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Subject: RECHARGE AND REPRESSURIZATION OF A BEDDED SALT DEPOSITORY	

SUMMARY

A study of depository recharge and repressurization, performed by Golder Associates, has been reviewed. Specific consideration has been given to the validity of two initial assumptions in that study. The first was a decision to ignore lateral flow and end effects into the depository. The second was a decision to ignore thermal effects.

The review has been made with particular concern to assessing the sufficiency of the Golder model for estimation of "worst-case" (minimum) recharge-repressurization time (RRT) in a bedded salt depository. It has been concluded that several errors by Golder may have little net effect on this worst case scenario. Combination of lateral flow and thermal effects may, however, reduce the value of the Golder model for estimation of minimum RRT in a bedded salt facility. Several subjects for further model development are suggested, though the availability of data to support such models is not addressed.

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1.

INTRODUCTION

Estimates for the rate of migration of nuclear wastes from a depository are predicated on the specification of a key initialization time. This marks the point at which the depository first becomes recharged and repressurized by ground water subsequent to sealing of the facility. Errors in estimating the recharge-repressurization time (RRT) affect the waste migration predictions not only as a simple bias, but more importantly because the isotopic composition of the waste changes significantly during the early phases of containment. A "worst case" (minimum time) estimate of the depository recharge-repressurization period was made by Golder Associates (Ref. 1). The purpose of the study reported herein has been to review the adequacy of the referenced study with regard to RRT. The present study has been restricted to consideration of a bedded salt depository with specific concern for possible thermal effects. The effort has consisted of a brief literature and data review. Its scope permitted neither modeling studies nor numerical verification of the results in Ref. 1. The conclusions have therefore been non-rigorously developed, but represent rather the professional judgements of this author. They are, thus, intended purely as guidance for the development of more comprehensive modeling efforts.

2.

TECHNICAL DISCUSSION

The approach taken in assessing the recharge-repressurization problem was to review the methods used by Golder Associates (Ref. 1) and to evaluate them regarding specific application to "worst case" (minimum) recharge-repressurization

time (RRT) estimates for a bedded salt depository. The intent was to assess the approach used in the referenced study, but not to verify their numerical results. Unlike the Golder effort, however, specific consideration was to be given to the importance of thermal effects in estimating "worst case" RRT to assess the need for further model development.

In reviewing Ref. 1 (Section 3.2.1.6) several items were found which deserve further consideration. Perhaps most significant is the assumption ignoring lateral flow in recharging the depository. To date, modeling efforts at TASC have assumed a permeability of 10^{-9} cm/sec in the depository layer for unflawed salt (Ref. 2). More recent considerations have suggested that a value of 10^{-12} cm/sec may even be justified (Ref. 3). Both of these values have, however, been based upon consideration of rock salt on a macroscopic scale where the material is (perhaps reasonably) assumed to be hydrologically isotropic. Depository designs vary, but eighteen feet may be taken as a probable value for the height of the excavated facility (Ref. 1). A depository in undisturbed, bedded rock salt would then have a vertical dimension sufficient to cross-cut a substantial number of bedding planes. Consequently, it is the intra-formational, rather than intra-bed, permeabilities of rock salt that must be considered. Partings along bedding plans, horizons of terrigenous detritus, and cyclic inhomogeneities in the evaporite phases may all result in major increases in flow parallel to the bedding. Since cross-bed flow rate is basically limited by the horizontally continuous halite beds the cross-bed (vertical) permeability should, however, be assumed to be anisotropic, with the permeability parallel to bedding (horizontal) being substantially greater than the experimentally determined values for homogeneous (macroscopically isotropic) rock salt. This author has not determined an appropriate value for the effective

horizontal permeability. It would appear, however, judging from observed micro-stratigraphic studies in undisturbed, bedded rock-salts (Ref. 4), that the effective horizontal permeability could be at least two orders of magnitude greater than the (vertical) values (10^{-9} cm/sec) now being used. If this is true, the net lateral flow through the walls of a typical depository (Ref. 1) would approach in magnitude (see Appendix A) to the total flow through the floor and ceiling as given by Eq. 2-1, [Ref. 1, p. 3-39, Eq. (1)]

$$Q_0 = 2 K_v \frac{H}{D} A \quad (2-1)$$

where:

