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COMPUTER THERMAL MODELING FOR
THE SALT BLOCK II EXPERIMENT

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Sandia National Laboratories

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COMPUTER THERMAL MODELING FOR THE SALT BLOCK II EXPERIMENT*

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The Salt Block II experiment consisted of a cylindrical block of bedded salt which was heated from within by a cylindrical electric heater. It was an extensively instrumented laboratory experiment that served, among other things, as a touchstone against which to measure the validity of a computer thermal model. The thermal model consisted of 282 nodes joined by 572 conductors, and was constructed for use with the CINDA heat transfer code. Both transient and steady-state temperature distributions within the salt were computed for heater power levels of 200, 400, 600, 1000 and 1500 watts. Temperature versus time plots are presented for 23 locations throughout the Block over a 58-day period. Comparisons of the model results and experimental results are shown for both transient and steady-state conditions. The computed steady-state results were used to develop equations describing both the temperature and the temperature derivative as functions of radial location.

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INTRODUCTION

Burial of nuclear waste canisters in bedded salt has been under consideration for a number of years. It is known that such burial will create thermal gradients in the salt. There has been recent concern that these gradients might cause fluid to migrate toward the canisters, resulting in possible deleterious effects. Studies of the effects of temperature and temperature gradient on brine migration have been reported in References 1 and 2.

The purpose of the Salt Block II experiment was to measure both the quantity and rate of water transport through heated geologic salt in a controlled laboratory environment. A cylindrical electric heater was used as a heat source. Numerous thermocouples were emplaced in the salt block and conditions at the block's surfaces were carefully controlled. Since the experiment was well instrumented and controlled, it was appropriate that a computer thermal model be created to examine the validity of such a model and to provide detailed temperature mappings for use in post-test analyses. The results from the thermal model are currently being used to study thermal stress effects in the salt block.

THE EXPERIMENT

Figure 1 is an elevation sketch of the experimental set-up. The salt block was one-meter tall and one-meter in diameter. An annulus of finely crushed reagent-grade salt separated the heater from the bedded salt. This crushed salt was continually irrigated with dry nitrogen to extract and measure the water which migrated toward the heater. Calculations showed that the amount of thermal energy extracted from the experiment by the irrigation was insignificant. Twenty-two thermocouples and nine heat-flux gages were located at points throughout the heater and salt block. Four of the thermocouples were inside the heater cylinder and are not shown on the sketch. Locations of the

remaining thermocouples, TC5-TC22 and the heat-flux gages, RT1-RT9 are shown.

The cylindrical steel shell which surrounded the salt block was kept at a fairly constant 18°C by circulating tap water through a series of tubular coils around the shell. The lower transite pedestal for the experiment rested on a concrete floor which had a constant temperature of 18°C. The remaining thermal boundary for the experiment was the steel lid which was exposed to the laboratory ambient air which was maintained at a temperature of approximately 22°C.

Five heater power levels were used: 200 watts, 400 watts, 600 watts, 1000 watts and 1500 watts. Changes from one power level to another were accomplished within less than 1/2-minute in all instances. The experiment took place over a period of 139 days.

A detailed description of the experiment and some of its preliminary results can be found in Reference 3. A description of post-test mineralogical examination of the salt block is given in Reference 4.

THE THERMAL MODEL

The Chrysler Improved Numerical Differencing Analyzer (CINDA) computer code⁵ was used to develop the thermal model. This model consisted of 282 nodes which were joined by 572 conductors. It was assumed that the thermal output from the heater was conducted through the crushed salt into the bedded salt and was also conducted vertically through a steel sleeve up to the steel lid. At the bottom of the experiment, heat was conducted from the bedded salt through the Teflon-transite-steel-transite layers into the concrete floor. Heat transfer at the curved outer surface of the salt was by both conduction and radiation to the constant-temperature steel shell (calculations of the Rayleigh number in this region showed that free convection was negligible). Heat loss at the top of the salt block was by conduction through the Teflon-transite layers, and by free convection and radiation from the transite plate upward to the steel lid. Heat flow from the lid was by both free convection and radiation to the surroundings and by conduction to the constant-temperature steel shell.

