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IMPORTANCE OF CREEP FAILURE OF HARD ROCK IN THE NEAR FIELD OF A NUCLEAR WASTE REPOSITORY

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ABSTRACT

Potential damage resulting from slow creep deformation intuitively seems unlikely for a high-level nuclear waste repository excavated in hard rock. However, recent experimental and modeling results indicate that the processes of time-dependent microcracking and water-induced stress corrosion can lead to significant reductions in strength and alteration of other key rock properties in the near-field region of a repository. We review the small data base supporting these conclusions and stress the need for an extensive laboratory program to obtain the new data that will be required for design of a repository.

1. INTRODUCTION

Design of a nuclear waste repository involves unique engineering and scientific challenges. In the long history of underground construction, assuring integrity of deep workings in a hot, wet environment for times so extensive that they approach the geologic has never been faced. The added societal constraint that man must be protected by an extremely high confidence in design success makes the challenge awesome.

A key aspect of the problem is that mine openings must be maintained for a minimum time of 100 years to allow retrieval of waste and monitoring of repository performance. The question then arises: what is the potential for creep failure of the host rock and how can allowance for rock response be incorporated in design?

Here we assess likelihood of brittle creep failure of the most prominently studied hard rock repository media: granite, basalt, and tuff. We show that, although data available are pitifully small, creep failure is likely in all hard rock media based on current preconceptual design parameters. This means that much expanded investigation of creep properties of hard rock media must begin so that early consideration can be given on how to control time-dependent rock deformation.

2. THE EVIDENCE

First, we establish a time frame for our considerations. Assume that the average low confining pressure failure strain (linear) of hard rock is approximately 0.005. The exact value is of small importance; a factor of 2 or 3 in either direction makes little difference to our conclusions. Current broad design constraints require controlled access to stored waste for a time period of 100 years. The strain rate of most immediate interest is then calculated simply as 0.005 ÷ 100 years, or 1.6×10^{-12} per second.

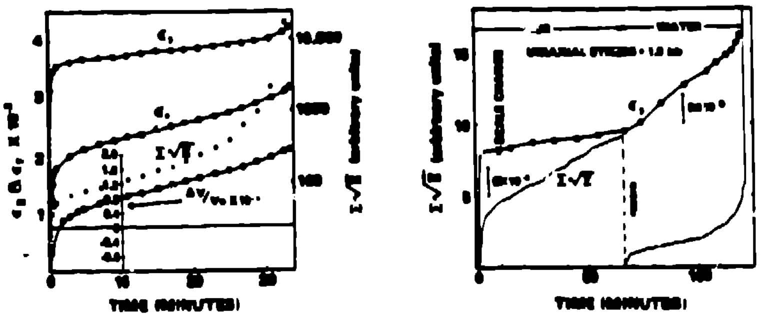
Immediately our first problem arises: there is no constitutive relation for any crustal hard rock that allows extrapolation of mechanical response to 10^{-12} s^{-1} strain rates under the environmental conditions of a nuclear waste repository. The minimum magnitude of extrapolation in strain rate from the meager laboratory data available is five orders of magnitude! Clearly, it will not be easy to estimate potential rock failure at these extended times. However, we will show that there are sufficient published data to indicate the magnitude of a creep failure problem.

Next we consider mechanisms of creep deformation under temperature and pressure conditions expected near a waste repository. We recognize three fundamental mechanisms: (1) time-dependent tensile microcracking, (2) slow continuous or episodic frictional sliding on discontinuities, and (3) ductile flow of weak or thermodynamically unstable minerals. Water is an extremely important catalytic agent for all three mechanisms.

There is extensive evidence that the mechanism of compressive shear failure of hard rock in the brittle regime derives from cumulative tensile microcracking accompanied by dilatant volume strains [1] [2]. Most of this evidence originates from short term uniaxial or triaxial compression tests. However, Figure 1a [3] indicates that the same mechanism is responsible for time-dependent or creep failure of rock.

