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DRAFT GENERIC TECHNICAL POSITION:
INTERPRETATION AND IDENTIFICATION OF THE EXTENT OF THE DISTURBED ZONE IN THE HIGH-LEVEL WASTE RULE (10 CFR 60)

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Generic Technical Position on Disturbed Zone

1.0 Introduction

The NRC staff has established performance objectives for high level radioactive waste (HLW) repositories which include numerical performance criteria for the geologic setting and engineered barrier systems (10 CFR 60, Subpart E-Technical Criteria). One of these criteria, commonly referred to as the ground-water travel time criterion, is stated as follows:

> "The geologic repository shall be located so that the pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1000 years or such other travel time as may be approved or specified by the Commission." (10 CFR 60.113(a)(2))

The "disturbed zone" cited in the above criterion is defined as:

> "That portion of the controlled area the physical or chemical properties of which have changed as a result of underground facility construction or as a result of heat generated by the emplaced radioactive wastes such that the resultant change of properties may have a significant effect on the performance of the geologic repository." (10 CFR 60.2)

Since publication of 10 CFR 60, studies (e.g. Chu et. al [1983]) have suggested that the disturbed zone definition requires additional clarification by NRC. In this paper, the disturbed zone concept is discussed, and guidance for identification of its extent is offered.

A second related draft generic technical position on application of the ground-water travel time criterion in repository performance assessment and licensing review has been prepared in conjunction with this draft generic technical position. The generic technical position on ground water travel time discusses the concepts and methods of calculation of "pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel," as required by 10 CFR Part 60.

2.0 Rationale behind the "disturbed zone"

The NRC staff considers that the waste isolation capabilities of the natural geologic setting in which an underground HLW waste facility is to be constructed constitute an important consideration in geologic HLW disposal. The pre-waste-emplacement ground-water travel time performance objective was established by NRC to serve as a quantitative measure of the waste isolation potential of the natural geologic setting at the candidate repository site. The travel time criterion forms part of a multiple-barrier approach to HLW isolation, which also includes numerical criteria for containment and release rates of HLW from the engineered barrier system. As stated in 46 FR 35281, the Commission established the 1000 year pre-emplacement ground-water travel time as one of three criteria that act independently of the overall performance to give confidence that the wastes will be isolated for the period when they are most hazardous. Since ground water is considered to be the primary transporting mechanism for radionuclide migration from the geologic HLW facility, the pre-waste-emplacement ground-water travel time criterion was developed to provide a conceptually simple measure of the quality (in terms of HLW isolation capability) of this geologic setting.

The ground-water travel time criterion is stated in terms of current (pre-emplacement) conditions because NRC considers that the ground-water travel time under measurable existing conditions has more limited information needs and thus can be estimated with greater confidence than a post-emplacement travel time. Seismic events, surface morphology changes, climate changes, and other potential perturbations to existing hydrogeologic conditions need not be considered in evaluation of compliance with the pre-emplacement travel time criterion. The pre-waste-emplacement ground-water travel time, based on unperturbed conditions, provides a simpler and more easily quantifiable measure of the quality of the geologic setting, in terms of ground-water flow, than would a post-emplacement criterion. The post-emplacement ground-water movement will also require evaluation as part of a demonstration of compliance with the overall system standard (10 CFR 60.112).

The volume of the rock which contributes to isolation of HLW from the accessible environment clearly has its outer boundary at the accessible environment. For the inner boundary, the edge of the underground facility would at first seem a sensible choice. However, the staff has two considerations to account for in establishing this inner boundary which preclude adoption of the edge of the facility as the origin for travel time calculations.

First, the travel time criterion is intended to provide for far-field natural barrier protection from HLW releases to the accessible environment, as part of the multiple-barrier approach to HLW isolation. The staff considers that the natural geologic barriers at a given site should not be permitted to depend exclusively or predominately on the favorable properties of the host rock directly adjacent to the underground facility. The staff considers that an acceptable repository site would be one where the bulk of the surrounding geologic setting contributes to isolation of HLW.

Second, the staff considers that credit towards the 1000-year pre-emplacement travel time should not be taken within that portion of the current geologic setting (the "near-field") which might be substantially disturbed by construction of the facility or by the thermal effects of emplacement of HLW (irrespective of the possible offsetting benefits of engineered barriers such as waste containers and backfill). Because of potential changes in the intrinsic rock properties, the geologic setting within this "disturbed zone" may not be well represented by pre-emplacement properties and conditions and thus it may be difficult to predict the contributions of this volume of rock to repository performance. Therefore a pre-emplacement analysis based on existing conditions within this zone would not supply an appropriate measure of the quality of the geologic setting for the purpose of assessing future performance. To avoid the uncertainties of characterizing the rock very close to the emplaced waste, the "disturbed zone" was defined and established as the inner boundary from which travel time calculations are to be made for demonstrations of compliance with 10 CFR 60.113(a)(2).

In sum, the pre-waste-emplacement ground-water travel time criterion was established to gain a simple measure of the HLW isolation capabilities of the geologic setting based on existing conditions; the "disturbed zone" was subtracted from the "geologic setting" for this criterion for two reasons. First, the zone directly adjacent to the underground facility should not be depended upon to provide the major portion of natural barrier protection from HLW releases to the accessible environment. Second, the "disturbed zone" would not be well-characterized by pre-emplacement conditions and prediction of its contribution to the actual performance of the geologic setting might be difficult and uncertain. Therefore, assumption of existing properties within this zone for use in travel time calculations may not result in a reasonably conservative measure of the HLW isolation capabilities of the geologic setting.

3.0 Interpretation of the "disturbed zone" definition

Having clarified the intent of the ground-water travel time criterion and the "disturbed zone" concept, the interpretation of the "disturbed zone" definition will be discussed. In the definition provided earlier (page 1), the disturbed zone is described as the zone of physical or chemical property changes resulting from underground facility construction or HLW heat generation that would significantly affect the performance of the repository. The extent of the disturbed zone may be interpreted to include completely the zone of increased temperatures and associated buoyancy effects; this is likely to be quite extensive and in some cases might extend beyond the boundary of the accessible environment. These effects may have a significant impact on ground-water movement and radionuclide transport in terms of overall repository performance, and they must be accounted for in assessing total system compliance with the EPA Standard. However, the staff considers that the measure of the quality of the existing geologic setting, as a component of the multiple barrier system, need only be based on pre-emplacement conditions, except where the intrinsic properties of the rock which affect ground-water flow are likely to be compromised as a result of HLW heat generation or underground facility construction.

As shown in Appendix A, an increase in intrinsic permeability, with other parameters remaining constant, will decrease the ground-water travel time; an increase in effective porosity will increase the ground-water travel time. For the purposes of evaluating the extent of the disturbed zone at a given site, the NRC staff considers that a change in porosity by a factor of about two, which in general would be associated with a change in permeability by a factor of about an order of magnitude in low-permeability media as discussed in Appendix A, constitutes a "significant adverse" effect on repository performance.

The movement of ground water through solid salt is not well understood at the present time, but such flow may be extremely slow or virtually nonexistant. In such situations, the disturbed zone for salt should satisfy the consideration that the natural geologic barrier at a given site not depend exclusively or predominately on the portion of the host rock directly adjacent to the underground facility.

Limiting the disturbed zone to the zone of intrinsic rock property changes which affect ground-water travel time can be construed as less comprehensive than the definition provided in 10 CFR 60.2. That is, it is possible that not all post-emplacement conditions outside of this zone will be identical to pre-emplacement conditions. For example, due to post-emplacement thermal buoyancy effects, the pre-emplacement travel time may not provide a completely accurate measure of actual post-emplacement performance. However, we consider that, while not necessarily affording as accurate a measure of actual repository performance as might be desired, the pre-emplacement ground-water travel time from the disturbed zone to the accessible environment does offer an approximate measure of the quality of the geologic setting, which provides a sensible and useful performance criterion for both repository siting and licensing. Further, the actual post-emplacement performance, including post-emplacement ground-water flow paths and directions, must be accounted for in assessments of compliance with the EPA Standard.

In sum, the disturbed zone used in pre-emplacement ground-water travel time calculations is considered to be defined by the zone of significant changes in intrinsic permeability and effective porosity caused by construction of the facility or by the thermal effects of the emplaced waste. The meaning of "significant" in this context is considered to be about a factor of two change in effective porosity, which, in low permeability media, would generally correspond to about an order of magnitude change in intrinsic permeability, as discussed in Appendix A. The volume of the geologic setting which is not included in the disturbed zone, but which does change due to waste emplacement or facility construction, may preclude identical pre- and post-emplacement conditions for assessments of compliance with the ground-water travel time criterion. However, the NRC considers that the pre-waste-emplacement ground-water travel time will still be an appropriate measure of the overall geologic setting performance for the purposes of licensing.

4.0 Calculation of the extent of the disturbed zone

The particular processes that would require consideration in delineation of the disturbed zone, and the status of current investigations into these processes have been identified by NRC. Based on the technical and policy considerations

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described above, NRC considers that the disturbed zone could theoretically be calculated through evaluation of the spatial extent of intrinsic rock hydraulic property changes caused by:

1) stress redistribution
2) construction and excavation
3) thermomechanical effects, and
4) thermochemical effects.

Each of these is discussed below. The analyses presented are not intended to be exact. Instead, they serve as approximations of complex coupled process behavior. NRC recognizes that the in-situ test facilities that may be constructed at many potential repository sites are likely to provide major advancements in our understanding of the complex process interactions governing changes in intrinsic rock hydraulic properties. However, the complex process interactions that would need to be considered in identifying the spatial extent of intrinsic permeability and porosity changes have, in general, not yet been sufficiently studied to provide ready guidance in rigorously estimating their effect on the extent of the disturbed zone at this time. Also, the general intent of the pre-emplacement travel time performance objective, as discussed in section 2.0, is to provide a relatively simple benchmark for the quality of the geologic setting. Therefore, the level of rigor applied in the following analyses is considered to be sufficient for the purposes of providing guidance for defining the disturbed zone in ground-water travel time calculations.

The discussion below is based on current conceptual HLW facility designs, and considers only rock types currently under consideration for geologic repositories. If the adopted design is greatly altered from the design considered herein, or if rock types of greatly different mechanical or geochemical properties were to be considered, the guidance offered below may not apply directly. The limit of the disturbed zone then should be recalculated on a site-specific basis.

It should be noted that in an attempt to illustrate methods of identification of the extent of the disturbed zone, the impact of local geologic anomalies at specific sites has not been addressed. These types of features would have to be considered by DOE on a case by case basis in evaluations of the extent of the disturbed zone.

