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**Final Report
The Salt Block I Test:
Experimental Details and
Comparison with Theory**

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Sandia Laboratories

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FINAL REPORT
The Salt Block I Test: Experimental Details
and Comparison with Theory
Prepared for
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TABLE OF CONTENTS

<u>Topic</u>	<u>Page</u>
I. List of Symbols	iii
II. List of Figures	iv
III. List of Tables	vi
Abstract	viii
IV. Introduction	1
V. Preliminary Small Scale Experiments	3
A. Scaled Salt Block Heater Test	3
B. Salt Thermal Conductivity Measurements	3
VI. Salt Block Test I - Experimental Details and Results	8
A. Instrumentation Utilized	8
B. Power Increases	14
C. Raw Data of Salt Block Test I	16
D. Observations on Instrumentation Performance and Axisymmetry of Thermal Field	16
E. Corrosion Coupons	21
F. Water Losses from Salt Due to Heating	23
VII. Theoretical Finite Element Modeling	25
A. Field Equations and Treatment of Boundary Values	25
B. Convective Heat Transfer Coefficient	27
C. Radiative Heat Transfer Coefficient	28
D. Discretization and Numerical Solution of the Problem	28
VIII. Experimental-Theoretical Correlations	30
A. Finite Element Model Selected	30
B. Material Property Values Used as Code Input	31
C. Steady State Comparisons	36
D. Transient Comparisons	55
E. Discussion of Discrepancies	55
IX. Summary of Results and Conclusions	60
X. References	63
Appendix I. Water Loss Data from Salt Block I (Part 1)	65
Appendix II. Water Loss Data from Salt Block I (Part 2)	70

1. LIST OF SYMBOLS

C_p	Heat capacity
Gr	Grashof number, $g\beta L^3 \Delta T / \nu^2$
g	Gravitational constant
h	Combined heat transfer coefficient
h_c	Convective coefficient
h_r	Radiative coefficient
k	Conductivity
L	Significant length of convecting surface
Q	Volumetric heat source
q_c	Heat flux due to convection
q_η	Applied heat flux vector components normal to boundary
q_r	Heat flux due to radiation
R	Outside radius of salt block
r	Radial coordinate of cylinder
T_{amb}	Ambient air temperature
T_s	Surface temperature
t	Time
z_0	Height of salt block
z	Axial coordinate of cylinder
β	Coefficient of thermal expansion
Γ	Boundary of Ω
ΔT	$T_s - T_{amb}$
ϵ	Emissivity of radiating surface
μ	Viscosity
ν	Kinematic viscosity, μ/ρ
ρ	Density
σ	Stephan-Bolzmann Constant
Ω	Material region

II. LIST OF FIGURES

<u>Figure Number</u>	<u>Topic</u>	<u>Page</u>
1	Vertical Section of Scaled Heater Experiment.	4
2	Vertical Section of Large Block Heater Experiment Number 1.	5
3	Thermal Conductivity of Rocksalt from Mississippi Chemical Co. of S. E. New Mexico, Potash Mine.	7
4	Machining of Salt Block I into a Cylindrical Specimen	9
5	Cutting of Core Specimen (and Heater Hole) from Salt Block I.	10
6a.	Locations of Thermocouples in Salt Block I.	11
6b.	Instrument Orientation of Heater Experiment	12
7	Heater Can and Element Showing Thermocouple Locations.	13
8	Initial Transformer Circuit for Powering Resistive Heater.	15
9	Revised Power Circuit for Increased Output Power.	15
10	Salt Block I Dimensions Including Thermocouple Hole Specifications.	18
11	Finite Element Numerical Model of Salt Block I.	32
12	Steady State Temperature Profile Comparison: $Q = 1000 \text{ W.}$	40
13	Steady State Temperature Profile Comparison: $Q = 525 \text{ W.}$	43
14	Steady State Temperature Profile Comparison: $Q = 225 \text{ W.}$	47
15	Steady State Temperature Profile Comparison: $Q = 525 \text{ W.}$	49
16	Steady State Temperature Profile Comparison: $Q = 750 \text{ W.}$	52

II. LIST OF FIGURES
(Continued)

17	Steady State Temperature Profile Comparison: Q = 1280 W.	54
18	Experimental-Numerical Comparisons of Temperature as a Function of Time at Four Radially Spaced Thermo- couple Locations: Day 1.	56
19	Experimental-Numerical Comparisons of Temperature as a Function of Time at Four Radially Spaced Thermocouple Locations: Day 2.	57
20	Thermal Conductivity of a One Meter Cube of Rocksalt from Mississippi Chemical Co. of S. E. New Mexico Potash Mine - Latest Data.	59
21	Section of Salt Block I Showing Locations of Sample Removal.	66
22	Percent Weight Loss as a Function of Temperature from Previously Unheated Salt Block I Samples (Ref. 17)	69

