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Heat-Induced Moisture Movement Within a Clay-Based Sealing Material

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ABSTRACT

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The bentonite–sand buffer material, which isolates the nuclear-fuel waste containers from the host rock mass, is a vital component of the multiple engineered barrier scheme advocated by the Canadian Nuclear Fuel Waste Management Program. This paper presents results of laboratory investigations which examine the influence of the container surface temperatures on the moisture migration within a compacted buffer in a borehole environment.

INTRODUCTION

Current Canadian concepts for the disposal of nuclear-fuel wastes concentrate on deep burial of the waste in a vault in a hard rock formation (Hancox, 1986). The principal components in the disposal facility include the vault system, the waste container, the buffer and the backfill. The vault system consists of a series of access galleries and shafts and a network of boreholes which are drilled into the base of the vault system. The container which houses the used fuel bundles would be fabricated of durable materials such as titanium alloys which are highly resistant to corrosion and radiation damage. Studies conducted by Atomic Energy of Canada Limited (AECL) indicate that at the time of placement, the waste containers could exhibit surface temperatures of the order of 100°C. The third component of the waste disposal scheme involves a mixture of bentonite and crushed sand, referred to as the buffer, which will fill the annular space between the container and the rock in a borehole environment. The buffer should act as a barrier to suppress the detrimental effects of the intrusive corrosive ground water to enhance the life of the waste container, it should serve as a diffusion barrier for radionuclides which may be released either by accidental damage or natural breakdown of the waste containers; provide sufficient strength to support the self weight of the containers; protect the container from harmful rock movements which can occur along fracture planes which may intersect the vault; act as a heat conducting medium to dissipate the heat which is generated by the waste

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containers; and be capable of swelling upon contact with groundwater to close any gaps, cracks and cavities which may be either left from emplacement or generated by moisture depletion. The fourth component in the disposal vault system is the backfill material which fills the major part of the galleries in the disposal vault system. The backfill is composed of a mixture of Agassiz clay and crushed rock. The major function of the backfill is to minimize the movement of ground water in the disposal vault (Cheung et al., 1983). Comprehensive studies of the performance of buffer and backfill materials are given by Gray et al. (1984), Radhakrishna (1984), Dixon and Gray (1985), Yong et al. (1985, 1986), Graham et al. (1986) and Cheung (1987).

This paper focusses on the experimental evaluation of the thermal performance of the buffer due to moisture depletion. Such a situation can occur in the early stages of operation of the vault where influx of groundwater is likely to be limited (Selvadurai, 1988a,b). In the absence of moisture influx into the buffer region, heat induced moisture transport can take place within the buffer region. Such transport phenomena can lead to shrinkage of the buffer in the moisture depleted zone. The shrinkage can in turn lead to the development of contact resistances at zones of separation either at the buffer–container interface or at the buffer–rock interface. The thermal integrity of the disposal scheme can thus be adversely affected by the contact resistances. The experimental investigations are performed on an approximately one-sixth scale model of the borehole waste emplacement configuration proposed for the Canadian Nuclear Fuel Waste Management Program. The experiments examine the manner in which moisture migration within the buffer in a borehole environment is influenced by the changes in surface temperature of the heat source. In these experiments two heater surface temperatures of 80°C and 150°C are considered.

THE EXPERIMENTAL FACILITY

The experimental research programme focusses on the study of heat conduction and moisture transfer in a single borehole configuration. The model heater, the buffer region and the simulated rock are arranged in such a way that the configuration displays axial symmetry in terms of the geometry and the heat and moisture flow phenomena. A general view of the experimental facility is shown in Fig.1. The rock is simulated by a cylindrical block of high strength concrete which measures approximately 1 m in diameter and 2.4 m in height. The cylinder contains a coaxial borehole measuring approximately 250 mm in diameter and 910 mm in depth. The cylinder is instrumented with 196 thermocouples (Type K, accuracy ±0.1°C) in the form of an array which is located along a diametral plane. The model heater has external dimensions 72.5 mm in diameter and 453 mm in length. The heater is powered by an independent 100 W power source, and the surface temperature is regulated at the mid-section of the heater by a closed loop controller. The buffer region is compacted to the upper level of the heater position to achieve a modified Proctor unit weight of approximately 20 kN/m^3 at a moisture content of

