Title

MECHANICAL AND THERMAL DESIGN CONSIDERATIONS FOR RADIOACTIVE WASTE REPOSITORIES IN HARD ROCK

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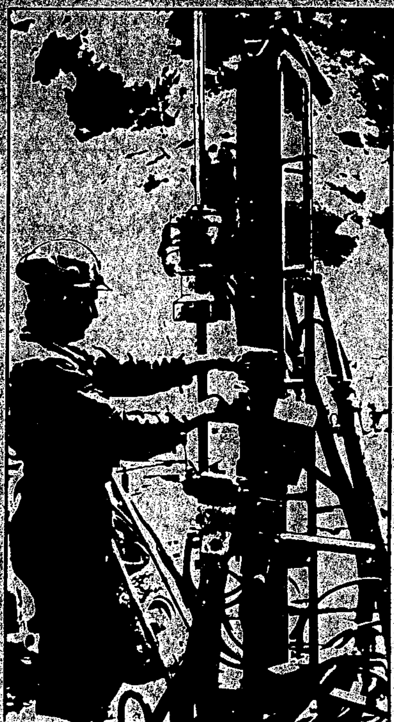

Technical Project Report No. 10

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Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Wastes,
Neville G. W. Cook

Part II: *In Situ* Heating Experiments in Hard Rock: Their Objectives and Design,
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October 1978

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MECHANICAL AND THERMAL DESIGN CONSIDERATIONS FOR RADIOACTIVE WASTE REPOSITORIES IN HARD ROCK

Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Wastes[1]

Part II: *In Situ* Heating Experiments in Hard Rock: Their Objectives and Design[1,2]

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October 1978

PREFACE

This report is one of a series documenting the results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U. S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL).

The principal investigators are L. B. Nilsson and O. Degerman for SKBF, and N. G. W. Cook, P. A. Witherspoon, and J. E. Gale for LBL. Other participants will appear as authors of the individual reports.

Previously published technical reports are listed below.

1. *Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns* by P. A. Witherspoon and O. Degerman. (LBL-7049, SAC-01).

2. *Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test* by Lars Lundström and Håken Stille. (LBL-7052, SAC-02).

3. *The Mechanical Properties of the Stripa Granite* by Graham Swan. (LBL-7074, SAC-03).

4. *Stress Measurements in the Stripa Granite* by Hans Carlsson. (LBL-7078, SAC-04).

5. *Borehole Drilling and Related Activities at the Stripa Mine* by P. J. Kurfurst, T. Hugo-Persson, and G. Rudolph. (LBL-7080, SAC-05).

6. *A Pilot Heater Test in the Stripa Granite* by Hans Carlsson. (LBL-7078, SAC-06).

7. *An Analysis of Measured Values for the State of Stress in the Earth's Crust* by Dennis B. Jamison and Neville G. W. Cook. (LBL-7071, SAC-07).

8. *Mining Methods Used in the Underground Tunnels and Test Rooms at Stripa* by B. Andersson and P. A. Halén. (LBL-7081, SAC-08).

9. *Theoretical Temperature Fields for the Stripa Heater Project* by T. Chan, Neville G. W. Cook, C. F. Tsang. (LBL-7008, SAC-09).

EDITOR'S NOTE

The two papers contained herein discuss some of the fundamental considerations on the thermomechanical aspects of repository design. Although fundamental in scope, both papers also contain specifics which have significantly influenced the design of the heater experiments at Stripa.

The first paper, "An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Waste," by Neville G. W. Cook, was first printed in October 1977, as LBL Report #7004. The second, "In Situ Heating Experiments in Hard Rock: Their Objectives and Design," by Neville G. W. Cook and Paul A. Witherspoon, was presented at the Seminar on In Situ Heating Experiments in Geological Formations held at Ludvika, Sweden, in September 1978. This meeting was sponsored by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD), in cooperation with the Swedish Nuclear Fuel Supply Company (SKBF). The latter paper is incorporated in the proceedings of that meeting.

*Part I**

AN APPRAISAL OF HARD ROCK FOR POTENTIAL UNDERGROUND REPOSITORIES OF RADIOACTIVE WASTES

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SYNOPSIS

Underground burial of radioactive wastes in hard rock may be an effective and safe means of isolating them from the environment and from man. The mechanical safety and stability of such an underground repository depends largely on the virgin state of stress in the rock, groundwater pressures, the strengths of the rocks, heating by the decay of the radioactive wastes, and the layout of the excavations and the disposition of waste cannisters within them. A large body of pertinent data exists in the literature, and each of these factors has been analysed in the light of this information. The results indicate that there are no fundamental geological nor mechanical reasons why repositories capable of storing radioactive wastes should not be excavated at suitable sites in hard rock. However, specific tests to determine the mechanical and thermal properties of the rocks at a site would be needed to provide the data for the engineering design of a repository. Also, little experience exists of the effects on underground excavations of thermal loads, so that this aspect requires theoretical study and experimental validation. The depths of these potential repositories would lie in the range from 0.5 km to 2.0 km below surface, depending upon the strength of the rock. Virgin states of stress have been measured at such depths which would retard the ingress of groundwater and obviate the incidence of faulting. A typical repository comprising three horizons each with a total area of 5 km^2 would have the capacity to store wastes with thermal output of 240 MW.

CONTENTS

1. INTRODUCTION

Nuclear wastes have had to be stored now for more than three decades. Large quantities of radioactive waste are currently stored at a number of surface sites, and the quantity is increasing each year.

Though every precaution is taken to protect the environment and man from the adverse effects of this material, surface storage does not appear to be an effective nor practicable long-term solution. Even the most carefully managed surface storage may not be adequately secure against events such as major meteorological or geological disasters, acts of terrorism, war and political turmoil.

Archeological and geological experience provides cogent evidence that subsurface burial gives long term protection to a wide variety of different objects against disasters such as those mentioned above, amongst others.

Some underground mines have been in existence for more than a century and many mines use excavations fifty or more years old. A wealth of experience exists concerning the design and construction of underground excavations for civil and mining engineering purposes. In the 18 countries of the OECD (Organization for Economic Cooperation and Development), this involves the annual construction of the order of 50,000 km of tunnels alone

This work was prepared under the auspices of the U. S. Department of Energy.
* *This report may be ordered separately as LBL-7004.*

(OECD Advisory Report on Tunneling, 1970). This experience covers most kinds of rocks in virtually every terrain and climate, beneath land and water, and down to depths approaching 4 km below surface.

Accordingly, it is logical to explore the feasibility of using appropriate underground storage for the effective isolation of radioactive wastes. This involves the study and evaluation of the many different aspects of this potential solution. One of these aspects concerns the safety and stability of the excavations of such a repository.

As a beginning, this necessitates an examination of the potential effects on such excavations of the virgin state of stress in the rock, the stability of, and interaction between, adjacent excavations and the consequences of heating of the rock by the radioactive decay of the waste. In this report, these questions are addressed in general terms.

2. THE VIRGIN STATE OF STRESS IN THE ROCK

In general the vertical component of the virgin state of stress in rock has a value close to that given by the weight of the overburden. Departures from this may occur in areas of uneven topography at depths below surface shallow compared with the relief, or in and close to inclusions and intrusions of rock with mechanical properties different from those of the surrounding rock.

A significant number of attempts has been made to measure the complete virgin state of stress in rock at different locations and depths throughout the world. These measurements have shown that the values of the horizontal components of this state of stress range from about a third to three times that of the vertical component. A compilation of many of these measurements has been done by Hoek and Brown (1977), and is shown in Figure 1. From this it can be seen that relatively high values of the horizontal components of stress tend to be a shallow phenomenon, possibly associated with the effects of rapid denudation (Voight, 1966).

The value of the vertical component of rock stress is, on average, some 2.7 times greater than the hydrostatic head of water at the same depth, that is, the value of the ratio of the hydrostatic head to the vertical stress is 0.37, as is illustrated also in Figure 1. This is a result of the ratio between the average density of rock and that of water.

For many reasons, the preferred depth of an underground repository for the storage of radioactive waste in rock is likely to be in the range from a half a kilometer to two kilometers below surface. Within this range, the virgin state of stress in the rock at any potential repository site should meet three criteria:

i) The value of the minimum horizontal component of this state of stress should be significantly greater than that of the hydrostatic head of water at the same depth. Otherwise, such near vertical joints and cracks as exist in the rock may not be tight against groundwater or could be opened by the pressure of its hydrostatic head.

ii) The ratio between the values of maximum and minimum components of this state of stress should be relatively small, so as to obviate the likelihood of faulting, even in the presence of hydrostatic water pressures. If the value of the minimum component of the state of stress is Lp, where p = the hydrostatic pressure, then the value of the maximum component must be less than Mp to preclude fault movement,

where

$$(M-1)p = [(\mu^2 + 1)^{\frac{1}{2}} + \mu]^2 (L - 1)p, \qquad (1)$$

and μ = coefficient of friction (Jaeger and Cook, 1976).

Equation (1) can be written as

$$M = [(\mu^2 + 1)^{\frac{1}{2}} + \mu]^2 (L-1) + 1 \qquad (2)$$

and solved for a range of values of μ and L, as given in Table 1 below. If the vertical component is the maximum principal stress, the value of M is about 2.7. This excludes those combinations of μ and L in the upper, left half of Table I.

TABLE I

Values of M (the ratio between the value the value of the maximum component of the virgin state of stress and the hydrostatic pressure at any depth) for different values of μ (the coefficient of friction) and L (the ratio between the minimum value of the virgin state of stress and the hydrostatic pressure at the same depth).

