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APPLICATION OF THERMAL CONDUCTION MODELS TO DEEPSEA DISPOSAL OF RADIOACTIVE WASTES

W. P. SCHIMMEL, JR. AND C. E. HICKOX

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APPLICATION OF THERMAL CONDUCTION MODELS
TO DEEPSEA DISPOSAL OF RADIOACTIVE WASTES

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ABSTRACT

Thermal problems associated with the emplacement of radioactive wastes in the deepsea sedimentary layer have been studied. In particular, the nature of the temperature field surrounding and the interstitial water velocity arising from a buried cask have been examined. Worst case estimates indicate that the velocity will be extremely weak and thus not likely to provide a primary transport mechanism for the radioactive material. This statement will, of course, only apply for moderately low levels of heat generation by the decaying radio nuclides. Because of the low interstitial water velocity, thermal conduction models can be used to predict the temperature field in the surrounding sediments as well as the cask surface temperature. This is equivalent to "decoupling" the energy and momentum conservation relationships thus simplifying the solution of the temperature field.

The present work considers in some detail the temperature field surrounding a vertical circular "cylinder" located a distance below a horizontal, isothermal, plane surface. Actually, the isotherm corresponding to the cask surface is an ellipsoid of revolution but the error will be small for large values of the length to diameter ratio. The resulting expression can be used to estimate temperature of the cask surface for material degradation studies and the effect of temperature upon the ion transport process in the sediments.

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INTRODUCTION

The "energy crisis" of the 1970's has made nearly every American citizen aware of the finite extent of our fossil fuel reserves. Because of this, ever increasing dependence must be placed upon alternatives for power generation. Of the near-term alternatives, virtually everyone agrees that light water fission reactors (LWR) represent the replacement source with the highest probability of success.

Although the potentially attractive schemes of utilizing solar, geothermal and tidal energy are presently being investigated, it is unlikely that any of these will have a significant impact upon the energy shortage for the near-term future. Likewise, the technological problems which exist in the field of controlled thermonuclear fusion make the prospect of contemporary power generation by this process rather dim. Nuclear reactors, on the other hand, exist and are generating electrical power today.

Unfortunately (or fortunately depending on your vantage point), the need for widespread dissemination of the LWR's comes on the heels of discovery that the environment is also finite in terms of its capability to handle pollutants. The power engineer must now be aware of "cost" in the broader sense of the word. Not only cost as associated with the capital expenditures of acquiring, transporting and processing a fuel but the ultimate strain on the environment because of using the fuel.

Nuclear fission reactors have their own form of costs in terms of ecological impact. One of these costs is the production of high-level radioactive waste (HLW) products. These waste products require almost perfect segregation from the environment.¹ Because some of the constituents are extremely long-lived such as ^{239}Pu with a half-life of 24,000 years and ^{129}I with a half-life of about 10 million years, they must be contained virtually forever. There is presently no evidence that any known material will be able to withstand the combined thermal and radioactive levels for more than a small fraction of the lifetimes of the toxic materials. It is therefore necessary to place as many barriers as possible between the reactor wastes and mankind's environment. The technology for transmutation of the long-lived isotopes or disposing of them outside the earth's atmosphere appears to be out of reach for the near term and thus will not be considered.

Of the terrestrial sites considered for possible use as repositories, the sea floor appears particularly attractive. There exist regions in the world's oceans of low biomass and relative geological stability. In addition, the desirable features of fairly deep water (4-6 km) and low non-tidal currents near the bottom (<5 cm/s) suggest the use of the mid-plate/gyre (MPG) regions. This view has been previously presented in References 1 and 2. Other areas in the sea could also be considered but the criteria listed above have eliminated most of them.

Initially, the thinking on seabed disposal was that the HLW would be simply "dumped" on the ocean bottom.³ Because of the remoteness of the dump site, any toxic wastes which escaped the cask

and waste form would be diluted before reaching mankind. This thinking dominates the studies of physical oceanographers for the past few years.⁴⁻⁶ Based on a recent investigation into the kinetics of thermally induced buoyant plumes,⁷ it appears that neither the dilution mechanism nor the specific release pathway to man is well known. One is, therefore, led to the next available option in seabed disposal--the emplacement of the HLW in the clay rich sediments underlying the MPG regions. The sediment can provide a "barrier" in terms of ion transport in a properly engineered disposal program.

The present study will consider the thermal effects arising from the emplacement of a localized heat source in the deep ocean sediments. Of particular interest to the waste disposal program are the temperature of the waste form cask and the velocity of the interstitial water in the sediments. Cask temperature and that of the surrounding medium will dictate the rates at which the various chemical reactions occur. Sorption coefficients in the sediments will also be modified by the presence of the temperature field. Interstitial water motion is a key parameter in the leach rate studies which determine the effectiveness of the sediment column as a barrier.

In the sections to follow, a series of theoretical attempts to characterize the situation will be presented. Because of the extremely low permeabilities in the largely clay sediments, it is expected that the temperature field will be essentially that of a conduction-dominated situation. This, as opposed to a convection-dominated situation in which the temperature field would exhibit a strong "plume-like" behavior. It is useful, therefore, to develop

thermal conduction models which ignore the velocity field and its resulting effect upon the temperature field. One particular geometric configuration, namely, a vertical finite length cylinder located some distance below a horizontal isothermal plane will be discussed in detail. This model obviously corresponds to the actual emplacement configuration. Results from the porous media convection studies^{8,9} confirm the conduction-like temperature field for the idealized source configurations considered.