Q_0 = flow to depository

A = area of depository

H = head drop between "aquifers" and depository

D = distance from "aquifers" to depository

K_v = vertical hydraulic conductivity of depository layer

The recharge time might then be estimated at nearly half that time postulated in that reference. In this regard it is interesting to note that the area of the depository specified in that equation is actually defined as the overall area of the depository, including all pillars. Since extraction ratios of 0.25-0.33 are commonly considered, this requires that 67-75% of the flow specified in the referenced equation must, in fact, enter the depository not by strictly vertical flow, but as water moving vertically until interception of the depository layer, then by lateral flow through the walls of the non-extracted pillars. The latter, of course, is a violation of the initial assumption, that there would be no lateral flow. More importantly, however, it requires a

horizontal permeability on the order of six times (for an extraction ratio of 0.25) the vertical permeability. As argued above, this is completely reasonable, but totally inconsistent with ignoring the overall effects of lateral flow within the depository layer.

Apart from the initial assumptions, several points should be noted with regard to the specification of equations and their algebraic development. One inconsistency in Eq. 2-1 was noted above. A second issue regarding that equation stems from the definition of head, H , as a constant for both aquifers. Where the lower aquifer is confined and the upper unconfined, it would seem to be completely arbitrary and probably unrealistic to assume the heads between each aquifer and the unpressurized depository to be equal.

Another matter arises from the equation for depository void volume, that volume which must be recharged before nuclide migration can occur. Reference 1 (p. 3-40, Eq. 2) suggests the relationship

$$V_m = LenA \quad (2-2)$$

where

V_m = void volume in depository after backfilling

L = height of rooms

e = extraction ratio

n = porosity of backfill material

A = area of depository

Though this equation may be quite adequate for most purposes, any sophistication in the calculation should recognize that

much of the unexcavated rock in the depository layer will have become dewatered during construction and waste emplacement. In addition, due to stress relaxation during excavation the porosity of this rock may be somewhat increased. Such considerations suggest an alternative equation,

$$V_m = L n_1 A + D n_2 \quad (2-3)$$

where

n_1 = porosity of backfill material

n_2 = porosity of dewatered, unexcavated rock

D = volume of dewatered rock

The magnitude of D would depend significantly on the operational history of the repository and the initial permeability of the unexcavated rock. Stress relaxation during excavation could be expected to increase the permeability of that material above the values cited in Ref. 2 for undisturbed salt in the depository layer. Assuming that complete dewatering occurred within the pillars and a zone ten feet wide surrounding the repository, the incremental V_m calculated (see Appendix B), in addition to that suggested by Golder's expression for that value, could be on the order of 30-35% (allowing for increased porosity in this zone from 0.01 to 0.02 due to stress relaxation). The recharge time would be similarly affected though an accurate assessment of that value should probably include the effects of anisotropy on the permeability. Likewise, a thorough evaluation of the impact of stress relief during excavation on porosity and permeability in relation to the dewatered zone would also be required for an accurate estimation of the RRT.

Golder's report next evaluates the time to repressurize the ground water in the sealed repository to its pre-excavation value. They assume that complete repressurization will occur in twice the period that would be required to repressurize the associated void space at the initial flow rate, Q_0 . This may be a reasonable estimate; it is, however, totally unsupported with any stated rationale. Additionally, their specification of the RRT suffers both from the assumptions and approximations previously discussed as well as from a further algebraic error. They suggest [Ref. 1, p. 3-41, Eq. (4)] that

$$V_R = DAHS_s \quad (2-4)$$

where

V_R = volume of water required to repressurize rock

D = distance from repository to aquifers above and below

A = depository area

H = head change in depository

S_s = specific storage of rock mass (the volume of water required to raise the pressure of water in a unit volume of rock by one unit of head)