μ	Values of M for:			
	L=1.33	L=1.5	L=1.75	L=2.0
0.4	1.73	2.10	2.66	3.20
0.6	2.04	2.56	3.35	4.13
0.8	2.43	3.16	4.24	5.32
1.0	2.92	3.90	5.34	6.80

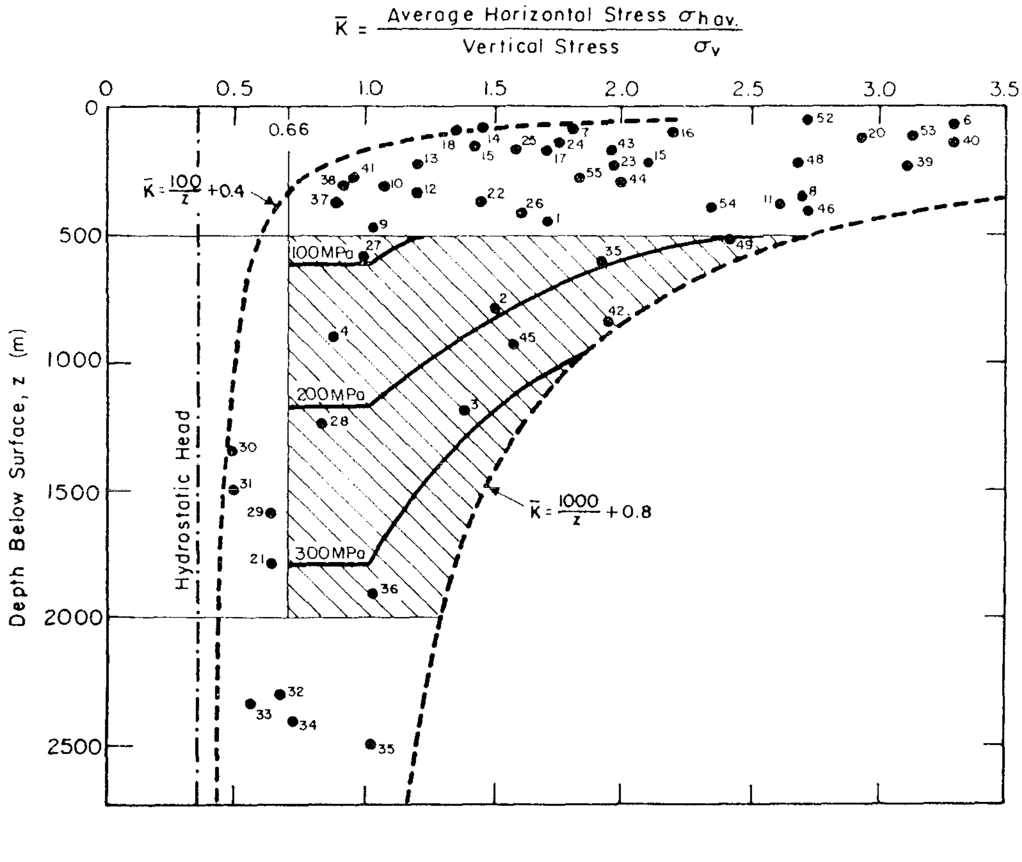

Figure 1. The ratio between measured values of the average of the horizontal components and the vertical component of the virgin state of stress as a function of depth. The hatched region between 500 m and 2000 m below surface represents those states of stress which would preclude faulting and diminish the ingress of groundwater. The contours marked 100 MPa, 200 MPa and 300 MPa define those parts of this region within which it is considered safe to place a repository if the uniaxial compressive strength of the rock has these values. (Data from Hoek and Brown, 1977)

Also, as it may be unsafe to assume that μ is greater than 0.6, the value of L should be 1.75 or more. Therefore, only the hatched region of Table I can be considered to represent safe combinations of μ and L, such that fault movement is not likely to occur even along pre-existing fractures.

iii) The maximum stress difference should be less than some safe value. An argument for a value for this difference of 25 MPa is presented below.

The upper bound to the values of the measured horizontal components of the virgin state of stress derived by Hoek and Brown can be expressed as:

$$\sigma_h - \sigma_v = 25 - 0.005z, \qquad (3)$$

where σ_h = the average value of the horizontal components of stress (MPa)

σ_v = the value of the vertical component, approximately 0.025z (MPa), and

z = the depth below surface (m).

Equation (3) suggests that the maximum stress difference which rocks near the surface can sustain may be about 25 MPa. However, the definition of σ_h as an average value introduces a degree of ambiguity into this interpretation. If the vertical component, σ_v, is the minimum principal stress, then $\sigma_{h1} \geq \sigma_{h2} \geq \sigma_v$, where σ_{h1} and σ_{h2} are the two horizontal principal stresses. In this case, the stress difference given by equation (3) is exact for $\sigma_{h1} = \sigma_{h2}$ or may correspond to only half this difference, that is, $(\sigma_{h1} - \sigma_v)/2$ if $\sigma_{h2} = \sigma_v$. If σ_{h1} is the maximum principal stress and σ_{h2} is the minimum principal stress then $\sigma_{h1} \geq \sigma_v \geq \sigma_{h2}$, and the stress difference by equation (3) corresponds to $(\sigma_{h1}/2) - \sigma_v$ for the extreme case of $\sigma_{h2} = 0$. Thus, the actual difference between the components of the virgin state of stress may be two or more times greater than, but not less than, the value defined by equation (3). Therefore, it seems reasonably safe to assume that the value of the maximum principal stress should not exceed the value of the minimum principal stress by more than 25 MPa.

Assuming that the value of the vertical component of the virgin state of stress is either the maximum or the minimum principal stress and that the values of the horizontal components are comparable, that portion of Figure 1 falling within the criteria described above is delineated and shown hatched.

3. THE STRENGTH OF ROCK AROUND EXCAVATIONS

Underground excavations can have many different configurations. In mining, these are dictated largely by the desire to extract a relatively high proportion of the ore. In civil engineering, large equipment must often be accommodated. Neither of these requirements seems to be important in laying out the excavations for an underground repository of radioactive wastes. Probably the most important consideration in this case is the safety, stability and security of the excavations. In general, therefore, such excavations are likely to take the form of a series of adjacent but more or less independent tunnels. This results in simple, safe excavations with a high degree of isolation between each tunnel.

Based on laboratory measurements of the strengths of small intact specimens of rock and theoretical analyses of the stresses around tunnel-like excavations, rock failure would not appear to be a significant problem. However, it is generally accepted that such a simple approach does not accord with reality. It neglects at least two important factors, namely, the effects of size and of geologic struture on the strength of rock.

Size is thought to have a significant effect on the strength of geologic materials but there is a dearth of quantitative data on this question. Jaeger and Cook (1976) devote a Chapter to this subject, discussing both experimental results and Weibull's statistical theory. Most of the experimental information that is available concerns more or less cubical specimens of coal. Evans and Pomeroy (1958) and Evans, Pomeroy and Berenbaum (1961) quote a wide range of crushing strengths for cubes of coal, the mean and modal values of which vary as

$$\sigma_c = Ka^{-d}, \quad (4)$$

where σ_c = the crushing strength;
K = a constant;
a = the side length of the cube,
and d = an exponent with values between 0.17 and 0.32.

From a statistical analysis of case histories of pillars in coal mines Salamon and Munro (1967) concluded that the strength of a pillar decreases inversely with size as its volume to the power 0.067, which accords well with the values for d given in equation (4) above. Data for hard rock are even more sparse than for coal. Pratt et al obtained the results reproduced in Figure 2 for laboratory and in situ specimens of quartz diorite, showing a pronounced effect of size on

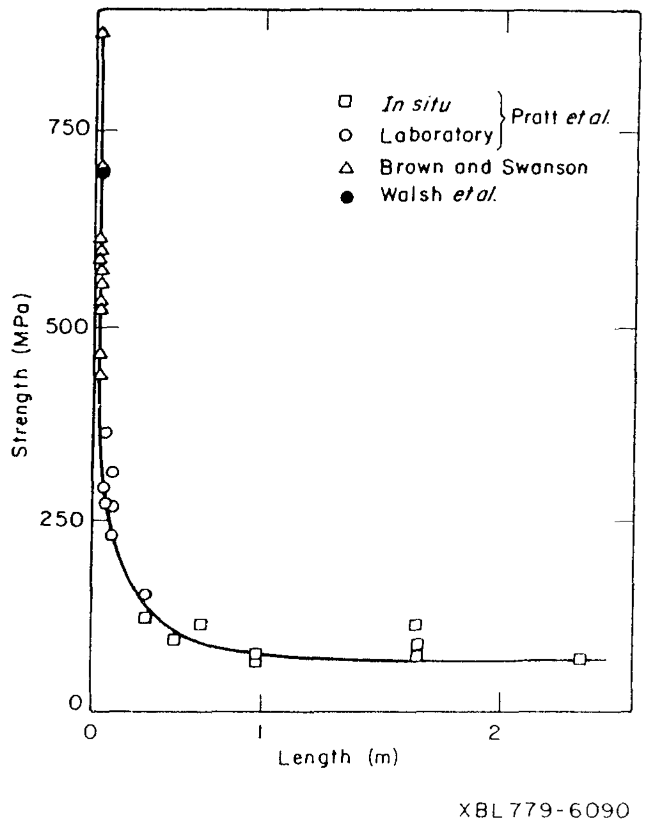

Figure 2. A diagram illustrating the effect of size on the uniaxial compressive strength of quartz diorite. (From Pratt et al, 1972)

strength. However, Obert et al (1946) and Hodgson and Cook (1970) found size to have little effect on strength. Clearly, this is an important matter that cannot be settled now for want of sufficient data.

In practice, the behavior of rock around many excavations is determined by its structure and the presence of geological discontinuities (Hoek, 1977). However, little is to be gained in terms of a general, as distinct from a site specific, attempt to evaluate this phenomenon. A worst case analysis always results in rock failure and any less demanding theoretical assumptions, no matter how obscure they are, merely beg the question of specific data on the frequency, character, orientation and properties of such discontinuities.

Nevertheless, it is necessary to form some idea of the magnitude of the effects of size and of geologic discontinuities on the strength of hard rock, in order to evaluate its potential as a location for an underground repository of radioactive wastes. Some guidance may be gained from an examination of the values of the field stresses known to have caused damage to tunnels in hard rock. Cook (1976) showed that failure by slabbing of the sidewalls of tunnels about 3m square occurred when the major component of the field stress to which these tunnels was subjected, reached a value of between 0.15 and 0.30 times the uniaxial compressive strength of laboratory specimens. The tunnels were in argillaceous and arenaceous quartzites of the Witwaterstrand System, in which the median spacing of all joints is of the order of 10 meters. These data, covering a range of uniaxial compressive strengths from 170 MPa to 336 MPa, are plotted in Figure 3. They suggest that the most likely value for the ratio of the value of the major field stress at which failure around such a tunnel becomes apparent to the uniaxial compressive stress is 0.18, and that this value increases as the strength of the rock decreases.

In the absence of any better information, assume that a safe value for the ratio of the field stress to the uniaxial compressive strength is 0.15. Those regions of Figure 1 in which it would then be safe to site tunnels in rocks with uniaxial compressive strengths of 100 MPa, 200 MPa and 300 MPa are shown by the relevant contours. From these it appears that the uniaxial compressive strength of the rock at a suitable site probably should be at least 200 MPa.

Probably a repository would comprise a number of adjacent tunnels. Any interaction between these tunnels will increase the likelihood of failure. It is probably desirable that they be so spaced as to virtually eliminate the effects of interaction. From experience it is known that adjacent tunnels interact adversely if their diameter is more than a third of their centre-to-center spacing. In Figure 4 is plotted the average stress concentration in the pillars between a series of adjacent, parallel tunnels and the maximum stress concentration at the circumference of such a series of tunnels of circular cross-section, as a function of the ratio between the tunnel diameters and their centers. Notice how the slope of the curves representing the stress concentrations increases as the ratio of diameter to center spacing. From this derives the propensity for instability. Accordingly, it seems advisable to choose a ratio of diameter to center spacing significantly less than a third, say, 0.2.

