EFFECTS OF SURFACE COOLING PERIOD ON THERMAL IMPACTS

J. S. Y. Wang, D. C. Mangold, and C. F. Tsang
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

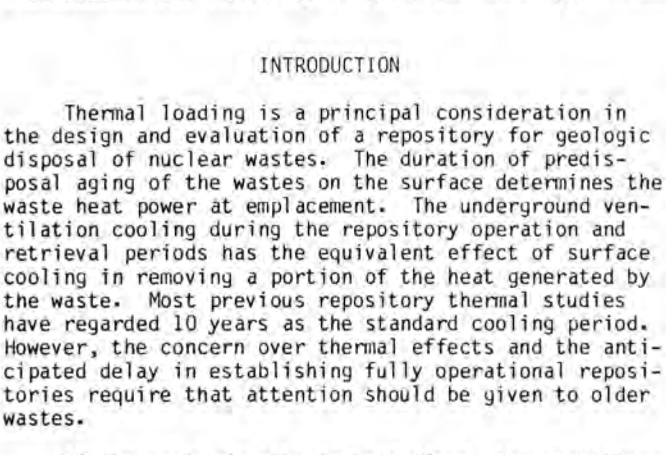
ABSTRACT

We have extended the calculations of repository waste loading to older wastes using the existing near-field thermomechanical criteria. For reprocessed high-level wastes, the older wastes could be emplaced at more concentrated densities, especially in hard rock repositories. For spent fuel with long-lived actinides, far-field criteria are also an important consideration in limiting the waste loading densities. The effects of surface cooling based on far-field criteria are discussed in the paper, including a gap in the current far-field criteria which do not quantitatively address the long-term vertical buoyancy flow from the repository to the surface. The limitations of waste loading densities of older wastes should be carefully determined by imposing both near-field thermomechanical stability criteria and far-field thermohydrologic perturbation considerations.

INTRODUCTION

Thermal loading is a principal consideration in the design and evaluation of a repository for geologic disposal of nuclear wastes. The duration of predisposal aging of the wastes on the surface determines the waste heat power at emplacement. The underground ventilation cooling during the repository operation and retrieval periods has the equivalent effect of surface cooling in removing a portion of the heat generated by the waste. Most previous repository thermal studies have regarded 10 years as the standard cooling period. However, the concern over thermal effects and the anticipated delay in establishing fully operational repositories require that attention should be given to older wastes.

If the waste density is held fixed, the repository temperature will decrease with longer surface cooling periods. Figure 1 illustrates the dependence of the repository temperature rise on surface cooling period for a 0.0083 MTHM/m^2 (33.6 MTHM/acre) spent fuel (SF) repository. This waste loading density corresponds to a standard thermal loading of 10 W/m^2 (40 kW/acre) for 10-year-old spent fuel. With lower temperature rises, the thermally induced strain in salt and stress in hard rocks decrease.



XBL 817-3274

Fig. 1. Temperature rise in a SF repository as a function of surface cooling period, constant waste density loading.

ALLOWABLE WASTE DENSITY WITH NEAR-FIELD THERMOMECHANICAL CRITERIA

If repository design takes advantage of the lower thermally induced impacts by emplacing waste in a more concentrated scheme, proper thermal criteria must be used to determine the optimal waste loadings. Existing criteria are based on the thermomechanical stability considerations for the waste package and repository structural components, and on the allowable surface uplift due to thermal expansion of the surrounding geologic setting. These criteria were developed mostly by studies of 10-year-old wastes.

The existing thermomechanical criteria in the Department of Energy (DOE) reports are expressed in terms of strain of room closure for salt and strength-to-stress ratios for hard rock repositories[1]. Imposing these existing criteria on older wastes enables allowable waste densities to be determined. The salt and nonsalt analyses are discussed in the following two subsections.

Reduction of Strain for Room Convergence in Salt

Room convergence in salt mines depends on the temperature, pillar stress, and time. In Project Salt Vault[2], the results of model pillar tests of rock salt from the Lyons mine were fitted with an analytic formula called Lomenick's formula. It has been frequently used in repository designs for salt as a plastic rock medium. In SI units the formula is

$$E = CT^{9.5}\sigma^{3.0}t^{0.3},$$

where E = cumulative strain, m/m, $T = T_{ambient} + \Delta T$, absolute temperature, K, σ = average pillar stress, Pa, t = time, s, and C = 3.4 E-50. The cumulative strain is therefore a nonlinear function of ΔT. This formula was employed in the National Waste Terminal Storage (NWTS) conceptual designs for domed and bedded salt[3-5], and in the NWTS conceptual reference repository description[6]. In this section we extend the NWTS results for 10-year-old wastes to older wastes.