Ideally, the computer model would have been created independently of the experimental results. This was impractical for Salt Block II for the following reasons: (1) the value of the thermal conductivity of the salt (which was a function of temperature) was unknown, and (2) the electric heater provided a vertically non-uniform heat flux, with the degree of nonuniformity being an unknown function of the power input to the heater. Two differing sets of data for the bedded salt thermal conductivity (k) as a function of temperature (T) were provided to assist with the modeling. The k -values from these two sets differed by a factor of 2; however, the shapes of the k vs. T curves were similar. Thus, when varying values of k in an attempt to match the experimental results, the general shape of the conductivity/temperature curve was retained. It was assumed that the values of k for the crushed salt would be a constant fraction of those for the bedded salt. In dealing with the nonuniformity of the heater flux, the flux was apportioned along the heater length in order to achieve the best match with the experimental salt temperatures.

THERMAL MODEL RESULTS

As was mentioned in an earlier section, the experiment took place over a 139-day period. Power to the heater was first turned on at time $t = 6.47$ days. At $t = 49.54$ days, the highest power level, 1500 watts, was achieved. While the experiment continued for another 89.46 days, the thermal model was run only in the period of $t = 6.00 - 64.00$ days, with heater "shut-down" occurring at $t = 53.50$ days. Sufficient data for model/experiment comparison were obtained in this 58-day period. The experiment shut-down occurred in steps; these steps were not included in the model shut-down. The table below shows the nominal heater output as a function of day number.

TABLE I. Heater Output as a Function of Day for the Model

<u>Day Number</u>	<u>Heater Output (watts)</u>
6.00 - 6.47	0
6.47 - 13.46	200
13.46 - 20.49	400
20.49 - 35.47	600
35.47 - 42.48	1000
42.48 - 42.50	0 (electrical power failure)
42.50 - 49.54	1000
49.54 - 53.50	1500
53.50 - 64.00	0 (thermal model shut down)

For purposes of modeling, the electric heater was divided into five cylindrical nodes of equal volume. The thermal outputs from these nodes were varied to achieve the best fit of the experimental data. The table below shows the output (in watts) which was used for each node at each heater output level. It can be seen that considerable stratification occurred at all power levels.

TABLE II. Heater Flux Distribution

<u>Heater Output</u>	<u>200 Watts</u>	<u>400 Watts</u>	<u>600 Watts</u>	<u>1000 Watts</u>	<u>1500 Watts</u>
Upper Node	66	115	165	240	320
Second Node	54	95	160	260	365
Third Node	40	80	115	200	315
Fourth Node	30	75	100	180	305
Bottom Node	10	35	60	120	195

Figures 2a-2c show a typical comparison of experimental and computer results for thermocouples TC5-TC22 (the ordinate in Figure 2c is expanded five-fold over

Figures 2a and 2b for clarity). The experimental and computer results show good correlation for both transient and steady-state cases.

Table III shows a comparison of the experimental and computed steady-state temperatures of thermocouples TC11-TC18 (Boreholes A and B) for each of the five heater power levels. For each thermocouple, the measured temperature is shown first followed by a / and the computed temperature. While the comparison between the experimental and computed values is quite good, a few words concerning possible sources of error in both the experiment and the model seem appropriate: Thermocouples TC11-TC14 and TC15-TC18 (see Figure 1) were inserted through radial Boreholes A and B, respectively. While every attempt was made to locate the thermocouples as precisely as possible, the locations of their temperature-sensing junctions cannot be determined exactly. Figure 3 shows the thermal model mesh for the bedded salt. For purposes of computation, each node in the mesh was assumed to have a uniform temperature (i.e., at any given time the computed temperatures through the salt varied by discrete steps rather than smoothly).

Equations which functionally relate temperature (T) and radial location (r) along Boreholes A and B for the steady-state cases have been determined by use of the computed results. The relationships have been differentiated to also provide dT/dr as a function of r . These equations are shown in Table IV. T has units of $^{\circ}\text{C}$ and r has units of cm measured radially outward from the heater centerline. The equations are valid only in the bedded salt; i.e., for $6.7 \text{ cm} \leq r \leq 50.0 \text{ cm}$.