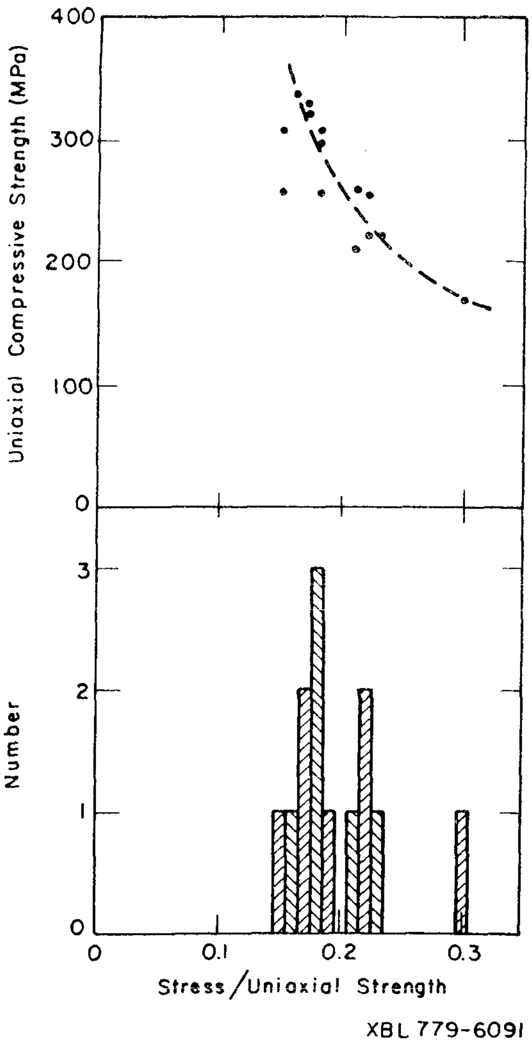

Figure 3. Diagrams showing the ratio between the maximum value of the field stress at which sidewall failure of tunnels in hard rocks occurred and the uniaxial compressive strengths of the rock concerned, and the numbers of these failures. (Data from Cook, 1976)

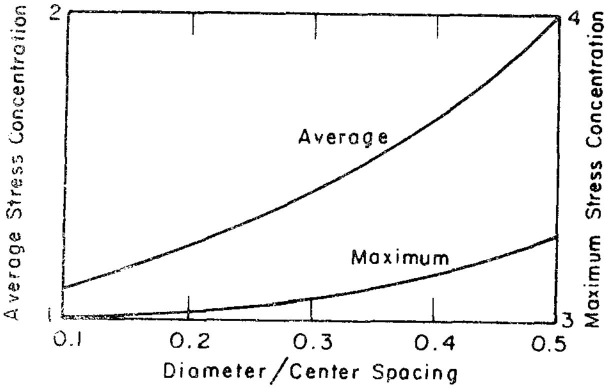

Figure 4. The average and maximum stress concentrations between a series of adjacent circular tunnels as a function of the ratio of the diameter to the center spacing.

4. THERMOMECHANICAL EFFECTS

4.1 Short-term, Local Phenomena

It seems likely that the radioactive wastes which may be buried in a repository will be sealed in steel cylinders probably measuring about 0.3m in diameter by about 3.0m in length (OWI, 1976). At this stage, the composition of these wastes is uncertain. If they were to be high-level wastes, they would have a time-dependent heat output such as is illustrated in Figure 5. The average thermal load from such a waste cannister after 10 years is of the order of 1 kw but the peak load is a strong function of the age of the waste.

It is well known that temperature is an important agent in the degradation of rock. Thermal degradation occurs in several ways.

Many minerals undergo changes as a result of increasing temperature. For example, some clay minerals change as a result of dehydration at temperatures of less than 200°C. Such changes are accompanied by changes in volume, which affect the mechanical properties of the rocks of which these minerals may be part.

Even in the absence of changes in composition slow, uniform heating of rock can have a major effect on its mechanical properties. Most rocks are polycrystalline aggregates of different minerals and cementitious materials. The thermomechanical properties of the various minerals usually differ from one another, and these properties for any one mineral are seldom isotropic. Therefore, even in the absence of thermal gradients, differential thermal expansion of individual crystals and between different crystals sets up high deviatoric stresses within the rock. The coefficients of linear thermal expansion per °C for

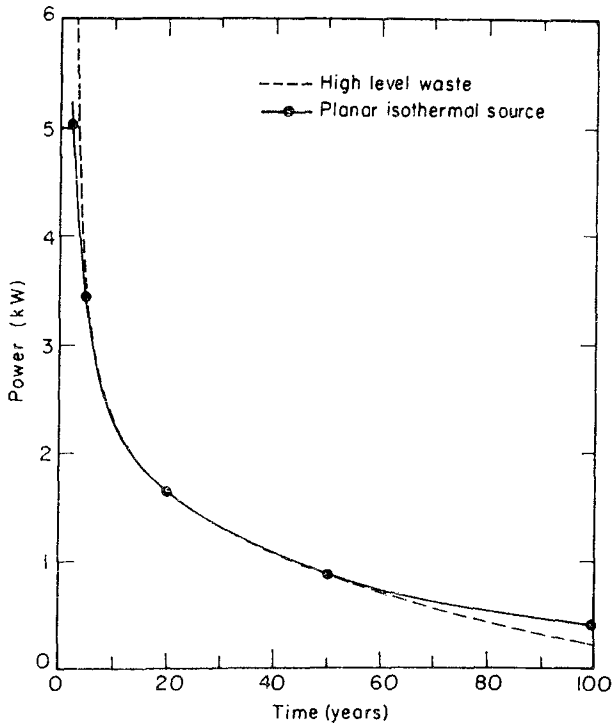

Figure 5. The power output of a standard, high-level waste cannister as a function of time and the heat flow from a planar isothermal source. (Data on radioactive waste from OWI, 1977)

common minerals lie in the range from zero to more than 10^{-5} for temperatures of up to 100°C (in certain directions some of these coefficients actually have negative values) (Clark, 1966). Thus, even modest increases in temperature, of the order of 100°C, can result in differential strains of the order of 10^{-3}. As the elastic constants of these minerals are of the order of 50 GPa this may give rise to differential stresses of the order of 50 MPa, which is of the same order as the cohesive shear strength of rock. It is not surprising, therefore, that changes in temperature of this order may degrade the mechanical strength of many rocks. However, this phenomenon does not appear to have been studied quantitatively to any great extent. Jaeger and Cook (1976) refer to the effects of slowly heating a sample of marble to 500°C and then allowing it to cool slowly. The permanent changes brought about by this thermal cycle are shown in Figure 6. From this Figure it can be seen that the uniaxial compressive strength of this marble was reduced from an initial value of about 75 MPa to about 15 MPa, but with increased confining pressure the triaxial compressive strength rapidly approached that of the original marble. What the effects of size, discussed in Section 3, on this phenomenon may be are not known.

There are many different ways in which the thermomechanical stresses induced

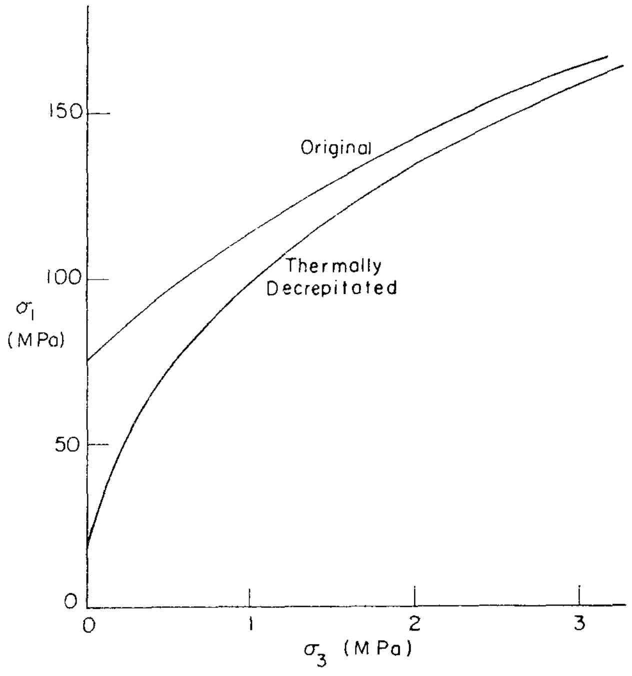

Figure 6. A diagram showing the effect of thermal decrepitation on the triaxial strength of marble. (From Jaeger and Cook, 1976)

by temperature gradients may be calculated. If the elastic and thermal coefficients can be regarded as independent of temperature, these stresses can be expressed very simply in terms of a thermomechanical factor, the mean and actual temperature changes, and a geometrical factor (Timoshenko and Goodier, 1951).

For short periods of time, the temperature field around a cannister approximates that from a line source and for intermediate periods of time it approaches that from a point source. The thermomechanical factor for both cases is

$$F = \frac{\alpha E}{(1-\nu)}, \qquad (5)$$

where α = the coefficient of linear thermal expansion ($°C^{-1}$);

E = Young's modulus (GPa), and

ν = Poisson's ratio.

Note that it is in fact this thermomechanical factor as a whole which must be more or less independent of temperature, rather than the individual constants.

Using the convention of positive compressive stresses, the radial and tangential stresses and their sums and differences for an infinite line source are given by:

$$\sigma_r = \frac{\alpha E}{(1-\nu)} \frac{\bar{T}}{2} \times 10^3 \qquad (6)$$

$$\sigma_\theta = \frac{\alpha E}{(1-\nu)} (T - \frac{\bar{T}}{2}) \times 10^3 \qquad (7)$$

$$\sigma_r - \sigma_\theta = \frac{\alpha E}{(1-\nu)} (\bar{T} - T) \times 10^3 \qquad (8)$$

$$\sigma_r + \sigma_\theta = \frac{\alpha E}{(1-\nu)} T \times 10^3 \qquad (9)$$

where σ_r = the radial component of stress (MPa);

σ_θ = the tangential component of stress (MPa);

$\bar{T}$ = the mean temperature change inside a radius r (°C), and

T = the actual temperature change at a radius r (°C).

Likewise, these stresses for a point source are given by:

$$\sigma_r = \frac{\alpha E}{(1-\nu)} \frac{2\bar{T}}{3} \times 10^3 \qquad (10)$$

$$\sigma_\theta = \frac{\alpha E}{(1-\nu)} (T - \frac{\bar{T}}{3}) \times 10^3 \qquad (11)$$

$$\sigma_r - \sigma_\theta = \frac{\alpha E}{(1-\nu)} (\bar{T} - T) \times 10^3 \qquad (12)$$

$$\sigma_r + \sigma_\theta = \frac{\alpha E}{(1-\nu)} (T + \frac{\bar{T}}{3}) \times 10^3 \qquad (13)$$

Notice that the geometrical factor for the line source in equations (6) and (7) is 1/2, and those for the point source in equations (10) and (11) are 2/3 and 1/3, respectively. These equations should, therefore, provide reasonably close bounds to the actual values of the thermomechanical stresses around cannisters.

