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SIMULATION OF HEAT TRANSFER AROUND A CANISTER PLACED HORIZONTALLY IN A DRIFT

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ABSTRACT

The Yucca Mountain Site Characterization Project is investigating the feasibility of locating a high level radioactive nuclear waste repository at Yucca Mountain, Nevada. The bore hole and the in-drift waste emplacement schemes are under evaluation as potential repository drift geometries. This paper presents a two-dimensional finite element thermal analysis of the nuclear waste canister placed horizontally in a drift. Simulation has been carried out for 1000 years and the peak temperatures at the walls of the drift and at the center of the canister have been determined. The effect of the three modes of heat transfer, conduction, natural convection and radiation, is also discussed.

THERMAL MODEL

The computational domain of the thermal model is shown in Figure 1. The model extends 300m above the center of the drift (ground surface) and 300m below the center of the drift (water table). The temperatures at the top and the bottom horizontal boundaries are set at 25°C and 35°C respectively.

All calculations have been done using the finite element code FIDAP.[4]

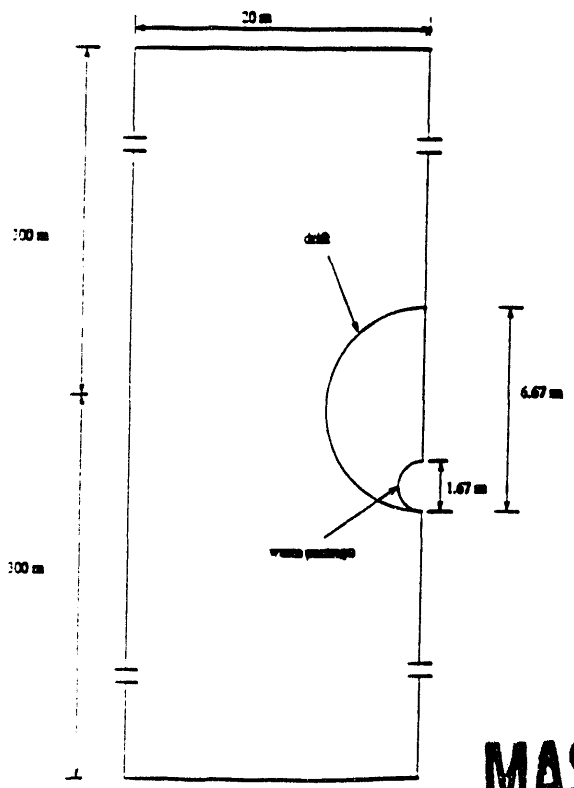

Fig.1 Computational Domain

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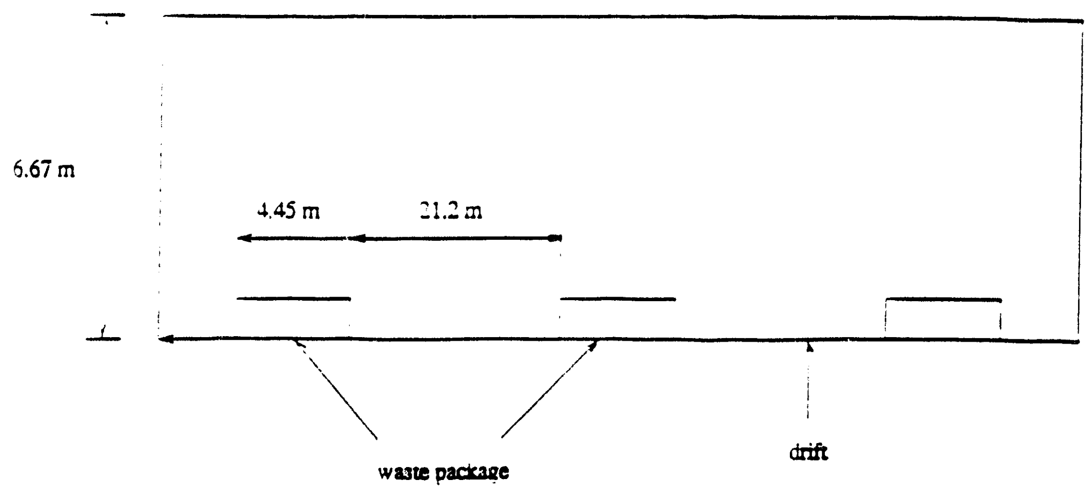