Table I. Allowable Waste Density Determined by the Near-Field Thermomechanical Criteria.

Surface Cooling Period (years)	Salt SF	Salt HLW	Granite SF	Granite HLW	Basalt SF	Basalt HLW	Shale SF	Shale HLW
	MTHW/acre		MTHW/acre		MTHW/acre		MTHW/acre	
10	126.0	145.2	159.6	183.9	159.6	183.9	100.8	116.1
40	216.1	288.7	282.7	409.2	322.5	474.6	178.5	258.4
100	318.2	450.0	598.1	1605.	711.8	1942.	377.8	1014.

The NWTS reference salt repository contained 10-year-old wastes emplaced at 37 W/m^2 (150 kW/acre) at 640 m (2100 ft) depth with an average pillar stress of 14.5 MPa (2100 psi). The waste storage rooms were 6.1 m (20 ft) wide and 4.8 m (15.ft 9 in.) high. After 5 years, however, the roof height had shortened by 0.23 m (9 in.). Older wastes stored in the same room and at the same waste emplacement density have a lower average temperature rise at 5 years, thereby reducing the cumulative room convergence (Fig. 2). If 0.23 m of room convergence (5% linear strain) is acceptable for safe operations in the repository, the waste emplacement density can be increased. The allowable waste densities for SF and reprocessed high-level waste (HLW) in salt are tabulated in Table I along with the results for hard rocks, discussed in the following subsection.

Reduction of strength-to-stress ratios in granite, basalt, and shale

The stress fields around a room in hard rocks such as granite, basalt, and shale depend on the temperature, the in situ stress field, and the change in load due to excavation. The thermomechanical stability limits for mined repositores in hard rock were established in the Generic Environmental Impact Statement (GEIS) study[7,8]. These near-field criteria determine the repository loading density of 10-year-old wastes.

The near-field thermomechanical criteria are expressed in terms of strength-to-stress ratios[8]. The repositories contain 10-year-old wastes stored at a thermal power density of 47 W/m^2 (190 kW/acre) in granite and basalt and 30 W/m^2 (120 kW/acre) in shale. At 5 years after waste emplacement, the sum of the thermally induced stress and the excavation-induced stress within 1.5 m of the openings is half the magnitude of the rock strength for granite and basalt and equal to the rock strength for shale. Older wastes stored at the same waste emplacement density have a lower average temperature rise after 5 years, and the thermally induced stress is less (Fig. 3). The temperature rises at the end of 5 years are used to determine the stress values. If the same strength-to-stress ratio criteria can be used for older wastes to ensure mine stability, the waste emplacement density can be increased to accommodate more wastes in the repository, as shown in Table I. The temperature dependence of the rock strength is taken into account. The corresponding thermal loading densities are less sensitive to the surface cooling period.

Increase of Waste Emplacement Density

The ratios of allowable waste densities of older wastes (tabulated in Table I) to the values of 10-year-old wastes are illustrated in Fig. 4. It shows that older wastes could be emplaced at more concentrated densities. These results are based on the assumption that the near-field thermomechanical criteria developed for 10-year-old wastes are acceptable independent of the surface cooling period. For reprocessed HLW with a small thermal contribution from the long-lived actinides, these conclusions may be valid. However, for spent fuel repositories, the long-term, far-field effects could become the limiting consideration. This is discussed in the next section.