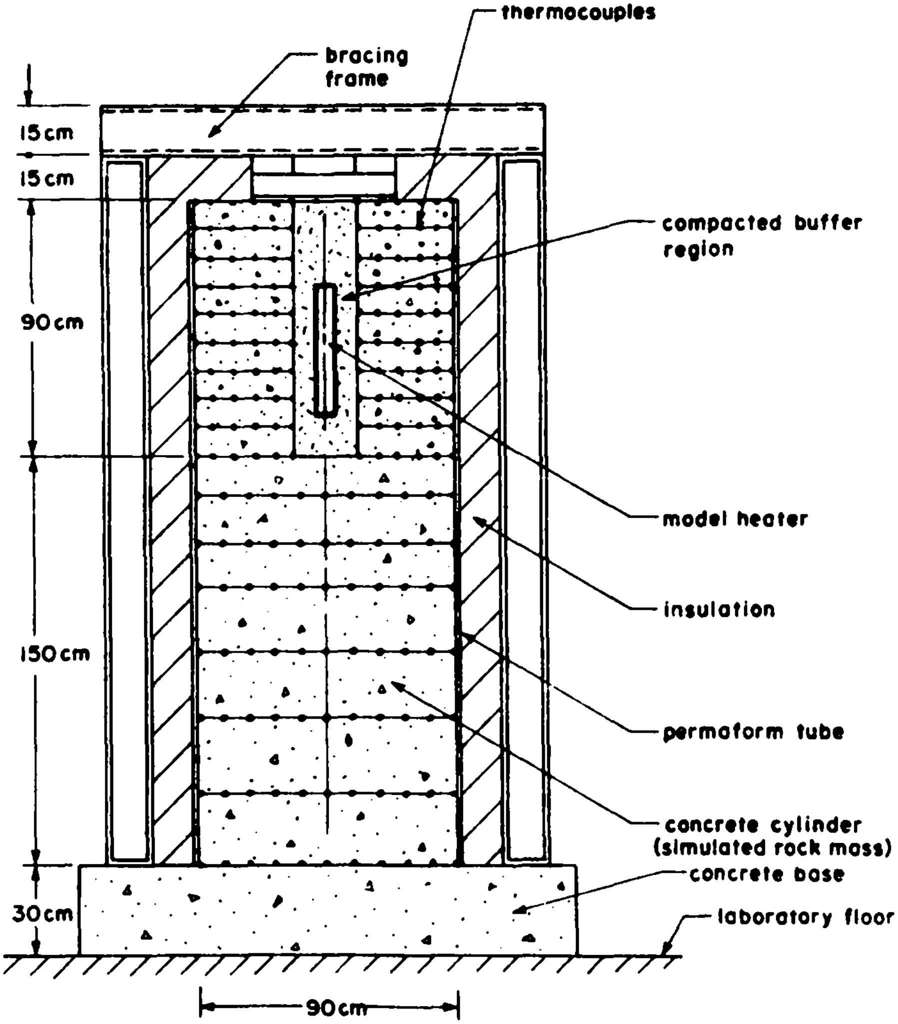

Fig.1. The experimental facility: axisymmetric single borehole model.

approximately 18.25% by weight. The density and mixing water content are those that have been adopted for the reference buffer material. Arrays of thermocouples are also placed in the buffer in radial directions at the upper, mid-section and lower levels of the heater. The buffer is cored by a diamond drill and the container placed in the cavity. The gap between the buffer and the model heater is filled with a fine quartz sand. The remainder of the emplacement borehole is compacted with the buffer material, to the level of the borehole surface. The upper surface of the buffer is partially sealed to minimize the loss of moisture during the heating process.

The thermocouples within the simulated rock, the buffer region and the heater are monitored via a HP3457 data acquisition system and a HP9836C microcomputer. A separate temperature controller and a power source are used to maintain the surface temperature of the mid-section of the heater at a specified value. The temperature readings are automatically recorded at hourly intervals. Detailed accounts of the construction of the experimental facility, the organization of the data acquisition system, the development of the data processing software, etc., are given by Selvadurai et al. (1986) and Selvadurai (1988a).

