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Mr. Jeff Pohle
Division of Waste Management
Mail Stop SS-623
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

RE: SALT

Dear Jeff:

I have enclosed a copy of the review of the following document:

1. Senger, Rainer K., 1985, Investigation of the Possible Effect of Fracture Zones on Ground-Water Flow in the Palo Duro Basin, West Texas: Texas Bureau of Economic Geology, Austin, Texas, OF-WTWI-1985-36.

Please contact me if you have any questions.

Sincerely,

Gerry Winter

Gerry W. Winter

GVW:sl

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WM Project 10, 11, 16
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WMGT DOCUMENT REVIEW SHEET

FILE #:

TEXAS BUREAU OF ECONOMIC GEOLOGY #: OF-WTWI-1985-36

DOCUMENT: Senger, Rainer, K., 1985, Investigation of the Possible Effect of Fracture Zones on Ground-Water Flow in the Palo Duro Basin, West Texas: Texas Bureau of Economic Geology, Austin, Texas.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: March 11, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report under review uses a numerical model to assess theoretically the possible effects of fracture flow on the hydrodynamics of the Palo Duro Basin. The report outlines both geologic and hydrogeologic evidence for the existence of fracture flow in the basin. The implications of fracture flow on the hydrodynamics of the basin are investigated using a two-dimensional cross-sectional model of the Palo Duro Basin. A computer program identified as FREESURF was used for this simulation. The report concludes that if a distinct fracture zone through the evaporite aquitard existed it would have a significant effect on the overall hydrodynamics of the basin if the fracture zone is located near the Caprock Escarpment. The report also concludes that a distinct fracture zone located in the central part of the basin would have much less effect on the regional potentiometric surface than on the deep aquifer.

We find no major problems with the report under review. The results of the study are sufficiently ambiguous that they do not warrant any significant concern. The most significant point presented in the paper is that flow through fractures in fact may occur.

BRIEF SUMMARY OF DOCUMENT:

The report states that the objective of the study is to "assess the potential for leakage through possible fracture zones across the Evaporite aquitard in the Palo Duro Basin on a regional scale" (p. 3). The theoretical effects of fracture zones are investigated using a two-dimensional groundwater flow model constructed along an east-west cross section through the Palo Duro Basin. The report presents both geologic and hydrogeologic evidence for supporting the contention that fracture flow does occur across the evaporite aquitard.

Geologic evidence for the presence of fractures in the Palo Duro Basin includes geophysical logs obtained from wells in the area and from core obtained from DOE wells in the area. Joints and fractures have been observed in outcrops of Triassic and Upper Permian rocks in the area. The report states that joint zones as wide as 40 m have been identified for up to 1 km in distance that extend vertically through the Permian and Triassic beds (Collins, 1984). DOE core indicates that the evaporite aquitard contains the lowest percentage of fractures as compared to the salt dissolution zone and those units below the salt section. The report states that "Fractures in the salt unit occur almost always in a thin mudstone, siltstone, and anhydrite layers" (p. 5). The veins are characterized by a fibrous halite. Open fractures or vein filled fractures are rare within the thicker salt sequences. Fracture trends are northeasterly and northwesterly in Deaf Smith County near the proposed repository site. The fracture trends parallel basement structural trends (p. 5). In-situ stress measurements (unpublished results) indicate that the principal compressive stress is oriented northeast-southwest.

Hydrogeologic evidence supporting the possibility of fracture flow through the evaporite aquitard is based on two pieces of evidence. The first piece of evidence presented in the report is that the measured permeabilities for in-situ salt are on the order of 10^{-2} to 10^{-5} m/d as measured at the WIPP site. The report compares these values to published values for the Pierre Shale in the South Dakota as being 10^{-5} m/d (Bredehoeft and others, 1982). The report states (p. 6) that a comparison of published values of permeability for interbed type materials as compared to the evaporite sequence infers that the "relatively lower permeability of the interbeds as compared to salt permeability may be a controlling factor for fluid flow through the Evaporite aquitard." The second piece of hydrogeologic evidence supporting the concept of leakage through the evaporite aquitard is based on the presence of meteoric waters in the deep basinal brines (Kreitler and others, 1984). Kreitler and others

(1984) suggest that fluid flow through the aquitard may be along fractures as opposed to diffuse flow along grain boundaries.

