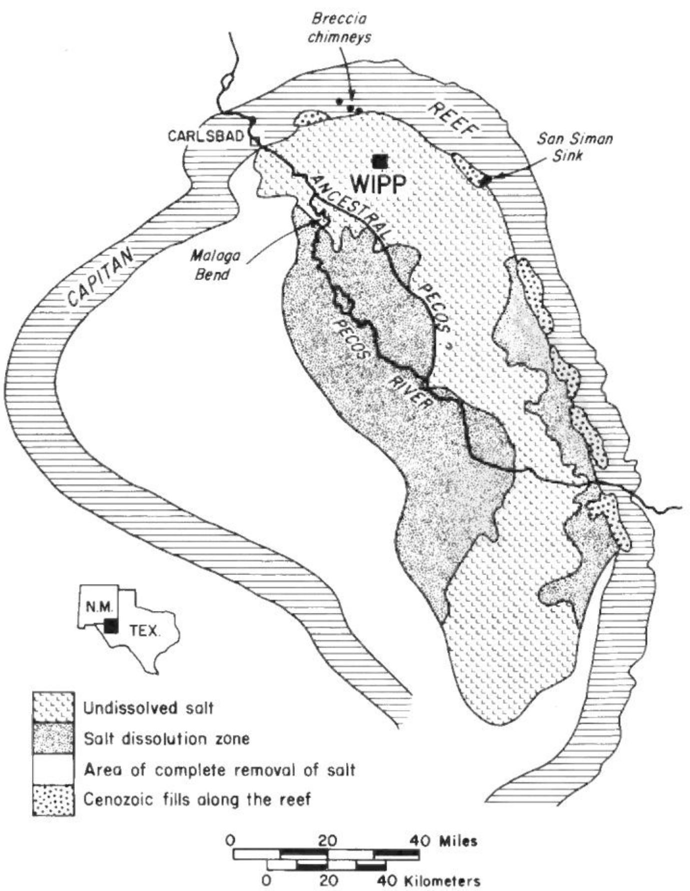

FIGURE 4. Regional extent of removal of salt from the Salado Formation.

the measured hydraulic heads, about 10 to 15 mi (16-24 km) north of the WIPP site. At the WIPP site, the three units are separated but are probably interconnected in Nash Draw, west and southwest of the site. Of the three Rustler units, the Magenta and the Culebra are of prime concern because they extend over the WIPP site, whereas the Rustler-Salado contact zone mainly produces water west of the WIPP site (Mercer, 1983). The majority of testing in the Rustler has concentrated on the Culebra because it is more transmissive than the Magenta and therefore better suited for analyzing bounding breach scenarios.

Results of several single-hole and multihole flow tests (Lappin, 1988) at the site indicate that the transmissivities of the Culebra aquifer at and near the WIPP site range from 1000 ft^2/day ($10^{-'}$ m^2/s) in Nash Draw to 10^{-2} ft^2/day (10^{-8} m^2/s) east of the WIPP site. Generally, transmissivity increases from east to west across the WIPP site. High transmissivity zones occur in the southeastern part of the site, in the area of boreholes DOE-1 and H-11 and in the north-central and northwestern parts in the vicinity of boreholes WIPP-13, DOE-2 and H-6 (Fig. 5).

Chemical composition of ground water from the Culebra aquifer varies widely within short distances at and near the WIPP site (Chapman, 1988). Three miles south of the WIPP site, the Culebra water typically contains 3000 mg/I of total dissolved solids (TDS). At the site itself, TDS varies from 12,500 mg/1 at H-2 (Fig. 5) to 139,500 mg/1 at H-5. Extreme variation in the chemistry of the Culebra water within short distances is illustrated by the TDS at H-2 (12,500 mg/I), H-3 (153,500 mg/I) and DOE-1 (118, 000 mg/I), within a distance of less than 2 mi.

The WIPP is situated in a mineral-rich area. Potash minerals. are mined around the WIPP site from the McNutt potash zone in the upper part of the Salado Formation, approximately 1500 ft (450 m) below the surface. Oil and gas are produced around the WIPP site from the Permian Delaware Mountain Group and Pennsylvanian Atokan and Morrowan strata.