EXPERIMENTAL RESULTS

Two heater experiments were conducted, where the mid-section level of the heater was maintained at 150°C. Fig.2 shows the variation of the surface temperature at three locations of the heater. The temperature controller maintained the mid-section temperature of the model heater at 150°C throughout these experiments. The two heater experiments which were conducted, lasted 2000 h (experiment MM2) and 4500 h (MM3). Fig.3 illustrates the time-dependent variation of temperature distributions within the buffer and the simulated rock at the mid-section level of the heater. Fig.4 indicates the

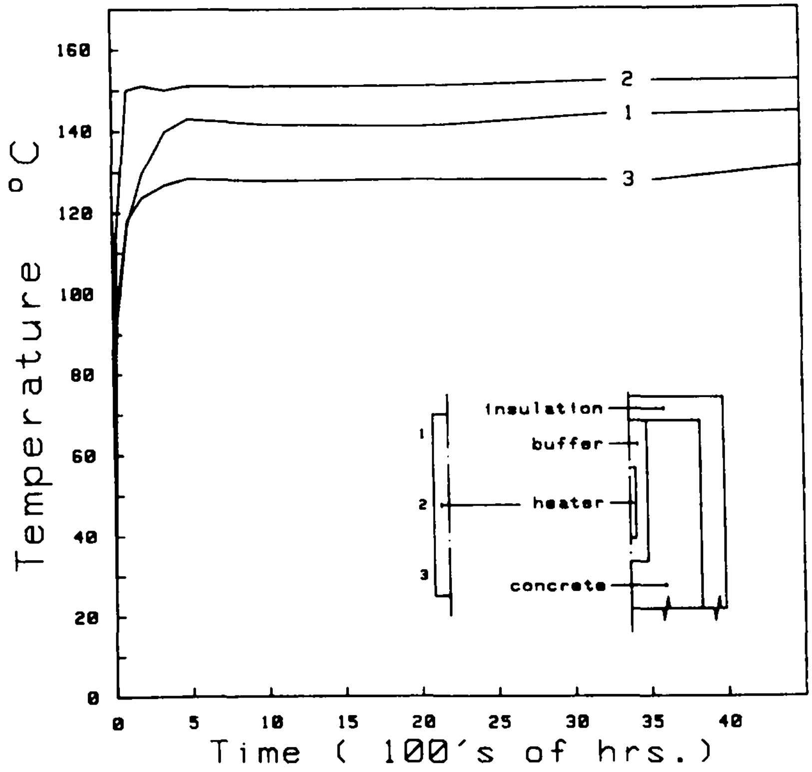

Fig.2. Time history of the surface temperatures of the heater (experiment MM3).