Figure 1a shows results of a uniaxial creep experiment on Westerly granite at room temperature. Axial (ϵ_z), radial (ϵ_r), and volume strains ($\Delta V/V_0$) are plotted along with acoustic emission energy (ΣE) as a function of time. Strain-time curves show the classic creep response. An initial primary creep region characterized by a decreasing rate of strain, followed by a long secondary or steady-state region in which strain rate is essentially constant, leading to a tertiary or accelarating creep phase in which strain rate increases rapidly to ultimate failure of the test sample. Note that these curves are mimicked by the microcrack acoustic emission curve. Also note that after an initial elastic compression (negative) the volumetric strain almost immediately becomes dilatant.

This evidence, together with the acoustic emissions, indicate that the mechanism of deformation must be time-dependent tensile microcracking, in as much as opening of tensile cracks is the only way sample volume can increase beyond its starting, uncompressed value. This observation is important because it means we can use much of the vast literature on slow tensile crack growth in glasses and ceramics to evaluate creep response of rock.



A MICROFRACTURING $\Sigma\sqrt{E}$, ϵ_z, ϵ_r AND $\Delta V/V$ AT 2.25 kbar

B MICROFRACTURING $\Sigma\sqrt{E}$ AND AXIAL STRAIN BEFORE AND AFTER WATER IMMERSION AT 1.9 kbar

Figure 1. Creep of Westerly granite at room temperature [3].
A. Uniaxial creep at 2.25 kbar: axial strain (ϵ_z), radial strain (ϵ_r), volume strain ($\Delta V/V_0$), and acoustic emission energy (Σ E).
B. Effect of water stress corrosion. Uniaxial creep in air at 1.9 kbar followed by immersion in water after steady state axial strain is attained.

Figure 1b [3] illustrates the corrosive effect of water on rock. The first part of the creep curve in Figure 1b shows axial strain and acoustic emission into the steady-state creep regime for a sample compressed in air of normal humidity. When the sample is then immersed in water, strain rate increases and acoustic emission first drops, then increases dramatically to tertiary creep failure. Wu and Thomsen [3] find that at 25°C creep failure time of granite is reduced by 2 orders of magnitude by immersion in water. They also find that drying by heating their unconfined samples above 100°C increases failure times.

Stress corrosion action of water has been known and studied for some time for glass and ceramics [4] [5] [6]. For example, Figure 2 shows a 4 order of magnitude reduction in the static fatigue life (failure time) of aluminum oxide due to presence of air of normal room humidity compared to dry air -- a dramatic stress corrosion effect [7]. The mechanism of water stress corrosion [8] is essentially the same as that proposed to explain hydrolytic weakening of quartz in the plastic flow regime [9] [10]. Namely, local hydrolyzation of strong silicon-oxygen bonds and their replacement with weak, hydrogen-bonded bridges. This is a highly temperature-dependent and diffusion-limited process which explains why it is particularly active over extended times.

We see implications of these creep deformation mechanisms in the next two figures. Figure 3 shows an extrapolation of data summarized by Kranz [11] for creep of granite at room temperature. These results build on much earlier work of Scholz [12], Cruden [13], Rummel [14], and others. The extrapolations indicate at least a 30 to 80% reduction in compressive strength of granite over the 100-year time range critical to a repository. Note that the full weakening effects of water and temperature are not contained in these data. Figure 4 shows the problem from a slightly different point of view. Data shown in Figure 4 are from subcritical tensile crack growth tests of Halleck and others [15]. These tests measure tensile crack velocity vs mode 1 stress intensity factor at room temperature in granite. In the figure we recast the data in terms of failure time for 1-m blocks, i.e., the time for a crack to propagate 1 m, vs tensile strength relative to that observed in rapid direct pull or Brazilian tests. Solid parts of the curves represent data. Extrapolation to low crack rates is problematical. Strength must lie between a simple linear extrapolation of the data and a limiting value expected from similar