The report summarizes previous efforts at the hydrogeologic characterization of fractured media. Several references are cited. The primary source for analysis of fracture flow is Snow (1965). Snow derived the following equation:

$$k_f = Nb^3/12$$

where:

k_f = intrinsic permeability,
n_f = porosity,
N = joints per unit distance, and
b = fracture aperture (p. 7).

Snow (1965) states that porosity can be expressed as:

$$n_f = Nb.$$

The report under review states that Snow's analysis does not take into account roughness of the fracture. The report cites other sources that indicate that the flow through a fracture is reduced by roughness and tortuosity. Flow rates can be reduced by up to one order of magnitude as opposed to flow through a parallel plate fracture of constant aperture. The flow rate can be reduced by more than two orders of magnitude if a large fraction of the apertures are small. (The reference to small apertures is not defined in the report under review.) The report also discusses the healing of fractures under applied stress; the report does not discuss mineral infilling of fractures.

Two modeling exercises were conducted for the report. The first exercise simulates fluid flow through a single fracture in a porous matrix. The second exercise simulates fluid flow through a hypothetical vertical fracture zone in the evaporite aquitard. A second exercise is performed within the context of a regional groundwater flow system in the Palo Duro Basin.

Numerical modeling was implemented with the computer program FREESURF. The program was developed by Neuman and Witherspoon (1970). The model simulates two-dimensional steady state groundwater flow in porous media; the program uses the finite element method of analysis. The first modeling exercise was constructed with a constant node spacing of 25 m in the vertical direction for a total thickness of 1,000 m. The node spacing increased from 0.1 m, by a factor of 1.5, to a maximum of 500 m for a total length of 2,000 m in the horizontal direction. This model exercise simulates the half space of fracture and matrix. No flow boundaries are assumed along the right and left boundary of the mesh, which represents the median of the fracture and the median of the porous matrix (the report does not define the term "median" in this context). A uniform recharge flux of 10^{-8} m/d is assumed for the upper surface of the mesh. A uniform hydraulic head of zero is applied to the lower surface of the mesh.

A fracture is represented by a 0.1 m wide element (column) along the left side of the mesh in Exercise 1. The report states that this is an unrealistically large fracture aperture. The hydraulic conductivity of the fracture is represented by a modification of the equation developed by Snow for the permeability of a fracture. The permeability of the fracture is reduced to simulate the fracture with an aperture of 0.1 mm. The fracture permeability is 8.3×10^{-6} cm^2 (hydraulic conductivity = 703 m/d). The porous matrix is assigned a homogeneous permeability of 2.8×10^{-5} m/d (K = 3.2×10^{8} m/d for brine properties) (p. 13).

Simulation T-1 assumes an idealized fracture with a constant fracture aperture of 0.1 mm. The assigned hydraulic conductivity for the aperture is 7.03×10^{-2} m/d. The computed head distribution in this simulation indicates that fluid flow in the vicinity of the fracture is toward the fracture. The maximum head difference along the fracture column is about 1 m. The head difference along the right boundary increases to 295 m.

The hydraulic conductivity of the fracture is reduced by three orders of magnitude to 7.03×10^{-5} m/d in Simulation T-2. The reduction in hydraulic conductivity simulates the effects of roughness and tortuosity in the fracture plane. The head distribution from this simulation indicates that hydraulic gradients near the fracture become largely vertical. Vertical leakage through the matrix portion of the model becomes important for transmitting fluid through the aquitard. The simulation indicates that the imposed flux and head boundary conditions along the surfaces of the mesh are primary controls on the flow pattern of the fracture.

Simulation T-3 assumes that the middle of the fracture is closed for a length of 75 m. The fracture aperture is simulated with a hydraulic conductivity of 7.03×10^{-2} m/d as was used in Simulation T-1. The hydraulic gradients in the vicinity of the closed fracture steepen. Hydraulic gradients above the fracture contact area indicate flow from the open fracture into the matrix. Fluid flow is toward the fracture in the vicinity of the open fractures.