THERMAL CONDUCTION MODELS

The actual configuration likely to be encountered in the deepsea disposal program is that of a finite length cylinder located some distance below the horizontal plane of the seabed. Present candidates for the emplacement process dictate that the axis of the cylinder will probably be vertical. If permitted to sink under its own weight, however, the cask could be horizontal. Both these cases, in addition to some more "idealized" configurations (in the mathematical sense), will be presented. Of the models considered, only the mathematical idealization of an infinite length cylinder will be used to predict transient behavior of the temperature field. This lack of transient information is not a serious consideration if the stable equilibrium of the emplaced cask is certain. If, however, some time-dependent stability mechanism takes place, it may be desirable to consider a transient description of the problem. An excellent compilation of transient conduction solutions which could be applied to the problem has recently been published.¹⁰ These,

solutions are somewhat more tedious than the present time independent ones but they could be used if required.

An additional point that should be made is that constant uniform heat flux is assumed over the cannister lateral surface. If the actual decaying source behavior is assumed, these models could be used in a piecewise fashion¹¹ to determine temperature response. Because it is likely that an emplacement engineer would use more sophisticated analytical (numerical) models for designing the cask and waste form, the present models represent only first-cut approximation to the actual situation.

The cylindrical conduction models to be presented are: (1) an infinite length cylinder in an infinite medium, (2) an infinite length cylinder in a finite medium, (3) a finite length cylinder in an infinite medium, and (4) a finite length vertical axis cylinder located some distance below an isothermal plane surface.

The first expression will be useful for short times but is has no equilibrium (infinite time) solution. The other three cases have only equilibrium solutions. The fourth solution is most applicable to the question of seabed disposal.

Assuming constant properties and a constant heat flux at radius R, the solution for an infinite length cylinder in an infinite medium is given in Reference 12:

$$T_s - T_o = \frac{-2q}{\pi k} \int_0^{\infty} (1 - e^{-\alpha x^2 t}) \left\{ \frac{J_o(xr) Y_o(xR) - Y_o(xr) J_o(xR)}{x^2 [J_1^2(xR) + Y_1^2(xR)]} \right\} dx \quad (1)$$

The solution for small values of $\xi = \frac{\alpha t}{R^2}$ evaluated at $r = R$ is,

$$T_s - T_o = \frac{Rq}{k} \left\{ 2\xi^{\frac{1}{2}} \left[\text{ierfc}(0) - \xi^{\frac{1}{2}} i^2 \text{erfc}(0) + \dots \right] \right\} \quad (2)$$

Inserting the tabulated values of the complimentary error function integrals evaluated at zero yields,

$$T_s - T_o = \frac{Rq}{k} \left\{ 2\xi^{\frac{1}{2}} \left[.5642 - \xi^{\frac{1}{2}} (.25) + \dots \right] \right\} \quad (3)$$

Likewise for large values of ξ ,

$$T_s - T_o = \frac{Rq}{k} \left\{ \frac{1}{2} \ln\left(\frac{4\xi}{C}\right) + \frac{1}{4\xi} \ln\left(\frac{4\xi}{C}\right) + \dots \right\} \quad (4)$$

where,

$$C = e^\gamma = 1.7811 \dots$$

and γ is Euler's constant, 0.57722 ...

This expression for long times will be referred to later because it is the same result one obtains when considering an infinite length line source emitting $(k/\alpha)Q$ units of heat per unit time per unit length. This result is usually written,¹²

$$T_s - T_o = - \frac{Q}{4\pi\alpha} \text{Ei}\left(\frac{-r^2}{4\alpha t}\right) \quad (5)$$

where,

$$\text{E}_i(x) = \int_{-\infty}^x e^u \frac{du}{u} \quad (6)$$

is the exponential integral and,

$$-E_i(x) = \gamma + \ln(x) - x + \frac{x^2}{4} + \dots \quad (7)$$

For large values of the argument, this becomes,

$$T_s - T_o = \frac{Q}{4\pi\alpha} \left[\ln\left(\frac{4\alpha t}{R^2}\right) - \ln C \right] , \quad (8)$$

where $\ln C = \gamma$.

Substituting that,

$$\frac{k}{\alpha} Q = 2\pi R q , \quad (9)$$

results in

$$T_s - T_o = \frac{qR}{2k} \ln\left(\frac{4\alpha t}{CR^2}\right) , \quad (10)$$

which is the same as Equation (4) for at least the first term.

Note that the equilibrium or infinite time solution for the cylinder increases without bound and thus there is a point beyond which the expression fails to describe an actual physical case.

The methods of potential theory and the technique of images can be used to deduce an equilibrium solution for an infinite length cylinder located a distance below a surface parallel to its axis. This is given in Reference 13.

$$T_s - T_o = \frac{qR}{k} \ln\left[h + \sqrt{h^2 - 1}\right] , \quad (11)$$

where $h = H/R$ which for $H \gg R$ becomes,

$$T_s - T_o \approx \frac{qR}{k} \ln(2h) \quad . \quad (12)$$

This result is clearly finite indicating that the presence of a surface has a stabilizing effect upon the cylinder surface temperature.