The mean and actual temperature changes at various radii from an infinite line and a point source have been calculated using the standard formulas for the conduction of heat in solids (Carslaw and Jaeger, 1959). The line source has a power output of 400 watts per meter, that is, 1 kW over 2.5 m of length, and the point source has a power output of 1 kW. The properties of the rock have been assumed as: conductivity 2.5 W/m °C; density 2600 kg/m^3, and specific heat 0.9 kJ/kg °C. Values of these temperatures for times of 15 days and 90 days are given in Tables II and III, and are plotted in Figure 7. No values for radii less than 0.5 m are given, because in practice the cannisters are intended to be placed in boreholes with a radius of about 0.2 m. A time of 15 days is sufficiently short for the temperature

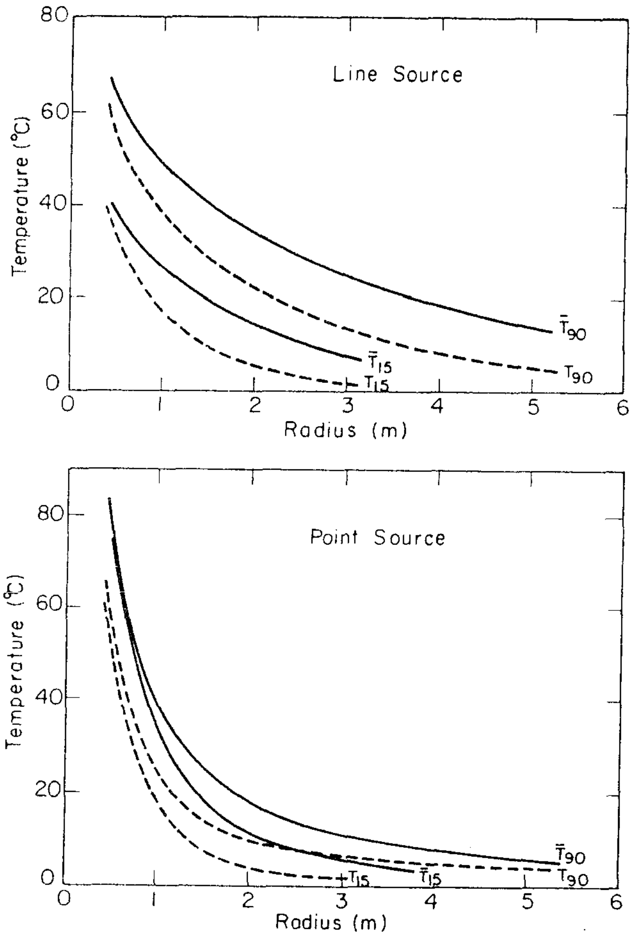

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Figure 7. The mean and actual temperature changes as a function of radius from a line and a point source at 15 days and 90 days. The line source has a power output of 400 W/m and the point source 1 kW.

field still to be distinctly transient in character, but at 90 days it is approaching the steady-state distribution of temperatures quite closely.

The values of the corresponding radial and tangential components of stress induced by these temperature distributions have been calculated from equations (6), (7) and (10), (11), assuming that the thermomechanical factor, equation (5), has a value of 10^{-3} GPa/°C. These are given in Tables II and III, and are plotted in Figure 8 for the infinite line source.

One of the most interesting and important features to emerge from this analysis is the modest values of the thermal stresses. True, these apply to a power output of 1 kW, but even if the power level were to be increased four fold to 4 kW the maximum compressive and minimum tensile stresses would only just approach the likely uniaxial compressive and tensile strengths of the rock.

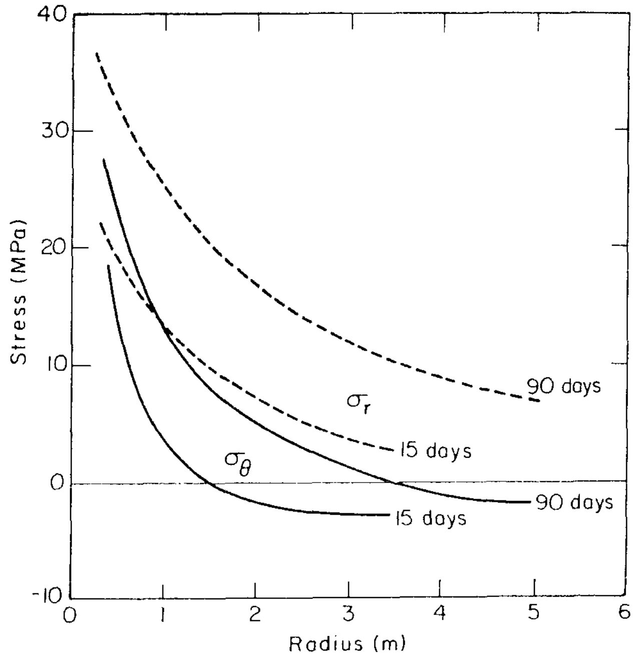

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Figure 8. The thermally induced radial, σ_r and tangential, σ_θ, stresses as a function of radius from a line heat source of 400 W/m at 15 days and 90 days. Note the negative (tensile) values of the tangential stress at large radii.

The sums and differences of the thermal stresses have been plotted on a Mohr diagram in Figure 9. The most generally accepted criterion for the failure of hard rock is the Coulomb criterion (Jaeger and Cook, 1976). Also a Mohr envelope for a Coulomb criterion with values typical of a hard rock with a uniaxial compressive strength of 200 MPa is shown in this Figure. It can be seen that nowhere does the rock approach failure, even if the thermal stresses were quadrupled by increasing the power output to 4 kW.

However, the above analysis is deficient in one important respect; it neglects the fact that the source of heat is likely to be placed in a borehole. The axial component of the thermal stress around a line heat source is the same as the tangential component at the surface of a borehole and both are given by

$$\sigma_z = \sigma_\theta = \frac{\alpha E}{(1-\nu)} T \times 10^3, \qquad (14)$$

where σ_z and σ_θ = the axial and tangential components of stress. The remaining symbols are as defined above.

These values are plotted for a borehole with a radius of 0.2 m in Figure 9 for times of 15 days through 90 days and

TABLE II

Mean and actual temperature changes at different radii from a infinite line heat source with a power output of 400 W/m, together with the corresponding thermal stress, 15 days and 90 days after the start of heating.

Radius (m)	Temperatures at 15 days (°C)		Temperatures at 90 days (°C)		Stresses at 15 days and 90 days (MPa)			
	Mean	Actual	Mean	Actual	σ_r		σ_θ	
0.5	38	33	64	55	19.0	32.0	14.0	23.0
0.75	32	23	56	45	16.0	28.0	7.0	17.0
1.0	26	17	50	38	13.0	25.0	4.0	13.0
1.5	20	10	40	28	10.0	20.0	0	8.0
2.0	14	5	34	22	7.0	17.0	-2.0	5.0
3.0	7	1	24	13	3.5	12.0	-2.5	1.0
4.0			18	8		9.0		-1.0
5.0			14	5		7.0		-2.0

TABLE III

Mean and actual temperature changes different radii from a point source and the corresponding thermal stresses for a power output of 1 kW 15 days and 90 days after the start of heating.

Radius (m)	Temperatures at 15 days (°C)		Temperatures at 90 days (°C)		Stresses at 15 days and 90 days (MPa)			
	Mean	Actual	Mean	Actual	σ_r		σ_θ	
0.5	74	50	77	60	49.3	51.3	25.3	34.3
0.75	49	29	51	38	32.7	34.0	12.7	21.0
1.0	34	18	39	26	22.7	26.0	6.7	13.0
1.5	19	8	25	15	12.7	16.7	1.7	6.7
2.0	11	4	18	10	7.3	12.0	0.6	4.0
3.0	6	2	11	7	4.0	7.3	0	3.3
4.0			8	5		5.3		2.3
5.0			6	4		4.0		2.0
6.0			5	3				1.2

Note: As in Table II the values of σ_θ must become negative at large radii to maintain equilibrium, but these negative values are lower than in Table II because of the large cross-sectional areas of a sphere at these radii.

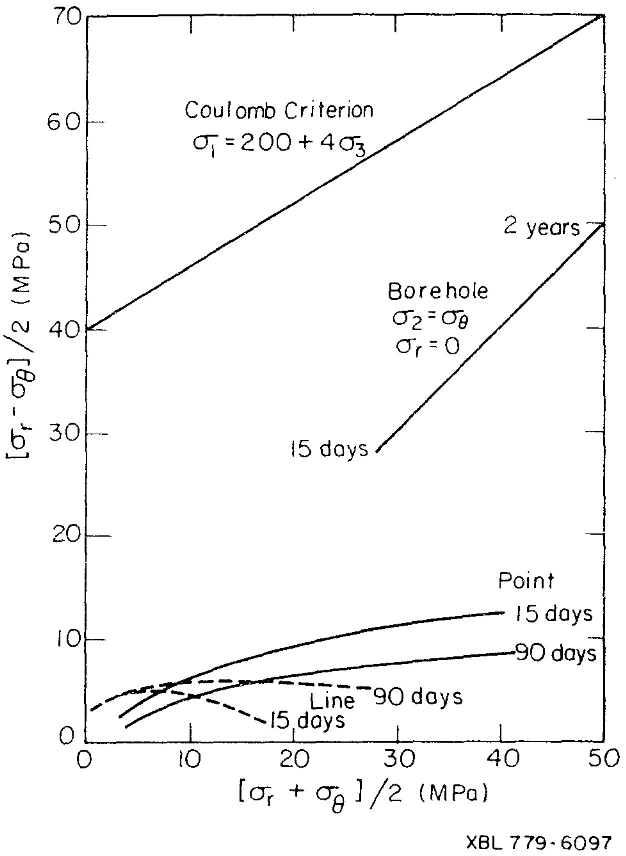

Figure 9. A Mohr diagram comparing the average values of the differences and sums of the principal thermally-induced components of stress around line (400 W/m) and point (1 kW) heat sources at 15 days and 90 days and the axial and tangential components of stress on the wall of a borehole, with the strength of a typical, hard rock.

are the greatest values of stress found around these heat sources.

According to equation (14), large thermal compressive stresses must be expected in directions parallel to the axis of, and tangential to the surface of, the borehole containing the cannisters. At 90 days, for a hole with a radius of 0.2m, the temperature is estimated to be about 80°C for a power output of 1 kW, corresponding to stresses of 80 MPa. As the minimum, or radial, compressive stress on the walls of such a borehole is zero in the absence of support, failure of the walls of the borehole in axial compression could possibly occur at a power output of 1 kW and is probable at a power output of 4 kW. Such failure is not likely to damage a well-designed cannister but would certainly make its retrieval a difficult operation.

4.2. Long-term, Regional Phenomenon

In the previous section, the short-term effects of heat flow from individual cannisters have been evaluated. At some time, the temperature fields between adjacent cannisters will interact to a significant extent. At this stage, the local effects become less important than the overall flow of heat into the surrounding rock from the whole array of cannisters in a repository.

Most concepts for underground repositories involve one or more near plane horizons of excavations, within which the cannisters are contained. As the lateral dimensions in this plane are envisaged to be of the order of a kilometer, the long-term heat flow can be approximated as one-dimensional flow into the surrounding rock mass normal to this plane.