Figure 2 Waste Packages in the Drift

The vertical boundaries of the model are planes of symmetry and are treated as adiabatic surfaces.The repository drifts are 6.7m in diameter and spaced 40m center to center. Each waste package is 1.67m in diameter and contains 30 kW of heat. Its length is 4.45m and the spacing between the waste packages is 21.2m as shown in Figure 2.

The canisters have been considered as infinitely long cylinders of heat source and a section has been modelled with heat flux imposed on the boundary of the canister. The rock is modelled as a continuum with average properties. The thermal conductivity, density and specific heat of the rock[1] are taken as 3.0 W/m/°K, 2640 kg/m^3 and 800 J/kg/°K.

SIMULATION APPROACH

The simulation of heat transfer between the waste package, air in the drift and the rock has been performed in two steps:

1) A transient state analysis has been done for the heat conduction in the rock and temperatures at different levels of the rock and on the drift have been determined.

2) The heat transfer inside the drift has been modelled as a steady state problem imposing the temperatures obtained from the first step as the boundary conditions.

A. Heat Conduction in the Rock in Transient State

A transient advection-diffusion analysis has been done for the heat conduction in the rock with heat flux imposed on the walls of the drift instead being imposed on the canister. It has been assumed that the heat flow from the canister is equal to the heat flow imposed on the walls of the drift.

Constant temperatures have been imposed on the top and bottom of the thermal model discussed in the last section.The simulation has been carried out for 1,000 years with a time varying heat flux.[3] Figure 3 shows the variation of heat flux over a period of 1,000 years. The initial condition for the temperature was taken as 25°C at all nodes in the rock.

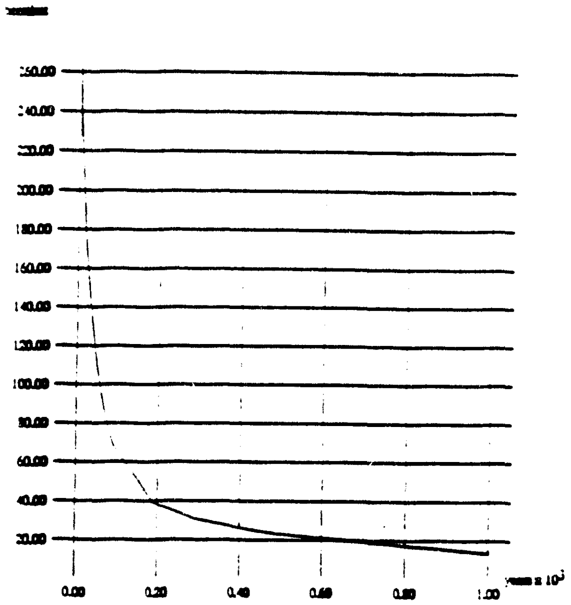

Figure 3 Variation of Heat Flux

The backward Euler implicit time integration scheme has been selected with a variable time step. The simulation was started with an initial time step of 100,000 seconds and the period of 1,000 years was covered in 28 time steps. The plot of the time step number versus time is shown in Figure 4. For the first few time steps time increments were of the order of initial time increment but as the temperature field built up, the time increments gradually became large. Successive Substitution iterative method with an acceleration factor of 0.8 obtained the solution at each time step of the time integration scheme.

The history of the temperatures at 10m from the center of the drift and at the walls of the drift is shown in Figure 5. The different levels in the rock reach the peak temperatures at different times. The drift reaches a peak temperature of 205 °C at around 29 years. The temperatures on the drift are almost uniform. The maximum temperatures at 10m, 50m and 150m from the center of the drift are 163°C, 130°C, and 87°C respectively at times 148 years, 263 years and 642 years respectively. A distinct maximum is observed in the temperature history curve at the drift, 10m and 50m but at 150m no obvious maximum is observed. This is probably due to the storage effect in the rock.