III. LIST OF TABLES

<u>Table Number</u>	<u>Title</u>	<u>Page</u>
I	Relationship Between Instrumentation Channel and Thermocouple Number	17
II	Evaluation of Influence of Thermocouple Hole Filler Material	20
III	Relationship of Experimental and Numerical Identifiers for Selected Points in Salt Block I	33
IV	Salt Conductivity Data	34
V	Comparison of Measured and Computed Temperatures: Q = 1000 W, (Insulated)	39
VI	Comparison of Measured and Computed Temperatures: Q = 525 W, (Insulated)	42
VII	Comparison of Measured and Computed Temperatures: Q = 225 W, (Uninsulated)	45
VIII	Comparison of Measured and Computed Temperatures: Q = 525 W, (Uninsulated)	48
IX	Comparison of Measured and Computed Temperatures: Q = 750 W, (Uninsulated)	51
X	Comparison of Measured and Computed Temperatures: Q = 1,280 W, (Uninsulated)	53

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ABSTRACT

A series of laboratory experiments has been completed at Sandia Laboratories to provide an understanding of the steady state and transient thermal response of a large salt block containing an internal heat source. In this report, details of the experimental program are presented along with results of related efforts, such as thermal conductivity experiments, done in support of the heater experiments (Salt Block I). Finite element temperature field predictions, both transient and steady state, are performed utilizing the COYOTE nonlinear heat conduction program. Comparisons of experimental and theoretical results are generally quite good.

SECTION IV
INTRODUCTION

A series of laboratory experiments has been performed at Sandia Laboratories over the past 2 yr for the purpose of generating data and information relating to the storage of radioactive wastes in salt. The experiments were conducted as part of the experimental program for the Waste Isolation Pilot Plant (WIPP) and serve as a prelude to subsequent in-situ experiments in the WIPP. These experiments have either been performed directly on what is known as Salt Block I or have been performed in support of the Salt Block I experiments.

The specific objectives of this series of experiments were

- (1) To develop a method to simulate the heating due to an emplacement of high-level waste in salt.
- (2) To determine if the thermal conductivity of bedded salt is isotropic.
- (3) To evaluate methods for backfilling of instrumentation holes in the salt.
- (4) To evaluate corrosion in a heat field in salt.
- (5) To obtain experience in instrumenting bench scale samples of salt prior to performing an in-situ experiment.
- (6) To obtain some preliminary data on brine migration in salt.
- (7) To develop and provide analytical tools which can take account of heat loads emplaced in salt.

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Documentation of the various phases of the experimental programs, as well as the later theoretical correlations, has to date been accomplished in the form of a series of internal Sandia Laboratories correspondence (see References 1 through 7). It is the purpose of this report, therefore, to combine these into a single reference.

In the following section, a preliminary set of small-scale heater and thermal conductivity tests is described. These tests were performed prior to running the full-scale salt block experiments described in Section VI. Also presented in Section VI are results on corrosion and water loss in a field of heated salt. Next, the theoretical finite element modeling details for providing temperature profile predictions are described in Section VII, followed by representative experimental-theoretical correlations with Salt Block I experimental data. A summary of results and conclusions completes the body of the report. This summary indicates how the above objectives have been met.

SECTION V

PRELIMINARY SMALL-SCALE EXPERIMENTS

A. Scaled Salt Block Heater Test

Before the full-scale thermal test was performed, a scaled heater/salt block test was performed using a small core from the first salt block. The scaled test utilized a geometry similar to the large block. A vertical section of the scaled heater experiment is shown in Figure 1. For purposes of comparison, a similar vertical section of the Large Salt Block Heater Experiment No. 1 is shown in Figure 2. It can be seen that slight differences do exist, such as in relative dimensions of heater and salt block. However, it is obvious by inspection of the two experimental configurations that, in a scaled sense, transient and steady state thermal behavior should be at least qualitatively the same.

Two simplified scale model tests were performed. One scale model was heated gradually over a period of 4 days to a peak temperature of 325°C, while the other was rapidly heated to 360°C in 30 min. No difficulties (such as severe decrepitation of the salt) were encountered in either experiment during the test itself as well as after the test upon sectioning the models.

B. Salt Thermal Conductivity Measurements

In addition, before performing the full-scale heater experiment, thermal conductivity measurements were performed on a rock salt sample taken from the large salt block to be subsequently used for the full-scale thermal test. The sample was furnished by the Mississippi Chemical Company and was taken from their potash mine located in southeast New Mexico.

The particular sample taken for thermal conductivity measurements was sectioned from a core removed from the large salt block for placement of the cylindrical heater shown in Figure 2.

