WPO 31296

Thermal Convection and Effects of Thermal Gradients

Qualitative Screening Arguments for Side Efforts S-10 and GG-4

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Screening Decision

Thermal convection has been eliminated from performance assessment calculations on the basis of low consequence to performance of the disposal system.

Screening Issue

Temperature differentials in the repository could initiate thermal convection or affect fluid viscosities. The resulting changes in fluid flow could influence contaminant transport. Potentially, thermal gradients in the disposal rooms could drive the movement of water vapor. For example, temperature increases around waste located at the edges of the rooms could cause evaporation of water entering from the DRZ. This water vapor could condense on cooler waste containers in the rooms and could contribute to brine formation, corrosion and gas generation.

Basis for Screening Decision

Nuclear criticality, exothermic reactions, and radioactive decay are possible sources of heat in the WIPP repository. It is assumed that nuclear criticality can be eliminated from performance assessment calculations on the basis of low probability.

Concrete hydration will result in short-term (a few decades) temperature increases in the vicinity of the concrete seals after emplacement (see Summary Memo of Record SP-7). Loken (1994) and Loken and Chen (1995) showed that, one week after seal emplacement, concrete hydration could raise the temperature of the concrete to approximately 53°C and the temperature of the surrounding salt to approximately 38°C.

Wang (1996) assessed the potential for the development of elevated temperatures in the repository as a result of backfill hydration. Wang (1996) showed that temperature increases in the waste disposal region as a result of such an exothermic reaction will be less than 3°C. The maximum magnitude of this thermal pulse will occur under disturbed conditions at a time in excess of 100 years (see Summary Memo of Record SP-7).

DOE (1980, p.9-149) estimated that radioactive decay of CH TRU waste will result in a maximum temperature rise at the center of the repository of 1.6°C at 80 years after waste emplacement (see Appendix 1). Sanchez and Trellue (1996) have shown that the total thermal load of RH TRU waste will not significantly affect the average temperature increase in the repository (see Appendix 1). Temperature increases of about 3°C may occur at the locations of RH TRU containers of maximum thermal power (60 watts).

The potential for heat from exothermic reactions and radioactive decay to result in significant thermal convection is discussed in Appendix 2. The short-term concrete seals will be designed to function as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized. The seal design program has investigated the durability of large-scale concrete seals, and has formulated Salado Mass Concrete (SMC) with the aim of achieving the seal design targets reported in Wakeley et al. (1995, p.6-8), which include objectives to minimize thermally-induced cracking. According to Wakeley et al. (1995, p.7), the SMC will be prepared and emplaced at low temperatures in order to minimize the difference between the maximum concrete temperature and the ambient temperature in the repository. Temperature increases resulting from cement hydration will be low enough to mitigate thermal stresses and eliminate the potential for significant cracking. Thus, Wakeley et al. (1995, p.43) concludes that "[t]hermally induced cracking is not considered likely because large concrete monoliths have been constucted in salt without cracking". Also, according to Wakeley et al. (1995, p.7), the concrete "is proportioned to minimize shrinkage, promote tight sealing between concrete and host rock, and thus help avoid formation of a preferred pathway for fluid flow at the seal-rock interface". Thus, because the seal permeability will be low, temperature increases associated with concrete hydration will not result in significant buoyancy driven fluid flow through the concrete seal system. Similarly, the buoyancy forces generated by temperature contrasts in the disturbed rock zone, resulting from backfill and concrete hydration and radioactive decay, will be short lived and negligible compared to other driving forces for fluid flow. Furthermore, the induced temperature gradients will be insufficient to generate water vapor and drive significant moisture migration. Repository-induced flow, pressure changes resulting from gas generation, or flow induced by borehole intersection of a waste panel, will dominate the development of the brine and gas flow fields for the duration of any thermal pulse. In summary, temperature changes in the disposal system will not cause significant thermal convection. Thus, thermal convection has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Temperature effects on fluid viscosity would be most significant in the disturbed rock zone surrounding the hydrating concrete seals (where temperatures of approximately 38°C are expected). The viscosity of pure water varies by about 18 per cent over a temperature range of between 27°C and 38°C (Batchelor, 1983, p.596). Although, at a temperature of 27°C, the viscosity of Salado brine is about twice that of pure water (Rechard, 1990, p.A-19), the magnitude of the variation in brine viscosity between 27°C and 38°C will be similar to the magnitude of the variation in viscosity of pure water. The viscosity of air over this temperature range varies by less than 7 per cent (Batchelor, 1983, p.594) and the viscosity of gas in the waste disposal region over this temperature range is also likely to vary by less than 7 per cent. The Darcy fluid flow velocity for a porous medium is inversely proportional to the fluid viscosity. Thus, increases in brine and gas flow rates may occur as a result of viscosity variations in the vicinity of the concrete seals. However, these viscosity variations will only persist for a short period in which temperatures are elevated, and, thus, the expected variations in brine and gas viscosity in the waste disposal region will not affect the long-term performance of the disposal system significantly.