Important questions which must be examined are the temperatures on the horizon of a repository as a function of the waste cannister density, and the heat flow into the surrounding rock as a function of time.

At present it is not the intention to produce high-level waste by reprocessing used fuel, but the characteristics of high-level waste do provide some guidance concerning the thermal characteristics of wastes which may have to be isolated in a repository. The power output of a standard cannister of high-level waste as a function of time has been shown in Figure 5, Section 4.1. The decline in power output with time of this waste becomes significant in the long term. It is convenient that this characteristic can be approximated closely by the power output of a plane, isothermal heat source, as is also indicated in Figure 5. Using the standard equations for linear heat conduction (Carslaw and Jaeger, 1959), and remembering that heat flows away from a repository both upwards and downwards, Table IV has been prepared, showing the power densities for different temperatures of the repository horizon and the corresponding areas required by each high-level waste cannister at 20 years after reprocessing, assuming that they are cooled for 10 years before burial.

Using the same equations, the distances, away from the plane of the repository, to which the isotherms representing 50 percent, 25 percent and 10 percent of the source temperature migrate as a function of time have been calculated, and are given in Table V.

These data show that the heat released by the decay of the wastes migrates only a

TABLE IV

The average power density for a planar repository at 10 years after loading and the corresponding area required for each cannister with a power output of 1.7 kW at 20 years after reprocessing for different temperatures of the repository horizon.

	Repository Temperature (°C)			
	50	100	200	300
Power density (W/m^2)	7.9	15.8	31.6	47.4
Area per H.L.W. Cannister (m^2) (1.7 kW at 20 years)	220	110	54	36

TABLE V

The normal distance away from a planar repository out to which the isotherms representing 50 percent, 25 percent and 10 percent of the source temperature migrate as a function of time.

	Time (years)	12.5	25	50	100
Distance (m)	50 percent	19.6	27.6	39.1	55.0
	25 percent	32.5	46.0	65.0	92.0
	10 percent	47.5	67.0	95.0	132

relatively small distance away from the plane of the repository even over long periods of time; this justifies the use of one-dimensional heat flow in the analysis. It shows also that it is practicable to consider a repository comprising a number of horizons separated by a normal distance of the order of 200 m.

The stresses induced in the rock mass around a repository horizon by thermal expansion resulting from the temperature field described in Table V, must be considered. In the absence of specific knowledge concerning the shape of a repository, detailed analysis is not warranted. The extent of the heated mass of rock in directions parallel to the plane of the repository is likely to be much greater than its extent normal to this plane. Therefore, the shape of the heated rock mass will tend to be elliptical or ellipsoidal. In general, the values of thermally-induced stresses around such shapes are significantly less in the vicinity of their short axis than they are in the vicinity of their long axis. The values of the tangential tensile stresses induced outside a circular cylinder or sphere, heated to a uniform temperature, are only half those at the ends of the long axis of a flat elliptical cylinder or of an ellipsoid (Timoshenko and Goodier, 1951).

Accordingly, equation (11) may be used to estimate the thermally-induced tangential stress normal to the plane of a repository, recognising that:

a) The temperature gradient along this plane outside the axis of the repository is so steep that temperature changes outside the repository can be disregarded in a first approximation, and

b) The maximum value of the stress tensile concentration normal to the plane of the equator of an ellipsoid is twice that around a sphere with a diameter equal to that of this equator. The results of such a calculation are as shown in Figure 10, for a repository heated by an average of 100°C. From this Figure, it can be seen that the value of the thermally-induced tension exceeds the value of the vertical stress caused by the overburden for radial distances from the edge of the repository of the order of a few hundred meters, depending upon the depth below surface and the average temperature of the repository.

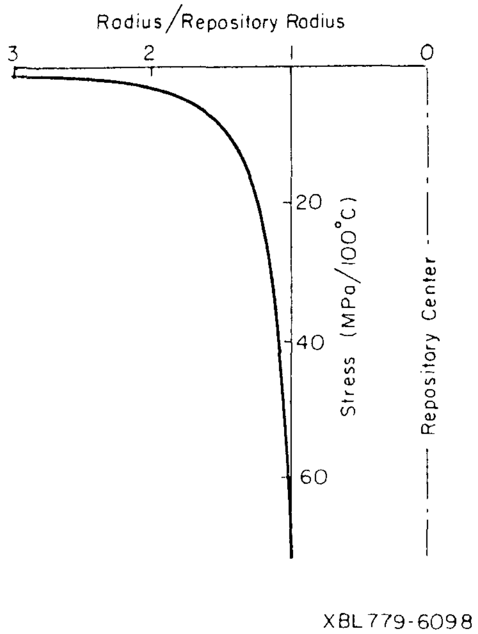

Figure 10. A diagram illustrating the thermally-induced tension nromal to a plane containing a circular repository as a function of radius, for an average increase in the temperature of the repository of 100°C.

4.3. Other Modes of Heat Flow

The processes of convection and mass transfer often overwhelm the effects of heat conduction. Therefore, it is important to estimate the order of magnitude of potential modes of convection and mass transfer on the temperatures around a repository.

The specific heat of water is about 4.2 kJ/ liter °C. Assume that any water flowing through the rock in the vicinity of a cannister may have its temperature increased by an average of 25°C. In this event, a flow of a little less than 0.01 liters per second would be sufficient to dissipate 1 kW of power. To estimate whether or not such a flow rate is feasible, assume that the cross-section of a plane through the volume of rock around a cannister, within which such flow may occur, has an area of 10^5 cm^2. The permeability of the rock mass at any suitable repository site is expected to be significantly less than 0.1 millidarcy. To achieve a flow of 10 cm^3 per second through an area of 10^5 cm^2 with a permeability of 0.1 millidarcy would require a pressure gradient of 1 bar per cm.

Two different values of the pressure gradient should be considered; the hydrostatic head, and that caused by a temperature difference of about 25°C. The hydrostatic head corresponds to a pressure gradient of almost 10^{-3} bar per cm. The coefficient of volumetric thermal expansion of water is about 0.5 x 10^{-3} per °C. For an average temperature difference of 25°C, this corresponds to a differential head of about 12 mm per meter or almost 12 x 10^{-6} bar per cm. Both these gradients are significantly less than that of 1 bar per cm which would be needed to generate a flow of about 10 cm^3 per second.

If heat flow were to take place by mass transfer as a result of boiling the water, the quantity of water needed to dissipate 1 kW of power decreases to less than 0.5 cm^3 per second, in virtue of the relatively high latent heat of water. The pressure gradient necessary to maintain this flow would decrease correspondingly to about 5 x 10^{-2} bar per cm. This value is greater than that corresponding to the hydrostatic head. A local pressure gradient comparable in value with the hydrostatic head could be generated as a result of the displacement of water by steam. It would appear, therefore, that heat flow by mass transfer as a result of boiling is not likely.

5. DISCUSSION

Although a number of questions, such as the effect of radiation on the rock around cannisters, has not been addressed in this appraisal, there appear to be no fundamental reasons why a repository for the isolation of radioactive wastes should not be excavated underground in hard rock. One question which does arise is whether or not such a repository would be able to accommodate a significant proportion of the waste to be generated. Amongst others, Blomeke and Bond (1976) suggest that the total installed nuclear capacity may reach 1200 GW by the year 2000, and indicate that the accumulated thermal power of the high-level wastes may be about 770 MW by the same date. For different repository temperatures, the area of repository required to isolate 10,000 high-level waste cannisters, assuming that they are cooled for 10 years before burial (cf Figure 5) and using the data from Table IV, is found to be of the order of a km^2 per year as given below in Table VI.

These areas are large but it seems quite practicable to think of a repository with an area per horizon of 5 km^2 and, say, 3 different horizons separated by 200 m, that is, a total area of 15 km^2 per repository. If a repository temperature of 100°C were chosen, one such repository would be adequate for the isolation of wastes with a power output of 240 MW at 10 years after burial, which comprises a substantial fraction of all the high-level wastes produced from 1200 GW of installed nuclear capacity, especially if they are cooled for 10 years before burial.

TABLE VI

The area of repository required to accomodate 10,000 waste cannisters after cooling for 10 years for different repository temperatures.

Repository Temperature °C	50	100	200	300
Area (km^2)	2.2	1.1	0.54	0.36

Another practical problem concerns the size and layout of the tunnels for a repository. To accommodate cannisters of the length currently envisaged, namely, about 3 m and for convenience of excavation, a tunnel with lateral and vertical dimensions of between 4 m and 5 m is preferred. However, in Section 3 it was advocated that these tunnels should occupy not more than 20 percent of the area of a repository. Accordingly, their center-to-center spacing would be 20 m to 25 m. If each cannister is to occupy no less than about 100 m^2 (cf Table IV) the spacing of the cannisters would have to be about 4 m apart for a single row of cannisters per tunnel, or 8 m apart if there were two rows per tunnel, as is illustrated in Figure 11. An uneven spacing for the cannisters of about 4 m x 25 m will give rise to local temperature concentrations along the axis of least spacing, with significant, thermally-induced tension normal to this axis between cannisters, especially in the short-term (cf Figure 8). Alternatively, staggered spacing on each side of the tunnel in either vertical or horizontal boreholes appears to have a number of advantages. In both cases, the increased spacing between cannisters reduces significantly the magnitude of the thermally-induced tension, and in the case of the vertical boreholes this tension is further offset by the radial compression from the cannister on the other side of the tunnel.