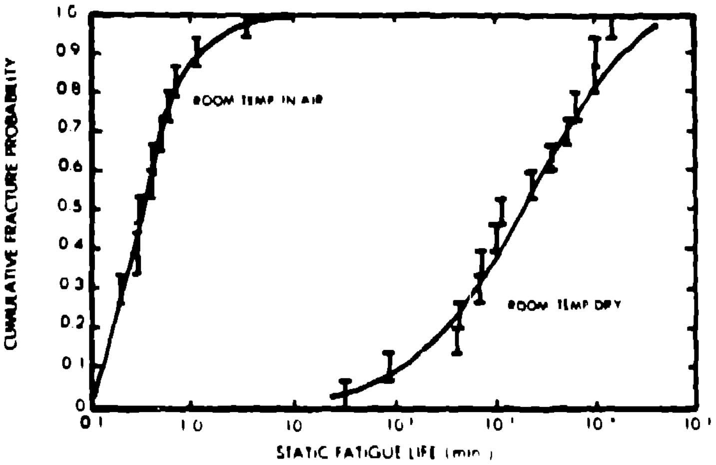


Figure 2. Static fatigue and stress corrosion of Al$_2$O$_3$ [7]. Static fatigue life as a function of probability of fracture for room temperature creep in dry air compared to air of normal room humidity.

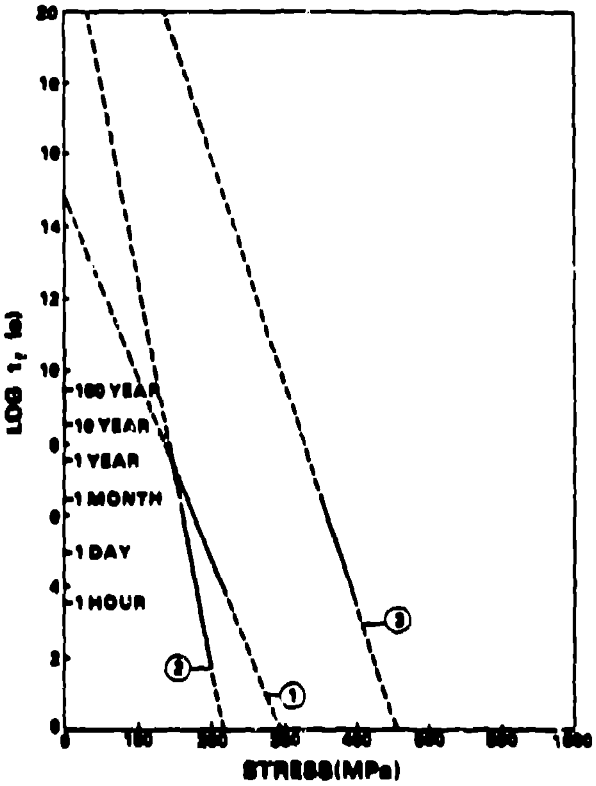


Figure 3. Room temperature creep failure stress of granite [11]. (1) Water saturated Westerly granite, 0.1 MPa confining pressure (data from Wawersik [19]). (2) Room humidity Barre granite, 0.1 MPa confining pressure. (3) Room humidity Barre granite, 53 MPa confining pressure.