PPENDIX 1

eat From Radioactive Decay

adioactive decay of the contact handled CH and remote handled RH TRU waste emplaced in he repository will generate heat. The importance of heat from radioactive decay depends on the effects that the induced temperature changes would have on mechanics, fluid flow, and geochemical processes. For example, temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

According to the Waste Acceptance Criteria (WAC), the design basis for the WIPP requires that the thermal loading does not exceed 10 kilowatts per acre. The WAC also require that the thermal power generated by waste in an RH TRU container shall not exceed 300 watts, but the WAC do not limit the thermal power of CH TRU waste containers.

A numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980, pp.9-149–9-150). This study involved estimation of the thermal power of CH TRU waste containers. The DOE (1980) analysis assumed:

- All CH TRU waste drums and boxes contain the maximum permissible quantity of plutonium. According to the WAC, the fissionable radionuclide content for CH TRU waste containers shall be no greater than 200 grams per 0.21 cubic meter drum and 350 grams per 1.8 cubic meter standard waste box (in Pu-239 fissile gram equivalents).

- The plutonium in CH TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram. Thus, the thermal power of a drum is approximately 0.5 watts and that of a box is approximately 0.8 watts.

- Approximately 3.7×10^5 cubic meters of CH TRU waste are distributed within a repository enclosing an area of 7.3×10^5 square meters. This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 cubic meters for all waste (as specified by the Land Withdrawal Act [LWA]) to be placed in an enclosed area of approximately 5.1×10^5 square meters.

- Half of the CH TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 9×10^5 drums and 10^5 boxes. Thus, a calculated thermal power of 2.8 kilowatts per acre (0.7 watts per square meter) of heat is generated by the CH TRU waste.

- Insufficient RH TRU waste is emplaced in the repository to influence the total thermal load.

Thorne and Rudeen (1980) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8 kilowatts per acre (0.7 watts per square meter) which decreases over time. Thorne and Rudeen (1980) attributed this thermal load to RH TRU waste, but DOE (1980), more appropriately, attributed this thermal load to CH TRU waste based on the assumptions listed above. Thorne and Rudeen (1980) estimated the maximum rise in temperature at the center of a repository to be 1.6°C at 80 years after waste emplacement.

Sanchez and Trellue (1996) estimated the maximum thermal power of an RH TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH TRU container corresponding to the maximum permissible surface dose; according to the WAC the maximum allowable surface dose equivalent for RH TRU containers is 1000 rem/hr. The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma-ray radiation corresponding to the maximum surface dose equivalent rate of 1000 rem/hr. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because, according to the WAC, the maximum dose rate from neutrons is 270 mrem/hr, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 MeV the maximum allowable gamma flux density at the surface of a RH TRU container is about 5.8×10^8 gamma rays per square centimeter per second.

- Determine the distributed gamma source strength, or gamma activity, in an RH container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor. The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies) is then calculated for a RH TRU container containing 0.89 cubic meters of waste. For the waste of greatest expected density (about 6,000 kilogrammes per cubic meter) the gamma source is about 2×10^4 curies per cubic meter.

- Calculate the total curie load of a RH TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total curie load to the gamma curie load was estimated through examination of the radionuclide inventory presented in the WIPP Baseline Inventory Report (BIR) (DOE, 1995). The gamma curie load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total curie load to gamma curie load of RH TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH TRU container from the total curie load. The ratio of thermal load to curie load was estimated through examination of the radionuclide inventory presented in the WIPP BIR (DOE, 1995). The thermal load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of thermal load to curie load of RH TRU waste was calculated to be about 0.0037 watts/curie. For a gamma source of $2x10^4$ curies per cubic meter the maximum permissible thermal load of a RH TRU container is about 70 watts per cubic meter. Thus, the maximum thermal load of a RH TRU container is about 60 watts, and the WAC upper limit of 300 watts will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH TRU container to be less than 1 watt. Also, the total RH TRU heat load is less than 10% of the total heat load in the WIPP. Thus, the total thermal load of the RH TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH TRU waste.