4.1 Stress redistribution

Rock permeability may be significantly altered in the region immediately surrounding repository openings as a result of stress redistribution. The extent of this region will depend on: (a) the rock characteristics (its mechanical properties, nature and extent of jointing and other discontinuities), (b) the in-situ (pre-construction) stress field; (c) the orientation and layout of the underground openings with respect to the in-situ stress field; (d) the size and shape of openings; and (e) the proximity of openings to one another. The immediate vicinity around the opening is most affected by the presence of the opening. The effect gradually dies down and at a certain distance from the edge of the opening, the rock essentially continues to be in its pre-excavation condition. There are experimental results, predominately on small scale laboratory samples, relating permeability changes to stress changes. However, these results are site- and rock-dependent. Therefore, there are no universal relationships which can be applied to all rocks under wide ranges of stress changes. A generic relationship between stress change and permeability change can be established by considering that for all practical purposes permeability will not change in the volume of rock beyond the surface of no stress change. Therefore this boundary can be used to define the region of no permeability change, i.e the limit of the disturbed zone resulting from stress redistribution.

Theoretical stress distributions are established in the literature (Hoek and Brown [1980]) for various opening shapes, with different orientations to in situ stress fields. The rock media are idealized for simplicity, i.e. the medium is assumed to be isotropic, homogeneous, and is assumed to behave in a linearly elastic fashion. Further, these solutions are generally for two dimensional cases. The distance to the contour of no stress change from the edge of the opening will vary depending on the size and shape of the opening and its orientation to the stress field. For a circular or semicircular opening, oriented as shown in Figure 1, a reasonable estimate of this distance for the idealized case will be about three diameters. For a noncircular opening, a reasonable estimate is roughly five times the height in most cases.

The anisotropy of rock (jointing, bedding planes, directional differences in mechanical properties, etc.) has a significant effect on the stress distribution. This anisotropy causes a shift in the stress redistribution (Goodman [1980]) and the contour of no stress change can be 4 to 5 diameters away from the edge of the opening. A third important consideration in stress distribution is the extent of rock fracturing (Coates [1970], Goodman [1980]) and subsequent yielding of rock. This yielding, again, changes the stress gradient and affects the redistribution in the rock mass.

Taking the envelope of the above stress distributions for a reasonable range of anticipated field conditions, the no-stress-change contour could be somewhat conservatively estimated in many cases to be about 5 diameters for circular openings or 5 times the opening height for noncircular openings. However, site-specific information must be utilized in order to gain a realistic estimate of the disturbed zone extent for a given site.

There will be openings of many sizes in the repository. The size will range from 1 to 10 meters for a majority of the openings (for a schematic of a layout of some repository openings, see Figure 2). Based on distances described in the literature for homogeneous, isotropic, and linearly elastic media, and taking into consideration the effects of host rock anisotropy, in-situ stress conditions, and fracturing and yielding, it is estimated that the disturbed zone caused by stress redistribution for the simplified example described above may extend to a distance of 5 diameters, or 5 to 50 meters, from the edge of the opening depending on the opening size.

The mechanical properties of salt rock are significantly different from other rocks, and therefore, a separate discussion is warranted. A unique feature of salt is its ability to creep into excavated openings over periods that extend from a few years to hundreds of years depending on the specific salt, its depth, prevailing stresses, and other geologic anomalies. Salt in the immediate vicinity of underground excavations undergoes elastic-plastic deformation and quickly goes into the creep phase. Numerous reports exist on excavations in salt that closed completely in a span of tens of years. This closure is expected to occur in a salt geologic repository in which the creep will be accelerated by the heat generated by the stored nuclear waste.

A second important difference between salt and other rocks is the applicability of the concept of ground-water flow and permeability. Traditional concepts of groundwater flow through porous media and jointed rocks are not applicable to pure salt. However, changes in permeability for the flow of brine or gas will occur as a result of excavation, stress redistribution, and creep. DOE must consider these changes on a site-specific basis in order to evaluate compliance with the EPA Standard. The 50-meter envelope around repository openings is considered to encompass a sufficiently zone to satisfy the consideration that the portion of the host rock immediately adjacent to the underground facility (i.e., within fifty meters of any opening) is not relied on exclusively or predominately to provide the natural geologic barrier to radionuclide release.

It should be noted that many geologic anomalies have been reported (Kupfer, 1979) in and around salt mines. These include shear zones in and around salt domes, gas pockets, and brine cavities. Gas pockets have extended up to 100 meters above the excavation and gas blowouts and brine migration are known to have occurred. This GTP is generic in nature and thus does not account for these site-specific features in salt and other media, which would have to be considered on a case-by-case basis.

The opening sizes discussed above mean those of the final completed excavation, and not the design dimensions. Large overbreaks can occasionally occur during excavations of underground openings resulting in the actual dimensions being significantly greater than the design dimensions. This potential problem can be minimized by using controlled blasting techniques and other construction methods. The extent to which the openings themselves may alter their position within salt media should be considered by DOE in delineating the boundaries of the disturbed zone in salt media through time. It is not known at this time whether the potential for post-emplacement gas blowouts or post-emplacement creep of the salt will be a significant consideration in this regard.

4.2 Construction and excavation

The zone of permeability change because of construction-induced effects is usually smaller than that due to stress redistribution (with perhaps the exception of massive unjointed rocks), and depends on: (1) the method of excavation (blasting or boring); and (2) the type or rock and its degree of discontinuities. The extent of porosity and permeability changes caused by dewatering of the facility should also be considered on a site-specific basis. It is reported in the literature that the extent of damage due to controlled blasting rarely exceeds one to one and a half meters away from the excavated openings. Furthermore the zone of altered permeability is estimated to be within half the opening diameter from the edge of the opening (Kelsall et. al. [1982]). Tunnel (and shaft) boring, on the other hand, produces smooth walls and normally results in little change in permeability of the surrounding rock.

Therefore, a 50 meter distance from the edge of the opening established as the minimum distance to the boundary of the disturbed zone resulting from stress redistribution might also conservatively cover the effects of construction induced changes in rock permeability.

4.3 Thermomechanical effects

The emplacement of nuclear waste in the host rock and the subsequent heat generation may result in a significant change in permeability in the region immediately surrounding the waste emplacement holes. Thermal stresses can create new cracks and open or close existing joints, therefore resulting in a permeability change. In the far field, thermal stresses may cause uplift and eventual subsidence effects. The resulting permeability changes may be more significant in salt than in hard rocks due to salt creep and a relatively high coefficient of thermal expansion. Thermal stresses and joint displacements are generally calculated using appropriate numerical models. These models require several input parameters such as the expected temperature range, the existing stress field, and rock thermal and mechanical properties (e.g., thermal conductivity, thermal coefficient of expansion, heat capacity, compressive strength, joint mechanical characteristics). One such study (Johnstone et. al. [1984]), using a finite element model for near-field thermomechanical analysis of four different host rocks at the Yucca Mountain site in southern Nevada, showed joint movement (slip, opening, or both), and significant associated change in permeability, at one diameter from the edge of the opening after 100 years. The above study noted that these model predictions of joint movement resulting from the thermal effects of waste emplacement were likely to be conservative. This conclusion was based on comparisons between model predictions (without the thermal feature) and underground observations of the joint movements in existing excavations near the site.

Experimental assessment (Daeman et. al. [1983]) of change in rock permeability as a result of heat application has shown that for several granites and gneisses tested (up to 2 meter cubes), permeability increases with temperature because of thermal cracking. However, confining pressure can strongly reduce permeability increases caused by heat. In a repository environment, this could mean that the permeability increase at or close to the repository wall will largely diminish as confining pressure increases in the surrounding rocks. In jointed rock, some or all of the thermal expansion may be absorbed by the closure of microcracks and joints resulting in overall reduction in both the permeability and thermal stresses.

Despite the modeling efforts and the laboratory and in-situ testing work available in the literature, the temperature-stress and temperature-permeability relationships are difficult to quantify, especially for large volumes of rock mass. Considering the above discussion, the disturbed zone which covers the effect of stress redistribution and construction might in many cases also be expected to include the zone of significant thermomechanical effects on permeability. However, DOE should demonstrate this on a site specific basis.

4.4 Consideration of Shafts and Surface Boreholes

In this GTP, shafts and surface boreholes are considered to be excluded from the disturbed zone. Therefore, the 50-meter disturbed zone described above does not apply around every shaft, incline, or borehole. The disturbed zone is defined, in part, to include the portion of the controlled area with properties significantly changed as a result of underground facility construction. The "underground facility" is defined to mean the underground structure "excluding shafts, boreholes and their seals" (10 CFR 60.2). However, it must be recognized that the rock immediately surrounding all openings will be disturbed to some extent, and may become a flow path connecting the repository to the accessible environment. This effect may be mitigated by following careful excavation techniques, and through installation of effective shaft and borehole seals. The performance of these seals should be assessed as part of the overall performance assessment of the repository system. The performance objectives explicitly state that "the geologic setting shall be selected and the engineered barrier system and the shafts, boreholes and their seals shall be designed" to assure compliance with EPA Standards (10 CFR Part 60.112). However, the groundwater travel time criterion is intended to provide a representative measure of the effectiveness of the far-field geologic setting as a barrier to radionuclide transport, and not of the overall quality of the repository system. Therefore, a discussion of the disturbed zone around the boreholes and shafts is beyond the scope of this GTP, although it should be considered in overall repository performance assessment.

4.5 Thermochemical effects

The perturbation to the geochemical environment caused by the heat generated by the high-level waste, and by the introduction of the mined facility and engineered barriers into the geologic environment, is the driving force for chemical reactions that can occur in the geological system. The extent of the perturbation depends on 1) thermal load of the repository, 2) thermal conductivity of the surrounding rock, 3) degree to which the engineered system is chemically out of equilibrium with the surroundings 4) mobility of components within the system and 5) the stability of pre-emplacement minerals.

Changes in mineral assemblages caused by the thermochemical perturbation could affect both the chemical and physical ability of the host rock to retard radionuclides. However, by defining the disturbed zone in solely hydrological terms, thermochemical effects to be considered in quantifying the extent of the disturbed zone involve only those reactions that either change the volume of solids ($\Delta V_s \neq 0$) or redistribute the solids in the repository system. These reactions include dissolution and alteration of pre-emplacement minerals, and precipitation of secondary minerals. The change in volume of the solids results in a change in the porosity and possibly permeability of the host rock. Redistribution of solid material, on the other hand, results in porosity increases in one portion of the repository and decreases in another. The relationship between intrinsic permeability and porosity has been discussed previously in section 3.0. The net effect on the flow may be favorable or unfavorable. It is demonstrated in Appendix B that even if the effect is unfavorable, it will be small and may on this basis generally be ignored.