The third case to be considered in this section is that of a finite cylinder in an infinite medium. Reference 14 presents the solution for this case,

$$T_s - T_o = \frac{qR}{k} \ln(\ell + \sqrt{\ell^2 + 1}) \quad , \quad (13)$$

where $\ell = L/D$, the ratio of length to diameter of the cylinder. Again, this solution will be finite indicating that limiting the length of the cylinder also stabilizes its surface temperature.

The final case to be considered is a vertical axis cylinder of length L and diameter D located a distance H below a horizontal isothermal plane surface. Details of the analytical procedure are presented in the appendix. In essence, the analysis follows the procedure outlined in Reference 15 for zero burial depth, and in fact, corrects some errors in the reference. The temperature of the cylinder predicted by this model is,

$$\frac{T}{Q'/2\pi k} = \ln(\ell + \sqrt{\ell^2 - 1}) + \frac{1}{2} \ln \left[\frac{2h + 3n - r_3}{2h + n - r_4} \right] \quad , \quad (14)$$

where the notation is the same as that of the previous models, except,

$$\ell = H/b \quad , \quad (15)$$

$$n = \sqrt{\ell^2 - 1} \quad , \quad (16)$$

$$r_3 = \sqrt{1 + (2h + 3n)^2} \quad , \quad (17)$$

$$r_4 = \sqrt{1 + (2h + n)^2} \quad , \quad (18)$$

$$b = D \left(\frac{\ell + \frac{1}{2}}{\frac{2 + 2\ell \sin^{-1} \epsilon}{\epsilon}} \right)^{\frac{1}{2}} \quad , \quad (19)$$

and,

$$\epsilon = \frac{1}{\ell} \sqrt{\ell^2 - 1} \quad . \quad (20)$$

Some results of this expression are presented in Figure 1 for various ℓ and h . Note that as h tends to infinity, Equation (14) reduces to Equation (13) except for the sign beneath the square root. It is not clear why this discrepancy exists but its effect is vanishingly small as ℓ becomes large. The smallest ℓ considered in the present work is two.

The experimental results to be presented in a later section of this report involve a spherical heater. For the case of pure conduction, it is possible to obtain a closed form analytical expression for the temperature profile throughout the conducting medium. For constant thermal properties and a constant heat flux at radius, R , the solution is given in Reference 12,

FIGURE 1. EFFECT OF BURIAL DEPTH AND ASPECT RATIO

$$T_s - T_o = \frac{Rq}{k} \left\{ \operatorname{erfc} \left(\frac{r-R}{2\sqrt{\alpha t}} \right) - e^{\left(\frac{r-R}{R} + \frac{\alpha t}{R^2} \right)} \operatorname{erfc} \left[\frac{r-R}{2\sqrt{\alpha t}} + \frac{\sqrt{\alpha t}}{R} \right] \right\} \quad (21)$$

which when evaluated at R becomes,

$$T_s - T_o = \frac{Rq}{k} \left(1 - e^{\xi} \operatorname{erfc} \sqrt{\xi} \right) \quad (22)$$

For large values of $\xi = \frac{\alpha t}{R^2}$, the solution approaches

$$T_s - T_o \rightarrow \frac{Rq}{k} \quad (23)$$

If, now a surface is considered in the medium and the sphere is located H below it, the expression is given in Reference 14,

$$T_s - T_o = \frac{Rq}{k} \left(1 - \frac{R}{4H} \right) \quad (24)$$

Note that the presence of the surface modifies the equilibrium temperature of the sphere by a small amount for $H \gg R$. In fact, if $H = 100 R$ for example, the results for the transient case of the sphere in the infinite medium will be within 1% of the actual case.

LABORATORY RESULTS

A spherical heater, 3.18 cm in diameter, was placed in a box of deep ocean sediments and its temperature-time history recorded. The dimensions of the plexiglass box are 30.5 cm x 30.5 cm x 35.6 cm deep and the sphere was placed 26.7 cm below the surface of the sediments. Initially, the heater flux was 0.62 w/cm^2 but it was later lowered

to be certain that the boiling temperature of the water was not reached. Figure 2 is the early portion of the temperature response curve. To help visualize the convective motion, a small gelatin capsule of waterproof ink was placed vertically above the sphere with the surfaces of the sphere and the capsule touching. This technique was used successfully in the saturated coarse sand experiments to be described later. The utility of introducing the dye this way is that no momentum component due to injection is present indicating that any transport is due to natural convection. Waterproof ink was used because the sediments had a remarkable ability to completely absorb the color of all the food dyes and other materials which were initially used. Thermocouples were placed at several locations within the mud but the main region of interest was at the surface of the sphere.

The experiment was run continuously for 72 hours. In the final equilibrium situation, the heater was set at about 8 watts (0.25 w/cm^2). The temperature rise of the sphere over that of the sediment layer adjacent to the box wall in the horizontal direction was 47.2 K. The so-called electrical analogy for heat transfer states that,

$$Q = \frac{\Delta T}{R_t} = qA_s, \quad (25)$$

where R_t is a thermal resistance. For the case of pure conduction, the resistance is,

$$R_t = \frac{L}{kA_s}, \quad (26)$$

Figure 2. Temperature Response of Sphere in Sediment

indicating that an experimental value of "thermal conductivity" could be deduced by measuring q , L and T . This apparent thermal conductivity is given by,

$$k_a = \frac{L}{R_t A_s} \quad , \quad (27)$$

but,

$$R_t A_s = \frac{\Delta T}{q} \quad ,$$

and therefore,

$$k_a = \frac{Lq}{\Delta T} \quad . \quad (28)$$

For this experiment, L is about 13.2 cm which yields a value of apparent thermal conductivity of about 0.073 W/cm-K.