STATUS OF WIPP-RELATED GEOLOGICAL ISSUES

History of WIPP site characterization

The geological site characterization for the WIPP began in 1974, following the abandonment of the Lyons, Kansas site in 1972. A 2 mi by 1.5 mi (3.2 km x 2.4 km) rectangular site was selected by the Oak Ridge National Laboratory (ORNL) about 7 mi (11.2 km) northeast of the present site. Cores from two boreholes (AEC-7 and AEC-8, Fig. 5) penetrating through the Salado Formation drilled at the northeast and the southwest corners of that site indicated acceptable geology. Sandia National Laboratories (SNL) was given the responsibility for site characterization for WIPP in 1975. A third borehole (ERDA-6), drilled by SNL in the northwest corner of that original site in 1975, encountered a pressurized brine reservoir and intense structural disturbance in the fractured upper anhydrite of the Castile Formation at a depth of 2709 ft (826 m). The present site was selected by the SNL and the U.S. Geological Survey (USGS) and a stratigraphic borehole (ERDA-9) was drilled in 1976 through the Salado Formation at the center of the new 2.5 mi by 2.5 mi (4 km x4 km) WIPP site.

Early site characterization activities focused on obtaining basic data on the stratigraphy, hydrology and potash resources at the WIPP site. As these studies progressed, several geologic features or processes that were potentially deleterious to a radioactive waste repository were identified. The EEG organized a meeting of geoscientists in January 1980, and a field trip in June 1980, to discuss these geologic issues (EEG, 1980; Chaturvedi, 1980). Based on the recommendations from these meetings and independent analyses by the EEG scientists, the EEG proposed preparation of a number of topical reports to address the geological issues that had surfaced at that time. These recommendations were accepted by the DOE and a Stipulated Agreement between the State and the DOE was signed on 1 July 1981, that included the DOE commitment to prepare eleven "topical reports" and six "additional investigations." As a part of additional investigations, the DOE deepened the borehole WIPP-12, located 1 mi north of the center of the WIPP site, from its 1978 completed depth of 2737.5 ft (834.5 m) at the top of the Castile, to a total depth of 3927.5 ft (1197.4 m). Pressurized brine associated with hydrogen sulfide gas was encountered at a depth of 3016 ft (919.5 m). As a result, the DOE, following the EEG recommendation, again relocated the repository about 1.25 mi (2 km) south of the planned location that would have brought the repository within a few hundred feet of the WIPP-12 borehole.

The WIPP topical studies were published in 1983 and the DOE claimed that the geologic site characterization issues were resolved. The EEG reviewed the reports and concluded (Neill et al., 1983) that the site characterization work completed until then warranted confidence in the site, but work still remained to be done to answer the remaining questions. Underground excavation began in 1982 and additional issues came to light from the observations underground.

The more important geologic issues relevant to WIPP are described below and the status of their resolution is discussed.

Dissolution of Salado salt

There is indisputable evidence that the Ochoan evaporite deposits (Castile, Salado, Rustler and Dewey Lake formations) have undergone erosion and blanket dissolution in the Delaware Basin. The edges of the Castile and the Salado halite can be traced west of the Pecos River essentially running parallel to it in a northwest-southeast direction (Anderson, 1981).

Based on a 600,000 year dating of the Pearlette **O** ash layer exposed at the ridge on the 200 ft (61 m) deep Nash Draw margin, Bachman (1980, 1981) calculated an average rate of 330 ft (100 m) per million years for the vertical dissolution. Assuming that the edge of the Salado salt has moved from the Capitan Reef front to its present location during the past 7 to 8 Ma (since Ogallala time), Bachman and Johnson (1973) concluded that the horizontal rate of movement of the blanket dissolution front is about 6 to 8 miles per million years. These are, of course, very rough average rates of movement; the front itself may have moved faster under less arid climatic conditions. Also, an advancing "tongue" of the front may reach a point faster than the front itself. Using the