A change in porosity or permeability of the host rock may result if pre-emplacement minerals undergo alteration due to increased temperature and/or altered groundwater composition. Commonly the solids that are involved in water/rock interactions in crystalline rocks are glass, silica phases, clays, zeolites, feldspars and micas. The silica phases include quartz, cristobalite, tridymite and amorphous silica. The clays generally include smectite and illite; zeolites are clinoptilolite, mordenite and analcime. Reactions involving these phases can result in either increases or decreases in solid volume (V_s). For example, under hypothetical repository conditions, the hydrolysis of alkali feldspar

$$3KAlSi_3O_8 + 2H^+ = KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + 2K^+$$

orthoclase muscovite quartz

results in a decrease in solid volumes ($\Delta V_s = -43\ cm^3$), whereas, the conversion of anorthite to clinoptilolite

$$CaAl_2Si_2O_8 + 5SiO_2 + 6H_2O = CaAl_2Si_7O_{18}\ 6H_2O$$

anorthite quartz Ca-clinoptilolite

increases solid volumes ($\Delta V_s = 98\ cm^3$). Large uncertainties in volume changes result from reactions involving phases whose molar volumes are variable. Smectite, a common secondary mineral found in the fractures of crystalline rocks, is notorious for volume changes due to variation in water content. Densities of smectites can vary from 2 to 3 g/cc (Deer, et al., 1966).

Dehydration reactions may also result in a net change in porosity of the host rock. Dehydration of hydrous minerals can occur in the region surrounding the canisters where temperatures are greatest. This will be of particular importance in a repository located in the vadose zone. Dehydration could occur at temperatures as low as 85°C, e.g., zeolites such as mordenite and clinoptilolite can react to form analcime, producing a reduction in molar volume of the solids. Such reactions may have an adverse affect on the permeability of the host rock, if the hydrous minerals occur in a significant amount in these regions.

Dissolution and re-precipitation of minerals under repository conditions may exhibit a profound effect on the ability of the host rock to transmit fluids. The system $SiO_2 - H_2O$ can be used as an example. This simple system is chosen to illustrate the chemical processes in a repository because thermodynamic and kinetic data are well established and significant amounts of silica are present in two of the sites being considered for nuclear waste disposal. A sample generic analysis of the extent and effects on porosity of silica dissolution is presented in Appendix B. Based on these generic calculations, silica dissolution is not expected to be significant beyond the previously-discussed mechanically-disturbed zone distance. It is apparent, however, that the distance to the edge of the thermochemically disturbed zone is strongly dependent on the thermal loading of the repository and the groundwater flux in the host rock. These factors would have to be considered carefully for any site specific analyses.

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While the silica-water system is not to be used as the only basis for establishing the extent of mineralogical effects to the host rock, the type of analysis presented here, i.e. the use of a simple, one-dimensional mass transfer model, is recommended to determine the effect of repository induced conditions on mineral stability and hence porosity. It is recognized that each site may have multiple-component reactions which could have a significantly different result from a simple two-component system. For that reason, we recommend that DOE perform chemical analyses on a site-specific basis, having fully characterized the hydrological, mineralogical and chemical data of the system to the point where they have sufficient confidence to determine the extent of significant thermochemical changes at a given site. These calculations will roughly indicate the suitability of the suggested fifty-meter minimum disturbed zone distance in encompassing the zone of thermochemical changes at the given site.

4.6 Summary

NRC considers that establishment of generic and easily evaluable guidance on the disturbed zone is desirable in order to simplify the demonstration of compliance with the groundwater travel time criterion (10 CFR 60.113(a)(2)) and maintain consistency with NRC's intent in the criterion and in the overall multiple-barrier approach to HLW isolation. Based on the information provided above, it appears that a distance of five opening diameters from any underground opening, excluding surface shafts and surface boreholes, would be a reasonably conservative distance for the extent of the mechanically-disturbed zone in some cases. Given current conceptual designs for underground HLW facilities, this would imply a distance of roughly fifty meters from the underground openings. The limit of one process (silica dissolution) contributing to the thermochemically disturbed zone, based on a simplified evaluation, appears to be less than the above-stated mechanically-disturbed distance from the underground facility. However, the thermochemically disturbed zone at a site should be calculated on a site- and design-specific basis, taking into account the hydrochemical, geochemical, hydrologic and thermal conditions for each site. The impact of each of the four processes listed on page 8 should be considered by DOE on a site- and design-specific basis.

In this paper, a detailed, updated interpretation of the "disturbed zone" has been presented, and sample calculations have been performed, which provide guidance to DOE in establishing the surface from which to calculate pre-waste-emplacement ground-water travel times for repository sites. It must be noted that post-waste emplacement ground-water flow paths and velocities must be evaluated by DOE in demonstrations of compliance with the overall system standard (10 CFR 60.112).

5.0 Statement of Technical Position

It is the position of the NRC staff that the disturbed zone may be considered to be 1) defined by the zone of substantial thermo-hydro-chemico-mechanical changes in intrinsic permeability and effective porosity caused by underground facility construction or by HLW heat generation and 2) should at least include the portion of the host rock directly adjacent to the underground facility in order that a proper measure of the quality of the far-field geologic setting may be obtained through the application of the ground-water travel time criterion. NRC considers that, based on consideration 2) above, a disturbed zone of five diameters for circular openings, 5 opening heights for noncircular openings, or fifty meters, whichever is largest, from any underground opening, excluding surface shafts and boreholes, may be the minimum appropriate distance for use in calculations of compliance with the pre-waste-emplacement ground-water travel time criterion (10 CFR 60.113(a)(2)). The disturbed zone at a given site may, however, extend further than this distance depending on the site and design characteristics. The extent of the disturbed zone should be calculated by DOE on a site-specific basis. These site-specific analyses should account for the effects of heterogeneities in the geologic system, local geologic anomalies, the magnitude of likely ground-water flux, magnitude of areal thermal loading of the repository, the geochemical and hydrochemical characteristics of the site, and changes in the facility configuration through time.

Investigators calculating the extent of the disturbed zone for use in 10 CFR 60.113(a)(2) ground-water travel time calculations should be prepared to support this finding through documented technical evaluation.

The post-emplacement ground-water flow directions and velocities, which may in some cases be substantially different than pre-emplacement conditions, must also be evaluated by DOE in demonstrations of compliance with the overall system standard (10 CFR 60.112).

If, for a particular site or repository design, DOE proposes to define a disturbed zone extending less than either fifty meters or five diameters (or opening heights) from any underground opening (excluding surface shafts and surface boreholes), DOE will be required to:

1) support this finding through a documented technical evaluation of the processes identified in this document; and

2) justify the propriety of siting a facility in a geologic setting in which substantial credit for HLW isolation must be taken within the first fifty meters or five opening diameters from the facility in order to attain compliance with the NRC ground-water travel time criterion 10 CFR 60.113(a)(2).

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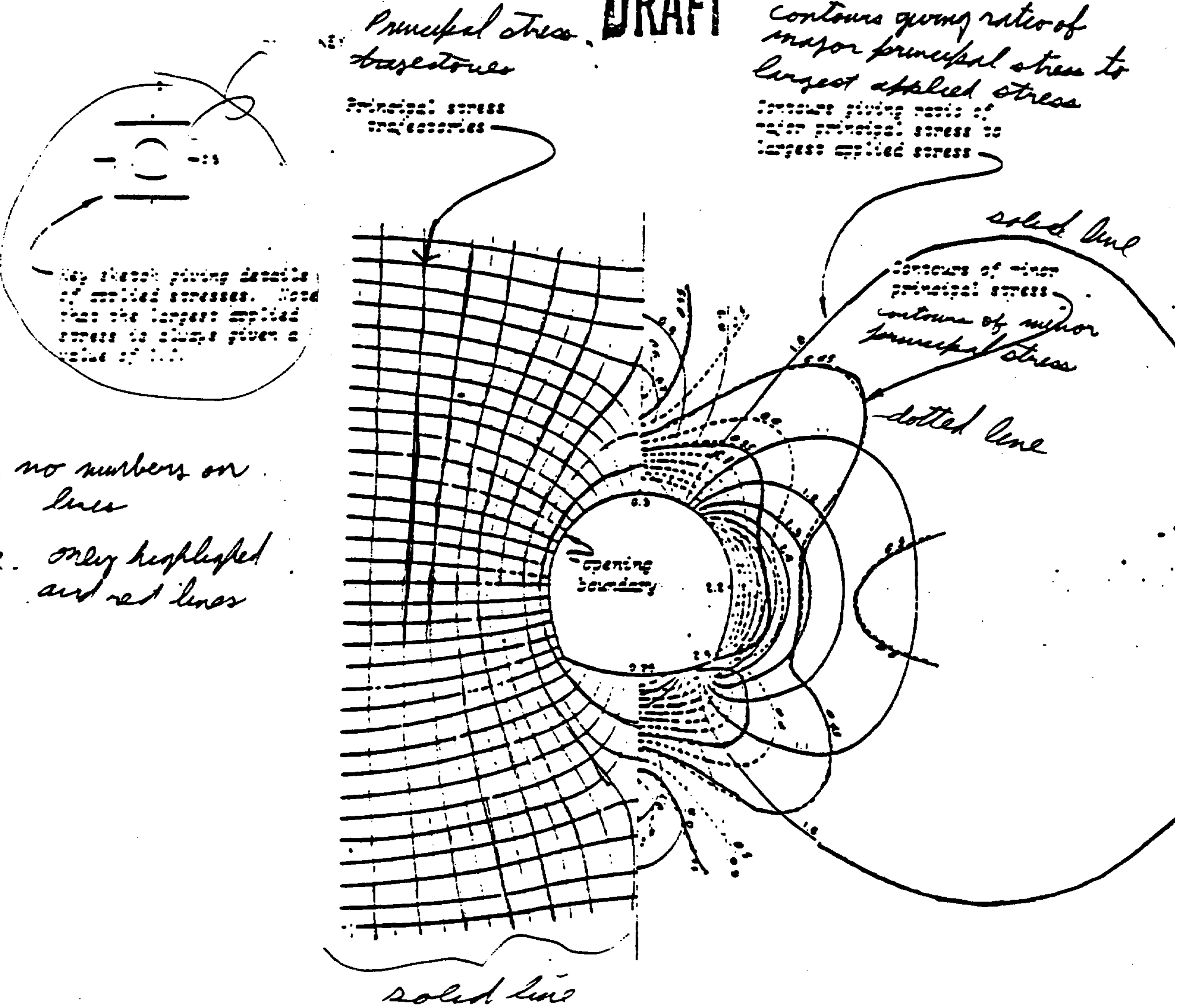