Figure 1. Vertical Section of Scaled Heater Experiment.

Figure 2. Vertical Section of Large Block Heater Experiment Number 1.

The thermal conductivity recorded as a function of temperature is shown in Figure 3.* As can be seen, values of thermal conductivity are in the vicinity of 3 W/m K. Fine cracks located at the ends of the core were removed when the sample was prepared. The thermal conductivity values through which the curve is drawn in Figure 3 were obtained during the heating phase. One data point (shown in Figure 3 with a different symbol) was taken during the cooling phase after the earlier readings were taken. The slightly (10%) lower value obtained at this later time may be due to water loss.

* However, see Section VIII, Subsection E for a discussion of more recently obtained bedded salt values.

Figure 3. Thermal Conductivity of Rocksalt from Mississippi Chemical Co. S.E. New Mexico, Potash Mine.

SECTION VI

SALT BLOCK TEST I - EXPERIMENTAL DETAILS AND RESULTS

The Large Salt Block Heater Experiment No. 1 was performed in a manner similar to the scaled heater experiment described in the previous section. Differences between the experimental configurations of full-scale (Figure 2) and small-scale (Figure 1) tests are worth mentioning at this point.

While both test setups include an asbestos insulator placed on top and bottom of the cylindrical sample, the large salt block also included heavy aluminum plates placed at the cylinder ends. These plates are held in place by large bolts running outside the sample and connecting the plates. Also, the large test is circumferentially confined by means of an outer steel cylinder.

The salt block at two stages of machining is as shown in Figures 4 and 5. Figure 4 shows the initial turning process used in forming the right circular cylindrical specimen while Figure 5 shows the removal of the core specimen, part of which was used for the thermal conductivity measurements reported in the previous section. The resulting axial hole in the salt block was subsequently used for heater placement followed by backfilling.

A. Instrumentation Utilized

The Salt Block I test was instrumented with a total of 51 thermocouples. The purpose of this large number of thermocouples was to define the thermal field created by the internal heater. In addition, four stress meters were utilized (rigid inclusion type).

Locations of 49 of the thermocouples are as shown in Figure 6a*, while placement of the stress meters is as shown in Figure 6b. Details of thermocouple locations within or on the heater

* Note that the last two thermocouples numbered 58 and 59 are located on the top aluminum plate at two radial locations and therefore are not shown in Figure 6a.

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Figure 5. Cutting of Core Specimen (and Heater Hole) from Salt Block I

1 METER DIA. X 1 METER HIGH

Figure 6a. Locations of Thermocouples in Salt Block I.

Figure 6a. Instrument Orientation of Master Experiment.

Not to Scale

Figure 7. Heater Can and Element Showing Thermocouple Locations

can are as shown in Figure 7. Note that the heater simply consists of a single resistive element surrounded by a cylindrical can.

B. Power Increases

Power to the resistive heater was initially supplied with the circuitry as shown in Figure 8.

Power to the salt block was initially set at a level of 25 W starting on January 11, 1977, and was increased 25 W three times a day, except on Friday and Monday. The use of small, incremental increases was done to minimize stressing of the block. Due to supply line voltage variation, some drop in power was experienced during morning hours and after weekends. On January 20, 1977, total power to the experiment exceeded 500 W, approaching the estimated limit of circuit power capacity using the circuit shown in Figure 8. The number of increases of power was reduced to once a day on January 25, 1977. By February 7, 1977, the limit of power available, 800 W, was reached, necessitating a change power circuit configuration.

The power circuit subsequently utilized is as shown in Figure 9. In this new circuit, the wattmeter was adjusted using the decade box shown to provide the same power reading at the same voltage level as was used in the circuit of Figure 8. The new configuration utilizes an uninterruptible power supply to increase voltage to the autotransformer and reduce power variations due to line voltage changes. The wattmeter's range was changed as shown in Figure 9 by using a voltage divider scheme to allow power output in excess of its 1,000-W limit.

Three power increases per day were reinstated on February 8, 1977, for 4 days a week until a maximum power output of 1,200 W was reached on February 18, 1977. No further changes were made in power output level until April 7, 1977. On this date, vermiculite insulation was placed about the top and bottom fixtures and power was reduced to 1,000 W. Power was maintained at this level until April 14, 1977, when it was further reduced to 900 W.

Figure 8. Initial Transformer Circuit for Powering Resistive Heater.

Figure 9. Revised Power Circuit for Increased Output Power.

On April 18, 1977, power was reduced to 525 W in approximately 100 W increments and the original transformer circuit (Figure 8) was reinstalled for comparison to the 525-W power level in the initial phase of the experiment.

The Salt Block I experiment was terminated on April 18, 1977, by dropping power in 100 W increments.

