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DEPARTMENT OF ENERGY AND ENVIRONMENT

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ABSTRACT

A research program at Brookhaven National Laboratory (BNL) studies ground coupling, the use of the earth as a heat source/sink or storage element for solar heat pump space conditioning systems. This paper outlines the analytical and experimental research to date toward the development of an experimentally validated model of ground coupling and based on experimental results from December, 1978 to September, 1979, explores sensitivity of present model predictions to variations in thermal conductivity and other factors. Ways in which the model can be further refined are discussed.

1. INTRODUCTION

A research program at BNL studies ground coupling, the use of the earth as a heat source/sink or storage element for solar heat pump space conditioning systems. The goal of this research program is to determine the feasibility of ground coupling and if feasibility is confirmed, to create a handbook which specifies optimal ground coupling devices for various climates, soil types and applications. A key step toward this goal is the development of an experimentally validated model of ground coupling which will facilitate the reliable design of optimal ground coupling devices on paper.

Recently, as part of this effort, the sensitivity of model predictions to variations in thermal conductivity has been studied. Some of these results are presented and discussed below.

2. THE SOLAR GROUND COUPLING RESEARCH PROGRAM AT BROOKHAVEN NATIONAL LABORATORY

2.1 Analytical Research

2.1.1 Literature Search

The solar ground coupling research program at BNL began with a search of the literature in technical areas including ground thermal behavior, ground coupling, and heat flow modeling. Some of the results of this search were discussed previously[1,2] and are not elaborated upon in this paper.

2.1.2 Heat Flow Modeling

Initially, analytical models were used to study both steady-state and time-dependent heat flow in simple geometries. Next, finite difference equation models were used to solve somewhat more realistic problems. Eventually a FORTRAN computer program called GROCS was written to solve complex three-dimensional underground heat flow problems. Some features of GROCS include the use of 20 (at present) finite elements or "free blocks" of earth whose temperatures are determined by finite difference heat flow equations and by heat inputs used to simulate the effect of a ground coupling device, and 10 "rigged blocks" which provide realistic far-field depth and time dependent temperature boundary conditions. The major approximations used by GROCS at present are:

(1) Twenty finite size free blocks of earth,
(2) A finite time step interval,
(3) One constant thermal conductivity (k) for every block,
(4) One constant volume heat capacity (cρ) for each block,
(5) Horizontal boundary conditions a finite distance from the device modeled,
(6) Linearly interpolated boundary conditions,
(7) No consideration of variations in ground moisture content, of moisture flow, or of freezing,
(8) Weekly heat inputs (for the version which produced the results presented in this paper).

Copies of the program GROCS as well as an integraced GROCS-TRNSYS program[3] are available from the author at nominal cost.

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2.2 Experimental Research

One group of experiments is designed to measure underground thermal properties under normal conditions, and when perturbed by the influence of heat flows created by ground coupling devices. Based upon the soil property experiments completed to date, the average undisturbed thermal properties of the moist sandy soil at the solar ground coupling research facility at BNL are:

$$c\rho = 1.7\times10^{6}\ J/m^{3}\text{-}^{\circ}C\ (26.\ Btu/ft^{3}\text{-}^{\circ}F)$$

$$\alpha = 1.6\times10^{-6} m^{2}/sec\ (0.062\ ft^{2}/hr)$$

where $c\rho$ is volume heat capacity, $\alpha = k/c\rho$ is diffusivity and k is conductivity.

The major experimental effort is the operation since December, 1978 of nine heat flow experiments. Four of these are buried water tanks, and five are fields of buried serpentine plastic pipe in various configurations and lengths from 100 to 300 meters (300 feet to 900 feet). Three contain an antifreeze solution, and two contain pure water. Depths range from 0.6 to 4 meters (2 feet to 12 feet). Heat is added to or withdrawn from each experiment as dictated by an integrated GROCS-TRNSYS computer program which simulates a residential heating load, solar heat pump space conditioning system, and ground coupling device. Each experiment is operated according to a different scenario in order to evaluate the value of various strategies for operating ground coupling devices. Heat flows and fluid and earth temperatures are measured. The design, construction, and operation of these experiments has been described in detail in an earlier work[4].

