ANALYSIS OF TRANSIENT HISTORY OF UNDERGROUND EXCAVATIONS
FOR RADIOACTIVE WASTE ISOLATION

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Analysis of transient thermal history of underground excavations for radioactive waste isolation

ANALYSIS OF TRANSIENT THERMAL HISTORY OF UNDERGROUND EXCAVATIONS FOR RADIOACTIVE WASTE ISOLATION

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The constraints and phenomena which must be modeled in realizing a rational prediction of temperature history in a radioactive waste repository are presented. The effects of conductive and radiative heat transfer between the waste package and host rock are presented. Results of numerical investigations are utilized to present specific situations wherein analytical approximations to the waste canister geometry may be utilized. The paper also presents the results of approximations to the mean underground repository temperatures. The reliability of both methods of predicting temperatures is assessed through the comparison of predicted temperatures with measured temperatures from the Project Salt Vault field experiment. The design of experiments for model verification is discussed and a specific heater experiment which has been proposed is presented.

Les contraintes et les phénomènes, qu'il faut modeler pour produire une prédiction rationnelle de la température progressive dans un stockage de déchets radioactifs, sont discutées. Les effets de la transmission de la chaleur, par conductibilité et par rayonnement de la caisse de ces déchets à la roche qui l'environne, sont présentés. Des résultats des recherches numériques sont utilisés pour décrire des cas spécifiques dans lesquels des approximations analytiques de la forme de la caisse de déchets sont convenables. En plus, les résultats des approximations des températures souterraines de stockage sont décrites. La précision relative des deux méthodes de la prédiction des températures prédites en comparaison des températures réalisées en cours de l'expérience Project Salt Vault. Le développement des expériences spécifiques d'appareil de chauffage qu'on a proposée est décrite.

Die Zwänge und Phänomene, die bei Verwirklichung einer rationalen Voraussage der Temperaturgeschichte in einer radioaktiven Müllablage modelliert werden müssen, werden dargelegt. Die Wirkung von leitender und strahlender Wärmeübertragung zwischen dem Abfallpaket und dem Aufnahmegestein werden aufgezeigt, Ergebnisse von zahlenmäßigen Untersuchungen werden benutzt, um spezifische Situationen darzulegen, in denen analytische Annäherungen an die Abfallkanistergeometrie ausgenutzt werden können. Der Vortrag behandelt auch die Ergebnisse von Annäherungen an die mittleren Temperaturen unterirdischer Ablagen. Die Zuverlässigkeit der Methode des Vorhersagens von Temperaturen wird durch einen Vergleich von vorhergesagten mit gemessenen Temperaturen vom Feldversuch Project Salt Vault geschätzt. Die Gestaltung von Versuchen für Modellkontrolle wird erörtert, und es wird ein vorgeschlagener spezifischer Erhitzerversuch erklärt.

INTRODUCTION

The emplacement of radioactive wastes into underground excavations results in thermomechanical design problems not generally encountered in normal rock excavation operations. The requirement that the geological formation must contain the waste for up to hundreds of thousands of years necessitates the utilization of unprecedented site reconnaissance, rock properties testing and mathematical modeling in order to design a repository with a high assurance of long term waste containment. The testing of any mathematical method used in predicting the formation response to the radiogenic heat input is an essential segment of the repository design, since real time experience will not conclusively establish the long term rock response. Therefore, the real time experiments should be utilized to test a prior mathematical predictions of rock response.

In formulating a mathematical model for the prediction of temperature fields occurring in a repository after emplacement of heat generating waste, one should be cognizant of what physical

situations must be modeled and to what degree of accuracy the modeling need be extended. The modeling accuracy in a material or geometric area must be correlated to the degree of accuracy that can be had in determining the material response in the laboratory and in the field, and the geometric accuracy which can be obtained in practice. Previous investigations have illustrated the concept of using only as sophisticated mathematical modeling as is justified by the geometric and material properties input data. When the repository site and material properties were fairly well defined, Cheverton and Turner (1972) utilized a numerical method to predict the temperatures in a specific repository as a function of several variables which due to other ongoing studies, they were able to vary in optimizing the waste package density subject to several maximum temperature criterion. In other investigations in which the geometry of the repository and the materials properties were merely bounded over a wide range (Mucci, 1971; Ratigan, et al., 1976; Schneider and Platt, 1974)

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less expensive analytical methods for predicting temperature fields were employed.

The intent of this paper is to delineate the important geometric and rock properties of a repository site which should be modeled in obtaining a rational prediction of temperature fields arising due to the emplacement of heat generating waste. In this regard the assumptions, methodology and results will be presented for a variety of investigations concerned with the prediction of both near field temperatures and far field temperatures. In utilizing the results of previous investigations, the adequacy of economical analytical methods will be assessed. A currently proposed field heater experiment and a description of the mathematical modeling utilized in the design will be presented.