1. no numbers on lines

2. only highlighted and red lines

FIGURE 1

AN EXAMPLE OF STRESS DISTRIBUTION AROUND SINGLE OPENING IN AN ELASTIC, ISOTROPIC, HOMOGENEOUS MEDIUM (AFTER HOEK AND BROWN, 1980)

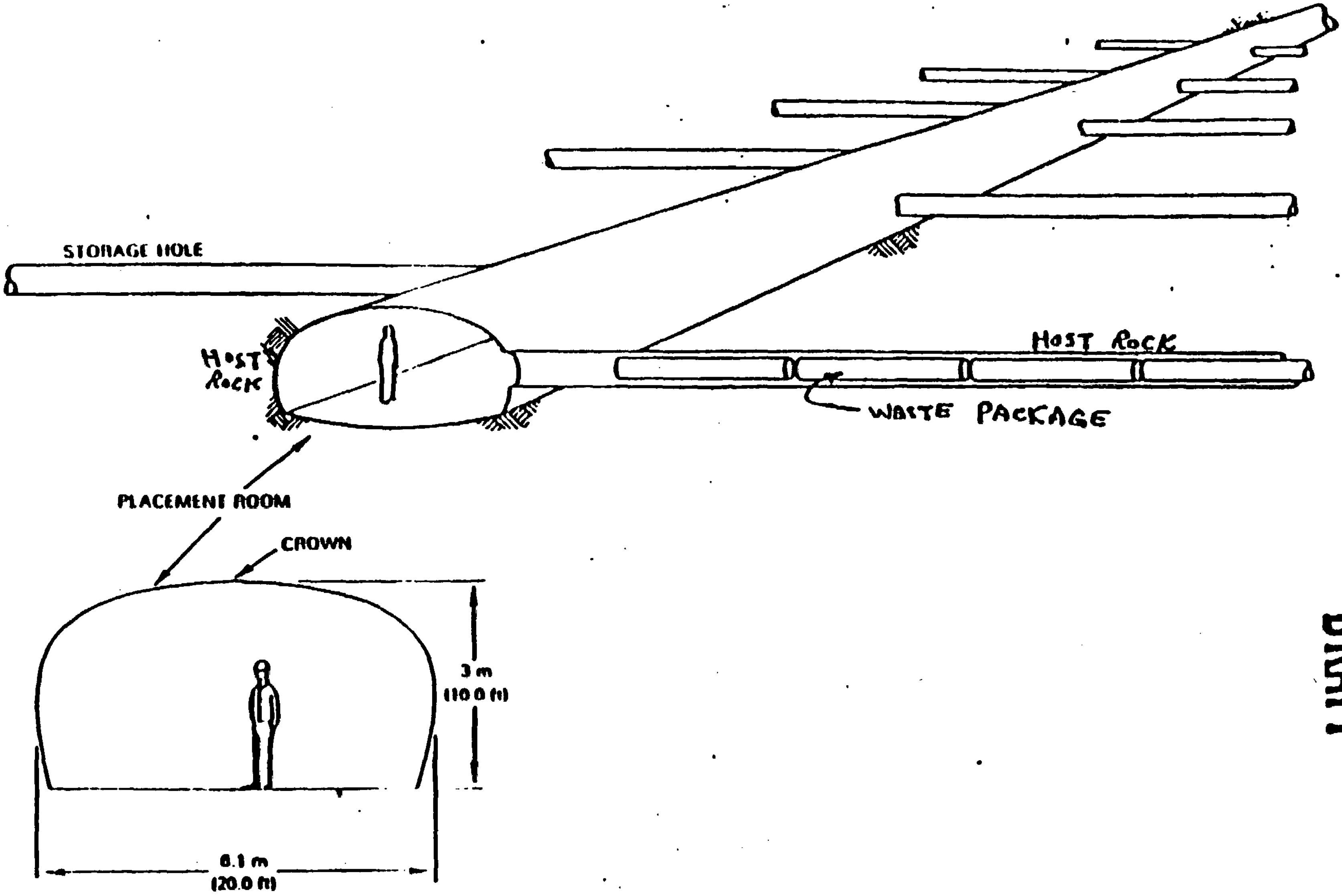

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FIGURE 2
AN EXAMPLE OF REPOSITORY LAYOUT SHOWING PLACEMENT ROOMS AND HORIZONTAL STORAGE HOLES
(AFTER SITE CHARACTERIZATION REPORT, BWIP-DOE, 1982)

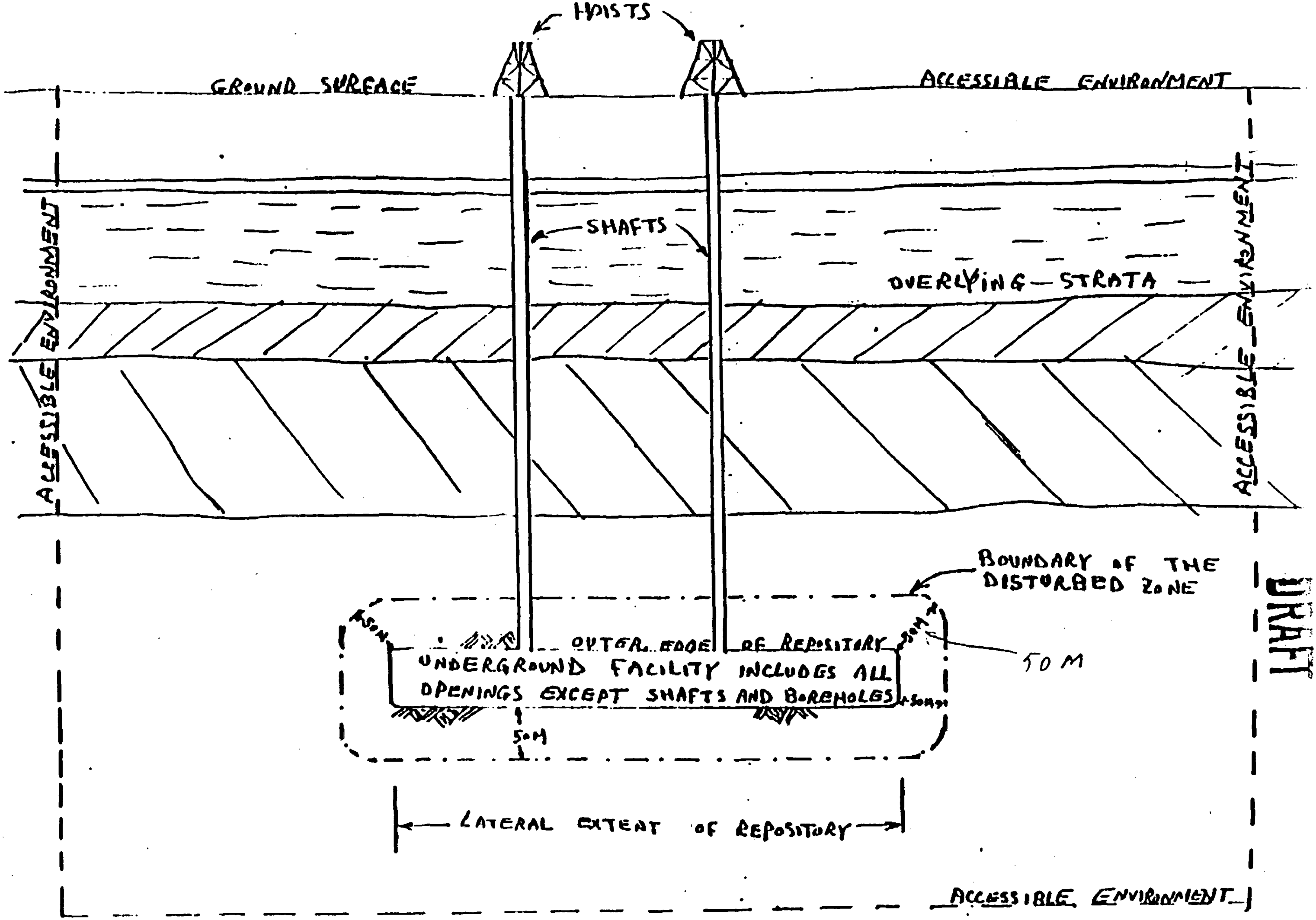

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FIGURE 2

APPENDIX A

Intrinsic Rock Properties Affecting Ground-water Travel Time

The governing equation for ground-water travel time in a saturated medium may be written as:

$$(T)^{-1} = v/(Dn_e) = \frac{-(k\rho g/\mu)\nabla h}{D\ n_e}$$

where T = ground-water travel time [t]
v = specific discharge [L/t]
n_e = effective porosity [dimensionless]
k = intrinsic permeability [L^2]
ρ = fluid density [M/L^3]
g = gravitational acceleration constant [L/t^2]
∇ = grad (operator) [1/L]
h = potentiometric head [L]
μ = fluid dynamic viscosity [M/Lt]
D = effective path length [L]

This equation can also be applied to unsaturated media, where h is then the sum of the matric and gravitational head, and k and n_e are functions of the matric head. Based on this equation, the intrinsic properties of the geologic setting which are anticipated to directly affect groundwater flow for fractured and porous media include only the intrinsic permeability and effective porosity of the geologic medium. Changes in the intrinsic properties of the geologic medium may also cause changes in the head gradient, but effects on the head gradient caused by the changes in these rock properties are expected to be minimal compared to changes in the intrinsic permeability and effective porosity. Therefore, for the purposes of evaluating the extent of the disturbed zone, fluid and rock density changes, fluid and rock viscosity changes, fluid and rock specific heat changes, and fluid and rock thermal conductivity changes need only be considered in delineation of a disturbed zone insofar as they significantly affect the intrinsic rock properties of intrinsic permeability and effective porosity. (The meaning of "significantly" in this context is discussed in the main text of this document.) All of these complex process interactions, including post-emplacement ground-water flow directions and velocities which may be affected by post-emplacement processes such as fluid buoyancy, will however need to be considered in assessment of compliance with the overall system standard (10 CFR 60.112).