3. MODEL VALIDATION

3.1 Validation Approach

Model validation is accomplished as follows: A physical model of each experiment suitable for GROCS is created. This, together with weekly experimental heat addition/withdrawal data for the experiment provide the input for GROCS along with values of k and cρ deduced from the underground thermal property experiments. The GROCS output is the underground temperature of each free block at selected regular time intervals. These temperatures, particularly those of blocks which represent a ground coupling device, are compared to those experimentally observed, and the goodness of the fit of the GROCS predictions to the experimental results indicates the validity of the model. This procedure has been carried out on some of the experimental results for the period December 3, 1978 to September 15, 1979[5]. Sensitivity of the GROCS model predictions to variations in thermal conductivity and other factors are now explored for 3 of the 9 experiments. Then, ways in which the model can be further improved are discussed.

3.2 Sensitivity of GROCS Temperature Predictions to Variations in Soil-Thermal Conductivity

3.2.1 Tank Experiments

Tanks C and E are buried vertical axis cylinders made from precast concrete rings and are each 2.4 m (8 ft) high, 2.4 m (8 ft) outer diameter and 2.2 m (7 ft 4 in) inner diameter placed with their bases 3.7 m (12 ft) deep. Since they are identical in design, both tanks use the same GROCS physical model.

Figures 1 and 2 contain the computer vs experimental results for Tanks C and E respectively. The experimental weekly heat withdrawal or addition data, used as imput for GROCS, is shown as a histogram using the right hand scale in each figure. The resultant computer generated midweek tank temperatures are shown for the ground thermal conductivity values indicated and compared to tank temperatures from experimental runs selected for typicality and nearness to midweek, all using the left hand scale in each figure.

There are two important approximations which affect the computer results. First, the computer program evenly divides the weekly heat inputs into hourly pieces while the experiments were actually operated a small fraction of the time at high heat flow rates. Second, the far-field underground temperatures used as boundary conditions in GROCS are historical, i.e. based on experimental data averaged over a number of years. As discussed previously[5], the presumed effect of using the historical data for computer modeling, as in this paper, is to lower the computer predicted temperatures for the summer of 1979 by a few degrees, without altering the winter of 1978-9 results significantly.

Figures 1 and 2 show that for the winter of 1978-9, the computer generated temperatures for all 3 values of k shown are very close to each other and to the experimental tank temperatures for both tanks. It is interesting to note that the Tank C winter computer results are slightly higher than experiment while the Tank E winter computer results are about equal to or slightly lower than experiment (depending on k) in view of the fact that both tanks use the same computer model. Note also that the lowest thermal conductivity simulated usually yields the highest winter tank temperature predictions for both tanks (this was further verified with computer runs using k=0.69 J/m-sec-°C (0.4 Btu/ft-hr°-F) not shown). This means that given the winter of 1978-9 weekly heat withdrawal data, the computer tank temperatures are more heavily influenced by the heat losses to the surface of