In the vertical direction, the temperature difference was 65.5 K and the distance was 20.3 cm between the heater surface and the surface of the sediment. The apparent thermal conductivity in the vertical direction was thus about 0.078 W/cm-K. Note that the slight difference could be due to a multitude of things, e.g., the locations of the sensors, inaccuracies in reading the thermocouples or a slight amount of natural convection. The initial portion of the temperature-time curve appeared to be that of a heated sphere losing energy by conduction in an infinite medium. Because the heat flux was reduced during the experiment, this transient curve has no bearing upon the equilibrium temperature. In the next section of this report, a similar experiment in coarse sand will be described and there, the transient behavior will be of interest.

At the conclusion of the experiment, the region above the sphere was carefully examined to see if the dyes had been transported upward. There was no evidence of any measurable motion in the vertical direction although again the mud appeared to absorb most of the color of the indicator. It is clear that no appreciable channeling occurred and thus the convection was indeed low.

Finally, it should be mentioned that the "apparent thermal conductivity" determined above is only an approximation to the actual thermal conductivity of the sediments. The sample lost a large portion of its water during the duration of the test and thus behaved more like a moist clay. In spite of this, the early portion of the test during which the mud was saturated with water did not show evidence of a significant amount of natural convection. In fact, the reported value of thermal conductivity from Reference 16 for this type sediment is about 0.08 W/cm-K indicating that the situation is indeed conduction dominated.

A series of experiments were also conducted in sand to verify the analytical models of Reference 17. This section will present those cases in which the largest amount of natural convection was observed. The transient response was determined for the previously described 3.18 cm diameter sphere in a container of water saturated sand. The sphere was located about 25 cm below the surface of the sand and the container was about 30 cm in diameter in the horizontal direction. Also, plotted on Figure 3 is the predicted response curve for a sphere in a purely conducting medium of infinite extent. The values of thermal conductivity and thermal diffusivity used in the analysis were respectively 0.021 W/cm-K and $0.006 \text{ cm}^2/\text{s}$. Note that

Figure 3. Temperature Response of Sphere in Coarse Sand

except for the earliest experimental point, the agreement between predicted and observed response is excellent. The power level of the sphere was about 40 watts corresponding to a heat flux of about 1.26 W/cm^2 .

In the next section of this report, the results of an experiment carried out in the North Pacific will be presented and analyzed.¹⁸ In this reference, the point is made that the response of the implanted heater behaved as if it were in a purely conducting medium for all times except those near the start of the experiment. Note that in the present case, the same statement could be made. Reference 18 argues that the disagreement between experiment and analysis is due to the thermal lag of the system. In fact, it should be pointed out that presenting the data in the manner of Figures 5 and 6 and Reference 18 tends to over-emphasize the early time response. The only reason for doing it here is to compare with the reference.

The record seems to indicate that the situation is pure conduction although the existence of a fairly large amount of natural convection was demonstrated using the dye-filled gelatin capsule technique. It was experimentally observed and analytically predicted by both the boundary layer and the analytical solutions that a plume velocity of some 10-46 cm/hr exists at about 36 watts. The exact value of the velocity is unimportant. The important thing is that it was non-zero. If one asked the time required for a parcel of water to breach a 100 m column of this coarse sand, he would be astounded to learn that it was about one month even at these very low velocities. If nothing else, one important conclusion can be drawn from these experiments. That is: THE MERE EXISTENCE OF "CONDUCTION-LIKE"

BEHAVIOR DOES NOT GUARANTEE THAT CONVECTION IS ABSENT. Recall that it was stated above that the value of thermal conductivity was slightly higher than the literature value. This is analogous to the apparent thermal conductivity discussed earlier. It is also the argument used in attempting to correlate the data of Reference 18. Finally, experiments conducted in sand under different heating rates and permeability show both conductive dominant and convective dominant behavior depending on values of the experimental parameters.

To conclude this section, a pilot experiment described in Reference 18 was fielded by the Geology/Geophysics group at Lamont-Doherty to determine the point at which conduction heat transfer "gave way" to convection heat transfer in the sea floor sediment layer. A steel probe approximately 3.5 cm in diameter and 1.0 m long was constructed with a 300 watt internal heater. Two temperature sensors were bonded to the surface of the heater to furnish transient temperature-time data. Unfortunately, the exact location of the sensors is unknown but it was known that each is at least $\frac{1}{4}$ m from the end of the probe. Details of the experiment are presented in the reference--only the results will be summarized here.

The heater current and probe temperature for two separate runs of the device are presented in Reference 18. In the reference, the expression for an infinite line source previously mentioned is used to correlate the data. The long time expansion is used as it would be for thermal conductivity measurements with a needle probe.¹⁶ A better approximation to the physical case is provided by the infinite length (but non-zero radius) cylinder in the finite medium, namely,

$$\frac{T_s - T_o}{Rq/k} = (1.128\xi^{\frac{1}{2}} - .5\xi + \dots) \quad (29)$$

Note that $\xi = \frac{\alpha t}{R^2} = 1.0$ for times on the order of about,

$$\frac{R^2}{\alpha} = \frac{(1.75)^2}{.0022} = 1392 \text{ s} = 23.2 \text{ min} ,$$

(values of α taken from Reference 15).