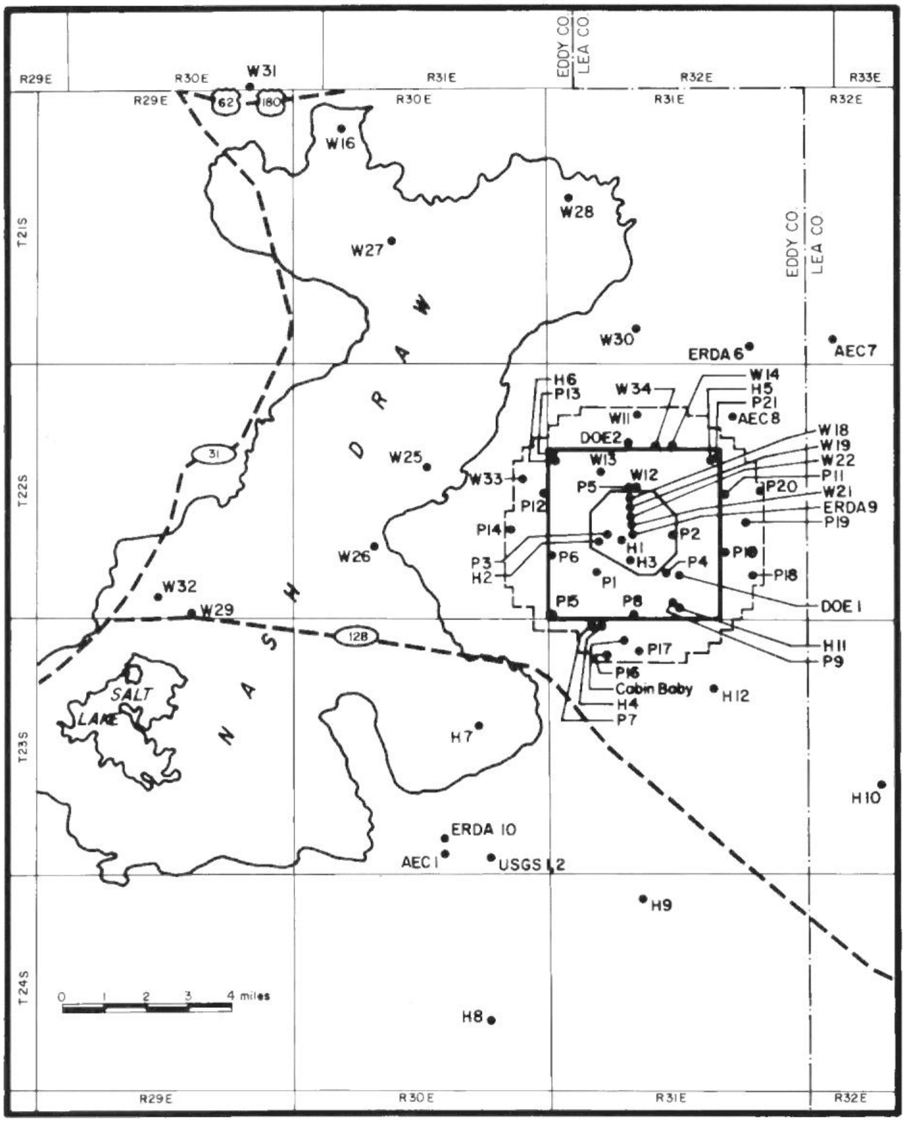

FIGURE 5. The location of boreholes drilled in connection with the WIPP project.

above rates for horizontal and vertical dissolution, it would take approximately 225,000 years for the front to travel approximately 2 mi to reach the western edge of the WIPP site and start dissolving salt from the upper Salado, about 1500 ft (457 m) above the repository horizon. It would then require at least 2 to 3 Ma for the removal of 1500 ft (457 m) of salt by dissolution, at the rate of 330 to 500 ft (100 to 150 m) per million years. In spite of the very approximate nature of the estimated rates of advance of the dissolution front and the possibility of a more rapid advance of a segment of the front, these calculated rates provide sufficient safety from an advancing front of blanket shallow dissolution of salt toward the WIPP site.

In addition to the blanket dissolution of salt described above, Anderson et al. (1972) raised the possibility of a different kind of dissolution process acting at depth from the margins of the basin by noting that large quantities of bedded salt were missing from the middle of the evaporite sequence near the center of the basin. Using the correlation of acoustic logs across several lines in the Delaware Basin, Anderson (1978) concluded that (I) the preferred horizons from which salt has been removed by dissolution occur between the Halite III salt of the Castile Formation and the 136 marker bed of the Salado Formation and (2) the large depressions in the basin, first identified by Maley and Huffington (1953), were the result of selective dissolution of lower Salado salt beds. Anderson (1981) further developed the idea of deep-seated dissolution and concluded that such dissolution has occurred around the margin of the basin where the Capitan aquifer is in contact with the Permian evaporites, and within the basin where selective dissolution in the lower Salado has undercut the overlying salt beds. He calculated that more than 70% of the original salt has already been removed from the lower Salado horizon in the basin.