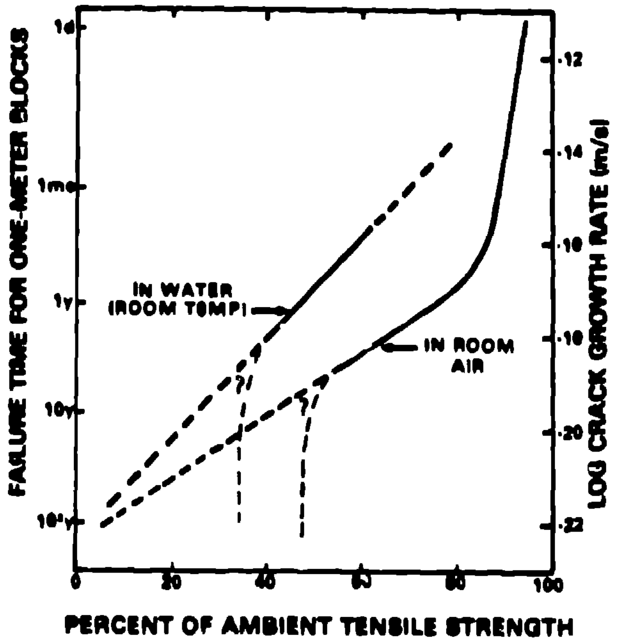


Figure 4. Subcritical crack growth of Berkeley granite at room temperature [15]. Failure time of one-meter blocks refers to the time required to extend a crack one meter based on the crack velocities measured in 3-point bend tests. Percent of ambient tensile strength is calculated from mode I stress intensities from the 3-point bend tests compared to the tensile strength measured in rapid direct pull or Brazilian tests.

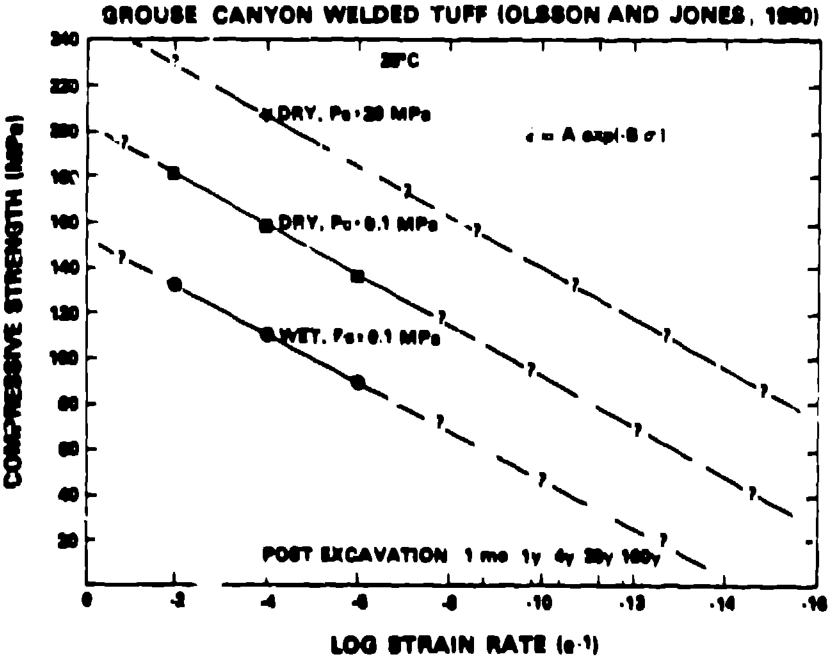


Figure 5. Compressive strength of welded tuff from the Nevada Test Site as a function of strain rate [17]. P_c is confining pressure; all tests at room temperature.

studies on glass and ceramics. Position of any limit for granite is unknown at present. In any case, these results indicate a very substantial reduction of tensile strength of granite within 100 years. Similarly, Waza and others [16] show the velocity of tensile cracks in water-saturated basalt to be 2 to 3 orders of magnitude greater than in room-dry samples.

Figure 5 shows preliminary data for compressive strength of Nevada welded tuffs as a function of log strain rate at room temperature [17]. Again note the marked weakening effect of water. We know that the simple exponential extrapolation shown is not correct, especially in view of the very limited experimental data. However, we can nevertheless use these data to estimate the impact of time-dependent rock weakening on a repository design.