Three closed fracture segments are placed at constant intervals throughout the total length of the fracture in Simulation T-4. Although not stated, it is assumed that the hydraulic conductivity is the same as used in Simulation T-1 and T-3. Simulations with the three closed fracture segments indicate that hydraulic gradients steepen in the vicinity of the contact areas. The total hydraulic head difference across the fracture increases from 130 m in Simulation T-3 to 210 m in this simulation (T-4).

General conclusions derived from this first exercise are that the general flow pattern is governed by the relative permeability contrast between the fracture and the porous matrix. Imposed boundary conditions also govern the flow pattern. The fracture essentially acts as a drain for large values of fracture permeability. The fracture serves as a pathway for fluid flow through the matrix. Fluid flow through the matrix becomes more important as the contrast between fracture and porous matrix becomes less. The hydraulic head perturbations in the vicinity of the fractures is largely controlled by the overall hydraulic regime imposed by the boundaries of the model for low values of effective fracture permeability (p. 17).

The second excercise of this fracture flow investigation used the cross-sectional model across the Palo Duro Basin that was used by Senger and Fogg (1984). This exercise investigated the potential effects of localized leakage through the evaporite aquitard. Hydraulic conductivities that were assigned to the different hydrogeologic units are attached to this review as table 1. These value "correspond largely to those used in Simulation A-3 of Senger and Fogg (1984)." This second exercise investigates the effects of a hypothetical fracture zone that extends through the evaporite aquitard at two different locations. The first simulation (C) assumes that the matrix permeability is extremely small (10^{-7} m/d) (p. 19). Fracture zones are not included in Simulation C (control case). The maximum head difference simulated across the evaporite aquitard is about 400 m. The total flow rate across the aquitard is less than 10^{-6} m^3/d (p. 20).

Simulations E-1 and E-2 test the effect of a fracture zone just west of the eastern Caprock Escarpment. The hydraulic conductivity assigned to the element column representing the fracture zone in Simulation E-1 is 7×10^{-6} m/d. The simulation assumes a fracture spacing of five joints per meter within a 50 m wide fracture zone. The effective fracture aperture in this zone is 0.017 mm. The report states that the actual permeability of the fracture zone is 2.05×10^{-11} cm^2 (hydraulic conductivity = 1.7×10^{-3} m/d) based on Snow's equations. The computed hydraulic heads in the deep section increased as compared to Simulation C. Maximum head difference across the aquitard decreases from about 400 m to about 350 m. Flow across the evaporite aquitard is limited to the fracture zone at about 2.17×10^{-2} m^3/d.

The hydraulic conductivity assigned to the fracture zone element column in Simulation E-2 is increased by one order of magnitude to 7×10^{15} *m/d*. This represents a fracture permeability of 2.05×10^{-10} cm^2. The simulation shows a drastic increase in overall heads in the deep section that reduces the maximum head difference across the aquitard from 315 m in Simulation E-1 to 240 m in Simulation E-2. Hydraulic heads in the deep section become higher than land surface east of the Caprock Escarpment. The report states that these results do not agree with observed potentiometric surfaces in the area. The report states further that the hydraulic conductivity assigned to the element column representing the fracture zone is too high.

Simulation F-1 assigns a hydraulic conductivity of 7×10^{-6} m/d to the fracture zone elements. This hydraulic conductivity is equivalent to the value used in Simulation E-1. The fracture zone in Simulation F-1 has been moved to the approximate center of the basin. The hydraulic heads in the deep section show a maximum difference across the aquitard of about 390 m. Fluid flow across the evaporite aquitard is primarily through the fracture zone. Fluid flow is about 1.35×10^{-2} m^3/d.

The hydraulic conductivity of the fracture zone is increased by one order of magnitude to 7×10^{-5} m/d in Simulation F-2. There is a general increase in hydraulic head in the deep section; the maximum hydraulic head difference across the aquitard decreases to only 340 m. Hydraulic heads east of the Caprock Escarpment do not exceed land surface significantly.

The report notes that it must be remembered that this is a two-dimensional problem. A three-dimensional analysis would alter the hydraulic head distribution due to the interconnectedness of the fracture zones. Hydraulic potential can dissipate in only two directions in a two-dimensional model.