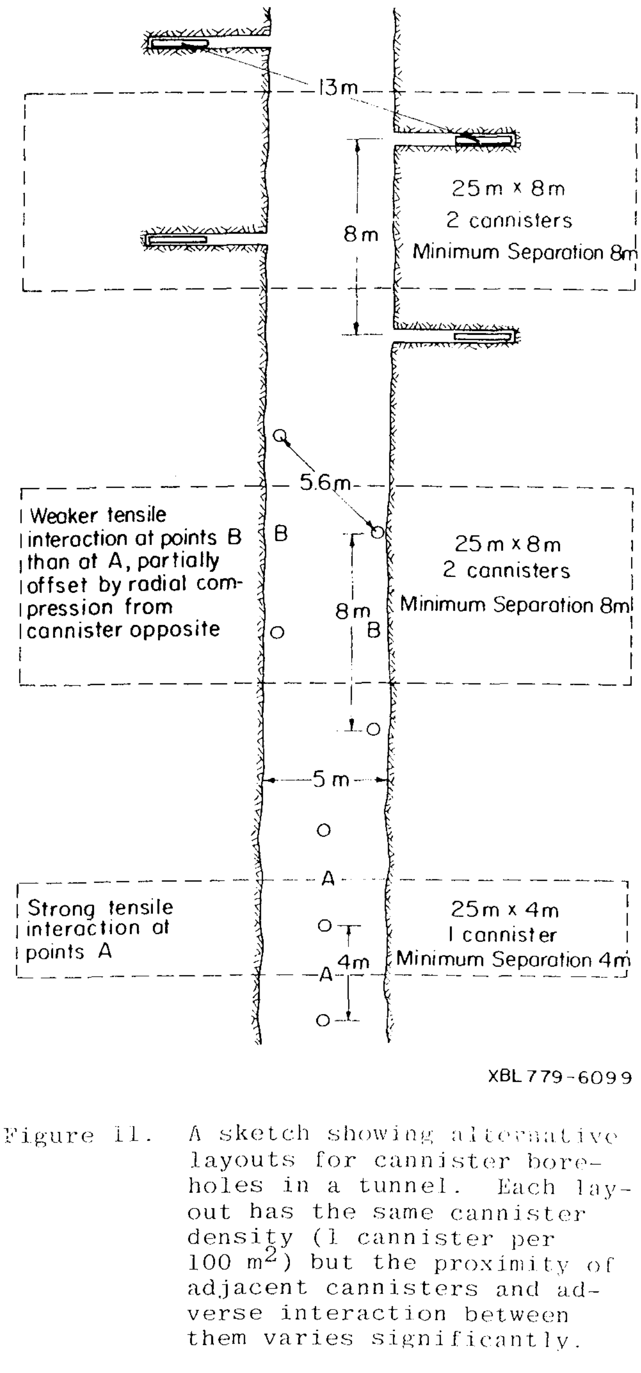

Figure 11. A sketch showing alternative layouts for cannister boreholes in a tunnel. Each layout has the same cannister density (1 cannister per 100 m^2) but the proximity of adjacent cannisters and adverse interaction between them varies significantly.

6. CONCLUSION

The results presented in this report suggest that there are no fundamental reasons of a geomechanical nature why hard rock should not form a potentially satisfactory site for an underground repository for the isolation of radioactive wastes.

Virgin states of stress have been identified which would retard the ingress of groundwater and obviate the occurrence of faulting, even in the presence of water pressure equal to the hydrostatic head, in rock around repositories situated between 0.5 km and 2 km below surface. To meet these requirements the value of the minimum horizontal component of this state of stress must be greater than two thirds that of the vertical component, and the maximum value of the stress difference should be less than 25 MPa.

It is recommended that the area of the excavations in any one horizon occupy no more than 20 percent of the area of that horizon, to obviate adverse interaction between excavations. For depths of up to 1.2 km, the laboratory uniaxial compressive strength of the rock should be 200 MPa. Measurements of size effects on specimens up to about a meter need to be made, and site specific investigations of geological structure will be required.

Neither local, short-term nor regional long-term thermomechanical stresses appear to pose serious difficulties, provided that power densities are kept below about 16 W/m^2 and temperatures below 100°C. If this temperature is exceeded significantly even in the rock immediately around a cannister, thermal decrepitation of the borehole is likely to occur, making retrieval of the cannister difficult unless the borehole is cased. However, there is little experience concerning the effects of thermal loading on underground excavations and this aspect requires thorough experimental and theoretical investigation. There appear to be distinct advantages in certain dispositions of cannisters within individual tunnel-like excavations to obviate adverse interaction of the thermomechanical stresses induced around the cannisters.

A single repository comprising 3 horizons each with a total area of about 5 km^2 separated by about 200 m appears to have the capacity to store waste with power output at 10 years after burial of the order of 240 MW corresponding to a significant fraction of the 770 MW of high-level waste produced by 1200 GW of installed nuclear capacity, especially if the waste has been cooled for 10 years before burial.

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*Part II**

IN SITU HEATING EXPERIMENTS IN HARD ROCK: THEIR OBJECTIVES AND DESIGN

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SYNOPSIS

Of the many alternatives that are being considered for the disposal of nuclear wastes, deep underground burial is favored. The wealth of experience concerning the design and construction of underground excavations does not include the unique effects of heating excavations by radioactive decay, nor the issue of long-term isolation. The effects of heating are important in establishing the feasibility of this method of disposal, and are essential for the design of an underground repository. Near-field phenomena around individual canisters can be studied by full-scale experiments, using electrical heaters. The thermal diffusivity of rock is so low that information concerning the interaction between full-scale heaters and of the effects of heating a large volume of rock cannot be measured in full-scale experiments lasting less than a few decades. To overcome this difficulty, a time-scaled heating experiment has been developed in which a reduction in linear scale is accompanied by an acceleration of the time scale to the second power. In this experiment, the linear scale is about a third, so that the time scale is about ten fold.

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I. INTRODUCTION

Successful disposal of nuclear wastes by deep burial requires that the heat produced by the radioactive decay of these wastes should not compromise the ability of a suitable geologic site to isolate the wastes from the biosphere over long periods of time, nor should this heat create difficulties during the commissioning of an underground repository.

It is generally agreed that significant quantities of nuclear wastes will have to be isolated from the biosphere for periods of time which are unprecedented both in the history of human social institutions and in the durability of most engineered structures [1, 2, 3]. The characteristics and properties of geologic sites which are now stable, and have been stable for long periods of geologic history, are not likely to change within the geologic near future, such as the next million years. In addition to their stability, some of these sites may have virtually no connection to the biosphere. Accordingly, such sites have the potential for isolating from the biosphere nuclear wastes through burial in repositories excavated deep below surface [4, 5].

The practical utility of suitable geologic sites hinges upon the extent to which the ability of a site to isolate nuclear wastes from the biosphere may be impaired by excavating, commissioning and sealing of an underground repository. The effects of excavating underground are understood relatively well. For example, the 24 countries of the OECD develop about 50,000 kilometers of underground tunnels each year [6]. Unfortunately, this experience does not include the effects of loading excavations with nuclear wastes which produce heat, nor of sealing such excavations over long periods of time. The sealing of these excavations is amenable to technological solution. However, the effects of the thermal loads imposed on the rock around a repository by the radioactive decay of the waste is fundamental to the utility of the concept of deep geologic disposal.

The objective of in situ heater experiments is to measure the response of the rock to thermal loading, so as to provide an understanding of the effects of thermal loading, and quantitative data sufficient to ensure that underground repositories for nuclear wastes can be designed with adequate safety.

Although in situ heater experiments have been done in salt [7, 8], and an experiment in granite has recently been completed [9], the design of these experiments in hard rock must at present be based largely on theoretical predictions because of the small amount of experience available. As current experiments get underway and yield results, this situation will change rapidly.

II. THERMAL LOADING

The way in which the temperature of the rock influenced by the release of heat from the nuclear wastes, changes with time is of crucial importance to the safety of an underground repository.

If the rate at which nuclear wastes release heat decayed so slowly with time as to be virtually constant, temperatures in the rock around individual canisters and in a repository as a whole would increase continuously until they caused a failure of some kind. Fortunately, this is not the case. The rate at which heat is released by spent fuel from light water reactors and by reprocessed high level waste from such reactors, decays as a function of time as is illustrated in Figure 1 [2]. From this figure it can be seen that this rate decays more rapidly than time to the power -1/2. According to the theory of the conduction of heat in solids [10], it follows that the temperature must reach some peak values in the rock around any source where the rate at which heat is released decays more rapidly than time to the power -1/2. If the decay in the rate of release of heat were less rapid than this, it would be necessary to design a repository so as to make use of divergent radial heat conduction to ensure that temperatures in the rock reached some peak value rather than increasing continuously.

It has been shown [11, 12] that the thermal loading of a repository with nuclear wastes having characteristics such as those illustrated in Figure 1, results in a thermal pulse such as one of those illustrated in Figure 2. This figure shows that the temperature in a planar repository reaches a maximum value

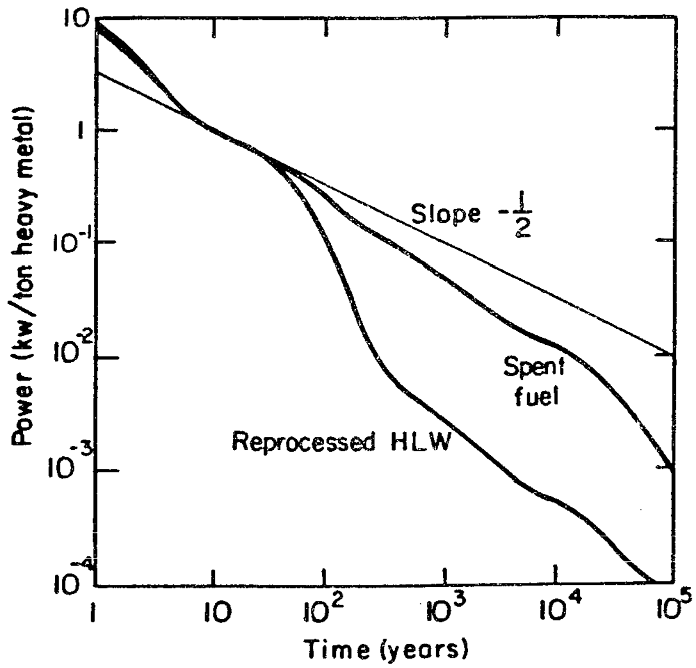

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Fig. 1. The decay with time in the rate at which spent fuel and reprocessed high level waste release heat, per ton of heavy metal, after removal from a reactor. The straight line with a slope of -1/2 illustrates the decay with time of the heat flux by conduction in one dimension from an isothermal source.

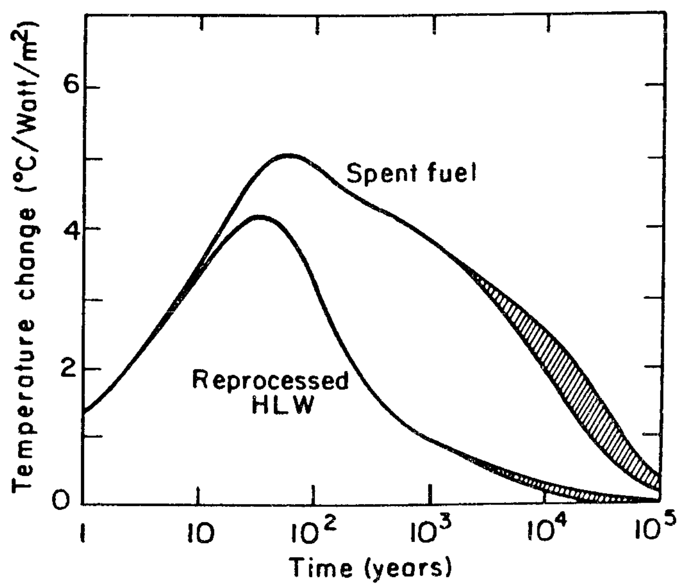

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Fig. 2. Curves showing how the average temperatures of a planar repository for spent fuel and reprocessed high level waste are expected to change with time. The hatched tail of each curve represents the range of temperature differences caused by different depths of the repository below surface.

some 25 years after emplacement of the waste, for reprocessed high level waste, and some 40 years after emplacement of the waste for spent fuel assuming both to be emplaced 10 years after removal from the reactor. The value of this peak temperature is directly proportional to the initial power loading density of the repository. In addition to the fundamental importance to the design of a safe practicable repository of a peak temperature as distinct from a temperature which increases indefinitely with time, it is most encouraging that this peak temperature is reached within such a short period of time. This allows predictions concerning the thermal pulse to be verified within the foreseeable future, and before waste need be sealed finally in a repository.