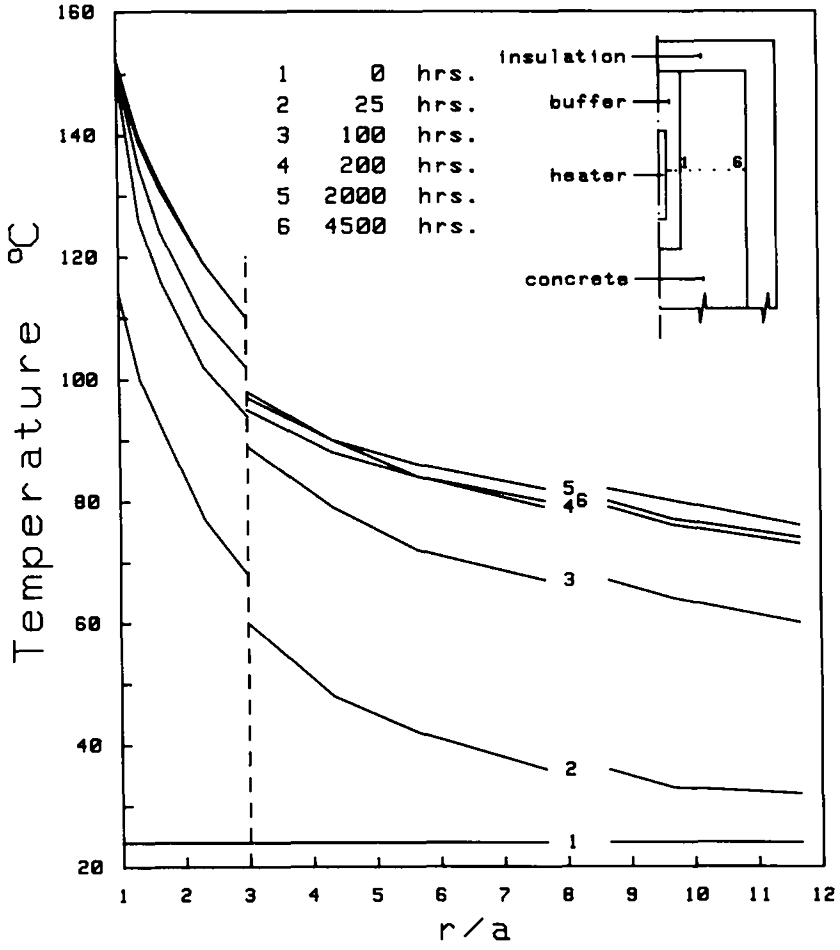

Fig.3. Time-dependent variations of the temperature distributions within the buffer and the simulated rockmass-midsection level of the heater (experiment LPD1).

variation of heater temperatures for the experiment in which the mid-section heater temperatures were maintained at approximately 80°C (experiment LPD1). The analogous results for the time dependent variations in the temperature at the mid-section of the heater are given in Fig.5. A comparison of the steady state temperature distributions within the simulated rock derived for the two sets of heater temperatures (namely 150°C and 80°C) is shown in Fig.6.

Upon completion of the heater experiments the experimental facility was allowed to reach a thermal equilibrium with the laboratory surroundings. In the experiments where the heater temperatures were maintained at 150°C, the cooling down period lasted approximately 150 h. Samples of the buffer were obtained from various locations of the buffer region to determine the moisture distribution near the termination of the test. Fig.7 illustrates the contours of

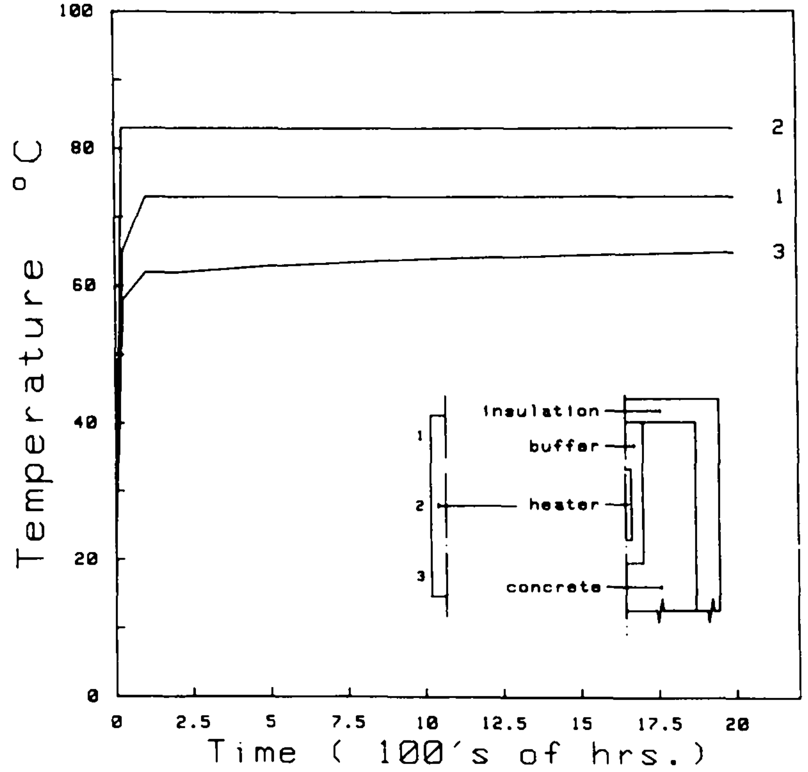

Fig.4. Time history of the surface temperatures of the heater (experiment LPD1).

volumetric moisture content (volumetric moisture contents $\theta = m\gamma_d/\gamma_w$ where m is the moisture content based on weight, γ_d is the dry unit weight and γ_w is the unit weight of water) observed in the buffer at the termination of the heater experiments. Fig.8 provides a similar comparison except that the experiment MM3 had a heater temperature of 150°C at the mid-section and the experiment was terminated at 4500 h. In both Figs. 7 and 8 the contours are expressed as a proportion of the initial volumetric moisture content of 25%. It is also important to record the physical condition of the buffer that is observed at the termination of the various experiments. In the case where the heater temperature was 150°C the buffer exhibited considerable shrinkage (an axial shrinkage of approximately 8 mm and a radial shrinkage of approximately 5 mm) and cracking in a region above the base of the heater. In the case when the heater experiment lasted 4500 h, it was possible to manually remove portions of the buffer in either annular or sector shaped block forms. Both radial cracks emanating from the inner boundary of the buffer and horizontal flat cracks at various levels within the location of the heater were observed. Below the base level of the heater the buffer maintained good contact with the whole boundary of the borehole.