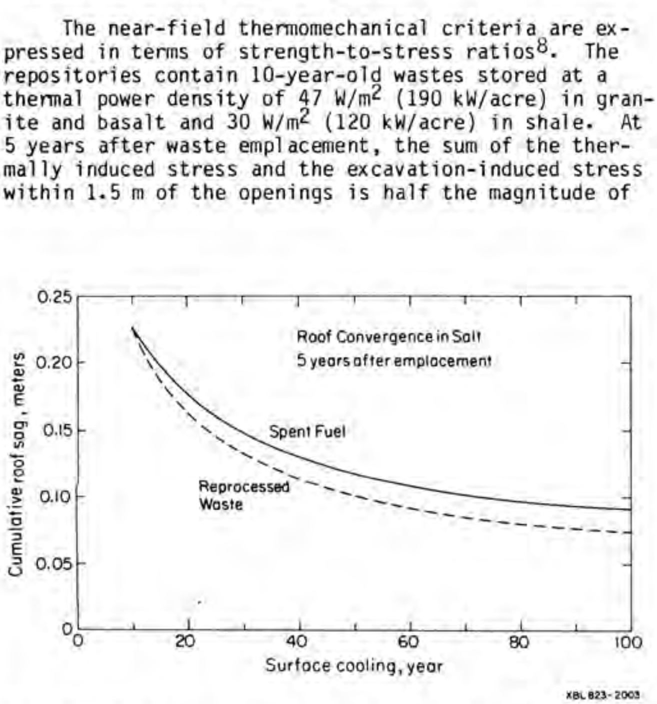


Fig. 2. Roof convergence in salt as a function of *surface cooling period* in SF and HLW repositories.

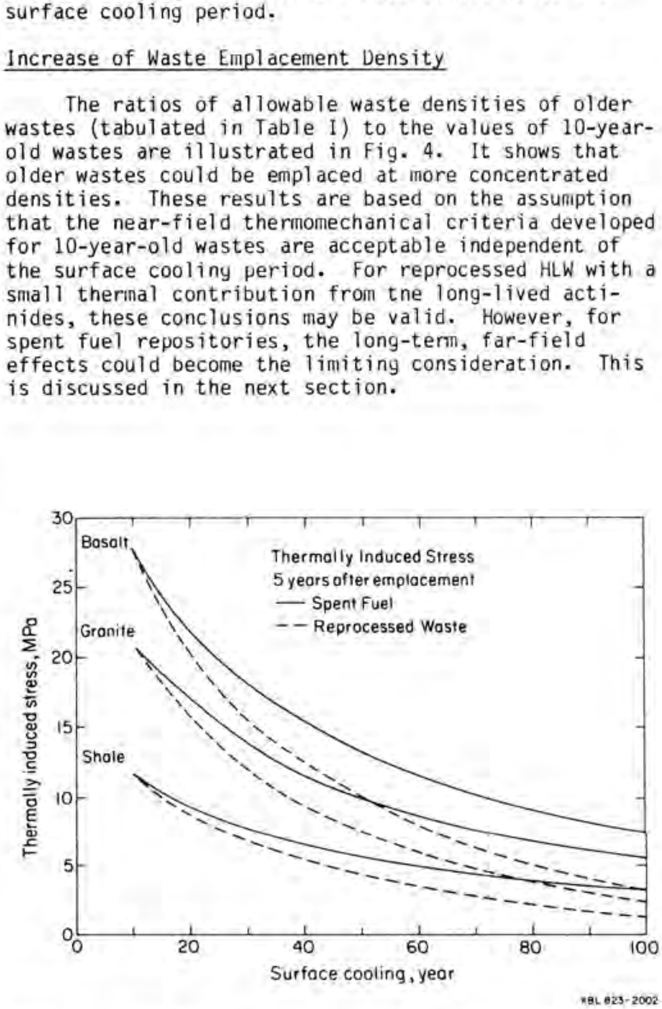


Fig. 3. Thermally induced stress in granite at 47 W/m^2 (190 kW/acre), basalt at 47 W/m^2 (190 kW/acre), and shale at 30 W/m^2 (120 kW/acre) as a function of surface cooling period in SF and HLW repositories.