C. Raw Data of Salt Block Test I

For completeness, it should be noted that the thermocouple numbers are not the same as the channel numbers utilized in the original raw data. Corresponding thermocouple numbers and channel numbers are as indicated in Table I.

D. Observations on Instrument Performance and Axisymmetry of Thermal Field

1. Influence of Filler Material used in Thermocouple Installation Holes

As shown in Figure 10 (also compare thermocouple locations shown in Figure 8), thermocouple holes are drilled parallel to the longitudinal axis of the cylinder. One concern was that the material used to backfill these thermocouple holes following thermocouple placement could provide a significant variation in measured temperature reading. For this reason, one additional objective of the test was to compare two different materials--Sacerisen cement and fine salt--for use as filler materials in thermocouple installation holes.

The relative influence of these two materials was evaluated as follows:

Referring to Figure 10, thermocouple holes 4 and 5 are seen to be longitudinal holes located 5.12 in. from the center of the block. Each of these holes contained three thermocouples (27, 28, and 30 in hole 4, and 32, 33, and 35 in hole 5), and each hole was subsequently filled with Sacerisen cement.

TABLE I
**RELATIONSHIP BETWEEN INSTRUMENTATION CHANNEL
 AND THERMOCOUPLE NUMBER**

<u>Channel No.</u>	<u>Thermocouple No.</u>	<u>Channel No.</u>	<u>Thermocouple No.</u>
005	1	035	31
006	2	036	32
007	3	037	33
008	4	038	34
009	5	039	35
010	6	040	36
011	7	041	37
012	8	042	38
013	9	043	39
014	10	044	40
015	11	045	41
016	12	046	42
017	13	047	43
018	14	048	44
019	15	049	45
020	16	050	46
021	17	051	47
022	18	052	48
023	19	053	49
024	20	002	58
025	21	003	59
026	22		
027	23		
028	24		
029	25		
030	26		
031	27		
032	28		
033	29		
034	30		

Similarly, longitudinal holes 3 and 6, both located at the same radial distance of 9.12 in. from the center of the block, also contained three thermocouples each (thermocouples 22, 23, and 25 for hole 3 and thermocouples 37, 38, and 40 for hole 6). However, while hole 3 was again filled with Sauerbisen cement, hole 6 was filled with fine salt.

A representative sample of the temperature data recorded at the total of 12 thermocouples located in these 4 holes is shown in Table II at various days indicated in column 1. Note that the relative positions of the various thermocouples can be deduced from Figures 6 and 10. For simplicity, the first entry under each of the four holes corresponds to the thermocouple located near the top of the heater; the second entry corresponds to the thermocouple located near the center of the heater; and the third entry corresponds to the thermocouple located near the bottom of the heater.

Referring to Table II, a comparison of respective thermocouples in holes 4 and 5 (i.e., 27-32, 28-33, and 30-35) at various times gives a measure of thermocouple variation at the "same" axial and radial positions in the salt block* with the same thermocouple hole filler material. On the other hand, comparison of respective thermocouples in holes 3 and 6, also located at the "same" axial and radial positions in the salt block (though different from holes 4 and 5), gives a measure of variation introduced by varying the hole filler material.

As can be seen by inspection of Table II, the only significant (greater than 4°C) spread in readings occurred at the bottom of holes 4 and 5. Since both these thermocouple holes are filled with the same material (Sauerbisen cement), it is concluded that the material used to fill the thermocouple hole did not affect the readings.

* Any variation is, of course, due in part to variation of individual thermocouples, as the thermocouples utilized - standard Type E - were not individually calibrated. They are, however, accurate to $\pm 1.7^{\circ}\text{C}$ in the temperature range of this test.

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TABLE II
EVALUATION OF INFLUENCE OF THERMOCOUPLE HOLE FILLER MATERIAL

<u>Day</u>	<u>TC 27</u>	<u>Hole 4 TC 28</u>	<u>TC 30</u>	<u>TC 32</u>	<u>Hole 5 TC 33</u>	<u>TC 35</u>	<u>TC 22</u>	<u>Hole 3 TC 23</u>	<u>TC 25</u>	<u>TC 37</u>	<u>Hole 6 TC 38</u>	<u>TC 40</u>
1	18.5	18.2	17.9	18.5	18.3	18.0	18.4	18.2	17.9	18.8	18.5	18.2
5	35.9	39.1	34.9	36.3	39.3	35.7	32.4	33.7	31.6	32.8	34.0	31.9
10	51.6	61.4	51.9	52.1	61.6	54.2	43.4	47.7	43.1	43.8	48.0	48.6
15	68.2	70.8	59.5	58.5	71.2	62.4	48.5	54.0	48.5	48.0	54.7	49.1
20	82.8	77.9	64.9	63.0	78.0	68.2	51.8	58.4	52.3	52.2	58.7	52.9
25	98.2	85.7	71.3	68.1	85.6	75.0	58.0	63.6	56.9	58.0	63.4	57.4
30	79.5	102.9	84.5	79.0	102.9	89.0	64.1	74.2	65.7	64.0	74.1	68.4
35	89.1	118.1	95.6	88.1	118.3	101.0	70.9	83.4	73.0	70.7	83.3	74.0
40	108.8	140.2	112.3	102.1	140.0	119.0	82.1	97.3	84.8	81.3	96.5	85.5
45	101.7	138.0	110.4	100.2	138.0	117.3	80.5	95.6	83.5	79.6	95.0	84.3
48	97.8	133.6	108.3	96.5	134.0	113.4	76.9	91.9	79.8	78.5	91.7	80.9