As requested by the EEG, Lambert (1983) prepared a topical report on the dissolution issue for the WIPP project. Another WIPP project report (Wood et al., 1982) examined the viability of the Delaware Mountain Group aquifer removing the dissolved salt, as hypothesized by Anderson (1981). The EEG (Chaturvedi, 1980; Neill et al., 1983; Chaturvedi and Rehfeldt, 1984) examined the deep-dissolution hypothesis and concluded that although the timing and the mechanism were not fully explained by the hypothesis, the evidence from geophysical well logs did indicate that a large amount of salt from the lower Salado units was missing. However, there were eight WIPP project boreholes (AEC-7 and AEC-8 to the northeast, ERDA- 10 to the southwest, WIPP-11 to the north and WIPP-9, 12, 13 and DOE-1 within the WIPP site, see Fig. 5), which had obtained cores of the Salado Formation but did not show any evidence of extensive dissolution. From this, the EEG concluded (Chaturvedi and Rehfeldt, 1984) that the Salado Formation does not appear to have been affected in and around the WIPP site by past regional dissolution at depth, although an area located 2 mi (3.2 km) north of the center of the WIPP site was suspected as a potential area of point-source dissolution. At the urging of the EEG, the DOE drilled a 4325 ft (1319 m) deep corehole (DOE-2, Fig. 5) to investigate the origin of this feature, which was identified as a structural depression on the basis of observed depression in the anhydrite/clay marker-beds in the potash industry boreholes.

The core from the DOE-2 borehole confirmed the existence of the structural depression but showed no indication of this being due to dissolution at depth. The absence of any dissolution residue and a thickened halite section can best be interpreted as due to gravity-driven salt flow in the area (Borns, 1987). The WIPP repository is no longer considered to be threatened by the effects of the Salado salt dissolution at depth.

Breccia chimneys

A breccia chimney is a solution-subsidence structure formed by dissolution of an evaporite layer at depth that results in collapse of the overlying layers, thus forming a brecciated chimney up to several thousand feet in diameter with its base in the collapsed cavity. These features are found in many evaporite basins of the world. With respect to the WIPP, the concern was that a breccia chimney may form under the WIPP repository sometime in the future, thereby providing a potential pathway for breach of the repository.

Vine (1960) identified as possible breccia chimneys several domal structures in the Delaware Basin that have been explored during the investigations for WIPP. After extensive investigation, the existence of only two chimneys (Hills A and C) was confirmed. Geophysical and geological studies show that two others (Hills B and Wills-Weaver) are also likely breccia chimneys, although they were not cored. All of these features appear to be situated over the Capitan Reef limestone, which is a prolific aquifer in the area. Davies (1983) pointed out that the Hill "C" breccia pipe is located at the southern edge of the buried Capitan Reef and since the borehole WIPP-16, drilled to explore this chimney, was drilled only to the level of the McNutt potash zone of the Salado Formation, it is not clear whether the Hill "C" breccia chimney roots in the Capitan aquifer.

Besides boreholes WIPP-31 and WIPP-16, which were drilled at Hills A and C, respectively, to investigate the breccia chimneys, three other boreholes were drilled at suspected breccia chimney locations in the basin. Borehole WIPP-32 was drilled in a small topographic high in Nash Draw, which had been described by Vine (1963) as a domal karst feature. These features (domal karst) have been extensively studied by Bachman (1980, 1984). Boreholes WIPP-13 and WIPP-33 were also drilled to explore for possible breccia chimneys. There is a marked electrical resistivity anomaly at WIPP-13 and a prominent topographic depression exists at the location where WIPP-33 was drilled. Collapsed breccia was not found at either of the wells.

Anderson and Kirkland (1980) described the occurrence of collapse breccia in a borehole in Culberson County, Texas, about 55 mi south of the WIPP site. Anderson (in Chaturvedi, 1980) described occurrences of "castiles," which are mounds of brecciated rock that crop out a few miles south of the New Mexico—Texas border, south of the WIPP site. Both occurrences are in the exhumed western part of the Delaware Basin, which has already undergone extensive dissolution.