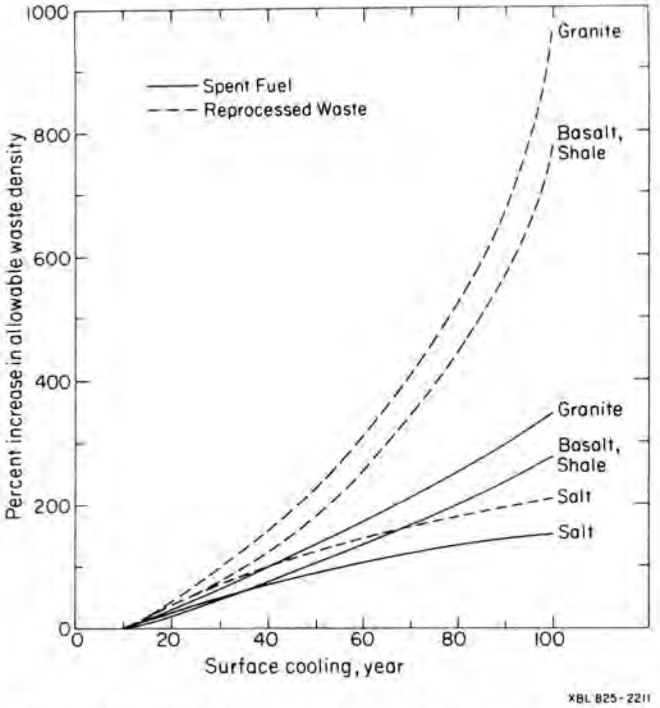


Fig. 4. Percent increase in allowable waste density in four major rock types as a function of surface cooling period for SF and HLW repositories.

Figure 4 also shows that the increase in allowable waste density is modest for salt compared to the results for hard rocks. For salt, the increase in allowable waste density grows at a slower rate for the longer surface cooling times. Thus the option of a longer surface cooling period may be less attractive for salt than for hard rock repositories. The difference in the form of the curves for salt and for hard rocks comes mainly from the different thermomechanical behaviors assumed in the analyses. For salt, the plastic creep strain is proportional to $(T_{amb} + \Delta T)^{9.5}$, where T_{amb} is the ambient temperature in kelvins and ΔT is the waste-induced temperature rise (see Lomenick's formula above). For hard rocks, thermoelasticity is assumed for the stress changes, and the thermally induced stress is proportional to ΔT. As longer surface cooling periods lower the temperature rise, ΔT, the nonlinear temperature dependence of the creep for salt shows less sensitivity to ΔT, resulting in a smaller increase in allowable waste density.

The thermolasticity assumed for hard rocks may be oversimplified in view of the potential nonlinear contributions from the presence of fractures. Additional research is required to study the thermomechanical behavior of fractured rock masses. The temperature dependence of the elastic constants are also not taken into account in the calculations. The dependence of rock strength on temperature, however, is taken into account. Within the temperature range of interest for these calculations (below 120°C or 250°F), granite exhibits a noticeable change in rock strength with temperature, whereas the basalt and shale strengths are almost temperature independent[7]. For cooling periods of 10 to 100 years, this gain in strength with lower temperature permits an approximate increase of 20% in waste density for granite relative to its allowable limit for a fixed strength at 120°C. Since the mechanical properties and rock strengths are highly site specific, the quantitative conclusions in these calculations should be carefully re-evaluated for any specific rock type and any potential repository site.

LIMITATION OF LOADING BY LONG-TERM, FAR-FIELD CONSTRAINTS

The long-term, far-field thermohydromechanical effects depend on the temperature rise in the host rock, especially in the region between the repository and the surface. The temperature rise from the repository to the surface determines the surface uplift and the buoyancy flow. The repository loading density could be limited by these far-field constraints. These constraints are discussed in the following two subsections.

Surface Uplift Considerations

To illustrate that the surface uplift considerations can determine waste loading densities, we will summarize the results of the final Environmental Impact Statement (EIS)[1] on the effect of waste age for salt, granite, basalt, and shale. The existing thermal criteria were used to determine the maximum thermal loading for both SF and reprocessed HLW at 5, 10 and 50 years of age. The loading takes into account the temperature and thermomechanical limits. These limits include the maximum allowable temperatures at waste centerline, canister surface, and borehole wall; the maximum room closure for salt; strength-to-stress ratios for hard rocks; and the maximum allowable surface uplifts.

The final thermal loadings used in the EIS study are shown in Table II. The far-field average loading takes into account the unused passive areas for corridors, etc. A safety margin of two-thirds is included in the results. The limiting parameter is denoted by

Table II. EIS Thermal Loadings for Waste Repositories (W/m^2).