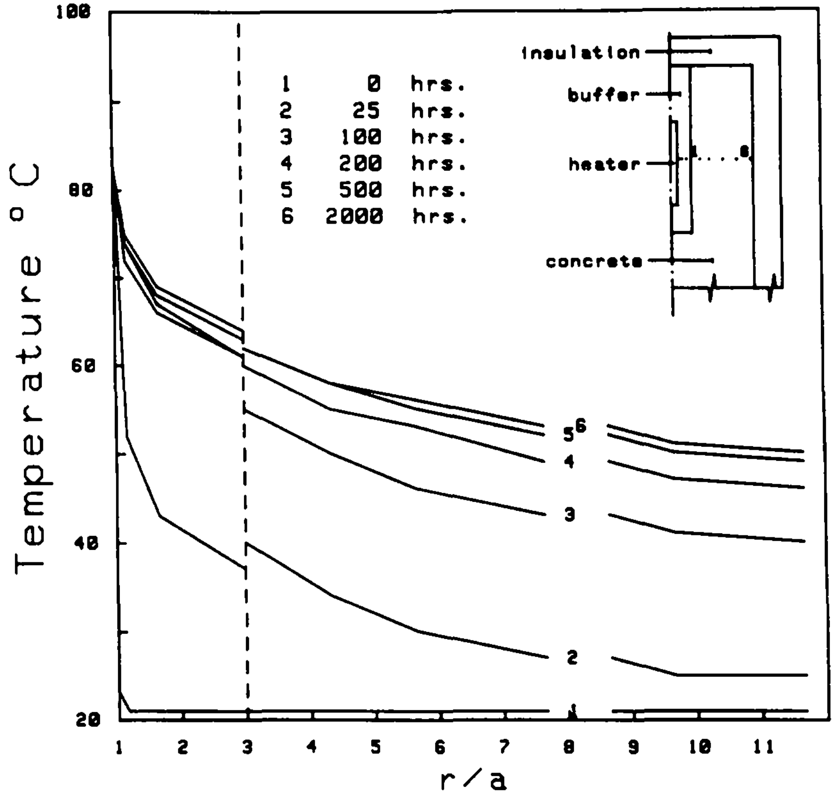

Fig.5. Time-dependent variations of the temperature distributions within the buffer and the simulated rockmass-midsection level of the heater (experiment LPD1).

DISCUSSION AND CONCLUSIONS

The experimental research discussed in this paper focusses on the evaluation of the thermal performance of the buffer region in a situation where there is no influx of moisture into the buffer region from the host rock. This category of experiment is intended to simulate a worst-case scenario which may occur in the very early stages of operation of the vault. The study of the performance of the buffer under such adverse conditions is of course essential in developing an all encompassing concept assessment of the waste disposal scheme. The results of the experimental investigations can be summarized by the following points:

(1) When the heater is operated at the higher temperature (150°C) loss of moisture from the buffer region occurred in a non-uniform fashion resulting in the development of cracks and separation gaps at regions of the buffer closest to the heater. These gaps contribute to thermal jumps at the buffer–borehole interface. These thermal jumps however do not exceed 7% of the peak value of the temperature at any plane considered. At the lower temperature (80°C), the