For the particular values of power, surface area and thermal conductivity in the experiment, there results

$$\begin{aligned} A_s &= \pi DL = 1099 \text{ cm}^2 \\ Q &= 300 \text{ W} \\ q &= Q/A_s = .273 \text{ W/cm}^2 \\ k &= 0.008 \text{ W/cm-K} \\ \alpha &= 0.0022 \text{ cm}^2/\text{s} . \end{aligned}$$

Thus, for the first two terms,

$$T_s - T_o = 1.81t^{\frac{1}{2}} - .02t + \dots ; \quad t \text{ in s.}$$

This expression will correlate the data up to about $\xi = 0.6$ or $t \approx 13.9$ minutes with very little error (Figure 4). Beyond $\xi > 2$ or $t > 46.4$ minutes, the long term relation can be used with little error. For the present L/D ratio of about 28.6, the equilibrium time is about 660 minutes beyond which the equilibrium expression holds. There will be a finite depth limit as well, but no information is given on the burial depth of the device. Presumably, the L/D effect dominates as mentioned earlier.

Figure 4. Temperature Response of Cylinder in Ocean Sediments, North-Central Pacific

An attempt was made to reproduce the theoretical predictions of Reference 18 using the equation given as,

$$T_s - T_o = \frac{\tilde{Q}}{4\pi k} \left[\ln\left(\frac{4\alpha t}{CR^2}\right) + \frac{R^2}{2\alpha t} + \frac{(\beta - 2)}{2\beta\alpha t} R^2 \ln\left(\frac{4\alpha t}{CR^2}\right) + \dots \right] \quad (30)$$

where β is the ratio of volumetric heat capacity of sediment to probe and the other variable notation has been changed to agree with the present paper. For $\beta \approx 2$ as mentioned in the reference, the last term disappears. Using the values of,

$$k = 0.008 \text{ W/cm-K}$$

$$\alpha = 0.0022 \text{ cm}^2/\text{s}$$

$$R = 1.75 \text{ cm}$$

$$C = 1.7811 = e^\gamma ,$$

and $\tilde{Q} = 300 \text{ W/100 cm} = 3 \text{ W/cm}$, the equation becomes,

$$T_s - T_o = 29.84 \left[\ln(.097t) + \frac{11.63}{t} \right] , \quad (31)$$

with t in minutes.

For $t = 2.5$ minutes, the value obtained from this expansion is 96.54 C. Referring to the original reference of this technique¹⁹ or its sequel,²⁰ Jaeger proposes the use of,

$$T(r,t) - T_o = \frac{\tilde{Q}}{4\pi k} E_i - \left(\frac{r^2}{4\alpha t}\right) , \quad (32)$$

where $T(r,t)$ is the temperature at a distance r from the line-source and E_i is the exponential integral function. Note that if $r = 0$ is inserted in the expression, the exponential integral of zero is

negative infinity indicating an infinite temperature at the probe surface. It is clear that Equation (32) is not the best one to use for short to intermediate times.

The question now to be addressed is: Given that the surface temperature of a heated object immersed in a liquid-saturated, porous medium follows a predicted conduction response, can one conclude that convection is not present? The answer as pointed out in the section on experiments in coarse sand is "no." This does not mean that conduction solutions are worthless, however, it simply means that the temperature field is "conduction-like" but no information on the coupled velocity field can be gained from the temperature results.

CONCLUSIONS

A model has been developed for the temperature field surrounding a buried vertical circular cylinder. The cylinder is located some distance below a horizontal, isothermal surface. The only thermophysical property used in the analysis, thermal conductivity is assumed constant. Results obtained from application of the model can be used to estimate cask surface temperature as well as the temperature field surrounding the cask. This latter information can be used as input to the ion transport studies in which the various sorption coefficients are temperature dependent.

In future thermal studies, the emphasis will be on determining instability mechanisms which could provide a pathway through the sediments. Possible candidates might be fluidization of the sediment particles at the sediment water interface or a "burp" induced by

heated buoyant fluid below the cooler surface. Unlike the present work and thermal studies which have preceeded it, this future work will be largely experimental. In fact, a series of experiments is planned to be carried out in situ. This will provide information not available from the laboratory scale tests.

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APPENDIX

In this section, an expression will be developed for the temperature field surrounding a finite length distributed line source located vertically below an isothermal surface. This approximates the burial of a heated vertical cylinder in a semi-infinite conducting medium (Figure A-1). As previously mentioned, this is essentially the situation which prevails in the placement of a waste cannister in the deepsea sediments. The line of reasoning taken in the analysis follows that developed in Reference 15 (for zero burial depth), except that an error in the reference will be corrected.