Snyder and Gard (1982) studied the known occurrences of breccia chimneys in the Delaware Basin. They studied in detail the Hill "C" breccia chimney, which is also encountered at the McNutt potash zone of the Salado Formation in the Mississippi Chemical Company potash mine, 1200 feet (366 m) below the surface. From study of this exposure, the core of WIPP-16 drilled in this chimney and the core of WIPP-31 drilled in the Hill "A" breccia chimney, Snyder and Gard (1982) concluded that the breccia chimneys are formed by collapse of the overlying rocks in solution cavities in the Capitan Reef aquifer. Bachman (1980) hypothesized that the location of all the known breccia pipes in a small area over the reef is due to the presence of an old submarine canyon in the reef in this area. On the basis of the presence of Mescalero caliche over the breccia pipes, Bachman (1980) also concluded that the collapse occurred prior to the deposition of this caliche layer, i.e., more than 0.5 Ma.

Davies (1984) also studied chimneys A and C and concluded that they were produced by salt dissolution at the base and within the lowermost portion of the Salado Formation, through incremental subsidence rather than catastrophic collapse of the overlying strata. The EEG concluded (Neill et al., 1983) that the probability of a breccia chimney forming under the WIPP site was fairly remote and that this phenomenon did not appear to pose a threat to the WIPP repository.

Brine reservoirs

Within a few miles of the WIPP site there are at least sixteen reported encounters of pressurized brine in the upper anhydrite layer of the Castile Formation (Fig. 6). Two of these encounters (ERDA-6 and WIPP-12, Fig. 5) were in the WIPP project boreholes and the rest have been reported by oil and gas drilling companies. When borehole WIPP-12, located 1 mi (1.6 km) north of the center of the WIPP site, hit brine at a depth of 3016 ft (919.5 m), brine started flowing out of the well at a rate of 350 gallons per minute (22 liters/sec) and more than 1.14 million gallons (4.3 million liters) of brine flowed out before the well was controlled. Based on an extensive series of flow tests, the brine reservoirs penetrated by the WIPP-12 and ERDA-6 boreholes were estimated to contain 17 million barrels (2.7 billion liters) and 630,000 barrels (100 million liters) of brine, respectively (Popielak et al., 1983). The different pressure potentials and geochemical data from the two encounters suggested a lack of communication between the ERDA-6 and WIPP-12 brine reservoirs. There was no consensus on the origin and the age of the brine reservoirs.

The planned configuration of the WIPP repository and the WIPP experimental areas would have brought the waste within 460 ft (140 m) south of the WIPP-12 borehole. The EEG recommended moving the repository in 1982 and the DOE rotated the repository configuration to relocate the nonwaste experimental area to the north and the repository 1.2 mi (2 km) south of WIPP-12. In 1983, EEG formally proposed geophysical investigations to delineate the extent of pressurized brine in the Castile Formation underlying the WIPP site and particularly under the new location of the repository. The work was performed in 1987, and the results gave a clear indication of the presence of brine under parts of the WIPP repository (Earth Tech. Corp., 1988).

The presence of brine reservoirs in the Castile Formation is a major geological issue affecting the anticipated performance of the repository. Since there are good geophysical indications of the presence of brine in the Castile Formation, 800 ft (244 m) or so below the repository, the inadvertent drilling to a brine reservoir through the repository is a scenario that the WIPP project has to evaluate. Such a drilling sometime during the next 10,000 years would allow pressurized brine to flow into the repository. Several pathways for injection of such contaminated brine into the Rustler Formation or directly to the surface have been postulated.