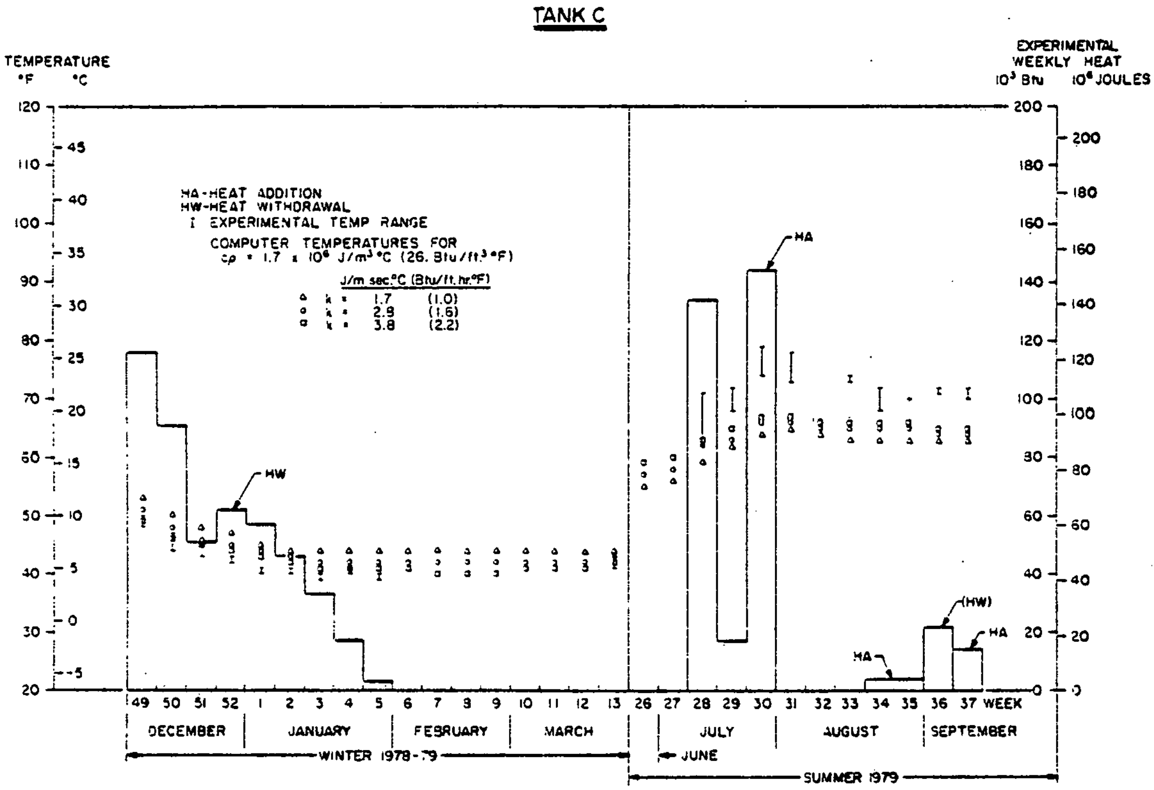

Fig. 1.

the earth than by the heat experimentally extracted from the ground by the tank. That is, winter tank temperatures should increase (as observed) with decreasing k if ground surface heat losses dominate, but should fall with decreasing k if experimental heat extraction dominates. Further, although the range of conductivities shown is large, the resultant variations in tank temperature are small so that this is a small effect.

As can be seen from the heat addition histograms in Figures 1 and 2, Tanks C and E were operated differently during the summer of 1979 with Tank C usually idle while Tank E received large heat additions to simulate solar energy collection. The Tank C summer computer temperatures are very weakly dependent on k (this holds even for k=0.69 J/m-sec°C) and average about 4°C below the center of the 1979 experimental range. The Tank E computer temperature predictions vary quite strongly with conductivity with the best fit provided by k=2.8 J/m-sec°C (1.6 Btu/ft-hr°F) yielding temperatures averaging less than 3°C below the center of the experimental and the next best fit provided by k=1.7 J/m-sec°C (1.0 Btu/ft-hr°F) which yielded results about 4°C high.

Several conclusions can be drawn from these summer results:

1. For Tank C the computer summer temperatures are systematically low for all values of k while for Tank E they are low for the two higher k values shown. Correcting the error caused by using historical far-field data should raise all summer temperatures a few degrees, at least partially closing this gap.
2. Of the three values shown, k=2.8 J/m-sec °C (1.6 Btu/ft-hr°F) obtained from unperturbed soil property experiments, as discussed in section 2.2, provides the best single fit to the data.
3. The dissimilar operation of these two identical tanks provided a sensitive measure of the optimal thermal conductivity by removing other variables from consideration. This is evident by noting that for Tank C the summer computer temperatures increase with conductivity while for Tank E, they decrease. This can be understood by extension of the argument used above for the winter results and means that the systematically low summer computer temperatures cannot be explained solely by a lowered conductivity in the summer (such as via soil drying) because lowering k can improve one fit, but only at the expense of the other.

3.2.2 Field Experiment

Field C contains 162 m (530 ft) of nominal size 1-1/2" polyethylene pipe in a serpentine