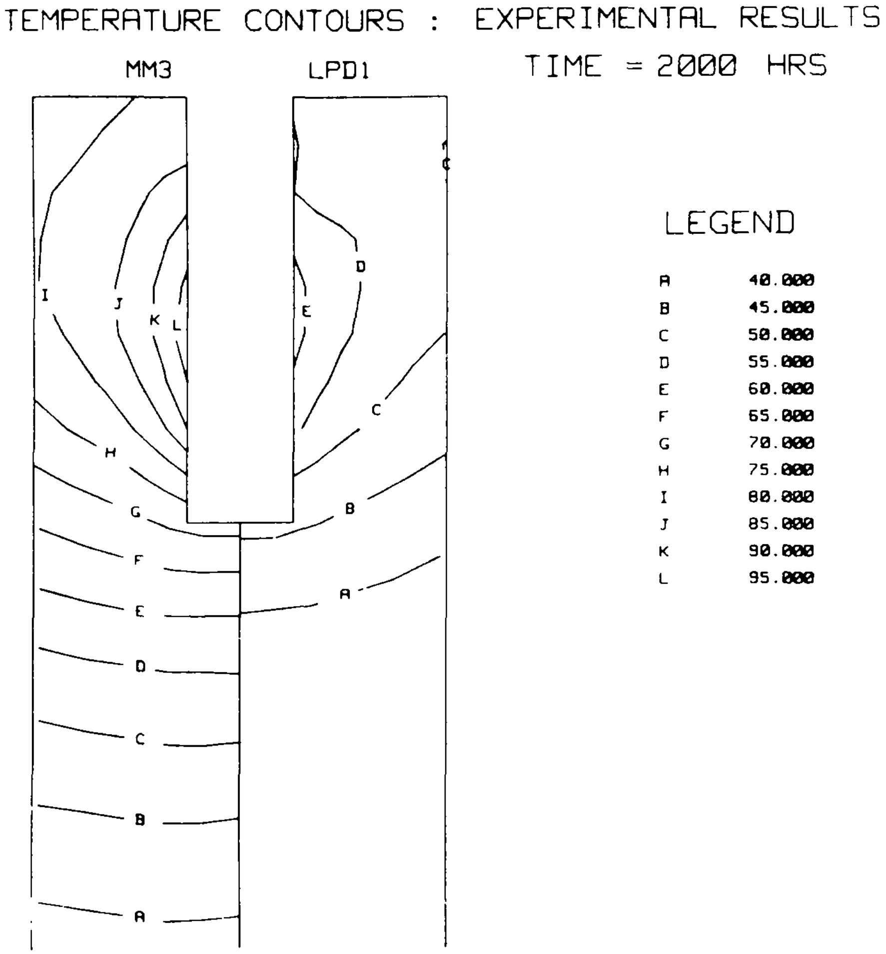

Fig.6. A detailed comparative representation of temperature contours within the simulated rockmass.

buffer does not exhibit any observable shrinkage and maintains good contact at the buffer borehole interface. Small-scale cracking occurs only in the vicinity of the heater location. In this case there are noticeable thermal jumps at the buffer–borehole interface.

(2) The overall heat transfer process is not adversely affected by the occurrence of separation gaps at the buffer–borehole interface. For both temperatures, the heat transfer processes within the system reach a steady state relatively quickly.

(3) The moisture distribution within the buffer region can be effectively determined only at the termination of each experiment. With experiments at the higher temperature (150°C), the time lapsed during the cooling down period (approximately 150 h) can result in a redistribution of the residual moisture within the dry buffer region. The experimentally derived volumetric