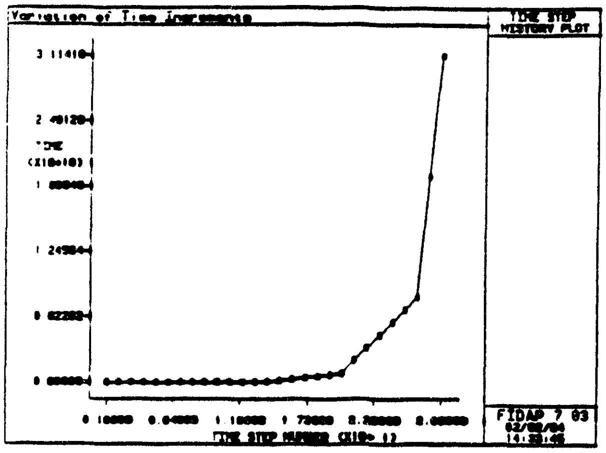

Fig.4 Variation of time increments

The temperature variation in the rock 300m above and 300m below the center of the drift at 105 years and 1000 years is shown in Figure 6(a) and Figure 6(b) respectively. The temperature contours are concentrated around the drift in early years but as the time progressed the temperature contours gradually spread out in the whole domain. Maximum temperature is at the walls of the drift.

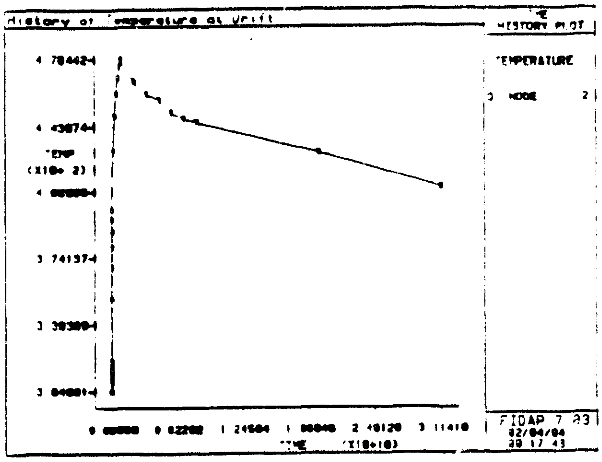

Fig.5(a) History of Temperature at the drift

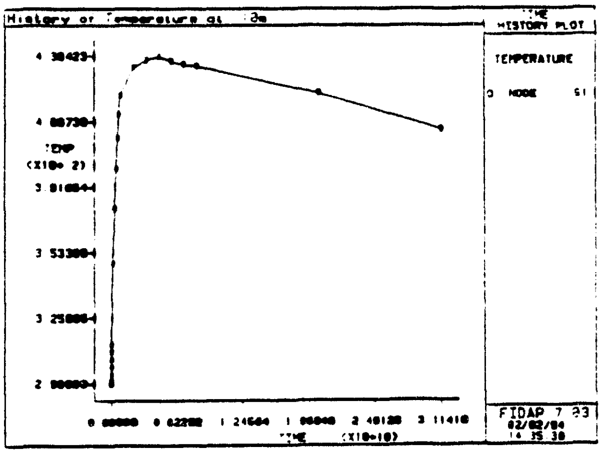

Fig.5(b) History of Temperature at 10 m

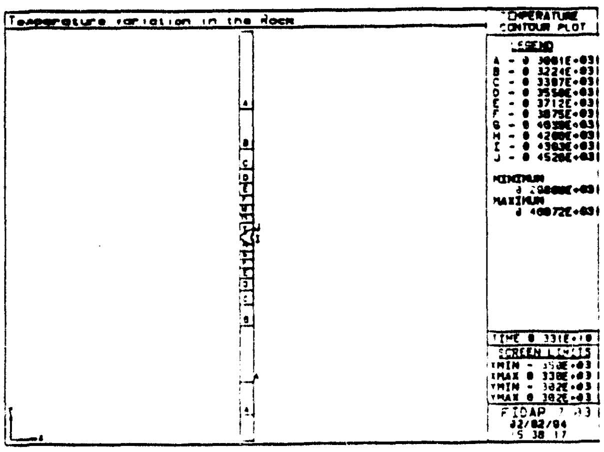

Fig.6(a) Temperature Variation at 105 years

Note: In the figures time is in seconds and temperature is in °K.