Maximum ΔT (Hole 4 - Hole 5)

TC 27 - TC 32: 1.7°C

TC 28 - TC 33: 0.4°C

TC 30 - TC 35: 6.9°C

Maximum ΔT (Hole 3 - Hole 6)

TC 22 - TC 37: 0.7°C

TC 23 - TC 38: 0.6°C

TC 25 - TC 40: 1.1°C

This comparison also indicates the high degree of axisymmetry of the thermal field. This fact is important in later sections where correlations with an assumed axisymmetric theoretical model are made and suggests that thermal conductivity of bedded salt may be isotropic.

2. Comparison of the Corrosion of Stainless Steel and Inconel 600 Thermocouple Sheaths in the Heated Salt Block Environment

After the heater was shut off in the Salt Block I experiment, several stainless steel and Inconel 600 sheaths were examined. There was no obvious corrosion of either material.

3. Stressmeter Results

It was found that the initial "preload" of the stressmeters during this test could not be maintained. In particular, at 500 W input and 10 days into the test, all the stressmeters were for all practical purposes released due to thermal expansion of the salt. Use of this rigid inclusion-type stressmeter is therefore not recommended in future experiments of this type. Inclusion of the stressmeters did, however, provide temperature behavior of the instrumentation at zero stress levels.

E. Corrosion Coupons

The corrosivity of several metal coupons was tested during the Salt Block I experiment as part of the corrosion program for identifying suitable materials for use in WIPP environments. One important problem in the materials selection process is the definition of the environment, and, in particular, the migration of brine inclusions in heated salt.

Coupons were made from 12 candidate alloys, representing a wide range of available materials. Included were the following:

1. Titanium.
2. Titanium-6V-4Al.
3. Hastelloy C-276.

4. Inconel-600.
5. Zircalium.
6. Zircaloy-2.
7. Zircaloy-4.
8. Carpenter 20Cb-3 stainless steel.
9. 17-4 PH stainless steel.
10. 70-30 brass.
11. Aluminum 6061.
12. 1018 carbon steel.

Note that these alloys are listed in order of expected increasing corrosivity, according to a brine corrosion literature survey.

Each coupon was machined to be 2.54 cm per side by 0.64 cm thick. One surface of each coupon was mirror polished and photographed so that a subsequent qualitative visual determination of any corrosion could be made. Finally, each coupon was weighed to the nearest 0.1 mg.

As shown in Figure 6b, a 3.8-cm-(1.5 in.) diameter hole (sample hole nearest the heater in Figure 6b) was bored parallel to the heater holes and 7.5 cm from the outside edge of the heater itself. The hole bottom was located at the vertical midplane of the salt block. The coupons were placed flat in the hole with approximately 1.5 cm of crushed salt between each one to prevent any corrosion accelerating galvanic effects. Also the coupons were ordered such that the most reactive were on the bottom.

Coupons were placed in position on November 9, 1976 (recall that the heater experiment was begun on January 11, 1977, and terminated on April 18, 1977). The measured thermal history at the bottom of the coupon hole was as follows

<u>Day</u>	<u>°C</u>
0	25
19	61
20	78
30	103
40	138
60	137
80	138
90	130
Termination:	48

A steep thermal gradient existed going up the hole with the temperature at the top sample lagging the bottom by 30 to 50°C.

Laboratory examination of the coupons following the test revealed no corrosion of any sample. All coupons (as well as the plain carbon steel heater shell) appeared exactly as they did at the time of original placement, except for the 70-30 brass, 1018 steel, and one of the stainless steel coupons. Each of these three had a thin, nonadherent, unweighable oxide film on the oxide surface, indicating the presence of moisture.

F. Water Losses from Salt Due to Heating (Brine Migration)

Two different sets of measurements of water loss due to heating were made with material from Salt Block I. In both experimental programs, three types of samples were utilized: samples near the center (highest temperature field), samples near the wall (lowest temperature field), and samples which had no prior history of heating.