For a given medium, there is likely to be a relationship between an increase in effective porosity and an increase in intrinsic permeability. For example, relationships such as laminar flow between parallel plates and in granular materials indicate that permeability increases roughly to the cube of the porosity. Therefore, the effects on velocity or travel time to a change in one of these parameters is likely to be offset to a degree by the effects to the corresponding change in the other. The media under consideration generally have small effective porosities. Thus small decreases in porosity can be expected to cause larger decreases in intrinsic permeability. Conversely, an increase in total porosity is likely to cause a larger associated increase in intrinsic permeability. In the case of the disturbed zone caused by the precipitation of solids, the relationship is likely to be even further exaggerated because precipitation will occur predominantly along the interconnected flow paths. Therefore, the sensitivity of intrinsic permeability to small changes in total porosity is expected to be, if anything, increased if one substitutes effective porosity for total porosity, particularly when considering chemical precipitation and dissolution.

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APPENDIX B
ANALYSIS OF THE DISSOLUTION OF SILICA NEAR HLW REPOSITORIES

Introduction

The potential for dissolution of minerals in the rock is a consideration in the design of high level geologic waste repositories. Dissolution of the rock could enlarge conduits for the passage of water, increasing the flux through the repository and the potential for migration of radionuclides from the waste. Conversely, precipitation of minerals dissolved from one area could plug conduits in another area. The present analysis considers as a worst case only the region where there would be increased flow caused by dissolution.

Silica is a common mineral in most of the rock types currently under consideration by DOE as geologic repository media. Its presence in these rocks has led to concerns that there might be a significant change in porosity caused by the dissolution of silica in the flowing groundwater. A numerical experiment was devised which would test this hypothesis for typical to conservative conditions expected near HLW repositories. This report describes the numerical experiment and its results, and the impact of the results on the definition of the Disturbed Zone. The techniques described might be useful for evaluating dissolution of other types of minerals, but each case should be considered carefully.

Description of the Heat Transfer Model

The heat transfer model has been taken from Ref. 1. The repository is assumed to be a thin rectangular plate parallel to the surface of the earth located in a saturated medium as shown in Fig. 1. Heat transfer is considered to be totally by conduction with constant thermal conductivity and heat capacity. This assumption is justified in most cases because heat transfer by flowing groundwater will almost certainly be smaller than conductive heat transfer. The bases for this assumption are presented in Ref.1. The effects of phase changes are also expected to be negligable.

Heat is being generated by 10 year old spent fuel, uniformly distributed across the area of the repository. Coefficients of the heat transfer model are given in Table 1.

Table 1 - Parameters of Repository Model

Repository length = 1600 m

Repository width = 1200 m

Depth of repository below earth's surface = 1200 m

Coefficient of Heat Transfer, $k = 7.25 \times 10^7$ joules/(m yr °c)

Heat capacity of rock, $C_p = 2.77 \times 10^6$ joules(m^3°c)

Initial Heat load, $Q_0(t) = 4.41 \times 10^8$ joules /(m^2 yr)

Groundwater flux, $U = 1$ meter/year

Ambient Temperature, $T_0 = 30°C, 50°C$

Density of Rock, $\rho = 2.2$ gm/cc

Transport Model

Groundwater is assumed to be moving in a straight line through a thin stream tube at a flux U meters/years, as shown in Fig. 1. The stream tube is aligned in one of two ways:

1. Parallel to the x axis (horizontal) passing through the point $y = 0$, $z = z_1$, or

2. Parallel to the z axis (vertical), passing through the point $x = 0$, $y = 0$.

Temperature along the stream tube is a function of time determined by the heat transfer model.

A mass balance on the segment of the stream tube of cross section A , as shown in Fig. 2, from x to $x + \Delta x$ is used to develop the relationship for the dissolution of silica:

Mass of silica entering at $x = U\,A\,C_x\,\Delta t$ (1)

Mass of silica leaving at $x + \Delta x = U\,A\,C_{x+\Delta x}\,\Delta t$ (2)

Change in mass of solid silica in time $\Delta t = \Delta M$ (3)

The change in porosity is taken as the change in the silica mass ΔM divided by the original silica mass in the segment, M_0:

$$M_0 = A\,\rho\,\Delta x \qquad (4)$$

where ρ is the density of the silica

The change of porosity at a point is therefore:

$$\Delta M/M_0 = \int_0^t (U/\rho)\ (\partial C/\partial x)\ dt' \qquad (5)$$

It is assumed that silica will be removed from both the conducting and non-conducting pores in the rock, so the change in either total or effective porosity can be expressed by this ratio.

The equilibrium concentration of silica in water can be described by an empirical relationship (Ref. 2):

$$K = 10^{(a + b\,T + c/T)} \text{ moles/liter} \qquad (6)$$

where T is the absolute temperature degrees Kelvin, and a, b, and c are constants which depend on the solid silica phase. Coefficients are given in Table 2 for several phases of silica.

Table 2 - Coefficients in Solubility Equation for Four Silica Phases

Phase	a	b	c	K at 100°C	$\partial K/\partial T$ at 100°C
Quartz	1.881	2.028×10^{-3}	-1560	8.75×10^{-4}	1.85×10^{-5}
Alpha-Cristobalite	-.0321	0	-988.2	2.08×10^{-3}	3.41×10^{-5}
Beta-Cristobalite	-.2560	0	-793.6	4.13×10^{-3}	5.43×10^{-5}
Amorphous	.3380	-7.889×10^{-4}	-840.1	6.19×10^{-3}	7.48×10^{-5}

Method of Solution

The heat transfer model was run to develop temperatures at points along the stream tube from times of 1 to 10,000 years. Time was calculated on a logarithmic scale $\tau = \ln t$, in order to take the conditions over a wide range of time into account. The temperature gradient is expressed by the first order difference between two points. Equation (5) in solved for $\Delta M/M_0$ in time at points midway between the temperature points using the trapazoidal rule:

$$(\Delta M/M_0)_{i+\frac{1}{2}}^{(\tau+\Delta\tau)} = (\Delta M/M_0)_{i+\frac{1}{2}}^{(\tau)} + (U\Delta\tau/2\Delta x\rho)\ (f_{i+\frac{1}{2}}(\tau) + f_{i+\frac{1}{2}}(\tau+\Delta\tau)) \qquad (7)$$

where $f_{i+\frac{1}{2}}(\tau) = (C_{x+\Delta x}(\tau) - C_x(\tau))\ e^{\tau}$

The concentration is assumed to be determined by the equilibrium coefficient:

$$C_x(\tau) = 0.06009\ K\ (T(x,\tau))\ , \qquad (8)$$

where the constant 0.06009 is a conversion factor from moles/liter to gm/ml.

Model Results

The model was run for the horizontal and vertical stream tubes using a flux of 1 meter per year and a time limit of 10,000 years. The ambient temperature was taken to be 30°C and 50°C. The amorphous silica phase was used as the base mineral because it is the most soluble form, and will result in the most conservative prediction. Results of these runs are shown in Figs. 3 and 4. In the horizontal stream tube case shown in Fig. 3, the maximum occurs close to the upstream edge of the repository. The peak values of $\Delta M/M_0$ are approximately 0.0006 and 0.0007 for T_o = 30°C and 50°C respectively.

No silica would dissolve downstream of the repository center, $x = 0$, because temperature and therefore solubility will decrease beyond this point. The model would predict precipitation of an equal amount of dissolved silica downstream from the repository centerline because of symmetry and the assumption of equilibrium. The present analysis conservatively excludes potential plugging of conduits by precipitated silica.

In the vertical stream tube case shown in Fig. 4, the maximum $\Delta M/M_0$ for $U = 1$ meter/year occurs at the intersection with the repository plane, and is about 0.0005 and 0.0006 for the cases of $T_0 = 30°C$ and 50°C respectively. The vertical stream tube differs slightly from the horizontal case because the fluxes may be upward or downward, and the temperature is not symmetrical around the plane $z = z_1$, because of the geothermal gradient. An increase in ambient temperature of 20°C caused only about a 20% increase in maximum dissolution, however, so the geothermal gradient, which is on the order of 5°C per 1000 meters, would not affect the results significantly.

In both cases, dissolution is directly proportional to the groundwater flux. An increase in the flux to 10 meter/year (3.2×10^{-7} m/sec) would therefore increase the maximum $\Delta M/M_0$ to 0.007 and 0.006 for the horizontal and vertical stream tubes respectively.

Simplified Model

The results of the model presented above indicate that silica dissolution is greatest where the temperature gradient is steepest, which is at the interface between the repository and the surrounding rock. In addition, the peak dissolution calculated for the horizontal and vertical stream tubes were roughly equal, even though the repository was represented as a thin plate horizontal to the earth's surface. These observations lead to the development of a simpler model which can be used for quick estimates of the maximum dissolution. Consider the case of the vertical stream tube, with flow along the z axis. By applying the chain rule, the concentration gradient in Eq. 5 can be rewritten:

$$\partial C/\partial z = (\partial C/\partial T)\ (\partial T/\partial z) \tag{9}$$

Equation (5) becomes

$$\Delta M/M_0 = \int_0^t (U/\rho)\ (\partial C/\partial T)\ (\partial T/\partial z)\ dt' \tag{10}$$

For an infinite horizontal plane source, conductive heat flux away from the upper and lower surfaces of the repository is $2k\ \partial T/\partial z$, where k is the thermal conductivity. The model assumes chemical equilibrium, so C = 0.06009 K as stated by Eq. 8. Therefore:

$$\partial C/\partial T = 0.06009\ \partial K/\partial T \qquad (11)$$

If we assume that $\partial K/\partial T$ can be represented by an average value β in Eq. 8:

$$\beta(\bar{T}) = (\partial K/\partial T)_{\bar{T}} \qquad (12)$$

and therefore taken outside of the integral, Eq. 10 becomes

$$\Delta M/M_0 = 0.06009\ U\ \beta(\bar{T})/(2\ \rho k) \int_0^t 2k\ \partial T/\partial z\ dt' = 0.06009\ U\ \beta(\bar{T})\ Q(t)/2\rho k \qquad (13)$$

where $Q(t)$ is the heat load, joules, integrated to time t per square meter of repository (top) area.

The coefficient β can be derived by differentiating Eq. 6, and is shown in Fig.5 for amorphous silica. Note that β changes by less than a factor of 2 between 300 and 373.1 °K, which is within the expected operating temperatures of planned HLW repositories. Taking β outside of the integral would not therefore lead to a great error. The integrated heat load can be expressed as

$$Q(t) = Q_0\ f(t) \qquad (14)$$

where Q_0 is the initial surface heat load, joules/(m^2 yr) and $f(t)\int_0^t =(Q/Q_0)dt'$.

The function $f(t)$ is shown graphically in Fig. 6 for 10 year old spent fuel.