Consider a line of steady point heat sources located along the negative y axis from $y = -H$ to $y = -H - N$ as shown in Figure A-2. In order to ensure that the surface $y = 0$ remains at T_0 , the initial temperature of the entire system, an identical row of negative steady point heat sources (heat sinks) is located from $y = H$ to $y = H + N$. The mathematical solution of the temperature field surrounding the source can be changed to that of the sink by reflecting it about the $y = 0$ plane and changing the sign. Because the resulting "negative" temperature field is with respect to the initial uniform temperature, no philosophical problems should arise. Incidentally, it will be shown later that the isotherms in the lower half space are approximately ellipsoids of revolution. The analysis requires the specification of only a single medium property, thermal conductivity and it will be assumed to be constant.

FIGURE A-1. SEABED EMPLACEMENT.

FIGURE A-2. ANALYTICAL MODEL.

The temperature rise in a medium initially at zero temperature due to the presence of a point heat source located at the origin is,

$$T = \frac{Q}{4\pi kr} \quad , \quad (A-1)$$

where $r = \sqrt{\rho^2 + y^2}$ in units of, say m, Q is the strength of the source in watts (W) and k is the medium thermal conductivity in W/m-K.

This expression is now summed over a series of points located along the vertical axis. In the limit, the temperature increase due to the line source occurs as an integral. In terms of the coordinate system of Figure A-2, this becomes,

$$T_1 = - \int_{-H-N}^{-H} \frac{Q'}{4\pi kr} ds \quad , \quad (A-2)$$

where Q' is the strength per unit length and ds is an infinitesimal length of the line source. Note that the contribution of the finite line source at $r \rightarrow \infty$ is zero and thus $T_1 \rightarrow 0$ as desired. In Reference 15, a similar argument for the case of $H = 0$ was made except that the sign of the integral was taken as negative. If one integrates the integral with negative sign along an $r = r_c$ constant contour, it is obvious that,

$$T_1 = - \int_{-H-N}^{-H} \frac{Q'}{4\pi kr_c} ds = - \frac{Q'}{4\pi kr_c} \int_{-H-N}^{-H} ds$$

$$T_1 = \frac{-Q'}{4\pi kr} [-H - (H - N)] < 0$$

and, thus, the temperature rise will be negative for all positive source strengths. This is an obvious contradiction--the sign, therefore, must be positive.

It is now stipulated that a line of heat sinks will be located along the vertical axis for $y = H$ to $y = H + N$. Arguing as before, this results in a temperature "rise" at point r given by,

$$T_2 = - \int_H^{H+N} \frac{Q}{4\pi kr} ds \quad . \quad (A-3)$$

This temperature rise is, of course, negative because Q' corresponds to a line sink.

Now the net temperature rise at some arbitrary r will be given by the sum of the two integrals. From the figure,

$$r^2 = \rho^2 + (y - s)^2 \quad , \quad (A-4)$$

(since we are interested only in the $y < 0$ half space, the net temperature rise will be positive).

$$T = T_1 + T_2 = \int_{-H-N}^{-H} \frac{Q'}{4\pi kr} ds - \int_H^{H+N} \frac{Q'}{4\pi kr} ds \quad , \quad (A-5)$$

and thus,

$$T = \frac{Q'}{4\pi kr} \left\{ \int_{-H-N}^{-H} \frac{ds}{\sqrt{\rho^2 + (y - s)^2}} - \int_H^{H+N} \frac{ds}{\sqrt{\rho^2 + (y - s)^2}} \right\} \quad . \quad (A-6)$$

Substituting in the integrals

$$\begin{aligned} \xi &= y - s \quad , \\ d\xi &= -ds \quad , \end{aligned}$$

and noting that at

$$s = -H - N, \quad \xi = y + H + N$$

$$s = -H, \quad \xi = y + H$$

$$s = H, \quad \xi = y - H$$

$$s = H + N, \quad \xi = y - H - N$$

the expression becomes,

$$T = \frac{Q'}{4\pi k} \left\{ \int_{y+H+N}^{y+H} \frac{d\xi}{\sqrt{\rho^2 + \xi^2}} - \int_{y-H}^{y-H-N} \frac{d\xi}{\sqrt{\rho^2 + \xi^2}} \right\}. \quad (A-7)$$

This simplifies to,

$$T = \frac{Q'}{4\pi k} \left\{ \int_{y+H}^{y+H+N} \frac{d\xi}{\sqrt{\rho^2 + \xi^2}} + \int_{y-H}^{y-H-N} \frac{d\xi}{\sqrt{\rho^2 + \xi^2}} \right\}. \quad (A-8)$$

Carrying out the integration results in,

$$T = \frac{Q'}{4\pi k} \left\{ \ln \left[\frac{y + H + N + \sqrt{\rho^2 + (y + H + N)^2}}{y + H + \sqrt{\rho^2 + (y + H)^2}} \right] + \ln \left[\frac{y - H - N + \sqrt{\rho^2 + (y - H - N)^2}}{y - H + \sqrt{\rho^2 + (y - H)^2}} \right] \right\}. \quad (A-9)$$

Combining the natural log functions yields,

$$T = \frac{Q'}{4\pi k} \ln \left\{ \frac{\left[y + H + N + \sqrt{\rho^2 + (y + H + N)^2} \right]}{\left[y + H + \sqrt{\rho^2 + (y + H)^2} \right]} \times \frac{\left[y - H - N + \sqrt{\rho^2 + (y - H - N)^2} \right]}{\left[y - H + \sqrt{\rho^2 + (y - H)^2} \right]} \right\} \quad (A-10)$$