The first set of measurements, as described in Appendix I, was obtained by the heating of samples for three days at 250°C. The second set of measurements are described in Appendix II. In this case heating was at 500°C and was for a twelve day duration.

No attempt at interpretation other than what is made in Appendices I and II is given. The number of samples used was too small and other tests ideally should have been done.*

These Salt Block I results are included because, while limited, they will add to the expanding data base on brine migration. Presumably when coupled with other works, such as the analysis on Salt Block II, the data will help provide a systematic account of brine migration phenomena.

The results in Appendices I and II do, however, suggest that the impact of brine migration on storage of heat bearing wastes in salt may be small because in these studies, the differences in water content seen between samples in the maximum heat field (on the order of 200°C) and unheated samples are small. In other words, heating the salt in this configuration had only a small impact on the properties which were measured.

* Current efforts in this area are more concentrated on the analysis of the recently completed Salt Block II Experiment. Much more detailed analyses of that Salt Block Experiment, specifically designed to study brine migration, are being made.

SECTION VII THEORETICAL FINITE ELEMENT MODELING

Theoretical transient and steady-state temperature profile predictions for Salt Block I were performed by D. K. Gartling, 1261, utilizing the two-dimensional, nonlinear heat conduction program COYOTE.⁹ A brief discussion of the basic equations solved and assumptions utilized follows. The equations indicated here are specialized to this particular experiment. The equations that can be solved by COYOTE are considerably less restricted and the interested reader is referred to the User's Manual (Reference 9) for the more general anisotropic heat transfer equations that are within the capability of COYOTE. Note that only the theoretical aspects of the general field equations, boundary values, and numerical procedure are presented in this section. Specific input values of the various parameters such as thermal conductivities are discussed and presented in the following section, "Experimental-Theoretical Correlations."

A. Field Equations and Treatment of Boundary Values

The Salt Block I transient and steady state thermal response is taken as axisymmetric, the temperature field then being a function of the radial coordinate, r , and the axial coordinate, z , at a given time, t , i.e.,

$$\begin{aligned} T &= T(r, z; t) & 0 \leq r \leq R \\ & & 0 \leq z \leq z_0 \\ & & t \geq 0 \end{aligned} \quad (1)$$

where

T = temperature field,

R = outside radius of salt block

z_0 = height of salt block (and other modeled material at ends).

Within a given material region, Ω , the governing field equation describing the heat conduction process for this particular axisymmetric problem is given by

$$\frac{1}{r} \frac{\partial}{\partial r} \left(rk \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + Q = \rho C_p \frac{\partial T}{\partial t} \quad (2)$$

where ρ is material density, C_p is heat capacity, $k(T)$ is the conductivity, itself a function of the temperature field, and Q is the volumetric heat source. While the material within a given region of the salt block system is assumed isotropic, that is, thermal conductivity is direction independent, the thermal conductivity is still a function of the r, z coordinates due to temperature dependence. The heat source, Q , is a function of time in general.

Equation (2) simply states that the net rate of energy gain across the bounding surfaces of the material region by conduction, when added to the rate of energy generation within the region, just equals the time rate of change of energy stored in the mass of the region. The above equation is of the parabolic family when thermal transients are present and lies within the elliptic family in the steady state.

In either case, compatible¹⁰ boundary conditions are either Dirichlet, for which the value of the temperature itself is prescribed over a part of the boundary, Γ_T , of the enclosed region Ω , or Neumann, for which the normal derivative of the temperature--the heat flux--is specified over a part of the boundary, Γ_Q .

In the particular model developed for Salt Block I, only the latter type of boundary value was specified, since in the experiment no boundary was maintained at a specific temperature. The heat flux boundary condition can be expressed for this model as

$$q_r + k \frac{\partial T}{\partial r} + q_c + q_x = 0 \text{ on } \Gamma_q \quad (3)$$

where q_n is the component of the applied heat flux vector normal to the boundary Γ , q_c denotes the heat flux due to convection, q_r is the heat flux due to radiation, and n denotes the normal direction.

These convective and radiative heat fluxes are given by

$$q_c = h_c (T_s - T_{amb}) \quad (4)$$

$$q_r = h_r (T_s - T_{amb}), \quad (5)$$

where h_c and h_r are convective and radiative heat transfer coefficients and T_s and T_{amb} are surface temperature and ambient air temperature, respectively. h_c and h_r are determined as follows for the theoretical calculations performed on Salt Block I.