WASTE AND SITE CHARACTERIZATION

As far as prediction of thermal history of a repository containing heat generating wastes, one is generally concerned with either of two types of waste; reprocessed (high level waste) or unreprocessed (spent fuel). Figure 1 presents a comparison of typical transient heat generation for high level waste and spent fuel. The particular characterization of the curves depends on the type of reactor, time of reprocessing, etc. However, the curves are typical for a commercial PWR and are sufficient in displaying the marked difference between the heat dissipation of high level waste and spent fuel.

Figure 1. Transient Heat Generation for High Level Waste and Spent Fuel (Per Metric Ton Heavy Metal)

Due to the heat generating differences between high level waste and spent fuel, temperature predictions for a high level waste repository are only applicable to a spent fuel repository for a very short period of time, say 10-30 years.

Previous investigations of temperature history have for the most part been performed with typical stratigraphic columns, properties of which have been usually taken from the literature. Exceptions exist to this statement which are fortunately increasing as time goes on. To the authors'

knowledge all previous detailed studies have also only included the conductive heat transfer in the rock mass. Cheverton and Turner (1973) state that the forced convection heat transfer which occurs in aquifers above salt deposits containing a repository can be treated in a separate analysis due to its expected low significance. However, in a non-salt mass such as crystalline rock, the heat transfer mechanisms of free and forced convection may be of significance. Presently, studies of the importance of free and forced convective heat transfer are being performed in Sweden (Lindblom, et al., 1977).

In previous analyses of temperature history in repositories the domain of analysis has usually been divided into two regions; near field and far field. The near field analysis is generally concerned with the waste package, near rock temperature history and the temperature fields arising in the repository structurals (pillars, roof, floor). The near field predictions are essential in determining rock mass response which will dictate storage room support requirements and potential waste package damage. The near field temperature history is also important in assessing waste package corrosion, waste package retrievability and ventilation requirements.

Far field temperature predictions are utilized to analyze the gross movement of the geological formation, the temperature rise in potential aquifers and the temperature perturbation of the biosphere.

The near field temperature history is most dependent upon

- o Emplacement scheme
- o Package/rock interface
- o Rock mass thermal properties

The emplacement schemes referred to in this paper are generally centered around the room floor drill-hole concept (Bradshaw and McClain, 1971). However, studies by several investigators have indicated that other emplacement methods may show some merit.

The package/rock interface has been an area of considerable study over the past decade. The type of backfill (if any) used between the package and the drill-hole periphery has a significant influence on package retrievability and containment.

Since the rock mass is being utilized as a heat sink for the radiogenic heat dissipation, the thermal properties of the site rock are of particular importance in determining the near field temperature response. The thermal conductivity and diffusivity of the site rock are directly related to the maximum temperatures occurring in the near field and also to the times at which these maximums occur. In addition to the thermal conductivity and diffusivity of the site rock, the convective film coefficient on the excavation floor can play a major role in determining the heat loss to the repository ventilation. Additionally, any "coupled" rock mass responses in water bearing site rocks, such as permeability changes with temperature and stress may provide a major influence in the near field temperature history.

If an emplacement scheme which utilizes a large quantity of backfill material is employed, such as emplacement on the storage room floors, the near field temperature magnitude and transient history is highly dependent upon the backfill thermal properties.

Far field temperatures are most significantly influenced by waste type, repository depth and site rock thermal properties. Since the majority of the energy released by the waste will be initially transferred to the geological formation, a higher energy input (such as the case with spent fuel) will result in high temperatures which reside in the rock mass for long periods of time. The depth of the repository will dictate length of the path to the atmosphere and to some extent the amount of rock which will be available to receive the energy given off by the waste.

NEAR FIELD TEMPERATURE HISTORY

In the analysis of near field temperature history the four major areas which should be modeled are

- o Waste package
- o Waste package/rock interface
- o Rock mass
- o Repository ventilation

The thermal properties of the waste package are dependent upon the waste type and the material used in solidification, if reprocessing is being utilized. The rock near field temperatures are, however, only slightly influenced by a change in waste thermal properties, since the waste generally encompasses such a small volume. The waste packaging (usually assumed metallic) has an extremely low temperature gradient due to the large values of conductivity for metallic materials. It is therefore, usually assumed that the packaging temperature is approximately equal to the temperature on the outer periphery of the waste.

The waste package/rock interface modeling accuracy is dependent upon several variables. If one is concerned with the temperatures in the rock mass, the interface can be assumed to be conductive. If one is more concerned with waste package temperature history, the additional heat transfer modes of convection and radiation could possibly play a role if the interface is large and contains no backfill, e.g., an air gap.