Formation	Age of Waste at Emplacement (year)	Spent Fuel		HLW	
		Near-Field Local Loading	Far-Field Average Loading	Near-Field Local Loading	Far-Field Average Loading
Salt	10	12	10*	25*	19
	50	6	5*	17	13*
Granite	10	32*	26	32*	25
	50	23*	19	30*	23
Basalt	10	32*	26	32*	25
	50	23*	19	30*	23
Shale	10	20*	16	20*	15
	50	13	10*	20*	15

* Denotes limiting parameters.

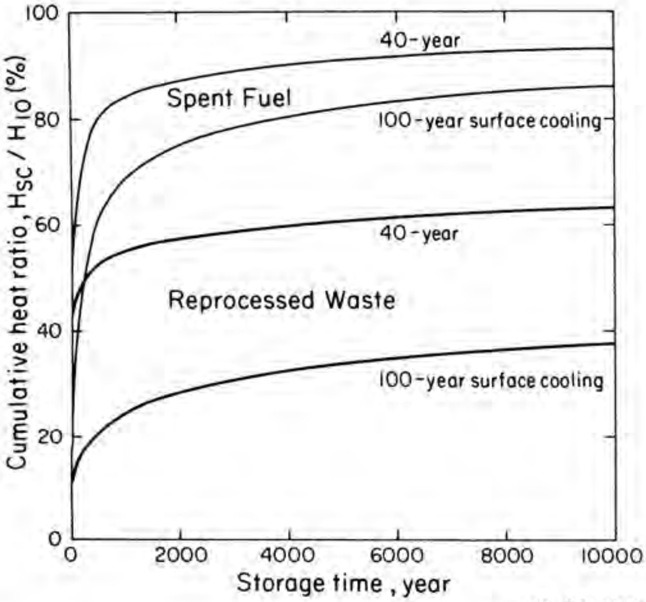
(Ref. 1)

an asterisk. Usually the near-field criteria determine the thermal loadings; however, the far-field surface uplift is also a limiting factor in a number of cases, including not only the SF repositories in salt but also 50-year-old HLW in salt and 50-year-old SF in shale. These results indicate that for older wastes, the far-field criteria become more important in determining the repository loading.

Surface Cooling, Cumulative Heat, and Far-Field Thermal Effects

The controlling quantity in assessing the far-field thermal effects is the cumulative heat released by the emplaced wastes. The waste heat will remain in the rock formation for a long period of time. SF releases more heat over a longer period of time than reprocessed HLW; extension of the surface cooling period removes only a small fraction of the cumulative heat released. On the other hand, the heat from reprocessed HLW is mainly released early. The cumulative heat of reprocessed HLW is much lower than that of SF; the heat removed by surface cooling is a significant fraction of the cumulative heat.

The ratios of cumulative heat released by 40- and 100-year-old wastes to that released by 10-year-old wastes are plotted in Fig. 5. This figure represents the relative dependence and sensitivity of surface cooling effects over the time range of interest. A lower ratio of cumulative heat energies indicates a greater advantage obtained from longer surface cooling. It is clear from the figure that the effect of surface cooling is more significant for reprocessed wastes than for spent fuel in terms of long-term, far-field effect. The potential advantage of a 100-year cooling period for reprocessed waste is to lower the surface uplift and buoyancy flow to less than half the magnitude of a 10-year cooling period[9]. The limitation on repository loading due to thermohydrological considerations of buoyancy flow has been examined by Wang et al[10].



XBL 817-3269

Fig. 5. Ratio of cumulative heat released by 40-year-old and 100-year-old wastes to that released by 10-year-old wastes.

European countries, including Belgium, Sweden, the United Kingdom, and West Germany, have also considered longer cooling periods for reprocessed waste[11]. The reasons range from near-field concerns over clay stability (Belgium), to backfill stability above 100°C (Sweden), to far-field buoyancy perturbation (United Kingdom). It is of interest to note that an unpublished United Kingdom report quoted by Bredehoeft and Maini[12] states that "if waste is allowed to cool for 40 to 60 or 70 years, depending on the waste type, the heat would be reduced to the point where buoyancy induced flow would not be significant."