B. Convective Heat Transfer Coefficient

Consider the outside lateral surface of the salt block experiment. For a vertical cylinder with constant surface temperature, the convective heat transfer coefficients are given in Reference 11 as

$$h_v = 0.29 \frac{(T_s - T_{amb})^{1/4}}{L} \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F} \text{ for laminar flow} \quad (6)$$

(Gr = 10^4 to 10^9)

$$h_v = 0.19 [(T_s - T_{amb})]^{1/3} \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F} \text{ for turbulent flow} \quad (7)$$

(Gr = 10^9 to 10^{12})

where

T_{amb}	=	ambient air temperature
T_s	=	surface temperature
Gr	=	Grashof number, $\beta g L^3 \Delta T / \nu^2$
g	=	gravitational constant
β	=	coefficient of thermal expansion of air
ν	=	kinematic viscosity of air, μ/ρ
ΔT	=	$T_s - T_{amb}$

- L = significant length of convecting surface
 ρ = air density
 μ = viscosity of air.

Similarly for the laminar free convection from the horizontal surfaces in air, the following relationship is given in Reference 12:

$$h_h = C \frac{(T_s - T_{amb})^{1/4}}{L} \text{ Btu/hr ft}^2 \cdot T, \quad (8)$$

- where C = 0.27 for upward facing heated plates
 and C = 0.12 for downward facing heated plates.

Note that in some instances, this convection coefficient is set equal to zero in the experimental correlations, as discussed later. Note that specific calculations of convective coefficients used in actual correlations with experiments are presented in Section VIII.

C. Radiative Heat Transfer Coefficient

Consider again the outside surfaces of the salt block. The radiation coefficients for the various surfaces are obtained from^{9,13}

$$h_r = \epsilon \sigma (T_s^2 + T_{amb}^2) (T_s + T_{amb}), \quad (9)$$

- where ϵ = emissivity of the particular radiating surface
 and σ = Stephen-Boltzmann Constant.

Again, in some instances, radiation from top and bottom surfaces of the Salt Block I test is taken as zero. Specific values of emissivity used for finite element calculations are given in Section VIII.

D. Discretization and Numerical Solution of the Problem

As described in Reference 9, the COYOTE heat conduction program solves the above boundary value problem for the transient and steady

state temperature fields by use of spatial discretization using finite elements. The interested reader is referred to Reference 9, which contains the development of the discrete matrix finite element equations from the continuum field equations and boundary values.

For the transient thermal response, an implicit central difference method related to the standard Crank-Nicholson scheme is utilized to determine the spatial and temporal temperature field. For the steady state analysis, the COYOTE code utilizes a simple Picard iteration method.

SECTION VIII

EXPERIMENTAL-THEORETICAL CORRELATIONS

This section contains comparisons of Salt Block Test 1 recorded temperature profiles (see Section VI) with the theoretical finite element predictions of COYOTE (see previous section). First, the finite element model is shown, followed by the material property values used as input to the numerical scheme. Actual transient and steady state temperature profiles are then overlaid with numerical predictions. This section is concluded with a list of general observations as well as difficulties encountered in modeling of Salt Block I.

A. Finite Element Model Selected

Considerable difficulty was initially encountered in obtaining reasonable agreement between calculation and experiment for both transient as well as steady state profiles. As a result of an extensive set of parameter variations with the COYOTE program, as well as a number of energy balance calculations, deficiencies in both initial modeling attempts, as well as in the experimental setup, were isolated and corrected. For example, radiation losses from the vertical walls were initially ignored but were later, as a result of energy balance calculations, found to be significant. Radiation losses were subsequently included in the numerical calculations. In addition, natural convection losses from top and bottom surfaces were originally ignored, but subsequently found to be significant. The layers of asbestos used in the original experiment design were found inadequate to prevent significant heat loss. The experiment was modified at that time to simplify numerical modeling. In particular, the salt block was heavily insulated on both top and bottom by means of two vermiculite "skirts," effectively blocking the natural convection losses from those surfaces. Top and bottom surfaces could then be realistically modeled as adiabatic.

The final axisymmetric model developed is as shown in Figure 11. Note the presence of the six basic material regions modeled: aluminum plates (top and bottom), asbestos insulation, the heater, the salt, the crushed salt, and the air space.

It is anticipated that significant thermal gradients are present in the Salt Block I experiment. If meaningful correlations with numerical calculations are to be performed, it is essential that experimental recording points are in the same geometrical position as the locations where temperatures are numerically predicted. Since temperatures are predicted at node locations in the COYOTE code, the modeling was done such that nodal locations matched thermocouple locations.

Table III presents a representative list of thermocouples generally located along radial lines at various heights in the block. (These same thermocouples will be utilized repeatedly for correlations to be presented subsequently.) First (column 1), the general height in the salt block at which the radial array of thermocouples is found is indicated, followed by thermocouple number (see Figures 6, 7, and 10). The corresponding raw data channel number is next presented, followed by the cylindrical coordinates locating the point of interest (see Figure 11). Then the corresponding element and node number of the COYOTE numerical model is presented.* This table forms the basis of comparisons to follow.