III. HEATER EXPERIMENTS

The heat released by the radioactive decay of the nuclear wastes must be dissipated in the subsurface rock mass without adverse effects. Temperatures reached by the canisters containing the wastes and by the surrounding geologic media must, therefore, be limited to some safe values. The principal objective of heater experiments is to measure the response of the rock to a thermal pulse, so as to determine what are these safe values.

Immediately after emplacing canisters the temperature of the rock around each canister increases. Later these individual temperature fields merge, increasing the temperature of the rock around the array of canisters comprising the waste repository. These temperature fields produce thermo-mechanical stresses in the rock which could cause it to fail. Two modes of rock failure have been identified as potentially hazardous [11, 13]. First, increased compressive stress parallel to the walls of the holes containing the canisters could cause decrepitation of the rock immediately around these holes. If this were to decrease the thermal conductivity of this rock sufficiently, the temperature of the canisters could rise to unacceptable values. Also, decrepitation may make retrieval of a canister difficult and could cause mechanical damage to it, unless the holes containing the canisters are cased. Casing would not necessarily prevent a decrease in thermal conductivity as a result of decrepitation. Accordingly, it is important to establish the conditions under which thermal decrepitation occurs and to measure its effect on the thermal conductivity of the rock. Second, the thermal expansion of the rock mass comprising the repository creates a compressive stress within it and a corresponding tensile stress in the rock outside it. The compressive stress may cause failure of the rock adjacent to the excavations comprising the repository. More, importantly, the tensile stress outside of it may enhance the hydraulic permeability of the site, particularly if it should decrease the value of the total stress to a level less than the hydraulic head of water at any place.

The magnitude and characteristics of these thermo-mechanical effects can be estimated by calculating conductive temperature fields and the resulting thermally induced stresses. However, the results of these calculations depend upon the values used for the thermal and mechanical properties of the rock. In general, few of these values have been measured and most of them have been obtained by laboratory measurement [14]. The properties of the rock mass _in situ_ can be expected to differ significantly from those of laboratory specimens of rock, particularly when the effects of geological discontinuities in the former are significant as is likely to be the case at the site of any subsurface repository. To resolve these uncertainties it is necessary to conduct appropriately instrumented, _in situ_ heater experiments underground, using electrical heaters to simulate the thermal effects of the radioactive waste canisters.

The non-linear compressive stress-deformation characteristics of a diamond saw-cut and an artificially induced tension fracture across a granite specimen, about a meter in diameter, are as illustrated in Figure 3 [15]. The effective virgin stress at a depth of about a kilometer, resulting from the difference between the weight of the overlying rock and the hydrostatic head, is about 15 MPa. If the discontinuities in the rock mass have deformation characteristics similar to those illustrated in Figure 3, and are separated by a mean spacing of the order of 1/2 meter, the resulting stress-deformation behavior of the rock mass about a mean effective stress of 15 MPa would be as is illustrated by the dashed curve in Figure 3. This may be compared with the solid line representing an elastic Young's modulus of 40 GPa, suggesting that the stress-deformation

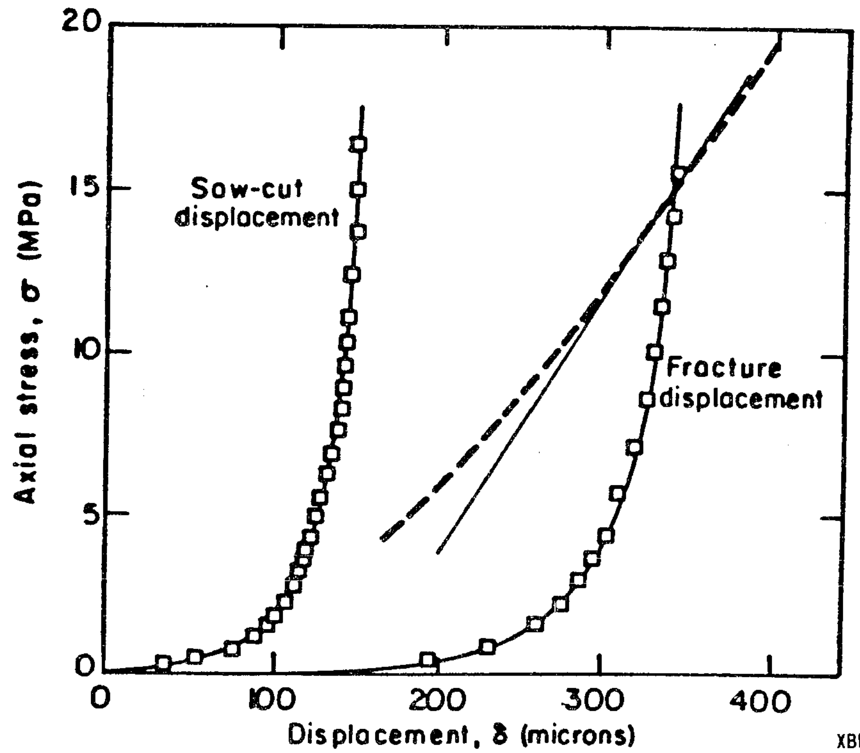

Fig. 3. Curves showing the deformation between adjacent surfaces of a diamond saw cut and an induced tension fracture across a specimen of granite about 1 m in diameter, as a function of normal stress. The effects of such joints with an average spacing of 0.5 m on the deformation of a rock mass about an effective stress of 15 MPa is illustrated by the dashed curve. The solid line represents the deformation of rock with a Young's modulus of 40 GPa.

characteristics of a jointed rock mass are likely to be non-linear and significantly more compliant than those of solid rock. According to the theory of linear thermo-elasticity, thermally induced displacements are determined by the coefficient of thermal expansion and Poisson's ratio and are independent of the value of Young modulus, but the values of the thermally induced stresses are linearly proportional to the value of Young's modulus [16]. The increased compliance introduced into the rock mass by geological joints has the effect of diminishing the Young's modulus of the rock. As a result, the values of both the thermally induced compressive stress components within the heated zone of a repository and the thermally induced tensile components outside the heated zone are likely to be less than those calculated from the theory of thermo-elasticity, using the value of the intrinsic Young's modulus for rock. Both these changes are advantageous, the latter particularly so, as the decrease in compressive stress across joints in the tensile zone leads to enhanced hydraulic transmissivity of these joints. The non-linearity in the deformation of the rock mass arises from displacements between adjacent joint surfaces which are related closely to the hydraulic transmissivity of the joints, and hence to the permeability of the rock mass, so that measurements of thermally induced displacements across joints are of fundamental importance.

The first phase of in situ heater experiments, therefore, should involve a detailed study of the temperatures, displacements and stresses induced in the rock mass by electrical heaters simulating the thermal output of canisters of radioactive wastes.

i) Full-scale experiments

The near field thermal effects, both in the short-term and in the long-term, can be studied in situ using electrical heaters to simulate the heat released by radioactive decay of the waste in canisters. Temperature change as a function of radial distance from the borehole containing a canister for various times after emplacement of the canister has been calculated using the theory of linear heat conduction [17] and the results are as illustrated in Figure 4. From this figure it can be seen that these temperatures approach their peak values rapidly; little change occurs in the second year. To simulate the near field effect of interaction between adjacent heaters, which occurs after decades in practice, the temperature of the rock around a heater can be raised rapidly by a number of peripheral heaters spaced evenly about a circle concentric with the main heater and extending axially for a significant distance above and below the main heater. Calculations show that 8 such heaters with a power output of 1 kW over a length of 4 m on a radius of 0.9 m will raise the temperature of the cylinder of rock within them by about 100°C in 30 days.

Displacements and stresses, calculated from the linear thermo-elasticity [18], as a function of radial distance through the midplane of the heater for various times after emplacement of the heater are illustrated in Figures 5 and 6.

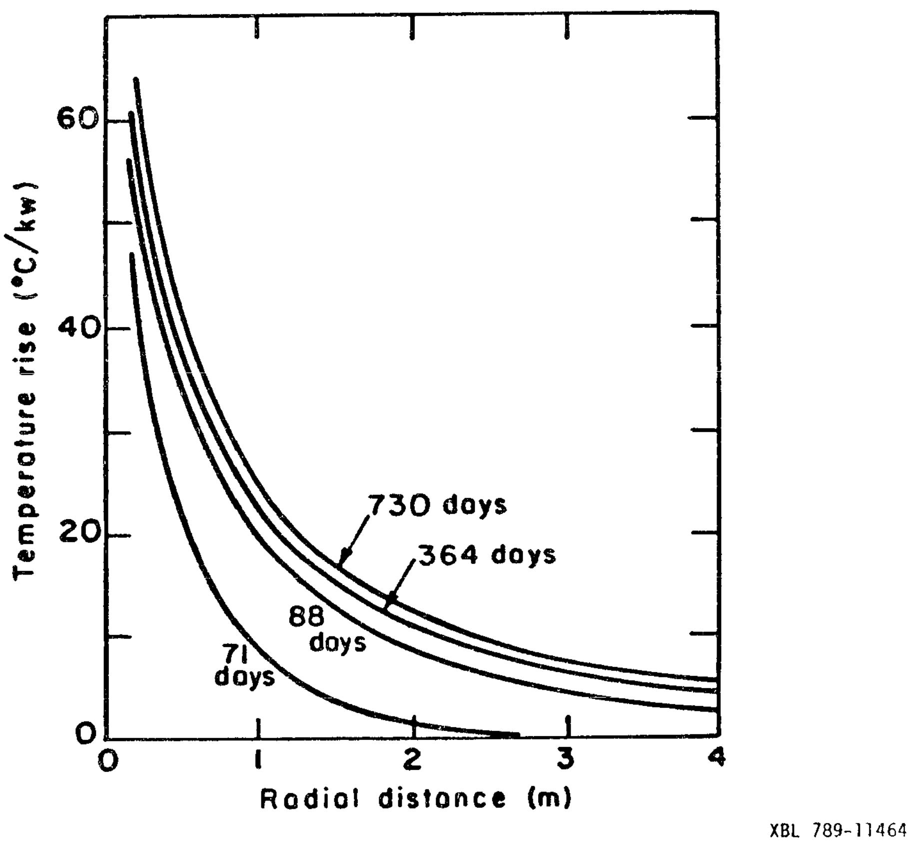

Fig. 4. Changes in temperature along a radius from the center of a cylindrical heat source 2.5 m long at various times, calculated using the theory of linear heat conduction.