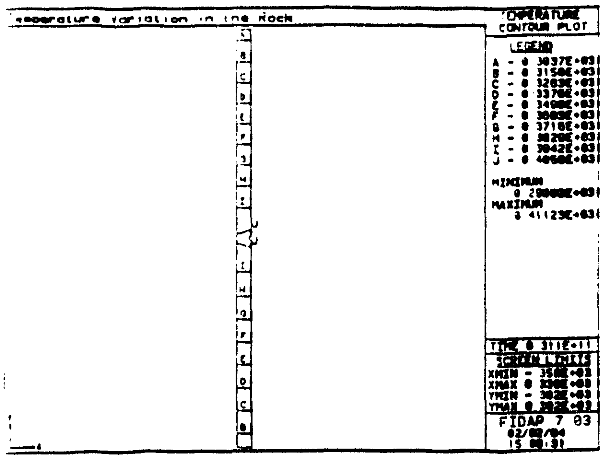

Fig.6(b) Temperature Variation at 1000 years

B. Steady State Analysis For The Combined Mode Of Heat Transfer In The Drift

A steady state analysis is performed for the heat transfer between the waste package and the drift. Combined mode of heat transfer, conduction, free convection and radiation, have been modelled. The time step for the transient run for the combined mode of heat transfer was quite small to capture the physics of natural convection.

Due to the typical geometry of the problem, paved mesh with quadrilateral elements has been generated. The total number of nodes for the solution is 3021, the mesh inside the drift being dense to catch the minute physical details.

The temperatures from the transient conduction run have been selected at 10m from the center of the drift at different time steps. These temperatures are imposed as boundary conditions on the horizontal and vertical lines in the computational domain shown in Fig 7. Heat flux at the selected time step is imposed on the walls of the canister.

The flow in the drift is buoyancy driven (strongly coupled) and the buoyancy term is included in the momentum equation. The Boussinesq approximation models the presence of the buoyancy force caused by density variation resulting from the variations in temperature. The form of this buoyancy force term is

$$(\rho-\rho_0)\,g_i=-\rho_0\,[\beta_T(T-T_0)]\,g_i$$

where
ρ_0 = density of air at the reference temperature
T_0 = reference temperature
β_T = coefficient of thermal expansion
g_i = gravity vector
ρ = density
T = temperature

ρ_0 has been taken as 1.17 kg/m^3 at a reference temperature of 25°C. The coefficient of thermal expansion has been modelled as a constant with an average value of 0.00335 /°K. The gravity vector has also been taken as a constant (9.81 m/s^2) and specify globally the magnitude and direction of gravity.

The Rayleigh numbers are of the order of 10^{12}, indicating that the flow in the drift is in the turbulent region. The distance between the centers of the drift and canister define the characteristic length. The Reynold's averaged equations have been solved. The two equation k-ϵ model has modelled the turbulence viscosity, using the eddy viscosity concept. The effective viscosity μ_e is computed by

$$\mu_e=\mu_0+\mu_t$$

where μ_0 is the laminar viscosity of the air and μ_t is the turbulent viscosity. The turbulent viscosity is computed by solving two additional transport equations, one for the turbulent kinetic energy 'k', and another for the turbulent dissipation 'ϵ'and then using the formula:

$$\mu_t=\frac{\rho C_\mu k^2}{\epsilon}$$

The initial values for the turbulent kinetic energy and the turbulent dissipation has been input as 0.002 each. C_μ is set at 0.09 . The laminar viscosity of the air is taken as 1.8 x 10^{-5} $N.s/m^2$.