Letting the burial depth, H, become zero results in

$$T = \frac{Q'}{4\pi k} \ln \left\{ \frac{\left[y + N + \sqrt{\rho^2 + (y + N)^2} \right] \left[y - N + \sqrt{\rho^2 + (y - H - N)^2} \right]}{\left[y + \sqrt{\rho^2 + y^2} \right]^2} \right\} \quad (A-11)$$

In Reference 15, the expression is given as,

$$T = \frac{Q'}{4\pi k} \ln \left[\frac{y + N + r_1}{y - N + r_2} \right] \quad (A-12)$$

where,

$$r_1^2 = \rho^2 + (y - N)^2$$

$$r_2^2 = \rho^2 + (y + N)^2$$

If this incorrect expression is evaluated along $y = 0$ where $r_1 = r_2 = a$ (see Figure A-2), there results,

$$T = \frac{Q'}{4\pi k} \ln \left[\frac{a + N}{a - N} \right] \quad (A-13)$$

Obviously, this is constant for various a if and only if $N = 0$.

Therefore, the assumption of the $y = 0$ surface remaining isothermal is clearly violated and, in fact, Equation (A-12) must be wrong.

Referring to Equation (A-11) evaluated along $y = 0$,

$$T = \frac{Q'}{4\pi k} \ln \left\{ \frac{(N + \sqrt{\rho^2 + N^2})(-N + \sqrt{\rho^2 + N^2})}{\rho^2} \right\}, \quad (\text{A-14})$$

or,

$$T = \frac{Q'}{4\pi k} \ln \left\{ \frac{\rho^2 + N^2 - N^2}{\rho^2} \right\}, \quad (\text{A-15})$$

which finally yields,

$$T = \frac{Q'}{4\pi k} \ln(1) = 0. \quad (\text{A-16})$$

This is in line with the assumption of zero initial temperature and zero temperature along the $y = 0$ plane for all values of x and z .

Returning to Equation (A-10) for the general case, it is natural to inquire into the shape of the isotherms. For this exercise, it is more convenient to set Equation (A-9) equal to a constant,

$$T = \text{Const} = \frac{Q'}{4\pi k} \left\{ \ln \left[\frac{y + H + N + \sqrt{\rho^2 + (y + H + N)^2}}{y + H + \sqrt{\rho^2 + (y + H)^2}} \right] + \ln \left[\frac{y - H - N + \sqrt{\rho^2 + (y - H - N)^2}}{y - H + \sqrt{\rho^2 + (y - H)^2}} \right] \right\}. \quad (\text{A-17})$$

For finite N and large H , the isotherms near the line source are described approximately by,

$$\frac{y + H + N + \sqrt{\rho^2 + (y + H + N)^2}}{y + H + \sqrt{\rho^2 + (y + H)^2}} = c. \quad (\text{A-18})$$

If the substitution is made for y ,

$$\xi = y + H + M , \quad (A-19)$$

where,

$$m = \frac{n}{2} ,$$

then,

$$\frac{\xi + m + r_2}{\xi - m + r_1} = c . \quad (A-20)$$

The constant, c , is evaluated at $\xi = 0$, where $\rho = a$ constant, b .

For r_1 and r_2 , this yields,

$$r_1 = r_2 = \sqrt{m^2 + b^2} . \quad (A-21)$$

The constant m is arbitrarily set equal to $a^2 - b^2$, where a is another constant, so

$$r_1 = r_2 = a . \quad (A-22)$$

Solving for c in Equation (A-20) results in,

$$c = \frac{a + m}{a - m} . \quad (A-23)$$

For the general case, Equation (A-20) specifies,

$$(\xi + m + r_2)(a - m) = (\xi - m + r_1)(a + m) , \quad (A-24)$$

which simplifies to,

$$\frac{\rho^2}{a^2 - m^2} + \frac{\xi^2}{a^2} = 1 , \quad (A-25)$$

but $a^2 - m^2 = b^2$, so finally,

$$\frac{\rho^2}{b^2} + \frac{\xi^2}{a^2} = 1 \quad . \quad (A-26)$$

This is the equation of an ellipse of major axis $2a$ and minor axis $2b$ centered at the origin. In terms of physical coordinates,

$$\frac{\rho^2}{b^2} + \frac{(y + H + N/2)^2}{a^2} = 1 \quad , \quad (A-27)$$

which is the same size ellipse centered about the $\rho = 0$, $y = -H - N/2$ point. The same procedure applied to the second part of Equation (A-17) indicates that the negative isotherms about the line sink are ellipses centered about $y = H + N/2$. The resulting isotherms due to the presence of both the source and sink can, in general, be obtained from,

$$\left\{ \left[\frac{y + H + N + \sqrt{\rho^2 + (y + H + N)^2}}{y + H + \sqrt{\rho^2 + (y + H)^2}} \right] \right. \\ \left. \times \left[\frac{y - H - N + \sqrt{\rho^2 + (y - H - N)^2}}{y - H + \sqrt{\rho^2 + (y - H)^2}} \right] \right\} = c \quad . \quad (A-28)$$

Selected isotherms are plotted in Figure A-3 for the case $H/N = 2$.

If one of these isotherms is selected as the physical object, the conductive field can be solved explicitly. Rather than making an arbitrary choice, the surface areas of the ellipsoid and the physical cylinder will be matched. Before doing this, the temperature rise of the ellipsoid will be determined.