Combining this with Eq. 2-1 and the assumption that repressurization time, t_R is twice the recharge time at initial flow rate, they suggest that

$$t_R = \frac{2 V_R}{Q_0} = \frac{D^2 S_s}{K_V} \quad (2-5)$$

Erroneously, however, the relationship is given in Ref. 1 [p. 3-41, Eq. (5)] as

$$t_R = \frac{V_R}{2 Q_0} = \frac{D^2 S_s}{2 K_V} \quad (2-6)$$

This error by a factor of two likewise appears in the similarly derived equation for total RRT. Reference 1 [p. 3-42, Eq. (6)] gives for the total unflawed resaturation time (RRT), t_o ,

$$t_o = \frac{LD}{2 K_V H} \left[\frac{DS_s H}{L} + en \right] \quad (2-7)$$

where the algebraically correct relation is

$$t_o = \frac{LD}{2 K_V H} \left[\frac{2 DS_s H}{L} + en \right] \quad (2-8)$$

In an unrelated matter an arithmetic error was made in the discussion of the impact of flaws on RRT. It was indicated [Ref. (1), p. 3-44] that (approximately) 150 failed boreholes per square mile would be required to cause a ten percent increase in hydraulic conductivity. Using Golder's relationship from that page of the reference,

$$K_V = 10^{-9} (1 + 0.007 m) \text{ cm/sec} \quad (2-9)$$

where m is the number of failed boreholes per square mile, it can readily be calculated that only fourteen failures per square mile would produce the specified increase.

On another subject, Golder Associates conclude that "whether the air" (in the depository) "is trapped or escapes" (during recharge and repressurization) "is not important in determining the time to resaturate the backfill unless the repository is shallow" [Ref. (1), p. 3-46]. This is quite

probably true. The potential for an important type of event during repressurization should, however, be recognized. Because of its low viscosity, there exists the possibility that pressurized air may lead to further propagation of incipient fractures within and above the depository layer. A significant increase in the permeability of affected zones could result. It is doubtful that this would occur early enough in the repressurization cycle to shorten appreciably the total RRT. It could, however, be an event of significance to the long term integrity of the repository. This mechanism is mentioned here only because its potential evolution arises from this phase of repository operation.

A final comment with regard to Golder's assessment of RRT concerns their case study evaluation [Ref. (1), p. 3-47]. A small mine was excavated in a copper porphyry orebody in Arizona in order to evaluate certain geohydrological parameters. The mine was then refilled and allowed to repressurize. Good agreement was found between the observed and theoretical rates of repressurization. In this case, however, repressurization resulted from a measured hydrologic conductivity of 2×10^{-5} cm/sec, approximately four orders of magnitude greater than that assumed for bedded salt. The assumption of model validity for an assessment of salt depository repressurization should then be made with caution. It is entirely possible that unmodeled factors play significant roles when the permeability of the surrounding rock is so substantially reduced.

One additional subject for consideration is the importance of thermal effects in estimating the "worst case" RRT. As mentioned previously, this was an area ignored by specific assumption in the study by Golder Associates (Ref. 1). The issue to be addressed here is whether further modeling to include such thermal effects is warranted in order to establish reasonable estimates of the minimum RRT.

Temperature can be addressed in regard to two separate classes of consideration - thermomechanical effects and thermochemical (solubility and phase equilibria) factors. With respect to the former the concern would be the impact of temperature on density, rheological behavior, and fracture criteria as they influence porosity and permeability. It is true that halite has a large coefficient of linear thermal expansion, $4.0 \times 10^{-5}/^{\circ}\text{C}$ for the range $20-100^{\circ}\text{C}$ and $4.4 \times 10^{-5}/^{\circ}\text{C}$ up to 200°C . (Ref. 5). Fracture should be considered as a possibility either as a result of differential expansion in heterogeneous material or due to stress relief in proximity to unconfined interfaces of the depository, where thermal expansion occurred more rapidly than could be accommodated by continuous flow deformation. It is important to realize, however, that such effects would be relatively local and could probably be regulated by proper planning of the thermal load in the depository. Furthermore, since no major phase changes would be anticipated in a bedded salt depository, the total void volume to be recharged would be relatively unaffected by such fracturing (assuming the overall structural integrity of the layer was uncompromised). The only significant factor influencing RRT would then be the enhanced flow rate resulting from the increased permeability.