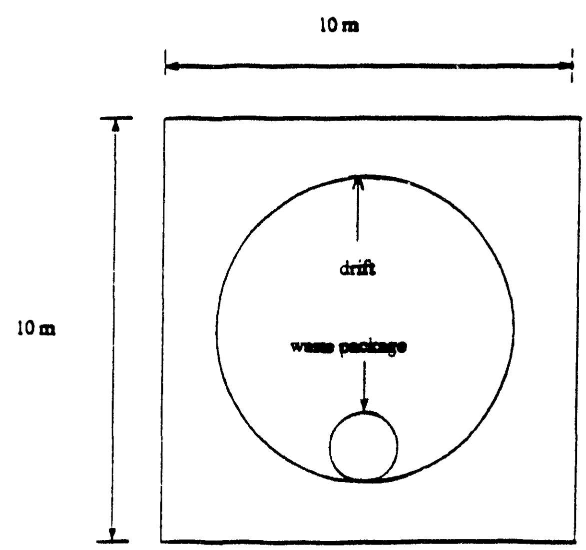

Fig.7 Computational Domain for Steady State Analysis

A clipping procedure has been employed to preclude unphysically unrealistic negative nodal values of temperature, turbulent kinetic energy and turbulent dissipation which can arise in the course of the numerical solution. If unchecked, such negative values, no matter how small, tend to have a disastrous effect on the stability of the numerical solution process, causing it to diverge violently in just a few iterations.

For the radiation problem, the air has been taken as a non - participating medium. Grey body radiation has been specified for the calculation of view factors. The emissivities[2] have been taken as constant, 0.6 for the canister and 0.75 for the walls of the drift. The penalty approach is chosen to discretize the pressure variable. The penalty parameter is set at 10^{-6}. The pressure approximation is discontinuous across element boundaries. The iterative method Successive Substitution obtains the nonlinear steady state solution. A value of 0.8 for the acceleration factor improved the convergence characteristics for the simulation.

The temperature and velocity fields at 30 and 130 years are shown in Figure 8 and Figure 9 respectively. At 30 years the average temperatures on the canister and the drift are 196°C and 190°C respectively . The temperature is maximum at the bottom of the drift and the maximum difference of temperatures at the top and the bottom of the drift is about 10°C. The maximum velocity of air due to natural convection at this time is 0.116 m/s. As the time progressed average temperature difference between the drift and the canister reduced. This is evident in the velocity vector plots which show a trend of decreasing velocities as the time progressed. The difference of temperatures between the top and the bottom of the drift also reduced with time. Two asymmetric cells were obtained for the streamline plot, indicating that the problem cannot be treated as symmetric along the vertical center line of the drift. Figure 10 shows a typical plot of the streamlines obtained at 10 years. There were two cells at all times.