Temperature increases will be greater at locations where the thermal power of a RH TRU container is 60 watts, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 watt RH TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 watts per cubic meter. These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3°C.

In summary, analysis has shown that the average temperature increase in the WIPP repository, due to radioactive decay of the emplaced CH and RH TRU waste, will be less than 2°C. Temperature increases of about 3 °C may occur in the vicinity of RH TRU containers with the highest allowable thermal load of about 60 watts (based on the maximum allowable surface dose equivalent for RH TRU containers).

APPENDIX 2

Thermal Convection

The Darcy velocity, V_i (m/s), of fluid component i in an unsaturated porous medium is given by Darcy's law:

$$V_i = -\frac{k_i}{\mu_i}\left(\nabla p_i + \rho_i g z\right) \tag{1}$$

where the parameters in equation (1) are as listed below.

Parameter	
p_i	Fluid pressure (Pa)
k_i	Intrinsic permeability (m^2)
μ_i	Fluid viscosity (Pa s)
ρ_i	Fluid density (kg/m^3)
g	Acceleration of gravity (9.79 m/s^2)
z	Unit vector in the upward z direction

Fluid density variations may be evaluated by setting:

$$\rho_i = \rho_{i0} + \Delta\rho_i \tag{2}$$

where ρ_{i0} (kg/m^3) is a reference density. Substituting equation (2) into equation (1) gives

$$V_i = -\frac{k_i}{\mu_i}\left(\nabla P_i + \Delta\rho_i g z\right) \tag{3}$$

where $P_i = p_i + \rho_{i0} g z$ is the nonhydrostatic pressure. The dependence of density on temperature, T (°C), can be linearized according to the Boussinesq approximation (Tritton, 1984, p.155; Green et al., 1995, p.2-8):

$$\Delta\rho_i = -\alpha_i \rho_{i0} \Delta T \tag{4}$$

where α_i (°C$^{-1)}$ is the coefficient of expansion of the *i*th component. The Darcy velocity then becomes

$$V_i = -\frac{k_i}{\mu_i}\left(\nabla P_i + \alpha_i \rho_{i0} g \Delta T z\right) \tag{5}$$

Thus, a characteristic velocity for convective fluid flow of the *i*th component is

$$V_i \sim -\frac{k_i}{\mu_i}\left(\alpha_i \rho_{i0} g \Delta T \right) \tag{6}$$

This velocity may be evaluated for the brine and gas phases expected in the waste disposal region using the parameter values listed below, which are appropriate for a temperature of approximately 30°C.

Parameter	Brine	Gas (hydrogen)
α (°C)	3×10^{-4} *	3×10^{-3} **
ρ (kg/m^3)	1.2×10^{3}	1.0 **
k_{DRZ} (m^2)	1×10^{-15} ***	1×10^{-15} ***
k_{SEAL} (m^2)	2.7×10^{-19}	2.7×10^{-19}
μ (Pa s)	1.6×10^{-3}	9×10^{-6}

• value for pure water used

** value for air used

*** upper range of expected value in the disturbed rock zone

Data sources: Rechard et al. (1990, A-19), Batchelor (1983, pp.594-596), Sandia WIPP Project (1992, Table 3.2-1)

For a temperature increase of 10°C, the characteristic velocity for brine in the DRZ is approximately 2×10^{-11} m/s (7×10^{-4} m/y), and the characteristic velocity for gas in the DRZ is approximately 3×10^{-11} m/s (1×10^{-3} m/y). For a temperature increase of 25°C, the characteristic velocity for brine in the concrete seals is approximately 1×10^{-14} m/s (5×10^{-7} m/y), and the characteristic velocity for gas in the concrete seals is approximately 2×10^{-14} m/s (7×10^{-7} m/y). These values of Darcy velocity are much smaller than the expected values associated with brine inflow to the disposal rooms or fluid flow resulting from gas generation.