CONCLUSION

We have extended the calculations of repository waste loading to older wastes using the existing near-field thermomechanical criteria. For reprocessed high-level wastes, the older wastes could be emplaced at more concentrated densities, especially in hard rock repositories. For reprocessed high-level wastes with small thermal contribution from long-lived actinides, the use of near-field thermomechanical criteria alone to determine the waste densities may be valid. For spent fuel with long-lived actinides, far-field criteria are also an important consideration in limiting the waste loading densities.

The effect of surface cooling based on far-field criteria are also discussed in the paper. There is a gap in the current far-field criteria because they do not quantitatively address the long-term vertical buoyancy flow from the repository to the surface. Therefore, the benefit of longer surface cooling periods in increasing the waste loading densities must be carefully evaluated, especially for spent fuel with long-lived thermal impacts. The assessment of surface cooling effects depend sensitively on the thermal criteria used, the waste type, and the rock type. If the repository loading designs based on 10-year-old wastes are scaled for different waste ages, the results must be carefully evaluated for each waste type and each rock formation to avoid nonconservative conclusions. The limitations of waste loading densities of older wastes should be carefully determined by imposing both near-field thermomechanical stability criteria and far-field thermohydrologic perturbation considerations.

ACKNOWLEDGEMENTS

This work was supported by the High Level Waste Technical Development Branch, Division of Waste Management, Office of Nuclear Material Safety and Safeguards, U. S. Nuclear Regulatory Commission, Washington, D. C. 20555, under Interagency Agreement DOE 50-80-97 N.R.C. FIN No. B 3109-0; and by the U. S. Department of Energy under Contract DE-AC03-76SF00098. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability of responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this report are not necessarily those of the U. S. Nuclear Regulatory Commission.

REFERENCES

1. Department of Energy, 1980. Management of commercially generated radioactive waste. U.S. Department of Energy, Washington, D. C., DOE/EIS-0046F, 320 p.

2. Bradshaw, R. L., and McClain, W. C., 1971. Project Salt Vault: A demonstration of the disposal of high-activity solidified waste in underground salt mines. Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL-4555, 356 p.

3. Kaiser Engineers, 1978. A national waste terminal storage repository in a bedded salt formation for spent unreprocessed fuel, conceptual design descriptions. Kaiser Engineers, Oakland, California, KE Report No. 78-58-R.

4. Kaiser Engineers, 1978. A national waste terminal storage repository in a bedded salt formation for spent unreprocessed fuel, basis of design decisions. Kaiser Engineers, Oakland, California, KE Report No. 78-79-R.

5. Stearns-Roger Engineering Co., 1979. Conceptual design, NWTS repository for storing reprocessed wastes in a dome salt formation, conceptual design descriptions. Vol. 2. Stearns-Roger Engineering Co., Denver, Colorado.

6. Bechtel Group, Inc., 1981. NWTS conceptual reference repository description (CRRD). Office of Nuclear Waste Isolation, Battelle, Columbus, Ohio, ONWI-258, Vol. 3.

7. Dames and Moore, 1978. Technical support for GEIS: Radioactive waste isolation in geologic formations: Thermomechanical stress analysis and development of thermal loading guidelines. Dames and Moore, White Plains, New York, Y/OWI/TM-36/20.

8. Department of Energy, 1979. Technology for commercial radioactive waste management. U. S. Department of Energy, Washington, D. C., DOE/ET-0028.

9. Wang, J. S. Y., Mangold, D. C., Spencer, R. K., and Tsang, C. F., 1982. Thermal impact of waste emplacement and surface cooling associated with geologic disposal of nuclear waste. Nuclear Regulatory Commission, Washington, D. C., NUREG/CR-2910, LBL-13341, 277 p.

10. Wang, J. S. Y., Mangold, D. C., and Tsang, C. F., 1982. Long-term thermomechanical and thermohydrological factors controlling the optimal design of a nuclear waste repository. In Scientific Basis for Nuclear Waste Management, Materials Research Society, Boston, Massachusetts, Vol. 6.

11. Harmon, K. M., Kelman, J. A., Stout, L. A., and Hsieh, K. A., 1980. Summary of non-U. S. national and international radioactive waste management programs, 1980. Battelle Pacific Northwest Laboratory, Richland, Washington, PNL-3333, 89 p.

12. Bredehoeft, J. D. and Maini, T., 1981. Strategy for radioactive waste disposal in crystalline rocks. Science, Vol. 213, No. 4505, p. 293-296.