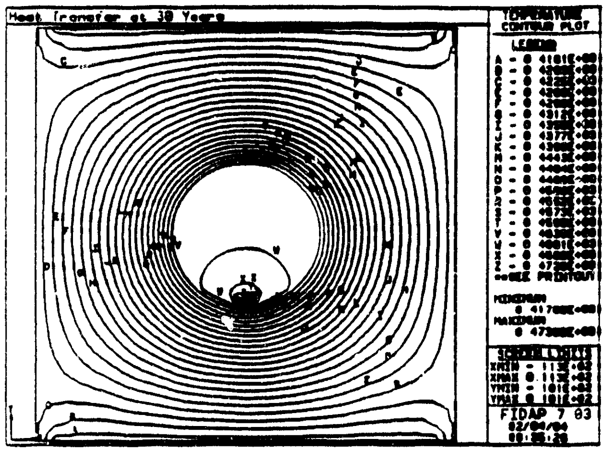

Fig.8(a) Temperature Contours at 30 Years

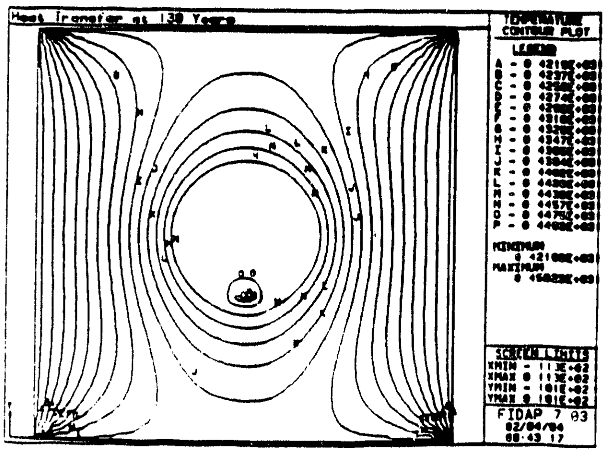

Fig.8(b) Temperature Contours at 130 Years

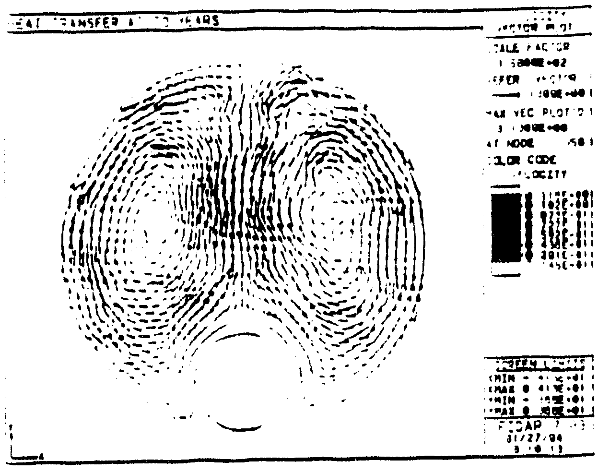

Fig.9(a) Velocity Vector at 30 Years

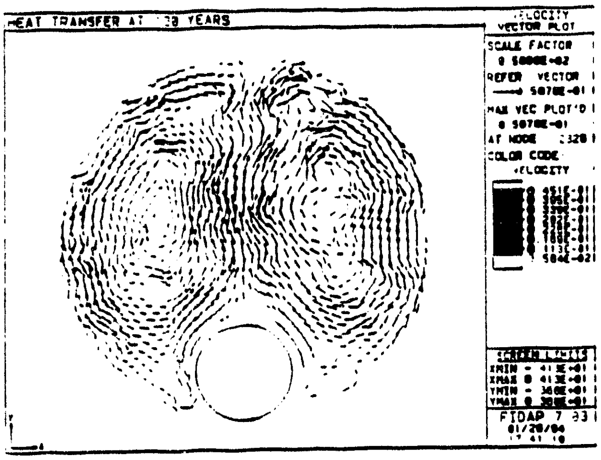

Fig.9(b) Velocity Vector at 130 Years

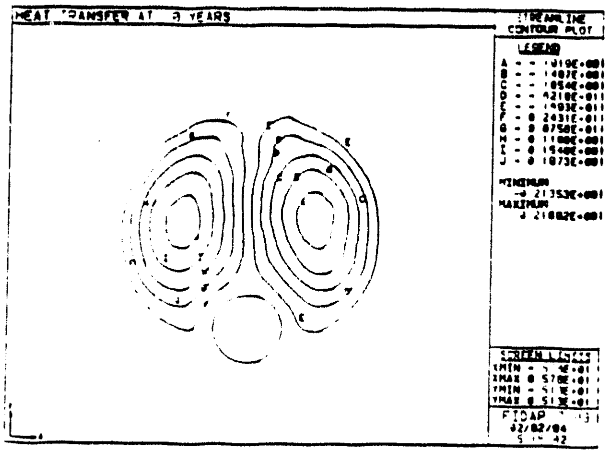

Fig.10 Streamline Plot

The Variation of the average drift wall temperatures for 1000 years for the combined heat transfer is shown in Figure 11. The maximum temperature on the drift is 192°C.