Figure 6a shows results of a preconceptual thermomechanical model of a repository in welded tuff [18]. The model predicts thermoelastic stresses around a repository room at 800-m depth with a spent fuel waste canister embedded in the floor of the room. Heat load is 100 kw/acre and ground water boiling is not allowed. Calculated stresses are compared to a Coulomb-type shear failure criterion based on data similar to that shown in Figure 5. The results are represented

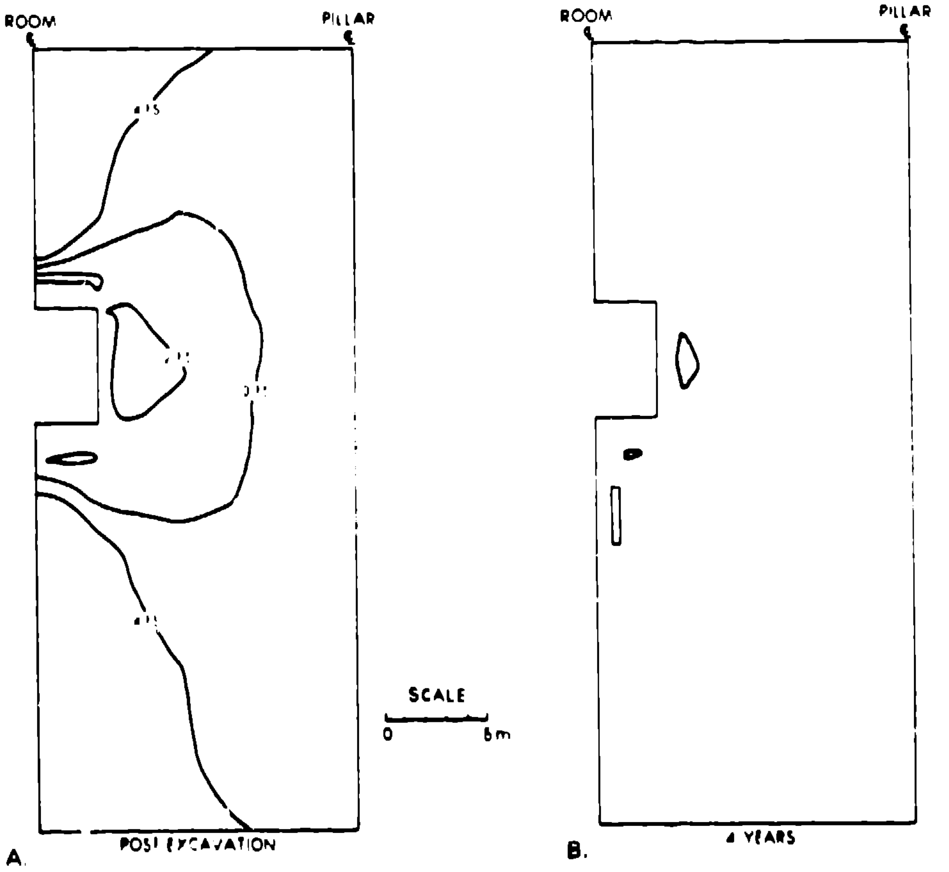
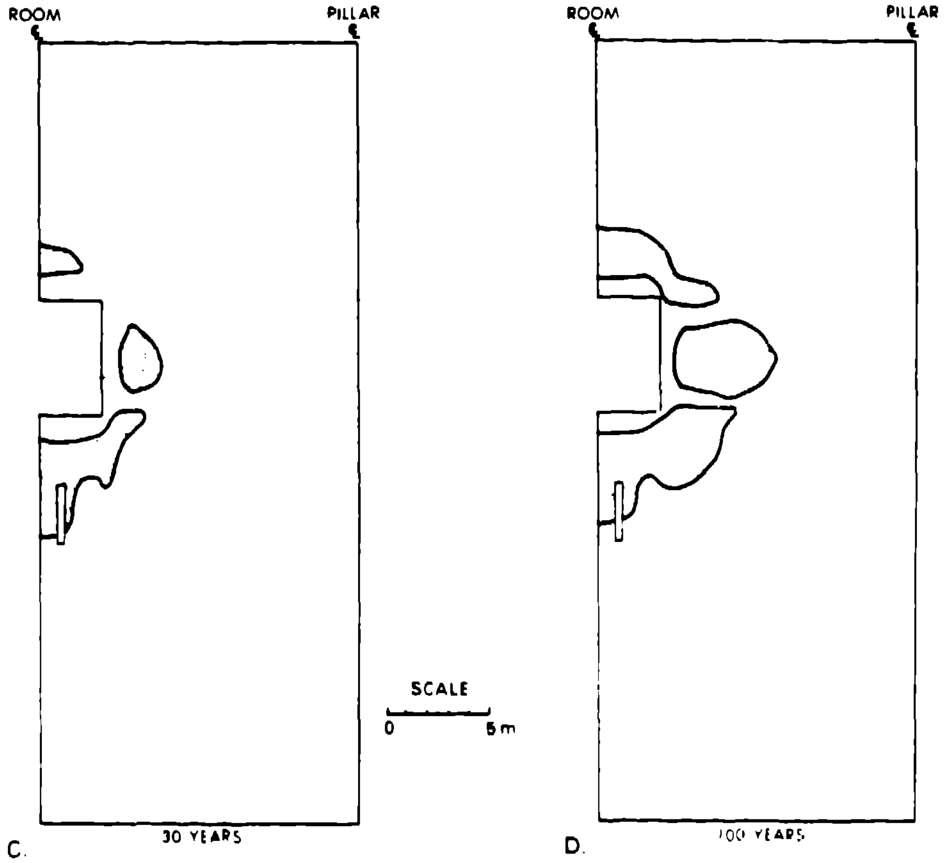