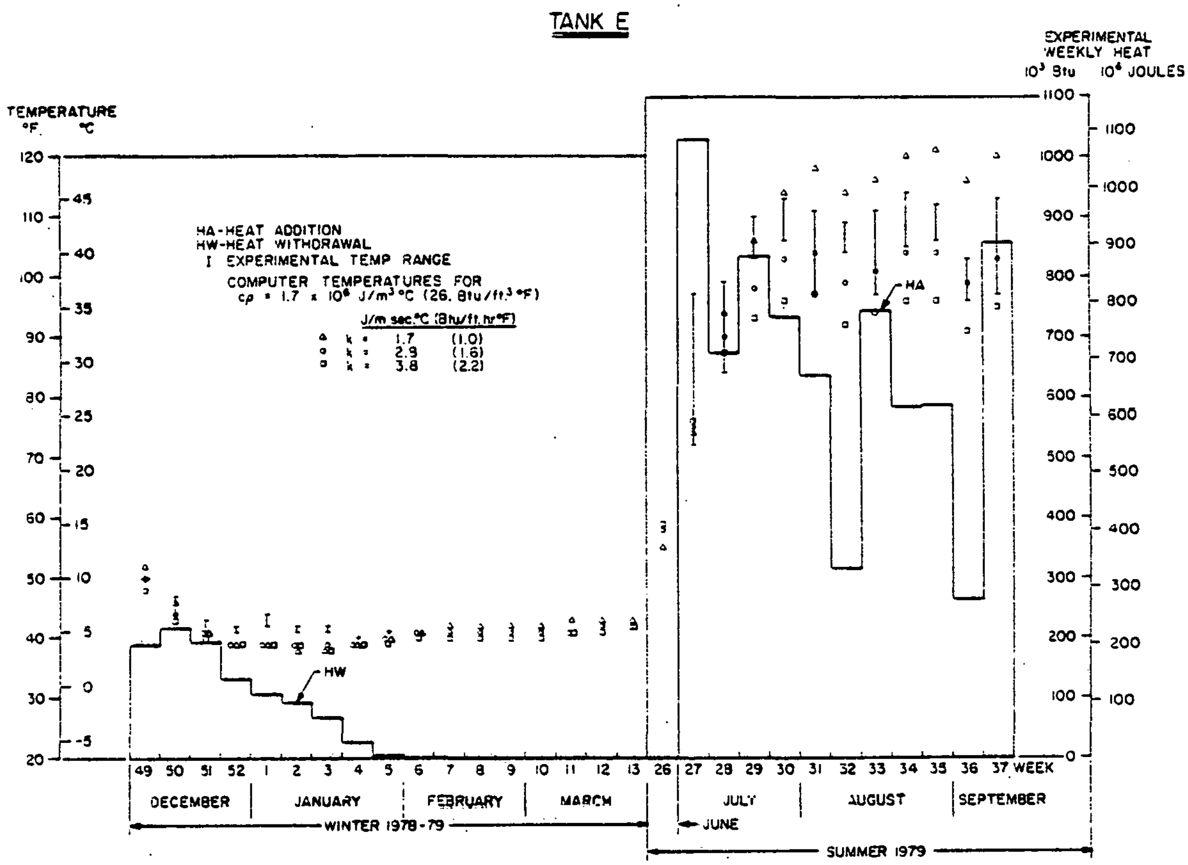

Fig. 2.

array 1.2 m (4 ft) deep with 0.9 m (3 ft) spacing between pipes in a rectangular area roughly 12 m (40 ft) x 10 m (32 ft).

Modeling the near-pipe behavior of serpentine pipe fields solely by finite element methods would require a great increase in the number of blocks used in GROCS and a reduction of the iteration time step. To avoid this, the method used to generate the results shown in Figure 3 uses GROCS to compute the temperatures of the block containing the pipe field. Then a hand calculation based on an effective local thermal resistance method which assumes that the near-pipe heat flow is approximately steady state is used to obtain the average field fluid temperatures.

Field C was operated using pure water from December 3, 1978 until February 16, 1979 when an antifreeze solution was added. As can be seen from Figure 3, the computer generated winter temperatures are very close together and very close to the experimental results with the lowest conductivity usually yielding the highest temperature (indicative of low heat extraction as above) through week 7 of 1979. Then, starting with week 8, as the antifreeze permitted operation below 0°C, the computer temperatures are spread out with temperatures now increasing with k (indicative of high heat extraction) while the temperatures predicted by the lowest k value drift downwards from the experimental results. The unperturbed conductivity value of 2.8 J/m-sec °C (1.6 Btu/ft-hr°F) provides a good fit to all of the winter data. (Note: During periods of high heat withdrawal such as weeks 8, 9, 10 and 13, the average experimental fluid temperature was usually near the bottom of the experimental range shown).