Figure 2 presents the results obtained by Callahan, et. al., (1975), in the analysis of the importance of the radiative heat transfer at the waste rock interface through the use of finite elements. In this study the waste package was taken to be a cylinder .27 m in diameter and 3 m in length. The air gap was taken to 9 cm and the rock mass was bedded salt. Allowing radiative heat transfer at the interface results in essentially the same temperatures in the salt mass as when assuming merely conductive heat transfer. However, the temperatures within the waste package are significantly altered by assuming the radiative mode. Subsequent package corrosion studies would obviously be significantly altered.

Figure 2. Transient Temperature in a Salt Repository Model for Radiative and Conductive Interfaces.

In the specific concept discussed by Callahan, et. al., (1975), one is forced to accept the higher waste temperatures which result from leaving an air gap or to accept the possibility of salt brine coming into immediate contact with the package if an air gap is not present. The actual heat transfer mechanisms which occur at the waste package/rock interface are of such importance in determining waste temperature history that in situ heater experiments have been and will be performed (Carter, et. al., 1977), in order to determine the actual mechanisms occurring at the interface. One of these experiments will be discussed later.

When one assumes only conductive heat transfer at the package/rock interface, the temperature history in the very near field rock can be easily assessed in terms of site rock thermal characteristics. Ratigan (1976) has shown that the temperature history in the very near field rock around a cylindrical waste package can be presented in a non-dimensional fashion by utilizing the Fourier number and the variables comprising the temperature dimension arising from the solution of a line heat source in an infinite medium. These results are for short periods of time and do not include any heat generation decay of the waste. However, a similar correlation for long periods of time could be obtained by comparing the solution of a decaying heat generating line in a finite medium given by Bradshaw, et. al., (1970), with the finite element model of Ratigan assuming a representative heat decay, such as those given in Figure 1.

One of the major variables affecting the temperature history in the storage room structural is the ventilation period after emplacement. For a wide range of Nusselt numbers (Lindblom, et. al., 1977) the presence of ventilation results in a significant reduction in storage room temperatures. In general, with a reasonable amount of ventilation, approximately one-half of the generated heat can be removed by the mine air during the period of ventilation, depending on waste age, ventilation system, etc.

Figure 3. Non-Dimensional Temperature at the Waste/Rock Interface as a Function of the Fourier Number.

While the majority of the previous investigations have been performed through the use of numerical methods (finite difference and finite element) several studies have been performed with strictly analytical methods which have provided insight into the effects of rock thermal properties, package spacing and repository depth in a very economical fashion.

FAR FIELD TEMPERATURE HISTORY

In predicting the far field temperature history of a rock mass containing a repository, one need only model the repository as a heat generating medium within the rock mass. Discrete modeling of the repository will be relatively adequate for large time, provided that the repository utilizes only one level. This type of model has been used previously (Cheverson and Turner, 1972; Callahan, et.al. 1977). In the far field analysis the stratigraphic column of the site is more important in the modeling than was the case in the near field analysis.

The initial geothermal temperature gradient is important in the mathematical model if temperature dependent material properties are to be employed. However, if all thermal properties are taken to be constant, the initial temperature state can be superposed on the temperature rises due to the heat generation to arrive at the absolute temperatures. In a far field analysis the model must be of such a large domain that it will naturally include the earth's surface. The choice of boundary condition at the earth's surface will usually be either constant temperature or convective. For modest values of thermal flux or gross thermal loading (CTL) both boundary conditions result in very similar temperature fields for the majority of the rock mass. However, for shallow depths, or low Nusselt numbers, the choice of the boundary condition can result in different temperatures for a large portion of the rock.

Previous investigations have assumed only conductive heat transfer in the rock mass and as previously stated, this approach is adequate with salt masses. However, forced and free convective transfer modes may play a significant role in water bearing crystalline rock masses.

In predicting the far field temperature history around a repository the waste type is an extremely important variable. The energy which is produced by spent fuel emplacement is so much greater than that for high level waste that temperatures throughout the geological structure are sustained at relatively high levels for extended periods of time. For a specific bedded salt repository analyzed by Callahan, et.al., (1977) the repository centerline temperatures for high level waste and spent fuel varied significantly as a function of time (see Figure 4). These repositories had initial G.T.L. values of 150, 75, 50, and 25 kw/acre and the waste was assumed to be 10 years old upon emplacement. Younger waste has a tendency to peak at a higher value and at an earlier time, whereas an older waste has a tendency to peak lower at a later time.