As discussed by de Marsily (1986, p.283) the potential significance of thermal convection can also be determined by evaluating the dimensionless porous medium Rayleigh number:

$$Ra_l = \frac{k_i \alpha_l \rho_{l0}^2 g c \Delta T L}{\lambda \mu_l} \qquad (7)$$

where L (m) is a typical vertical thickness over which the temperature difference acts, c (J/kg°C) is the specific heat of the fluid and λ (W/m°C) is the equivalent thermal conductivity of the porous medium. Setting $\Delta T = 10°C$, $L = 10$ m (estimated from Argüello and Torres, 1988, p.15), $\lambda = 5$ W/m°C (Sanchez and Trellue, 1996), and $c = 4 \times 10^3$ J/kg°C (Batchelor, 1983, p.596) for the brine phase in the DRZ, the Rayleigh number is $Ra = 2 \times 10^{-4}$. For the gas phase in the DRZ, with $c = 0.7 \times 10^3$ J/kg°C (Batchelor, 1983, p.594), the Rayleigh number is $Ra = 5 \times 10^{-8}$. Thermal convection will not occur for Rayleigh numbers less than unity.

On the basis of this analysis, thermal convection has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

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WPO 31290

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Qualitative Screening Arguments for Side Efforts S-10 and GG-4

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For Review
6/3/96

23 May 1996

Screening Decision

Thermal convection has been eliminated from performance assessment calculations on the basis of low consequence to performance of the disposal system.

Screening Issue

Temperature differentials in the repository could initiate thermal convection. The resulting fluid flow could influence contaminant transport. Potentially, thermal gradients in the disposal rooms could drive the movement of water vapor. For example, temperature increases around waste located at the edges of the rooms could cause evaporation of water entering from the DRZ. This water vapor could condense on cooler waste containers in the rooms and could contribute to brine formation, corrosion and gas generation.

Basis for Screening Decision

Nuclear criticality, exothermic reactions, and radioactive decay are possible sources of heat in the WIPP repository. It is assumed that nuclear criticality can be eliminated from performance assessment calculations on the basis of low probability.

Concrete hydration will result in short-term (a few decades) temperature increases in the vicinity of the concrete shaft seals after emplacement (see Summary Memo of Record SP-7). These short-term shaft seals will be designed to function as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al., 1995). Thus, temperature increases associated with concrete hydration will not result in significant buoyancy driven fluid flow through the shaft seal system.

Wang (1996) assessed the potential for the development of elevated temperatures in the repository as a result of backfill hydration. Wang (1996) showed that temperature increases in the waste disposal region as a result of such an exothermic reaction will be less than 3°C. The maximum magnitude of this thermal pulse will occur under disturbed conditions at a time in excess of 100 years (see Summary Memo of Record SP-7).

DOE (1980) estimated that radioactive decay of CH TRU waste will result in a maximum temperature rise at the center of the repository of 1.6°C at 80 years after waste emplacement (see Appendix 1). Sanchez and Trellue (1996) have shown that the total thermal load of RH

TRU waste will not significantly affect the average temperature increase in the repository (see Appendix 1). Temperature increases of about 3°C may occur at the locations of RH TRU containers of maximum thermal power (60 watts).

The viscosity of pure water varies by about 5 per cent over a temperature range of between 27°C and 30°C (Batchelor 1983, 596). Although, at a temperature of 27°C, the viscosity of Salado brine is about twice that of pure water (Rechard 1990, A-19), the magnitude of the variation in brine viscosity between 27°C and 30°C will be similar to the magnitude of the variation in viscosity of pure water. The viscosity of air over this temperature range varies by less than 2 per cent (Batchelor 1983, 594) and the viscosity of gas in the waste disposal region over this temperature range is also likely to vary by less than 2 per cent. The Darcy fluid flow velocity for a porous medium is inversely proportional to the fluid viscosity, and, thus, the expected variations in brine and gas viscosity in the waste disposal region will not affect fluid flow rates significantly.

The buoyancy forces generated by temperature contrasts of the order 3° C will be negligible compared to other driving forces for fluid flow (see Appendix 2). Similarly, the induced temperature gradients will be insufficient to generate water vapor and drive significant moisture migration. Repository-induced flow, pressure changes resulting from gas generation, or flow induced by borehole intersection of a waste panel, will dominate the development of the brine and gas flow fields for the duration of any thermal pulse.