Figure 6. Estimates of creep failure around a high level nuclear waste repository in welded tuff. Failed regions are based on a comparison of extrapolated failure stresses from Figure 5 compared to thermoelastic stresses calculated for a preconceptual thermomechanical model of a repository in welded tuff [18]. Details are given in the text. A. Factors of safety (FS) immediately after excavation but before implacement of a simulated waste container in the floor of the model room. B. Interpreted creep failure zone (stippled) 4 years after implacement of waste. C. Creep failure zone after 30 years. D. Creep failure zone after 100 years.



in Figure 6a as contours of factors of safety (FS) immediately after excavation but before implacement of the waste heat source. For example, a factor of safety of two indicates calculated stresses are half of those required for shear failure.

However, the failure criterion is based on laboratory tests at strain rates of 10^{-4} to 10^{-6} s^{-1}. If we compare stresses calculated at later times in the thermal history of this model and plot factors of safety, we can qualitatively evaluate possible time-dependent shear failure around the repository. For example, a factor of safety of two will outline a failure zone if the strength, based on extrapolations shown in Figure 5, has fallen by 50% at that time. Figures 6b through 6d show failure zones based on such extrapolations for the dry, 20 MPa confining pressure strength shown in Figure 5. Tuff strengths actually used in the model to calculate factors of safety are about a factor of four lower than those we use to estimate time-dependent failure, so if anything, we believe our approach is conservative. At 4 years (Figure 6b) we see a small failure zone in the rib of the model repository room. However, this failure zone grows dramatically at later times so that by 100 years the failed region completely encompasses the near field of the room and would likely prevent maintenance of access. Note that weakening effects of temperature and water are not included in this scenario.

Although these exercises are preliminary, we believe they illustrate the need to carefully evaluate effects of time on strength of waste repository host rocks.

3. CONCLUSIONS

Contrary perhaps to one's intuition, creep deformation of hard rock does occur at nuclear waste repository conditions and does pose design problems. Other coupled phenomena that we do not discuss here make this conclusion even stronger.

For example, dilatant microcracking can cause a decrease in thermal conductivity leading to higher rock temperatures than those predicted by current models.

Clearly, we need an extensive laboratory investigation of the creep deformation of hard rock waste isolation media at repository conditions of temperature, stress, and water pore pressure. Primary deformation and secondary coupled effects on thermal conductivity, permeability, etc. require careful study. Constitutive deformation equations derived from laboratory experiments must be based on physical mechanisms identified in experiments and verified in natural deformations. Only in this way can we be confident in the long time extrapolations required in the ultimate design and performance models. By their very nature, these experiments are time consuming; therefore this work should be carried out immediately.

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