Simulations G-1 and G-2 assign a permeability value of 2.8×10^{-5} md to the unfractured part of the evaporite aquitard. This permeability value is one order of magnitude lower than the permeability value estimated for the regional average used in the cross-sectional model. The hydraulic conductivity assigned to the fracture zone is 7×10^{6} m/d in Simulation G-1. The hydraulic head distribution shows a *maximum* head difference across the aquitard of 373 m in this simulation. This head difference is less than the 390 m found in Simulation F-1. Total flow through the fracture zone decreased from 1.35×10^{-2} m^3/d (Simulation F-1) to 1.34×10^{-2} m^3/d.

Simulation G-2 assigned a hydraulic conductivity of 7×10^{-5} m/d to the fracture zone. This increases the hydraulic conductivity by one order of magnitude. The computed hydraulic heads indicate a minor increase in the overall hydraulic heads in the deep aquifer as compared to Simulation F-2. In summary, local zones of increased permeability indicate that fracture zones near the Caprock Escarpment would have a more pronounced impact on the hydraulic head distribution in the deep system. The report also evaluates the effects of fracture flow on groundwater flow velocities. The report states that the groundwater flow velocities through the hypothetical fracture zones range from 3.15 m/d in Simulation G-1 to 11.8 m/d in Simulation E-2. The report states that groundwater flow velocities can be increased by a factor of two, whereas relative concentrations in a solute may increase by several orders of magnitude by doubling the aperture width from 0.017 mm to 0.034 mm (p. 28).

The report also addresses lateral flow through San Andres Cycle 4 dolomite (p. 28). The report states that the permeability of the carbonate strata ranges from 6×10^{-3} md to 2×10^{-1} md. Flow lines, from vertical leakage through the overlying aquitard, would be deflected horizontally in the carbonate unit due to its relatively higher permeability. The report also states that the overall hydraulic gradient is downward; flow lines in the San Andres Cycle 4 dolomite would be deflected downward into the lower part of the aquitard and then into the "Deep-Basin Brine Aquifer". The report estimates groundwater flow velocity in the carbonate unit based on a Darcian velocity of 9×10^{-7} m/d (p. 29). The velocity is estimated to be 9×10^{-2} m/d based on "a conservatively low estimate of fracture porosity of 10^{-5} (assuming the presence of continuous fractures)."

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

This report is important to the Waste Management Program for two reasons: 1) it evaluates the potential effects of a fracture zone near the Caprock Escarpment and near the center of the basin, and 2) it discusses the existing data that suggest the occurrences of fracture flow across the evaporite aquitard. The report addresses the effect on the hydraulic head distribution in the deep flow system below the evaporite aquitard. The head distribution is of importance because it determines the direction of groundwater flow and is a component in determining the velocity of groundwater flow. The analysis of fracture flow provides another piece in the puzzle regarding the concept of groundwater flow in the Palo Duro Basin.

PROBLEMS, DEFICIENCIES, OR LIMITATIONS OF REPORT:

The report states (p. 4 and 5) that fractures have been found in the strata via surface exposures, cores, and geophysical log interpretations. The report further states that the fractures in the salt unit occur almost always in the mudstone, siltstone, and anhydrite layers. These fractures are characterized by fibrous halite veins. The report under review does not address the possibility that there are zones of open fractures that have not been infilled. We emphasize that this concept is a new idea that has not been addressed by the Texas Bureau of Economic Geology or the Department of Energy. This concept is 'temporal hydraulic conductivity' associated with fracturing prior to the infilling of halite or other materials. The temporal hydraulic conductivity is a potential source of vertical leakage through the evaporite aquitard. The analyses conducted to date are essentially small volume analyses (core, geophysical logs and surface exposures). Of course, surface exposures have a different stress distribution than the formations at depth. The apparent relationships of surface fracturing and jointing to fracturing and jointing at depth are not stated.

The report compares analyses of the Pierre Shale in South Dakota to the siltstones and mudstones found in the evaporite aquitard. The assumption that the hydraulic properties of the materials are similar is not corroborated by evidence presented in the report under review. The report states that it may be inferred that the relatively lower permeability of the interbeds as compared to salt may actually be the controlling factor for fluid flow through the evaporite aquitard. The comparison of results of non-site related material is questionable. We recognize that in-situ testing in the Palo Duro Basin is at its infancy; future testing in the evaporite aquitard should clarify this problem.