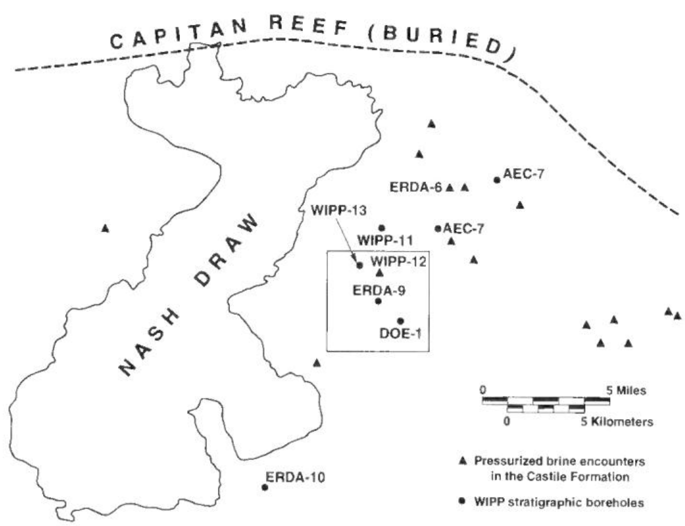

FIGURE 6. Pressurized brine encounters in the Castile Formation in the vicinity of the WIPP site.

Salado brine

A reason for selecting bedded salt deposits for isolating radioactive waste was the assumption that salt would be essentially dry. One of the surprises encountered by in situ underground studies at the **WIPP is that** the Salado salt yields a fair amount of water. A large percentage of boreholes drilled down from the **WIPP** excavations fill up with brine and the walls are covered with efflorescences and encrustations resulting from brine inflow from salt into the excavation and drying up by ventilated air. Several boreholes completed in the Salado Formation indicate fluid pressure buildup (Mercer, 1987). In situ Salado salt has low (10^{21} m^2), but measurable, permeability.

Bredehoeft (1988) proposed that the Salado salt is saturated with brine and exhibits Darcian flow. Nowak et al. (1988) calculated that for salt permeabilities of 10^{-21} to $10^{-2°}$ m2 (1 to 10 nanodarcies), between 4 m^3 to 43 m^3 of brine would accumulate in a typical WIPP repository room with dimensions of 300 ft x 33 ft x 13 ft (91.5 m x 10 m x 4 m). Since the WIPP CH-TRU containers are ordinary 55-gallon mild carbon steel drums that are not expected to last much beyond their 20-year design life, the brine would mix with the TRU waste and may form a slurry. Sandia National Laboratories (1987) calculated that if someone drills into such brine slurry and inadvertently brings a part of it to the surface, EPA Standards may be violated.

Corrosion of the metal containers and metal in the waste would produce hydrogen. Microbiological degradation of the organic material in the waste would produce carbon dioxide and methane. These processes require water to produce gas and the Salado brine inflow will satisfy that need. The rate of brine inflow in the repository is therefore a very important parameter for assessing breach scenarios. DOE has been monitoring and sampling the Salado brine from 13 boreholes in the WIPP underground since 1984 (Deal et al., 1991). After five years of observation, five 50 ft (15 m) deep holes have remained steady producers of brine, one showing increased brine production and five showing decreasing rates. One seep in the floor has produced between 0.15 to 0.2 gallons (0.5 to 0.75 liters) of brine per day for five years. Several holes in the roof and in the walls also have been producing brine.

Hydraulic testing of the Salado Formation at the WIPP repository horizon (Beauheim et al., 1993) shows the brine flow in the Salado salt to be Darcian in nature because the Darcy-flow models are able to replicate the flow and the pressure behavior observed during the entire testing sequences involving different types of tests. The estimation of brine inflow by Nowak et al. (1988) appears to be on sound theoretical basis. Estimation based on actual inflow observation for a long time, under progress now, would provide confirmatory evidence of this calculation.

Rustler Formation hydrology

The Culebra dolomite member of the Rustler Formation, being the most prolific of the three water-bearing zones overlying the WIPP repository, is the most likely pathway for transport of radionuclides after a breach of the repository. Based on three multiwell flow tests, several single-well flow tests and nonsorbing tracer tests at four hydropads, LaVenue et al. (1990) performed ground water flow modeling of the Culebra at the WIPP site**.** The flow model suggests that if radionuclides are injected into the Culebra directly above the repository panels near the center of the WIPP site, the fastest flow path out of the WIPP area would be to the south-southeast past the boreholes H-3 and H-11 (Fig. 5).