Similar effects could likewise be postulated as arising from continuous flow deformation in the bedded salt, especially recognizing the dependence of viscous flow rate on temperature. The same arguments would, however, apply. Total void space to be recharged would remain constant while local increases in permeability, due to the opening of new channels (fractures, partings, grain boundaries), could be quite significant. While continuous deformation could increase permeability, it must be stressed that such flow at other scales might have opposing, and hence, beneficial effects.

The importance of the thermomechanical effects discussed above must be placed in proper perspective. Relative to the recharge-repressurization problem they are significant only if occurring within a domain that includes a substantial portion of the hydrological pathways between the aquifers and the depository layer. Otherwise the permeability of the unaffected material would be sufficiently limiting that no effect on the RRT would be expected. Again, this domain of influence can be controlled to some degree by regulation of the thermal load.

Relatively high loading (158 kW/acre) was assumed in a study for the Office of Waste Isolation (Ref. 6). In this case temperatures continued to rise (for an unventilated repository) over the thirty year period studied. Modeled temperatures along a vertical profile through the pillar centerline had (apparently) not reached their maximum values. Yet, for distances approximately two hundred feet above and below the repository the calculations predicted a temperature elevation of about 22°C. This would cause an unconfined linear expansion in halite of over 26%. Considering the thermal gradient through this region it is quite probable that thermally induced fractures would be an important consideration in assessing permeability during recharge over a domain on the order of hundreds of feet in radius from the depository. Any proper evaluation of such mechanisms would require a comprehensive modeling of the thermal history and substantial data regarding the thermal behavior of bedded salt under relatively low confining stresses. Much of this data is available in the literature, including the results of Project Salt Vault (Ref. 7). No effort was made in the present study, however, to determine the sufficiency of available data for the indicated modeling task.

The problem with regard to thermochemical effects appears to be somewhat simpler. There are two aspects -- one regarding phase changes in minor constituents and the other a matter of solubility. If the bedded salt is comprised of reasonably pure evaporites, phase changes should have minimal influence on porosity and permeability. An impure salt, high in clay content, could, however, undergo substantial alteration due to the thermal regime, which might locally produce temperature increases on the order of 125°C (excluding areas in immediate proximity to the buried waste canisters). This and associated thermally induced stresses would be quite sufficient to cause at least some alteration, or dissolution and recrystallization, with subsequent change in the mineralogy and micro-fabric of the rock. Some changes in porosity and permeability must be anticipated. Proximity to the reduced confining stresses near the excavated areas would also tend to produce mobilizing phase disequilibria. The importance of recrystallization in influencing permeability and, hence, RRT must come primarily from laboratory study. Some data appropriate for mathematical analysis of this problem may exist in the literature, though such availability has not been assessed as part of this study.

Finally, with regard to solubility, the most abundant evaporite phase, halite, becomes more soluble in water as temperature increases. The increase is approximately 10% (at 1 atm.) over the range 30-100°C. In contrast, anhydrite has a maximum in its solubility curve at approximately 50°C. It must be anticipated that water infiltrating into the excavation will be saturated with respect to halite at all times. This carries the implication that, during the recharge and repressurization period, net solution of the rock in the depository layer will occur, amounting to perhaps 0.25% of the total recharge water volume. This, of course, would not

be of concern with regard to the actual recharge volume required. There is, however, the consequent factor -- the dissolved salt necessarily came from some region between the excavation and the aquifers. Permeability would be affected significantly only if the dissolution was distributed over a domain of substantial radius, on the order of several hundreds of feet, from the excavated depository. In that case RRT could be substantially reduced and a shorter, "worst-case" time indicated due to the increased flow rates. It is tempting to speculate, because of the high thermal gradient nearer the waste canisters, that dissolution would occur primarily in that area. This, however, is not necessarily true. The actual dynamics of this thermal dissolution scenario are further complicated by the dependence of solubility on pressure. A substantial modeling effort, including accurate calculation of the temperature field and hydrostatic pressure throughout the regions between the depository and aquifers would be required to assess the importance of solubility to minimum RRT estimation.

3.