Equation 13 is conservative because it considers only the steepest temperature gradient. The thermal gradient is also maximized because heat transfer is considered in only one dimension which fails to take heat loss perpendicular to the z axis into account. A conservative value of β must be chosen, however. A suggested value of $\overline{T}$ which has been shown to give conservative results is

$$\overline{T}\,(^\circ K) = (T_0 + 100)/2 + 273.1 \qquad (15)$$

where T_0 is the ambient temperature at the repository level, °C.

This model should be applicable to horizontal flows as well, since the silica dissolution fractions predicted from the numerical models of the previous section gave roughly equal results for the vertical and horizontal cases.

Example

Consider the repository presented in the previous section (Table 1). Calculate $\Delta M/M_0$ at 1000 and 10,000 years, for T = 30°C.

Solution

The representative temperature lies between ambient and boiling:

$$T = (30°C + 100°C)/2 + 273.1 = 338.1°K$$

From Fig. 4, $\beta = 5.85\times10^{-5}$ moles/liter °K

(a) for t = 1000 years, from Fig. 5, f(t) = 119, so:

$$\Delta M/M_0 = \frac{(1.0 \times 5.85\times10^{-5} \times 4.41\times10^{8} \times 119 \times 0.06009}{2 \times 2.2 \times 7.25\times10^{7}} = 5.8\times10^{-4}$$

(b) for t = 10,000 years, f(t) = 275, so:

$$\Delta M/M_0 = 1.34\times10^{-3}$$

The result at 10,000 years is about double the dissolution predicted by the numerical model of the previous section. The largest discrepancy is probably caused by the conservative choice of $\bar{T}$. Figure 7 shows the time dependent temperature rise above ambient at the repository center predicted by the numerical temperature model, indicating that the average temperature is probably considerably less than 338.1 ° K. The approximate solution is reasonable considering its simplicity.

Significance of Silica Dissolution

Silica dissolution will increase the porosity and hydraulic conductivity of the saturated rock, thereby increasing the groundwater flux through the affected region. For an equal value of $\Delta M/M_0$, rock with initially small porosity would be more greatly affected than rock with large initial porosity.

A reasonable estimation of the importance of silica dissolution can be made by considering the case of a repository with the bare minimum specifications of a 100 year travel time and distance to the accessible environment of 2000 meters horizontally. Since the pore velocity is the flux divided by the effective porosity, travel time t, distance L, initial effective porosity n_0 and flux U are related by the following equation:

$$U/n_0 = L/t = 2000 \text{ meters}/100 \text{ years} \qquad (16)$$

Equation 16 requires that the hydraulic gradient remains constant, which is conservative under the circumstances of a local increase in the hydraulic conductivity.

The change in the effective porosity relative to the initial effective porosity n_0 can be derived from Eq. 13:

$$\Delta n/n_0 = (\Delta M/M_0)/n_0 = (UQ_0 \ f(t) \times \beta(T) \times 0.06009)/2n_0\rho k \qquad (17)$$

Conservatively assuming the same conditions as in the previous example for 10,000 years,

$$\Delta n/n_0 = \frac{(2000 \times 5.85\times10^{-5} \times 4.41\times10^{8} \times 275 \times 0.06009)}{100 \times 2 \times 2.2 \times 7.25\times10^{7}} = 0.027$$

The effective porosity for the present case therefore would change less than 3% over a 10,000 year period. The permeability of a low-porosity medium and thus the groundwater flux would be proportional to the porosity cubed, providing that the hydraulic gradient and other properties remain the same:

$$\Delta U/U = 1 - (1 - \Delta n/n_0)^3 = 0.081 \qquad (18)$$

The flux through the affected area would therefore increase by about 8 percent in the present example.

The above analysis is conservative for the following reasons:

1. Equilibrium between water and silica is assumed at all times, with no consideration given to the rates of dissolution, which could be limiting in some circumstances;

2. The most soluble form of silica was assumed;

3. A known conservative value of the solubility coefficient was used in the dissolution model;

4. The simplified model overestimates dissolution and considers only its highest value;

5. Minimum specifications on travel time and distance to the accessible environment were used to estimate the ratio U/n_0;

6. The analysis for increased flow assumes that the hydraulic gradient driving the flow is constant, wheras a local increase in hydraulic conductivity might cause the gradient to be depressed (i.e., the flowrate may be controlled by the resistance to flow elsewhere); and

7. The blockage of flow in areas where silica is being precipitated is not taken into account. In addition, mineral alteration may in some cases lead to an increase in volume over tha unaltered mineral.

If the $\Delta M/M_0$ from the numerical model (Eq. 7) were used, along with a more reasonable 1000 year groundwater travel time, less than a 0.5% increase in flux would be predicted. These results are generally supported by other studies, e.g., Ref.3.

Conclusions

The importance of the dissolution of silica to the integrity of a repository was explored with several simple models. The models assumed conductive heat transfer only, and that groundwater was always saturated with silica at a concentration determined by an empirical function of temperature. The maximum dissolution ratio occurred where temperature gradients were greatest which was at the edges of the repository, and were directly proportional to the groundwater flux.

The importance of the silica dissolution was determined for a conservative case of a repository barely meeting the requirements of groundwater travel time and distance to the accessible environment. Conservative coefficients were used in a conservative, simplified model to predict that effective porosity would increase by less than 3% and groundwater flux by 8% over 10,000 years. More reasonable estimates of the coefficients indicate much smaller increases. It can be generally concluded from these results that increased porosity caused by silica dissolution is not a major consideration in the transport of groundwater or radionuclides near a geologic HLW repository in a saturated porous medium.

This may not necessarily be the case for dissolution or phase change of other minerals, however (or even in the case of silica if the circumstances were radically different from those used for the example). It will be necessary to perform an analysis for other types of minerals on a case-by-case basis. The techniques employed in this report may be useful for other minerals, especially if the change in $\Delta M/M_0$ is by dissolution or another process controlled by temperature gradient alone.

REFERENCES FOR APPENDIX B

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2. J. D. Rimstidt and H. L. Barnes, "The Kinetics of silica - water reactions," Geochimica et Cosmochimica Acta, Vol. 44, pp 1683 to 1699, 1980.

3. J.W. Braithwaite, F.B. Nimick, "Effect of Host-Rock Dissolution and Precipitation in a Nuclear Waste Repository in Tuff", SAND84-0192, Sandia National Laboratory, Albuquerque, N.M., Sept. 1984

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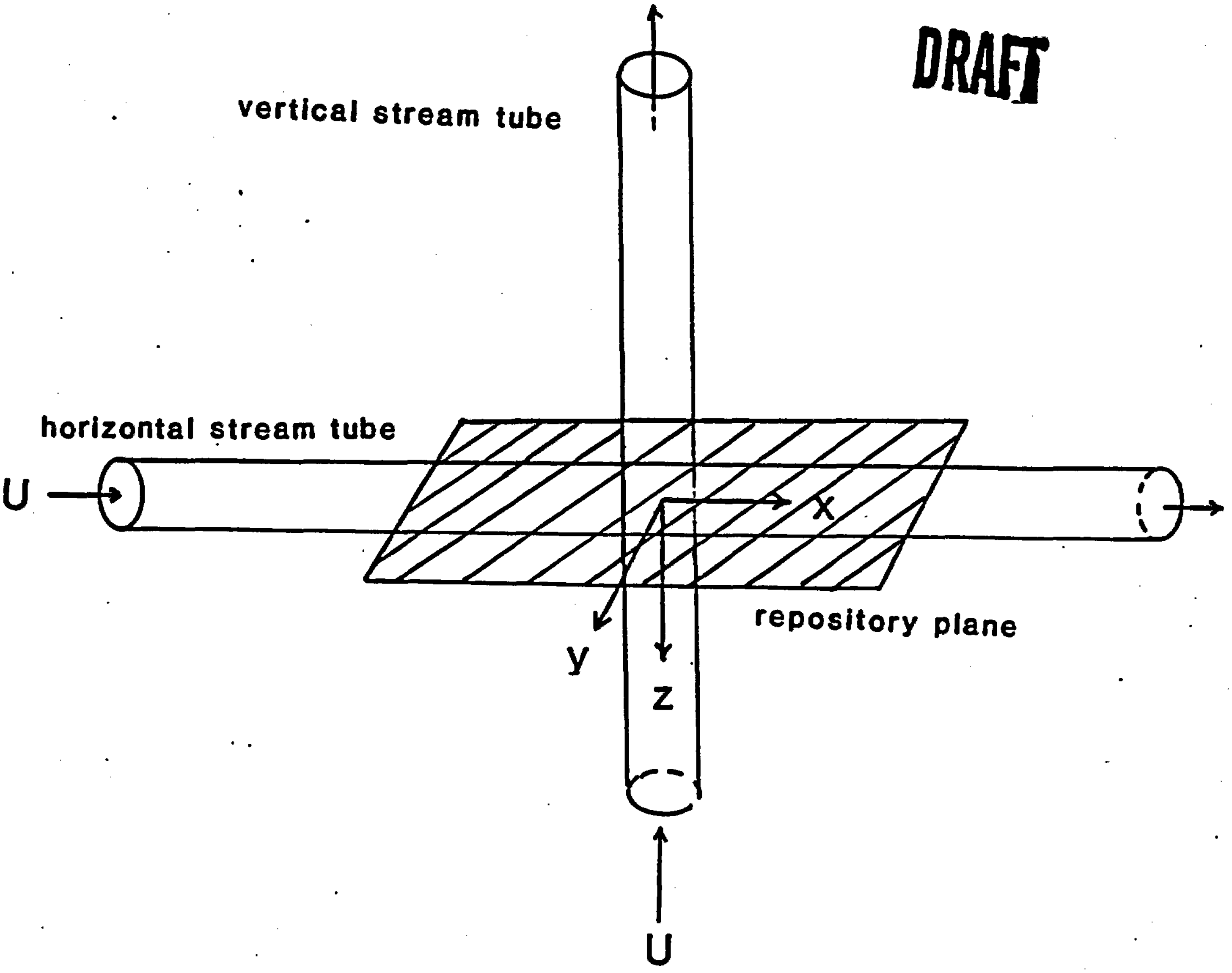