The calculated travel time for contaminant transport along this pathway, however, is very sensitive to assumptions of fracturing in the Culebra dolomite and distribution of contributing porosity between the rock matrix and the fractures. If double-porosity flow is assumed, with diffusion of contaminants in the rock matrix, the shortest travel time from the center of the WIPP site to the southern boundary is 14,000 years. If, on the other hand, transport is assumed through fractures only (single porosity), then the travel time would be less than 100 years. Additional multiwell flow tests are required to better define the transmissivity field at the WIPP site. Additional tracer tests designed to better define the fracture vs. matrix porosity flow are also needed. The breach scenario calculations have identified radionuclide retardation during contaminant transport through the Culebra as one of the sensitive parameters that control the magnitude and timing of the postulated releases of radioactivity to the environment. Field and laboratory experiments are required to provide reliable and justifiable numbers for physical and chemical retardation. Laboratory experiments are being set up and initial results are expected in 1993 or 1994.

The WIPP site is situated in a gypsum karst area. The subsidence feature called Nash Draw has been formed by the karstic process of solution and fill (Lee, 1925; Bachman, 1980, 1984). The depression in which borehole WIPP-33 (Fig. 5) was drilled is a karst sink. No positively identified karst feature has been encountered east of WIPP-33 in the WIPP area, nor have hydrologic tests in the area detected any channelized flow. Breach scenario calculations have not considered potential releases through channelized flow or through narrow transmissive layers due to vertical heterogeneity. Such conceptual models would result in greater releases, as shown by Chaturvedi and Channell (1985).

Beauheim and Davies (1992) have proposed a seven-well flow and tracer test to be fielded between H-3 and DOE-1. This test is designed to address the questions of vertical heterogeneity and matrix diffusion and would provide data to better characterize the flow mechanism. It is also intended to use the instruments for a field sorbing tracer test for providing data on chemical retardation processes and properties within the Culebra. This test is planned to begin in 1993.

Disturbed rock behavior

Before underground excavation at WIPP began in 1982, DOE scientists performed calculations to predict the closure history of the excavations. These calculations used the geomechanical properties of the rock strata at the selected WIPP repository horizon obtained from testing of the rock cores from boreholes. The calculations predicted that a **WIPP** room would "close slowly in a stable manner as the salt creeps" and "relative closure values of 0.21 m (8.25 in.) in the vertical direction and 0.28 m (11 in.) total in the horizontal direction are seen for the isothermal room after 10 years" (Miller et al., 1982). The WIPP excavations have behaved very differently than predicted. Vertical closure in the WIPP test rooms has varied between 3 in. (75 mm) and 4 in. (100 mm) *per year* and horizontal closure has ranged between 2 in. (50 mm) and 3 in. (75 mm) *per year.* A "disturbed rock zone" consisting of fractured rock surrounds all the excavations. In less than eight years after excavation, the roof of the first of the four test rooms fell in February 1991, due to fractures propagating above the roof and creating an up to 7 ft (2 m) wide unstable trapezoidal beam between the roof and a thin layer of anhydrite above the roof.

The difference between the predicted and measured closure rates has been explained on the basis of use of the wrong geomechanical models and not taking into account the details of the stratigraphy (Munson et al., 1989). While the faster closure rate will help entomb the waste sooner, it creates problems during operations. The WIPP repository rooms should be excavated just before they are needed for waste emplacement and backfilled soon thereafter. It will also create problems in maintaining retrievability of the waste. Due to its interaction with brine inflow and gas pressure from gases produced by the waste, the room closure rate also affects long-term performance of the repository.

Natural resources

The **WIPP** site is located in a region that contains substantial amounts of potash, natural gas and petroleum resources. Therefore, breach scenarios involving inadvertent drilling by future generations must be considered. The EPA Standards 40 CFR 191 (EPA, 1985, App. B) prescribed a limit of assuming 30 boreholes/km^2/10,000 years, which was based on the drilling frequency in the WIPP site vicinity in 1970s. Judging by the number of producing wells, drilling activity around the WIPP site in 1992 and the number of applications to the U.S. Bureau of Land Management for new drilling permits, the oil and gas resources in the WIPP area are much more prolific than previously considered. This fact must be taken into account in the assessment of the WIPP's compliance with the EPA Standards.

CONCLUSIONS

Since the WIPP repository is designed to rely on geologic isolation for 10,000 years, consideration of the various geologic features and processes are very important to assess the capability of the site to keep. the waste isolated from the environment. The impact of the potentially deleterious geologic factors on the repository will be judged on the results of consequence analyses of potential breach scenarios.

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