Figure 4. Comparison of Repository Centerline Temperatures for Spent Fuel and High Level Waste

As an illustration of the power of analytical methods in the prediction of transient temperatures, Figure 5 presents a comparison of the finite element results obtained by Callahan with the temperature history predicted by assuming a plate in an infinite medium generating heat representative of 10 year old spent fuel. The representation of the fuel consists of a linear combination of exponential sources with different half lives (Ratigan, 1977). Also presented in Figure 5 are the analytical predicted temperatures resulting from the addition of ventilation and the subsequent percentage of heat dissipated through the repository ventilation. The analytical solution assumes constant ventilation with time and as such is somewhat unrealistic for times greater than, say 30 years. However, Ratigan (1977) has presented the analytical solution for discrete-time-ventilation and states that in general the effect of ventilation is felt by the rock at the midplane of the repository for almost an order of magnitude longer, e.g., if ventilation occurs for 30 years the temperatures in the midplane are altered for almost 300 years.

Figure 5. Comparison of Finite Element and Analytical Temperatures for a Spent Fuel Repository.

The analytical plane source solution has the distinct advantage of being able to predict the maximum temperature rise and the time of occurrence as a function of the waste parameters, site rock characteristics and repository depth.

COMPARISON OF MATHEMATICAL MODELS AND FIELD RESULTS

No mathematical model, analytical or numerical is of any value in predicting rock response for subsequent repository design unless the model accurately represents the physical occurrences in the actual repository. For this reason, the models should be utilized in predicting a priori the rock mass response in typical repository situations in order to validate the models worthiness. Since field level experiments are expensive to perform, post facto predictions have been utilized to evaluate the predictive capability of numerical methods for temperature history calculations. Future efforts will encompass not only post facto predictions but also a priori predictions of typical repository situations (Van Sambeek, 1976).

Figure 6. Plan and Power Chronology for Project Salt Vault

As regards post facto predictions, the Project Salt Vault (PSV) (Bradshaw and McClain, 1971), experiment performed at Lyons, Kansas, USA, has been utilized for numerical model verification. The major part of the experiment was performed in four rooms as shown in Figure 6. Rooms 1 and 4 contain 2 m long heaters placed in an array with a midplane depth of 3 m. Rooms 2 - 3 contained 2 m heaters spaced about pillar 2 - 3 with a midplane depth of 3 m. The sequence for heater control is given in Figure 6 in terms of standard years.

Figure 7. Finite Element and Field Measured Maximum Temperatures for Project Salt Vault.

In modeling the PSV experiment a two-dimensional finite element model through the center portion of the experimental area was constructed. The external vertical boundaries of the model were taken at the center of pillar 2 - 3 and the barrier pillar west of room 1. The model was analyzed for several values of thermal conductivity. The mine ventilation was also modeled. The power-time characteristics of the experiment were also modeled with the exception that minor power failures were not accounted for. The results of the simulation given by Ratigan (1976) are very encouraging. As displayed in Figure 7, the temperature contours of maximum temperature as predicted by the finite element model are very similar to the experimentally determined values at most locations. Ratigan (1976) has also utilized a superposed array of point heat sources to predict the temperatures in Room 1 at a depth of 3 m. These results are presented in Figure 8. The comparison is not totally valid as the point heat source solution does not represent the array power boost, e.g., the power for the point source solution is constant at the boosted power level.

Figure 8. Analytical and Field Measured Maximum Temperatures in Project Salt Vault

IN SITU HEATER EXPERIMENT

In an effort to validate the methods for predicting rock mass response to repository situations and to assess the difference between dome and bedded salt response, the Energy and Development Research Administration Office of Waste Isolation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, has initiated plans for an in situ heater experiment in dome salt. The layout of the experiment will be briefly described and the preliminary thermal calculations discussed. The experiment will involve three distinct heater experiments combining different backfill material and peripheral heaters. A plan view typical member of the total heater experiment is shown in Figure 9. The instrumentation shown in the figure is not complete, however some of the major components are displayed. The positioning of the stress and temperature measuring instrumentation is extremely important in order that all significant events may be monitored. In the initial design of the instrumentation plan, superposed point heat sources were utilized to position the instrumentation appropriately (Van Sambeek, 1976). Based on the success of the point source solution in the prediction of PSV temperatures, the point source solution was again utilized in the preliminary experiment instrumentation design. The stress and deformation instrumentation is directly correlated to the temperature instrumentation positions for obvious reasons. The proposed experiment will be utilized for many purposes other than merely temperature monitoring. The thermomechanical response of salt, which is much more complicated than the thermal response, will be continually monitored. A priori predictions of the rock mass response will be performed throughout this calendar year and the results of the experiment will be utilized to assess the relative worth of the predictive methods.

Figure 9. Plan View of a Typical Member of a Proposed Heater Experiment

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