CONCLUSIONS

There are several operating assumptions and minor errors which compromise the results of Golder Associate's report (Ref. 1) in regard to the estimation of recharge-repressurization time (RRT). Unflawed resaturation time was underestimated due to an algebraic error and the impact of borehole failures was substantially understated due to an arithmetic error. Negligence of lateral flow (an initial assumption) is shown to be a non-conservative approach, possibly causing a 50% over-estimation of RRT. Since these various effects tend to be cancelling, it is doubtful that a reassessment considering these factors alone would produce substantially different estimates of the "worst-case" (minimum) RRT.

Thermal effects may, however, alter RRT calculations. Both thermomechanical and thermochemical effects, including fracture, flow, phase change and solubility, have the potential of increasing permeability. The zone and magnitude of influence for such effects can only be assessed through detailed modeling of the thermal history in the strata surrounding the depository. Particular emphasis must be placed upon "far-field" (50-200 m) solubility effects. Much of this detailed modeling of thermal effects is dependent upon laboratory or field data regarding the temperature dependent rheology and solubility of bedded (anisotropic) salt under relatively low confining stresses. It has not been determined that all of the requisite information is available.

The importance of thermal effects in estimation of "worst-case" RRT lies with the fact that several different mechanisms all have the potential to increase permeability and thus shorten resaturation time. These factors could all be substantially mitigated, however, by reduction of the thermal loading itself. This would simply entail the distribution of the waste canisters over a greater area. The high costs associated with such dilution of the thermal load do, however, indicate the importance of optimizing the canister distribution. Since radionuclide migration is directly keyed to the time of resaturation, an accurate assessment of the RRT, including both thermal and lateral flow effects may be desirable.

APPENDIX A

LATERAL FLOW CONTRIBUTION TO
DEPOSITORY RECHARGE

Assume that bedded salt is hydrologically anisotropic and that the horizontal permeability is two orders of magnitude greater than the vertical permeability. Then for a commonly proposed depository design (Ref. 1) with

ℓ = length of depository ($\sim 13,000$ ft)

w = width of depository (~ 6400 ft)

h = height of depository rooms (~ 18 ft)

the effective perimeter, P , susceptible to lateral flow is simply

$$P = 2 (\ell + w)$$

and the associated area, A_ℓ , has a value

$$A_\ell = Ph = 2h (\ell + w) \approx 7 \times 10^5 \text{ ft}^2$$

In comparison, the effective area, A_v , susceptible to flow through the floor and ceiling is

$$A_v = 2\ell w \approx 1.6 \times 10^8 \text{ ft}^2$$

The ratio, $A_v/A_\ell \approx 2 \times 10^2$. Given the initial assumption regarding relative horizontal and vertical permeabilities in bedded salt it is suggested that lateral flow may approach in magnitude the vertical recharge flow currently being modeled.

APPENDIX B

RECHARGE CHANGE WATER REQUIRED TO
RESATURATE DEWATERED ROCK

Reference 1 suggests that the volume, v_m , of recharge water required to fill the depository is

$$v_m = henlw \approx 1 \times 10^8 \text{ ft}^3$$

where

h = height of depository rooms (~18 ft)

e = extraction ratio (~0.25)

n = porosity of backfill material (~0.3)

l = length of depository (~13,000 ft)

w = width of depository (~6400 ft)

This relationship neglects the water required to resaturate dewatered rock surrounding the rooms. Assuming that the pillars are totally dewatered and an additional zone, ten feet wide and completely surrounding the overall facility are all dewatered, the adequacy of the above expression may be evaluated. Additionally, it will be assumed that the porosity, n , in this zone is increased from 0.01 to 0.02 due to stress relaxation in proximity to the excavation.

The volume, v_p , required to recharge the pillars is simply

$$v_p = h l w n (1-e) \approx 1.2 \times 10^6 \text{ ft}^3$$

The volume, v_b , to recharge the additional ten foot perimeter around the overall facility may be calculated approximately by

$$v_b = \{20[lw + h(l+w)] + 100 \pi (l+w)\} m \approx 3.3 \times 10^7 \text{ ft}^3$$

Summing these components, the net increase in water required is approximately $3.4 \times 10^7 \text{ ft}^3$, an increase of about one-third relative to that predicted by Ref. (1).

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