FIGURE 1 - REPOSITORY WITH VERTICAL AND HORIZONTAL STREAM TUBES

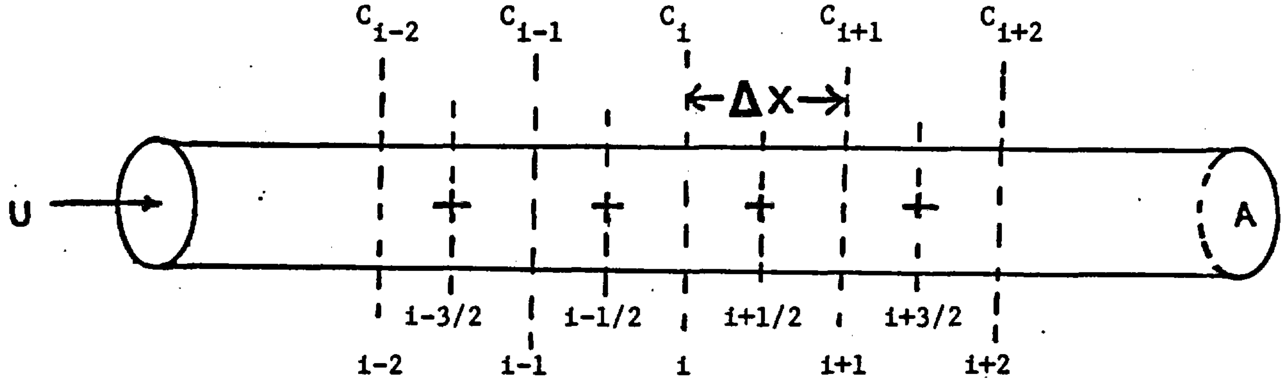

FIGURE 2 - STREAM TUBE TRANSPORT MODEL

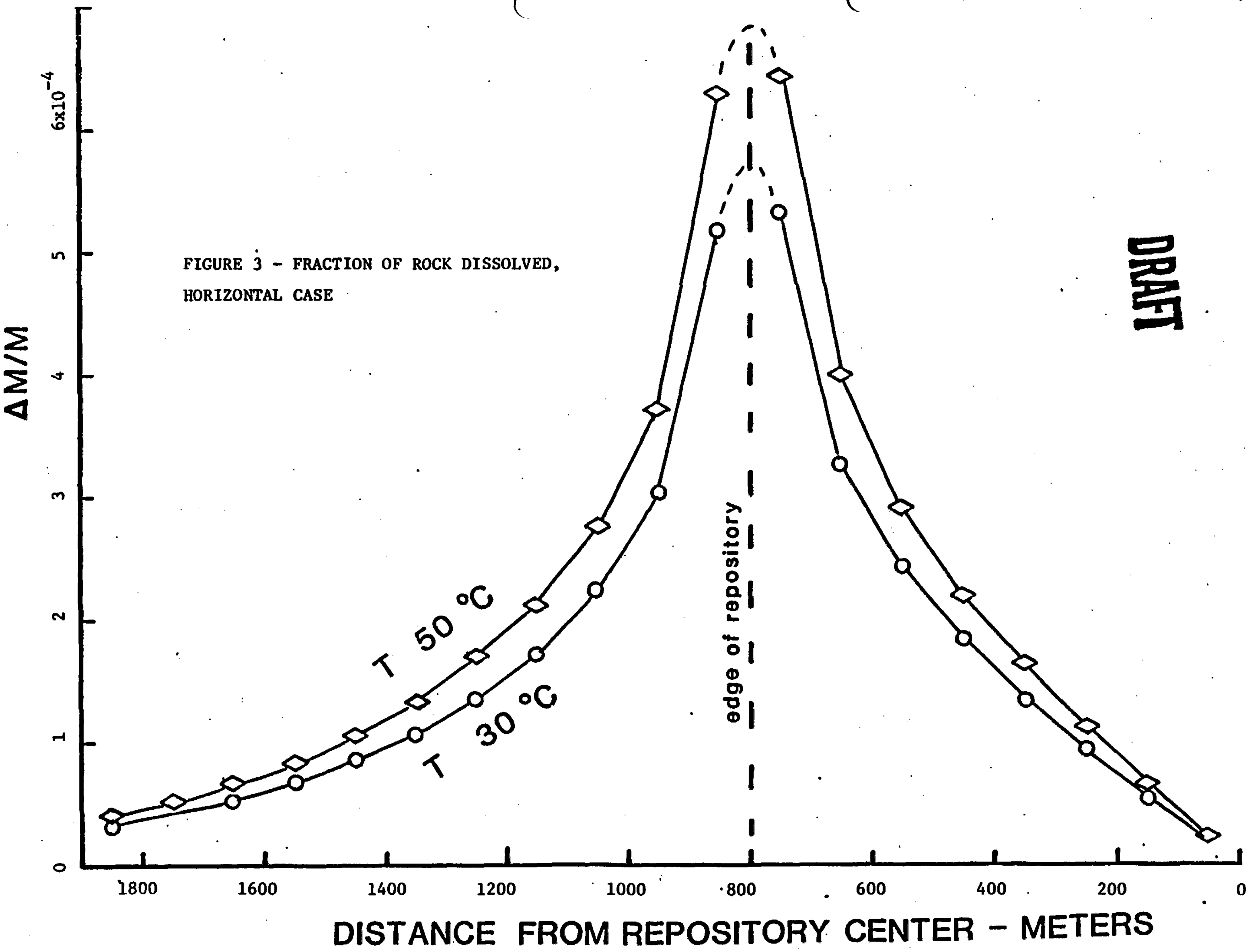

FIGURE 3 - FRACTION OF ROCK DISSOLVED, HORIZONTAL CASE

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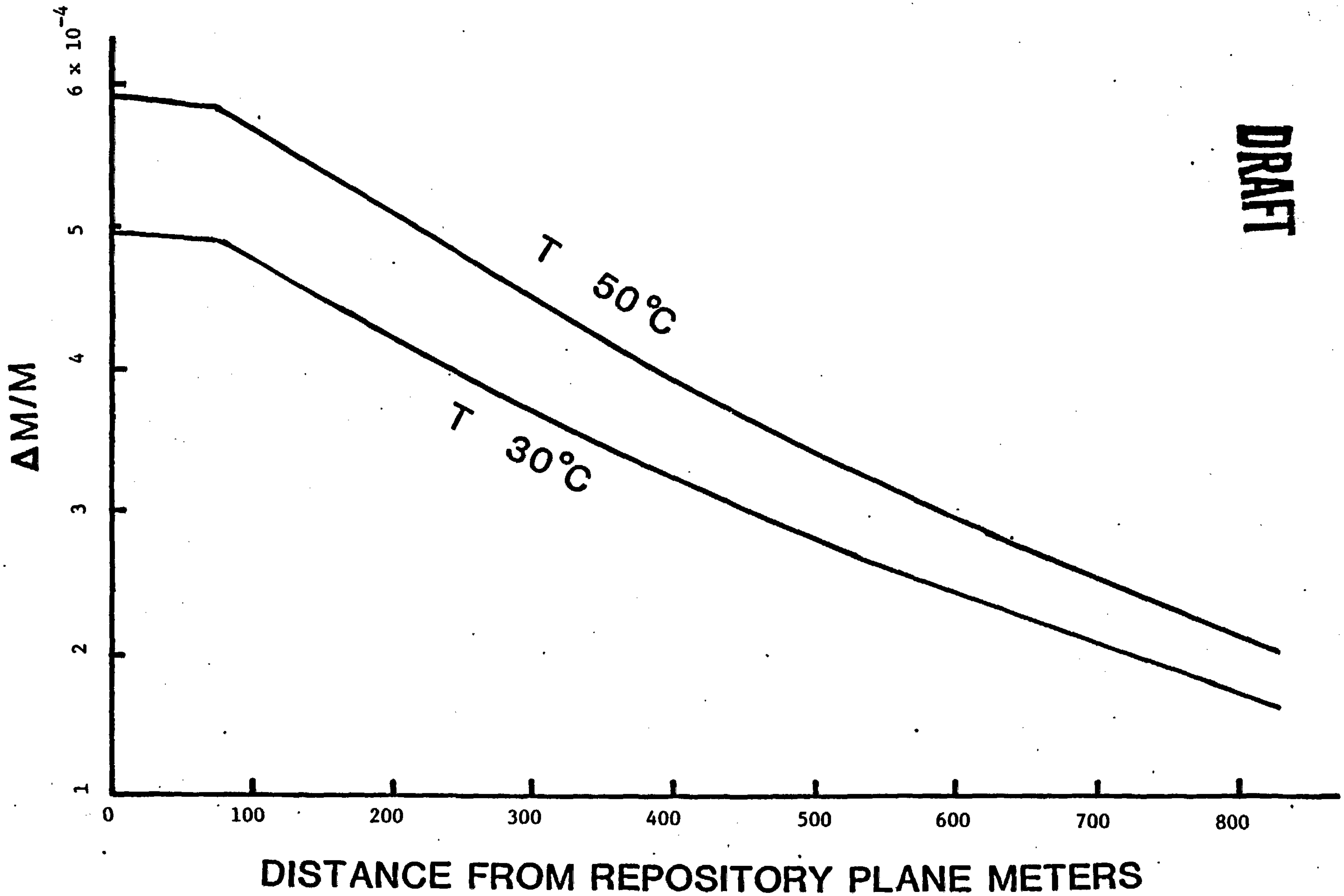

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FIGURE 4 - FRACTION OF ROCK DISSOLVED, vertical case