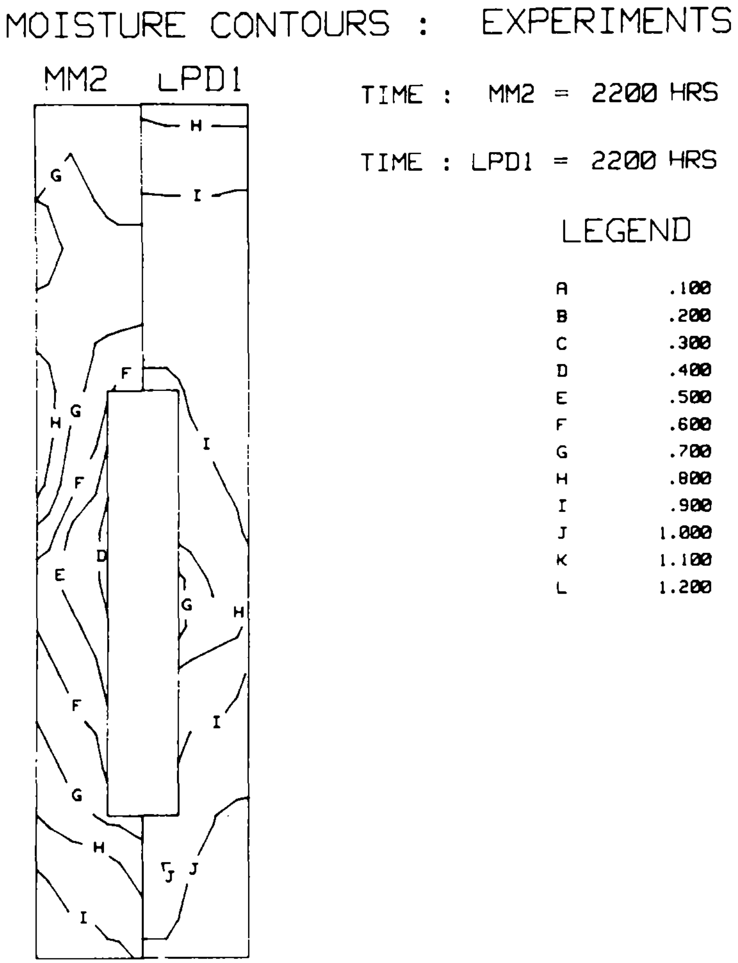

Fig.7. Volumetric moisture content distributions within the buffer region.

moisture content distributions can be used to calculate the total moisture loss from the buffer during each heater experiment. It is found that approximately 35% of the initial total moisture was lost during the heater experiment MM3 which lasted 4500 h and during which the heater mid-section temperature was maintained at 150°C. In the second experiment at the higher temperature MM2, which lasted 2200 h, approximately 26% of the moisture was lost during the heat induced moisture depletion. In the case of the experiment LPD1 at the lower heater temperature (80°C) approximately 9% of the initial moisture was lost during the 2200 h duration of the test.

The results of the research indicate that in terms of its thermal integrity, the buffer material performs adequately even under the adverse situation of no moisture influx into the borehole region. The moisture depletion effects continue at a much slower rate than the heat conduction process, and the rate

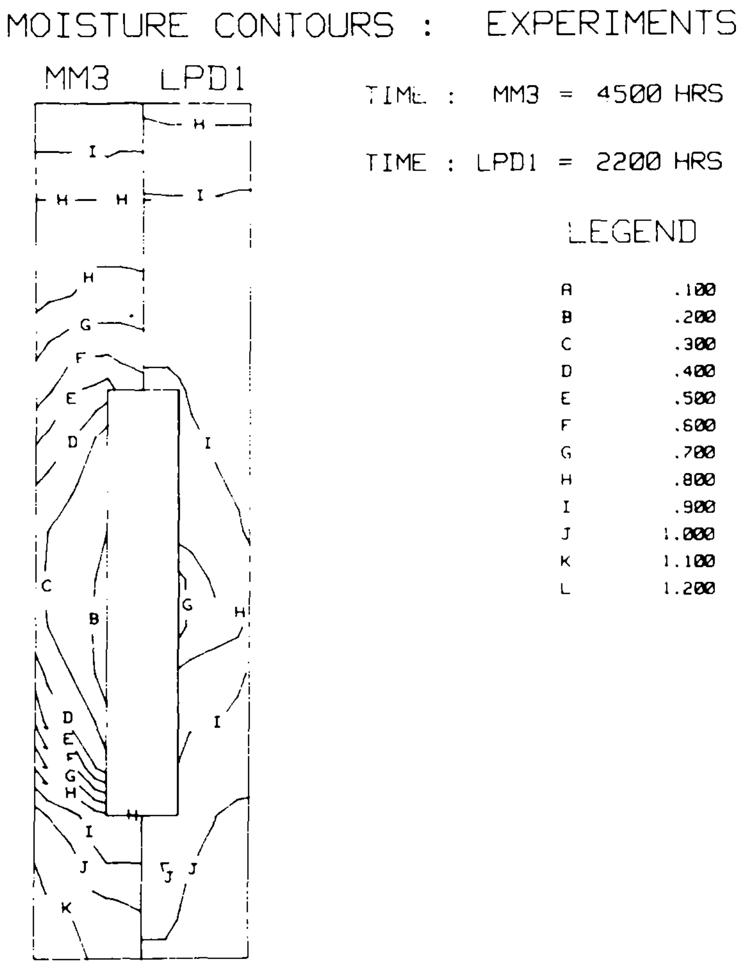

Fig.8. Volumetric moisture content distributions within the buffer region.

of moisture loss is influenced by the heater temperature. The ability of the desiccated buffer to fulfill its other performance criteria, in terms of retardation of moisture movement, radionuclide migration etc., will depend upon the ability of the buffer to swell and heal the cracked regions under moisture influx. These studies will be investigated in future phases of the research.

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