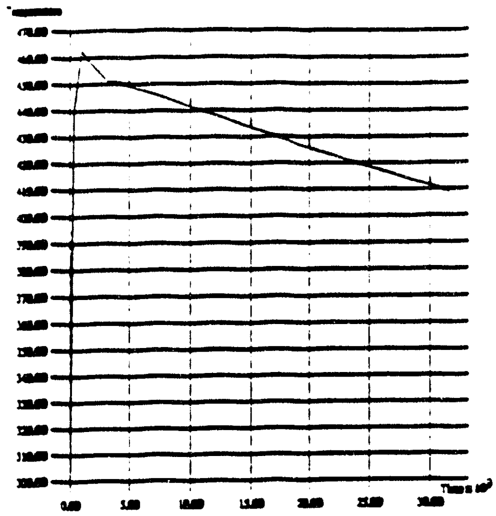

Fig.11 Variation of the Temperature on the Drift over 1000 Years for Steady State Analysis

Figure 12(a) and 12(b) show temperature contours inside the drift at 30 years and 130 years. These figures are zoomed plots of Figure 8(a) and 8(b) respectively. The difference in the temperatures due to natural convection is evident by the contours in the drift which show a maximum temperature inside the canister and the temperatures decrease as the contours move up towards the walls of the drift. The maximum temperature obtained inside the canister is about 200°C at around 30 years. This temperature decreased as the time progressed and the maximum temperature inside the canister is around 140°C at 1000 years.

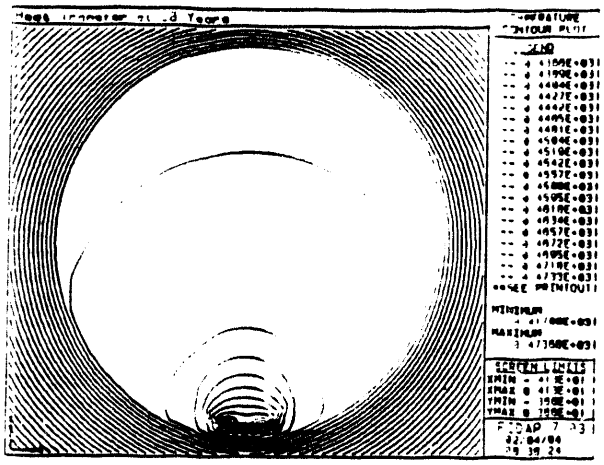

Fig.12(a) Temperature Contours in the Drift at 30 years

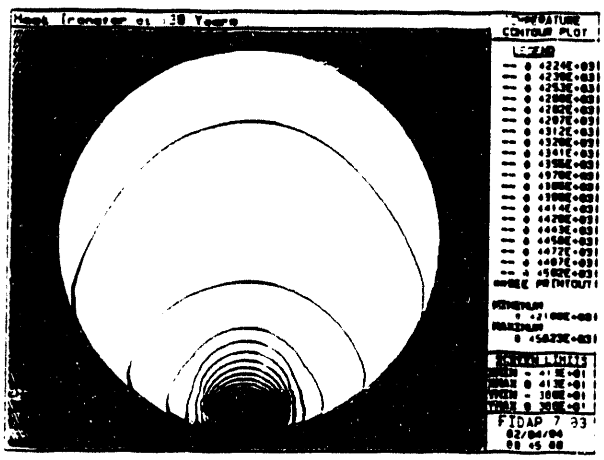

Fig.12(b) Temperature Contours in the Drift at 130 years

CONCLUSION

The above analysis show that radiation is a major mode of heat transfer between the waste package and the drift. Convection accounts for about 8-10%of the heat transfer. The comparison of the temperature distribution in Figure 5(a) and Figure 11 exhibits the effect of free convection as a mode of heat transfer. The maximum drop in the average temperature is about 13°C, about 8 % of the total heat transfer. The maximum velocity achieved is around 0.21 m/s.

The maximum temperature inside the canister is around 200°C, which is well below the thermal goal of 350°C for the zirconium alloy cladding.

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