The summer results shown in Figure 3 indicate that conductivities of 2.8 and 1.7 J/m-sec°C (1.6 and 1.0 Btu/ft-hr°F) yield temperatures averaging about 8 and 3°C respectively below the center of the experimental range. The former error is too large to be erased solely by the far-field correction so that it appears that, in contrast to the situation observed for Tanks C and E, a conductivity significantly lower than the unperturbed value provides a better fit to these field results. It is plausible that soil drying caused by the high near-pipe heat flux, has reduced the actual k near the pipes.

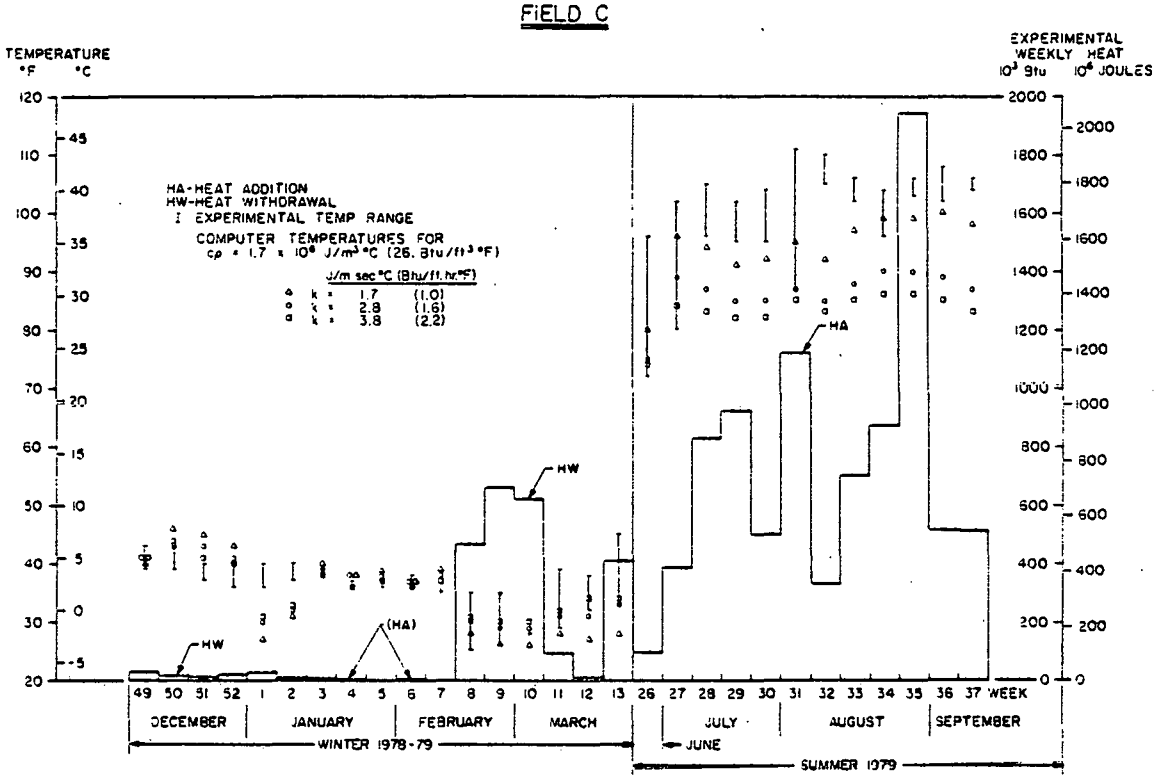

Fig. 3.

4. DISCUSSION AND CONCLUSION

Results have been presented exploring the sensitivity of the temperature predictions of a ground coupling model to variations in thermal conductivity for two buried tanks and one serpentine pipe field. A thermal conductivity derived from unperturbed soil property experiments, k=2.8 J/m-sec°C (1.6 Btu/ft-hr°F) fits all the data well except for the summer field data which requires a significantly lower conductivity. A hand calculation procedure for pipe fields which permits the use of a simple computer model appears to have considerable experimental validity.

In order to further validate the model more careful fitting of computer predictions to experimental results is required using actual far-field boundary conditions. Experimental in situ correlations of k and moisture content are needed. A computer model for pipe fields not requiring hand calculations is desirable (and one is incorporated in the GROCS-TRNSYS program[3]).

5. ACKNOWLEDGEMENT

I thank Mark Catan who performed some of the computer programming and analytical calculations required for this paper.

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