Figures 4a-4c are computer-generated plots showing the computed temperature/time histories at locations TC5-TC22 and HT5-HT9 over the 58-day period. There is a legend at the top of each graph showing which curve represents which location.

Table III. Comparison of Experimental and Computed Steady-State Temperatures

Thermo- couple # Heater Power (watts)		Temperatures in °C							
		11	12	13	14	15	16	17	18
200		35.2/36.8	30.5/30.6	26.8/27.5	23.9/23.9	28.1/27.4	26.2/25.8	24.5/24.5	22.4/22.5
400		53.1/55.6	43.2/43.1	35.5/36.8	29.5/29.5	39.3/38.9	35.1/34.6	31.2/31.7	27.2/27.1
600		70.8/75.2	54.5/55.4	42.0/45.9	32.2/35.0	48.7/49.5	42.0/42.8	35.6/38.4	29.1/31.5
1000		112.5/118.6	82.7/82.0	60.0/64.6	42.5/45.7	76.0/74.5	62.2/60.9	50.0/52.6	38.0/40.6
1500		175.0/181.2	123.5/117.1	84.0/88.8	53.0/58.4	110.0/109.4	87.0/85.4	67.0/71.1	48.0/51.5

Legend:

Experiment

Computed

Table IV. Equations for Boreholes A and B

$$6.7 \text{ cm} \leq r \leq 50.0 \text{ cm}$$

Borehole A

Heater Power (watts)

200	$T = 64.19 \text{ } r^{-0.25}$	$dT/dr = -16.05 \text{ } r^{-1.25}$
400	$T = 126.21 \text{ } r^{-0.37}$	$dT/dr = -46.70 \text{ } r^{-1.37}$
600	$T = 202.23 \text{ } r^{-0.45}$	$dT/dr = -91.00 \text{ } r^{-1.45}$
1000	$T = 416.43 \text{ } r^{-0.56}$	$dT/dr = -229.84 \text{ } r^{-1.56}$
1500	$T = 789.09 \text{ } r^{-0.66}$	$dT/dr = -520.80 \text{ } r^{-1.66}$

Borehole B

Heater Power (watts)

200	$T = 34.00 - 2.90 \ln r$	$dT/dr = -2.90/r$
400	$T = 54.20 - 6.85 \ln r$	$dT/dr = -6.85/r$
600	$T = 72.88 - 10.47 \ln r$	$dT/dr = -10.47/r$
1000	$T = 118.31 - 19.81 \ln r$	$dT/dr = -19.81/r$
1500	$T = 184.03 - 33.90 \ln r$	$dT/dr = -33.90/r$

Figure 5 presents the bedded salt conductivity/temperature curve which gave the best computational results. For the crushed salt, a k -value of 16% of that shown in Figure 5 resulted in a good fit of the data. These conductivities are appropriate for the bedded and crushed salts in the Salt Block II experiment. However, since the thermal conductivity of salt seems to be sample-dependent, it would be presumptuous to assume that these values are applicable to salt other than that used in this experiment.

CONCLUSIONS

The overall results of the thermal model compare quite well with the experimental data. It therefore appears that a model of this type can provide good predictive data to assist in the planning of future experiments if accurate material constants can be provided as input to the model.

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FIGURE 1. ELEVATION SKETCH OF THE EXPERIMENTAL SET-UP.

FIG. 2a. COMPARISON OF EXPERIMENTAL AND COMPUTER RESULTS.

FIG. 2b. COMPARISON OF EXPERIMENTAL AND COMPUTER RESULTS.

FIG 2c. COMPARISON OF EXPERIMENTAL AND COMPUTER RESULTS.

FIGURE 3. BEDDED SALT MESH FOR THE THERMAL MODEL.

Figure 4a. Thermal Model Results

Figure 4b. Thermal Model Results

Figure 4c. Thermal Model Results

FIGURE 5. BEDDED SALT THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE FOR SALT BLOCK 11.