Since the temperature of the ellipsoid surface is constant, it can be evaluated at any value of (ρ, y) consistent with the ellipse equation. Equation (A-9) is thus evaluated at $\rho = b, y = -H - m$. As before, $m = N/2$.

$$T = \frac{Q'}{4\pi k} \left\{ \ln \left[\frac{m + \sqrt{b^2 + m^2}}{-m + \sqrt{b^2 + m^2}} \right] + \ln \left[\frac{-2H - 3m + \sqrt{b^2 + (2H + 3m)^2}}{\sqrt{b^2 + (2H + m)^2}} \right] \right\} \quad (A-30)$$

Rewriting this slightly,

$$\frac{T}{Q'/2\pi k} = \frac{1}{2} \left\{ \ln \left[\frac{a + m}{a - m} \right] + \ln \left[\frac{-2H - 3m + \sqrt{b^2 + (2H + 3m)^2}}{-2H - m + \sqrt{b^2 + (2H + m)^2}} \right] \right\} \quad (A-31)$$

The first term can be rewritten,

$$\frac{1}{2} \ln \left[\frac{a + m}{a - m} \right] = \ln \sqrt{\frac{a + m}{a - m}} \quad (A-32)$$

Multiplying the numerator and denominator of the log function argument of $\sqrt{a + m}$ results in,

$$\ln \sqrt{\frac{(a + m)^2}{a^2 - m^2}} = \ln \left(\frac{a + m}{b} \right) \quad (A-33)$$

which becomes,

$$\ln(\ell + \sqrt{\ell^2 - 1})$$

The final temperature expression is,

$$\frac{T}{Q'/2\pi k} = \ln(\ell + \sqrt{\ell^2 - 1}) + \frac{1}{2} \ln\left(\frac{2h + 3n - r_3}{2h + n - r_4}\right), \quad (\text{A-34})$$

where,

$$h = H/b$$

$$n = m/b = \sqrt{\ell^2 - 1}$$

$$r_3 = \sqrt{1 + (2h + 3n)^2}$$

$$r_4 = \sqrt{1 + (2h + n)^2}.$$

All the depth of burial dependence is in the second term so that as h tends to infinity only the first term remains. This agrees with Reference 14 (except for the negative sign) which considers a finite length cylinder in an infinite medium. All that remains is to determine the relationship between the isothermal ellipsoid and the actual buried cylinder.

Recall that the surface area of a right circular cylinder is given by,

$$A_c = \pi D \left(L + \frac{D}{2} \right), \quad (\text{A-35})$$

where L and D are the length and diameter, respectively. For a prolate spheroid (ellipsoid of revolution about the major axis), the surface area can be calculated from,

$$A_e = 2\pi b \left(b + \frac{a}{\epsilon} \sin^{-1} \epsilon \right), \quad (\text{A-36})$$

where $2a$ is the major axis, $2b$ is the minor axis and,

$$\epsilon = \sqrt{1 - \frac{b^2}{a^2}} < 1.0 \quad .$$

Equating the two results in,

$$2b^2 + \frac{2ab}{\epsilon} \sin^{-1} \epsilon = LD + \frac{D^2}{2} \quad . \quad (A-37)$$

The following substitutions are made,

$$\ell = L/D$$

$$\beta = b/d$$

$$\alpha = a/D \quad ,$$

resulting in,

$$2\beta^2 + 2\alpha\beta \left(\frac{\sin^{-1} \epsilon}{\epsilon} \right) = \ell + \frac{1}{2} \quad , \quad (A-38)$$

where now,

$$\epsilon = \frac{1}{\ell} \sqrt{\ell^2 - 1} \quad . \quad (A-39)$$

In addition to matching the surface areas, it is desirable for the two objects to keep the same proportion so it is specified that,

$$\frac{\alpha}{\beta} = \frac{a}{b} = \ell \quad .$$

Equation (A-35) can thus be solved for β ,

$$\beta = \left\{ \frac{\ell + \frac{1}{2}}{\frac{2 + 2\ell \sin^{-1} \epsilon}{\epsilon}} \right\}^{\frac{1}{2}} \quad , \quad (A-40)$$

and α is given by,

$$\alpha = \ell \beta \dots \quad (A-41)$$

In terms of physical dimensions of the ellipsoid,

$$a = L \left\{ \frac{\ell + \frac{1}{2}}{2 + 2\ell \sin^{-1} \epsilon} \right\}^{\frac{1}{2}}, \quad (A-42)$$

and,

$$b = D \left\{ \frac{\ell + \frac{1}{2}}{2 + 2\ell \sin^{-1} \epsilon} \right\}^{\frac{1}{2}}. \quad (A-43)$$

Note that the quantity in brackets is only a function of ℓ and is tabulated below:

ℓ	$\left\{ \frac{\ell + \frac{1}{2}}{2 + 2\ell \sin^{-1} \epsilon} \right\}^{\frac{1}{2}}$
2	.61
3	.60
4	.59
5	.59
10	.58
20	.57
50	.57
100	.57

Using a value of 1.2 L for the major axis and 1.2 D for the minor axis, lengths of the ellipsoid should be sufficiently accurate for this model. This, then, is the correspondence between the model and the actual physical situation. Limits of applicability of the model are unknown at present, however, so care should be taken to avoid high heat flux to length values.

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