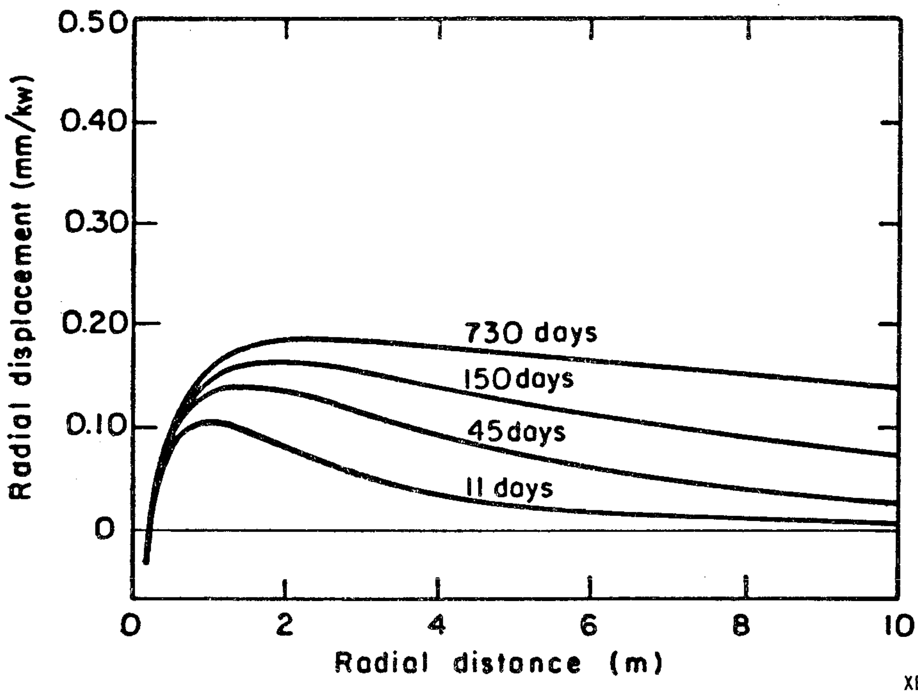

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Fig. 5. Thermally induced displacements along a radius from the center of a cylindrical heat source 2.5 m long at various times calculated using the theory of linear heat conduction.

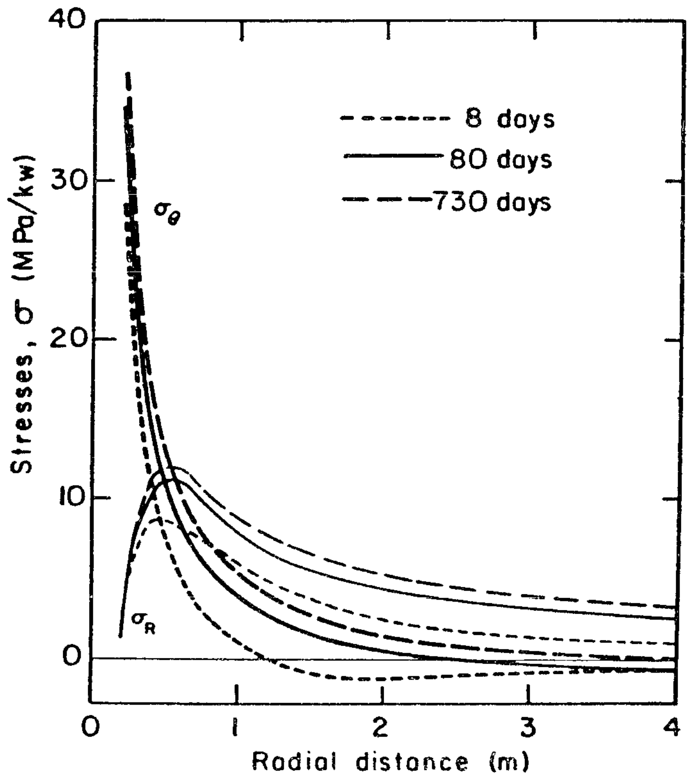

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Fig. 6. Thermally induced radial and tangential stresses along a radius from the center of a cylindrical heat source 2.5 m in length in a borehole 0.4 m in diameter calculated using the theory of linear thermo-elasticity.

ii) Time-scaled experiments

Full-scale electrical heaters can be used for in situ experimental studies of the near field, thermal effects of canisters of radioactive wastes on the rock. However, it does not appear practicable to study the far field, long-term thermal effects, even for the period of several decades required to reach peak temperatures, before the need arises to emplace canisters of nuclear wastes in a repository. Although valuable measurements can be made in any actual repository during this period, they will be done after some nuclear wastes have been emplaced. If the full-scale experiments with electrical heaters have established a high degree of confidence that canisters of nuclear waste can be retrieved during such a period, the risks of releasing radioactive materials to the biosphere would be minimal should measurements on an actual repository suggest that retrieval is necessary. Nevertheless, it is most desirable that some in situ experimental data be gathered concerning the far field, long-term effects before the design of a repository becomes too far advanced let alone before actual commissioning of a repository begins. Fortunately, time and linear dimensions occur in all solutions to problems of the linear conduction of heat in solids in the form kt/x^2, where k is the thermal diffusivity, t is time and x is a linear dimension [10]. As the far field, long-term changes in temperature are not likely to be large, and convective heat-flow in the fluid phase must be small in a successful repository, linear heat conduction may prove to be an adequate model for this aspect of the thermal effects of an underground repository for nuclear wastes. Accordingly, the concept of a time-scaled experiment, in which the relationship given above is used to accelerate time by an order of magnitude through reducing the linear scale to about a third of full size, is being tested in a limited and small way. Should this experiment be successful and useful, larger and more elaborate time-scaled experiments could become an important way of providing in situ experimental data to validate predictions concerning the longer term behavior of underground nuclear waste repositories at a relatively early stage in their design and construction. Figure 7 shows the predicted expansion of isotherms from the time-scaled experiment now being done underground at Stripa [19].

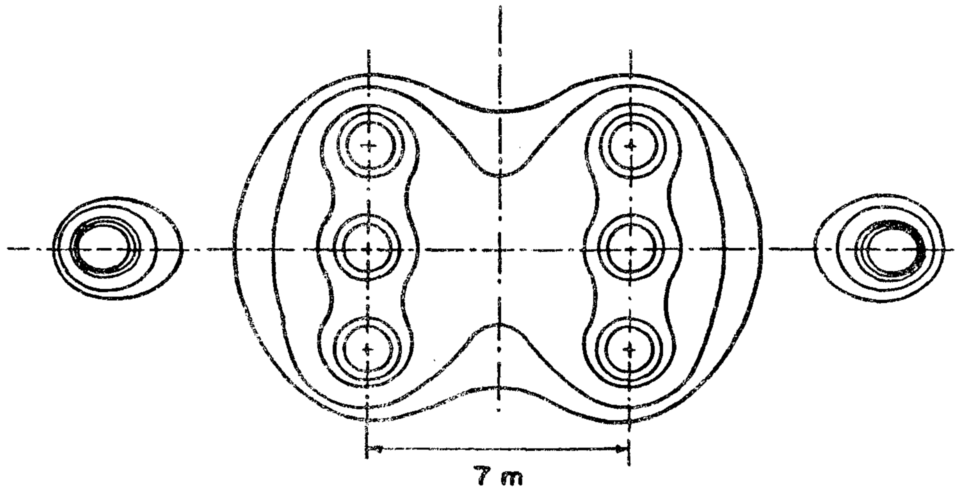

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Fig. 7. A plan view of the time-scaled experiment at Stripa showing the 30°C increment isotherms at times of 7, 30, 90, 365 and 730 days calculated using the theory of linear heat conduction. The scaling of this experiment is about 1/3 linear scale and 10 times time scale, so that the final isotherm corresponds to about 20 years in full scale.

IV. CONCLUSIONS

An important consideration in the disposal of nuclear wastes by deep burial is the effect of the thermal loading of the subsurface, both in the short-term while a repository is being commissioned, and in the long-term after final sealing.

Theoretical analyses of these effects, using the theories of linear heat conduction and thermo-elasticity, suggest that: the decay with time in the rate at which heat is released by spent fuel or reprocessed high level waste from boiling or pressurised water reactors is sufficiently rapid that the temperatures of the rock in the vicinity of an underground repository reach peak values within a few decades after emplacement, thereafter decreasing gradually with time, and that there are two zones where the thermally induced stresses may be of concern. First, increased compressive stress parallel to the surfaces of boreholes and excavations containing the wastes must be kept to safe values to avoid decrepitation of the rock adjacent to these walls. This decrepitation may impair the thermal conductivity of the rock and could make retrieval of the wastes difficult in the short term. Second, diminished compressive stress in the rock mass outside of the repository could enhance the hydraulic transmissivity of joints and other geologic discontinuities, thereby impairing isolation of nuclear wastes from the biosphere in the long term unless peak temperatures are limited to safe values.

The principal uncertainties involve the determination of these safe values and an understanding of the non-linear response of the rock to thermal loading. Non-linear behavior of the rock mass is expected on the basis of preliminary laboratory studies of the stress-deformation characteristics of joints in rock. As the hydraulic transmissivity of hard rock with low intrinsic permeability arises mainly in these joints, it is important that their thermo-mechanical and hydraulic properties be understood well before the adequacy of an underground repository for the isolation of nuclear wastes from the biosphere can be assessed accurately.

Detailed measurements of the temperatures, displacements and stresses induced in the rock around electrical heaters simulating canisters of nuclear wastes should provide an understanding of the phenomena involved in the short term. Initially, experiments should be run at rates of heat release sufficient to cause failure of the rock or, if this does not occur, at rates of heat release significantly greater than that of any nuclear waste canister, and at rates of heat release below either of these critical values. Careful interpolation, guided by suitable theoretical understanding, between the results of these two experiments should serve to define the limiting rate of heat release at which failure is likely to occur. However, it is necessary to design repositories for nuclear waste so that the probability of failure is negligible. This requires that additional data be gathered to establish how much below the limiting rate of heat release it is necessary to go to ensure that the probability of failure becomes negligible. The collection of this information is complicated by the relatively variable nature of geologic materials compared with other materials usually used in engineering. To acquire this information it will be necessary to run tests of heaters not only over a range of rates of heat release, but also to run many heaters at each rate of heat release so as to assess the geologic variability.

As it is unlikely that it will be practicable to test a near full scale repository over the period of several decades required to reach peak temperatures using electrical heaters only, before any nuclear wastes are emplaced, some means of accelerating the experimental study of the effects of thermal loading over the long term is needed. Fortunately the quadratic relationship between the time and spatial variables in linear diffusion phenomena provides a means of accelerating the time scale by an order of magnitude through a reduction in the linear scale to about a third of the full size. If the results of the first time-scaled experiment confirm the usefulness of this theoretical concept, more extensive and elaborate time-scaled experiments should be undertaken to provide an experimental basis for understanding and predicting the long-term behavior of an underground repository. Such extended time-scale experiments should encompass a sufficiently large volume of rock that they need not be duplicated as is required in the full-scale heater experiments, except to study fundamentally different kinds of rocks.

V. ACKNOWLEDGEMENT

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