In summary, temperature changes in the disposal system will not cause significant thermal convection. Thus, thermal convection has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

APPENDIX 1

Heat From Radioactive Decay

Radioactive decay of the contact handled CH and remote handled RH TRU waste emplaced in the repository will generate heat. The importance of heat from radioactive decay depends on the effects that the induced temperature changes would have on mechanics, fluid flow, and geochemical processes. For example, temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

According to the Waste Acceptance Criteria (WAC), the design basis for the WIPP requires that the thermal loading does not exceed 10 kilowatts per acre. The WAC also require that the thermal power generated by waste in an RH TRU container shall not exceed 300 watts, but the WAC do not limit the thermal power of CH TRU waste containers.

A numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980). This study involved estimation of the thermal power of CH TRU waste containers. The DOE (1980) analysis assumed:

- All CH TRU waste drums and boxes contain the maximum permissible quantity of plutonium. According to the WAC, the fissionable radionuclide content for CH TRU waste containers shall be no greater than 200 grams per 0.21 cubic meter drum and 350 grams per 1.8 cubic meter standard waste box (in Pu-239 fissile gram equivalents).
- The plutonium in CH TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram. Thus, the thermal power of a drum is approximately 0.5 watts and that of a box is approximately 0.8 watts.
- Approximately 3.7×10^5 cubic meters of CH TRU waste are distributed within a repository enclosing an area of 7.3×10^5 square meters. This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 cubic meters for all waste (as specified by the Land Withdrawal Act [LWA]) to be placed in an enclosed area of approximately 5.1×10^5 square meters.
- Half of the CH TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 9×10^5 drums and 10^5 boxes. Thus, a calculated thermal power of 2.8 kilowatts per acre (0.7 watts per square meter) of heat is generated by the CH TRU waste.
- Insufficient RH TRU waste is emplaced in the repository to influence the total thermal load.

Thorne and Rudeen (1980) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8

kilowatts per acre (0.7 watts per square meter) which decreases over time. Thorne and Rudeen (1980) attributed this thermal load to RH TRU waste, but DOE (1980), more appropriately, attributed this thermal load to CH TRU waste based on the assumptions listed above. Thorne and Rudeen (1980) estimated the maximum rise in temperature at the center of a repository to be 1.6°C at 80 years after waste emplacement.

Sanchez and Trellue (1996) estimated the maximum thermal power of an RH TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH TRU container corresponding to the maximum permissible surface dose; according to the WAC the maximum allowable surface dose equivalent for RH TRU containers is 1000 rem/hr. The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma-ray radiation corresponding to the maximum surface dose equivalent rate of 1000 rem/hr. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because, according to the WAC, the maximum dose rate from neutrons is 270 mrem/hr, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 MeV the maximum allowable gamma flux density at the surface of a RH TRU container is about 5.8×10^8 gamma rays per square centimeter per second.

- Determine the distributed gamma source strength, or gamma activity, in an RH container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor. The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies) is then calculated for a RH TRU container containing 0.89 cubic meters of waste. For the waste of greatest expected density (about 6,000 kilogrammes per cubic meter) the gamma source is about 2×10^4 curies per cubic meter.

- Calculate the total curie load of a RH TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total curie load to the gamma curie load was estimated through examination of the radionuclide inventory presented in the WIPP Baseline Inventory Report (BIR) (DOE, 1995). The gamma curie load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total curie load to gamma curie load of RH TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH TRU container from the total curie load. The ratio of thermal load to curie load was estimated through examination of the radionuclide inventory presented in the WIPP BIR (DOE, 1995). The thermal load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of thermal load to curie load of RH TRU waste was calculated to be about 0.0037 watts/curie. For a gamma source of 2×10^4 curies per cubic meter the maximum permissible thermal load of a RH TRU container is about 70 watts per cubic meter. Thus, the maximum thermal load of a RH TRU container is about 60 watts, and the WAC upper limit of 300 watts will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH TRU container to be less than 1 watt. Also, the total RH TRU heat load is less than 10% of the total heat load in the WIPP. Thus, the total thermal load of the RH TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH TRU waste.

Temperature increases will be greater at locations where the thermal power of a RH TRU container is 60 watts, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 watt RH TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 watts per cubic meter. These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3°C.