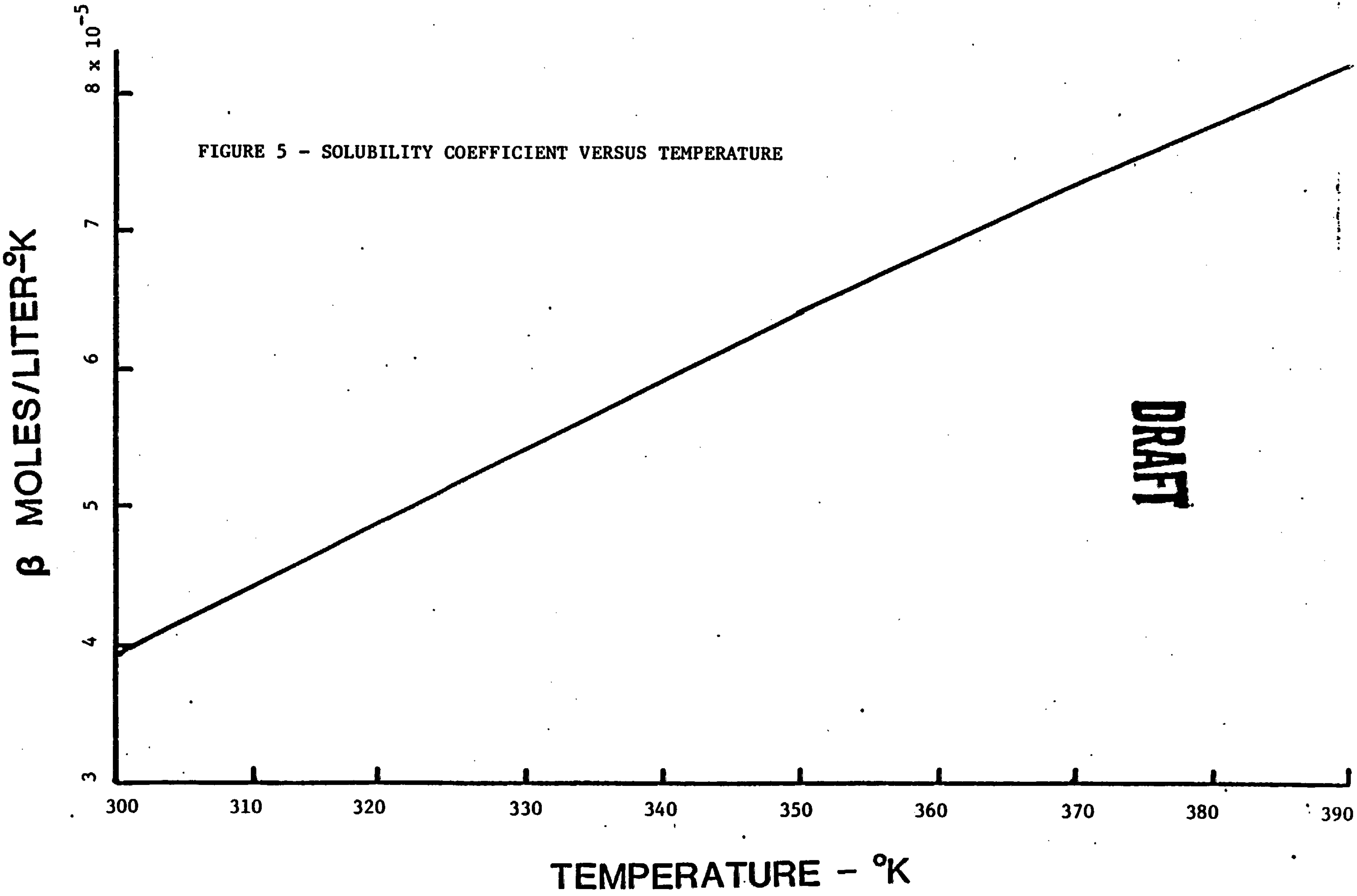

FIGURE 5 - SOLUBILITY COEFFICIENT VERSUS TEMPERATURE

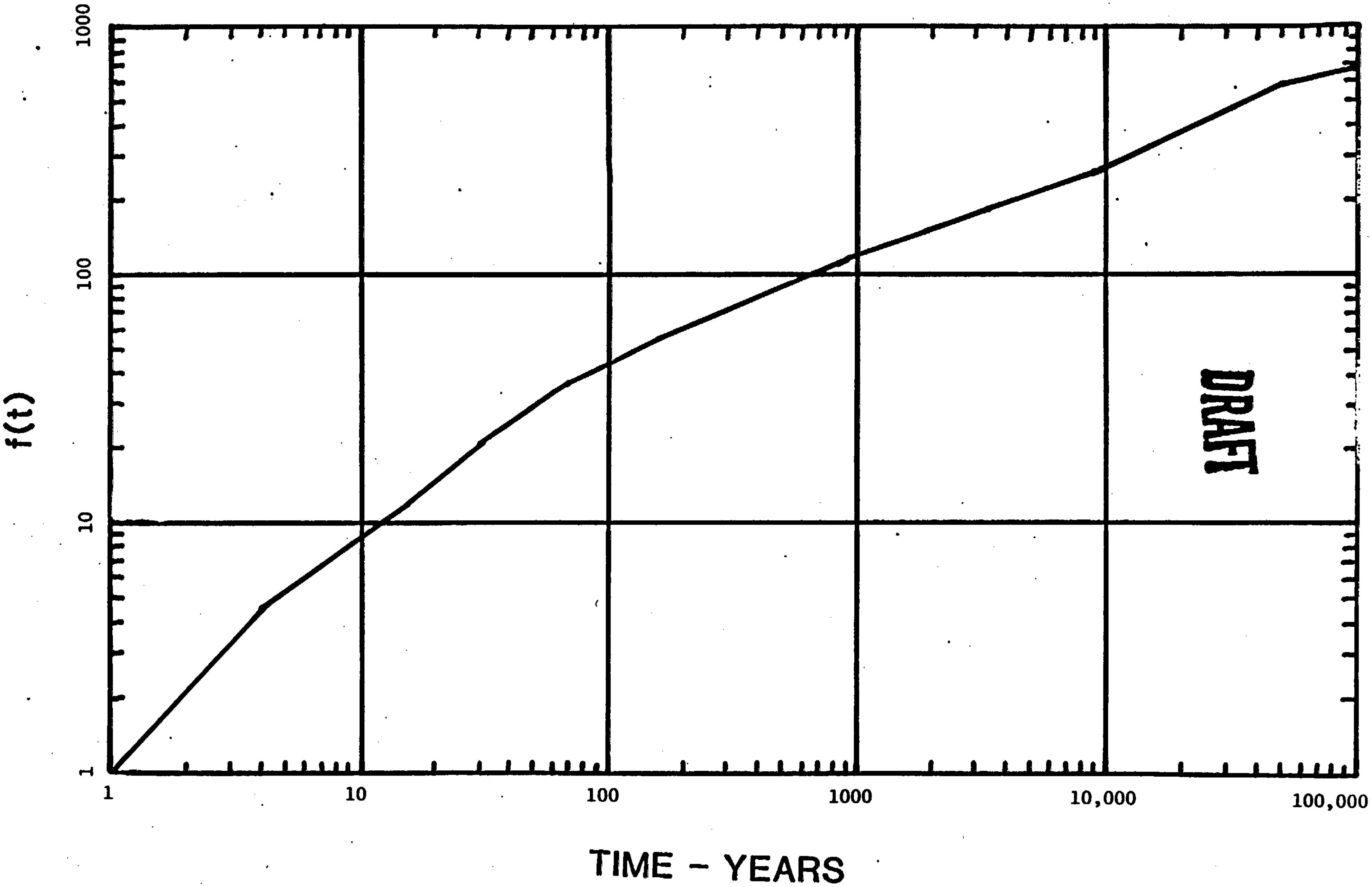

FIGURE 6 – FUNCTION f(t) VERSUS t FOR 10 YEAR OLD SPENT FUEL

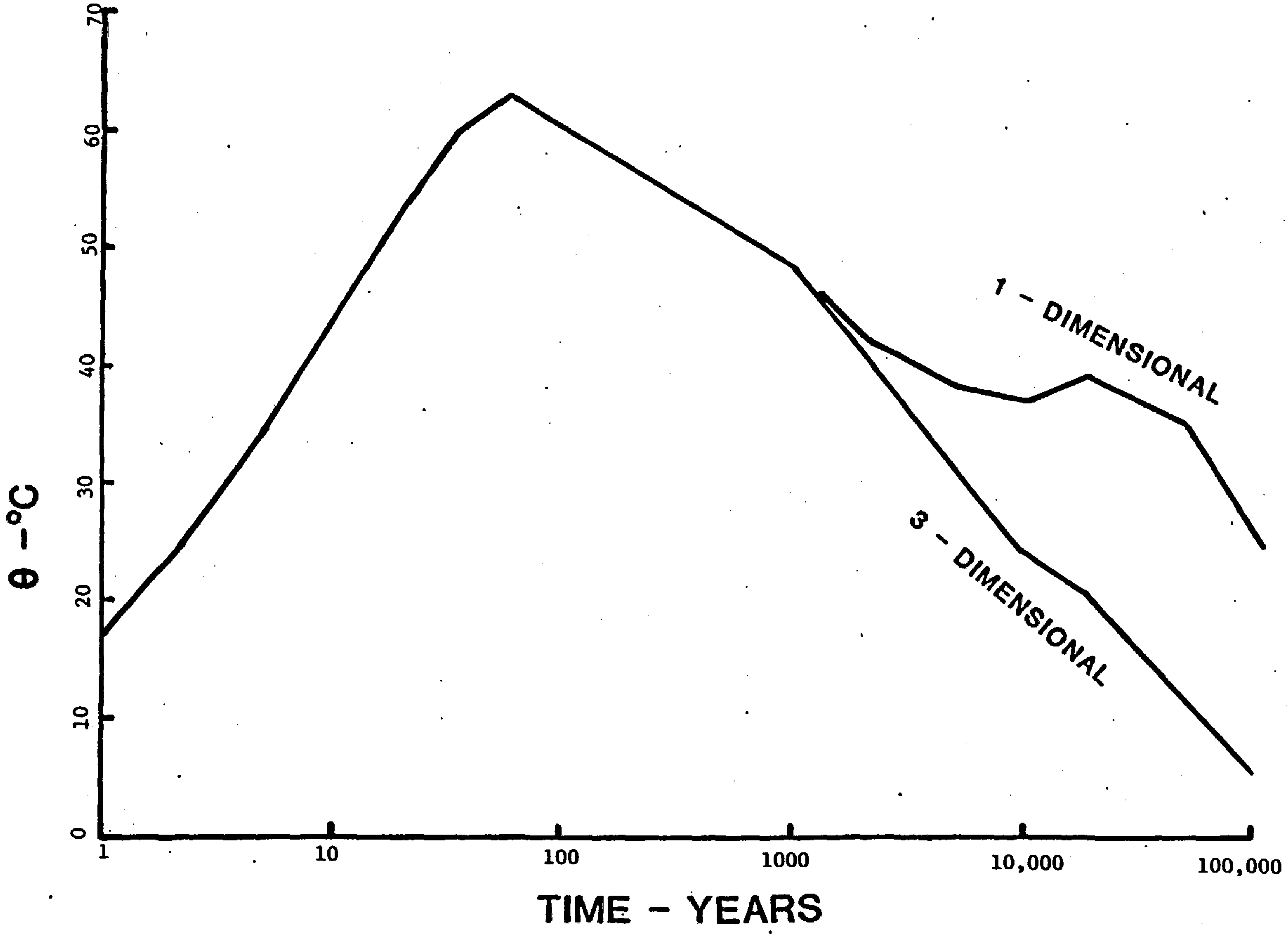

FIGURE 7 - TEMPERATURE AT CENTER OF REPOSITORY, 1-D AND 3-D MODELS

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