The report makes a simplifying assumption to facilitate the analysis of fracture flow. The report assumes that the fractures transect the entire volume of rock (p. 7). We recognize that this assumption was necessary for the modeling efforts; we wish to point out that this assumption is not unrealistic; but it is conservative. A three-dimensional analysis is the only proper means for establishing the relationship between fracture flow and the effect on hydraulic heads in the deep system. Conversely, data for a three-dimensional model are not available and probably will not be available in the near future. Fracture flow modeling is in its infancy; modeling capabilities far outstrip the field of data acquisition techniques.

This report refers to the "Deep-Basin Brine Aquifer"; we have commented on the use of this phrase in a previous review (Orr and Senger, 1984). We will not comment further on our objections to the use of the phrase.

The report states (p. 9) that "Potential fracture planes in these units can be assumed to have a relatively higher percentage of fracture contact areas under great stress as compared to granitic fractures." The units referred to in the quote are mudstone, anhydrite, salt, and carbonate units. References or support for this statement are not provided in the report under review. We are not confident as to the rationale for this statement. A rationale should be provided in the report.

The model uses a variable element spacing (p. 12) ranging from 0.1 m to 500 m in the horizontal direction; vertical spacing was a constant 25 m. The dimensional ratio near the simulated fracture (0.1 m) could create difficulties in the stability of the simulations in the model. The report does not present an evaluation of the sensitivity of the model to element size. We believe that such a discussion should be presented.

We find the general conclusions to be what would be expected for an analysis such as this. We find no major difficulties or concerns regarding the report under review.

REFERENCES CITED:

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Neuman, S.P., and Witherspoon, P.A., 1970, Finite Element Method of Analyzing Steady Seepage with a Free Surface: Water Resources Research, vol. 6, no. 3, p. 889-897.

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Senger, R.K., and Fogg, G.E., 1984, Modeling the Effects of Regional Hydrostratigraphy and Topography on Ground-Water Flow, Palo Duro Basin, Texas: Texas Bureau of Economic Geology, Austin, Texas, OF-WTWI-1984-32.

Snow, D.T., 1965, A Parallel Plate Model of Fractured Permeable Media: University of California, Berkeley, Ph.D. Dissertation, 331 p.

Table 1. Assigned hydraulic conductivity values for the major hydrologic systems.

Hydrologic Unit	Hydraulic Conductivity (m/day) Horizontal (K_x)	Vertical (K_z)
1. Ogallala fluvial system[1]	8.0×10^{0}	8.0×10^{-1}
2. Triassic fluvial/lacustrine system[1]	8.0×10^{-1}	8.0×10^{-2}
3. Permian (salt dissolution zone)[3]	8.2×10^{-2}	8.2×10^{-4}
4. Permian sabkha system[4]	$3.2 \times 10^{-8}/10^{-11}$	$3.2 \times 10^{-8}/10^{-11}$
5. Permian mudflat system[2]	8.2×10^{-5}	8.2×10^{-5}
6. Permian/Pennsylvanian shelf carbonates[4]	1.3×10^{-2}	1.3×10^{-4}
7. Permian/Pennsylvanian basinal systems[4]	1.1×10^{-7}	1.0×10^{-7}
8. Permian/Pennsylvanian mudflat and alluvial/fan delta system[2]	8.2×10^{-2}	8.2×10^{-4}
9. Permian/Pennsylvanian fan delta system	$12.-30. \times 10^{-2}$	$12.-30. \times 10^{-4}$
10. Inner shelf and coastal sabkha systems (San Andres Cycle 4 Dolomite)[5]	1.2×10^{-4}	1.2×10^{-4}

Sources of data:

1. K_x from Myers (1969); assumed $K_x/K_z = 10$.
2. Typical value of geologic material (Freeze and Cherry, 1979).
3. K_x from U.S. Geological Survey open-file data; assumed $K_x/K_z = 100$.
4. After Wirojanagud and others (1984).
5. After Dutton (1983).