In summary, analysis has shown that the average temperature increase in the WIPP repository, due to radioactive decay of the emplaced CH and RH TRU waste, will be less than 2°C. Temperature increases of about 3°C may occur in the vicinity of RH TRU containers with the highest allowable thermal load of about 60 watts (based on the maximum allowable surface dose equivalent for RH TRU containers).

APPENDIX 2

Thermal Convection

The Darcy velocity, V_i (m/s), of fluid component i in an unsaturated porus medium is given by Darcy's law:

$$V_i = -\frac{k_i}{\mu_i}\left(\nabla p_i + \rho_i g z\right) \tag{1}$$

where the parameters in equation (1) are as listed below.

Parameter	
p_i	Fluid pressure (Pa)
k_i	Intrinsic permeability (m^2)
μ_i	Fluid viscosity (Pa s)
ρ_i	Fluid density (kg/m^3)
g	Acceleration of gravity (9.79 m/s^2)
z	Unit vector in the upward z direction

Fluid density variations may be evaluated by setting:

$$\rho_i = \rho_{i0} + \Delta\rho_i \tag{2}$$

where ρ_{i0} (kg/m^3) is a reference density. Substituting equation (2) into equation (1) gives

$$V_i = -\frac{k_i}{\mu_i}\left(\nabla P_i + \Delta\rho_i g z\right) \tag{3}$$

where $P_i = p_i + \rho_{i0} g z$ is the nonhydrostatic pressure. The dependence of density on temperature, T (°C), can be linearized according to the Boussinesq approximation (Tritton 1984, 155; Green et al. 1995, 2-8):

$$\Delta\rho_i = -\alpha_i \rho_{i0} \Delta T \tag{4}$$

where α_i ($°C^{-1}$) is the coefficient of expansion of the ith component.

The Darcy velocity then becomes

$$V_i = -\frac{k_i}{\mu_i}\left(\nabla P_i + \alpha_i \rho_{i0} g \Delta T z\right) \tag{5}$$

Thus, a characteristic velocity for convective fluid flow of the *i*th component is

$$V_i = -\frac{k_i}{\mu_i}\left(\alpha_i \rho_{i0} g \Delta T\right) \tag{6}$$

This velocity may be evaluated for the brine and gas phases expected in the waste disposal region using the parameter values listed below, which are appropriate for a temperature of approximately 30°C.

Parameter	Brine	Gas (hydrogen)
α (°C)	3 x 10^{-4} *	3 x 10^{-3} **
ρ (kg/m3)	1.2 x 10^{3}	1.0 **
k (m2)	1 x 10^{-15} ***	1 x 10^{-15} ***
μ (Pa s)	1.6 x 10^{-3}	9 x 10^{-6}
* value for pure water used ** value for air used *** upper range of expected value in the disturbed rock zone Data sources: Rechard et al. (1990, A-19), Batchelor (1983, 594-596)		

The characteristic velocity for brine is approximately 7 x 10^{-12} m/s (2 x 10^{-4} m/y), and for gas the characteristic velocity is approximately 1 x 10^{-11} m/s (4 x 10^{-4} m/y). These values of Darcy velocity are much smaller than the expected values associated with brine inflow to the disposal rooms or fluid flow resulting from gas generation.

As discussed by de Marsily (1986, 283) the potential significance of thermal convection can also be determined by evaluating the dimensionless porous medium Rayleigh number:

$$Ra_i = \frac{k_i \alpha_i \rho_{i0}^2 g c \Delta T L}{\lambda \mu_i} \tag{7}$$

where L (m) is a typical vertical thickness over which the temperature difference acts, c (J/kg°C) is the specific heat of the fluid and λ (W/m°C) is the equivalent thermal conductivity of the porous medium. Setting $L = 10$ m (Argüello and Torres 1988, 15), $\lambda = 5$ W/m°C (Sanchez and Trellue 1996), and $c = 4 \times 10^3$ J/kg°C (Batchelor 1983, 596) for the brine phase, the Rayleigh number is $Ra = 6 \times 10^{-5}$. For the gas phase, with $c = 0.7 \times 10^3$ J/kg°C (Batchelor

1983, 594), the Rayleigh number is $Ra = 1 \times 10^{-8}$. Thermal convection will not occur for Rayleigh numbers less than unity.

On the basis of this analysis, thermal convection has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

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