B. Material Property Values Used as Code Input

1. Salt Conductivity

Salt conductivity values used for input to COYOTE are based upon direct measurements made on a core of Salt Block I as shown in Figure 3.** The data points shown in Table IV were utilized to curve fit the data.

*Both element and associated node number are needed. COYOTE does not utilize a global node numbering system.

**See also Reference 2.

It consists of nodes and elements. The maximum number of nodes is 1000 and the maximum number of elements is 10000. The mesh size is 10 mm.

Figure 11. Finite Element Numerical Model of Salt Block I

TABLE III
RELATIONSHIP OF EXPERIMENTAL AND NUMERICAL
IDENTIFIERS FOR SELECTED POINTS IN
SALT BLOCK I

<u>Location</u>	<u>Thermocouple No.</u>	<u>Channel No.</u>	<u>R-Coord</u>	<u>Z-Coord</u>	<u>Element No.</u>	<u>Node No.</u>
Midheight of Heater	4	008	5.08 cm	-55.56 cm	~ 147	1
	25	029	12.95	55.56	151	1
	20	034	23.11	55.56	153	1
	15	019	38.35	55.56	155	1
	10	014	49.98	55.56	196	2
Top of Heater	23	027	12.95	81.28	199	4
	18	022	23.11	81.28	201	4
	13	017	38.35	81.28	203	4
	9	013	49.98	81.28	204	3
Bottom of Heater	26	030	12.95	29.85	91	1
	21	025	23.11	29.85	93	1
	16	020	38.35	29.85	95	1
	11	015	49.98	29.85	96	2
Top Plate	58	002	23.11	111.43	273	4
	59	003	49.98	111.43	276	3

TABLE IV
SALT CONDUCTIVITY DATA*

<u>Temperature, K</u>	<u>Temperature, °C</u>	<u>k, W/m K</u>
350	77	3.15
400	127	2.90
450	177	2.70
500	227	2.52

* However, see Subsection E of this section for subsequently obtained conductivity values.

The data were fit to a polynomial of the form

$$k = a_1 + a_2 T + a_3 T^2 + a_4 T^3 \quad (10)$$

where

$$a_1 = 3.702 \text{ W/m K}$$

$$a_2 = -0.00887 \text{ W/m K}^2$$

$$a_3 = 0.252 \times 10^{-4} \text{ W/m K}^3$$

$$a_4 = -0.4 \times 10^{-7} \text{ W/m K}^4$$

The density and heat capacity of the salt are taken as

$$\rho = 135 \text{ lb/ft}^3 = 2.16 \text{ gm/cm}^3$$

$$C_p = 0.22 \text{ Btu/lb-°F} = 0.9209 \frac{\text{W-sec}}{\text{gm-°C}}$$

2. Heater

The heater is modeled as volumetric source. The conductivity and heat capacity are taken as those of the steel canister. The density is adjusted to give the appropriate energy capacity for the heater. In particular, density is calculated by dividing total weight of canister and heater element by total volume enclosed by the canister. The resulting thermal properties are as follows:

$$\rho = 3.19 \text{ gm/cm}^3$$

$$C_p = 0.11 \text{ Btu/lb}^\circ\text{F} = 0.4604 \frac{\text{W-sec}}{\text{gm}^\circ\text{C}}$$

$$k = 26 \text{ Btu/hr-ft-}^\circ\text{F} = 0.4499 \text{ W/cm}^\circ\text{C}$$

3. Airspace

The airspace above the heater is assumed to have the same properties as the heater:

$$\rho = 3.19 \text{ gm/cm}^3$$

$$C_p = 0.4604 \text{ W-sec/gm}^\circ\text{C}$$

$$k = 0.4499 \text{ W/cm}^\circ\text{C}$$

4. Crushed Salt

The space above the heater is backfilled with crushed salt. As demonstrated in Reference 14, Figure 1, considerable variation in thermal conductivity, for example, can be realized in crushed salt depending upon porosity among other things. Based upon Reference 15, the crushed salt properties were scaled as follows from the solid salt values presented above:

$$\rho = 72.5\% \rho_{\text{solid}} = 1.568 \text{ gm/cm}^3$$

$$C_p = C_{p_{solid}} = 0.9289 \frac{\text{W-sec}}{\text{gm-}^\circ\text{C}}$$

$$k = 7.18\% k_{solid}$$

5. Asbestos

The asbestos cloth insulation was assumed to have the following properties:

$$\rho = 36 \text{ lbm/ft}^3 = 0.576 \text{ gm/cm}^3$$

$$C_p = 0.25 \text{ Btu/lbm-}^\circ\text{F} = 2.9 \times 10^{-4} \frac{\text{W-hr}}{\text{gm-}^\circ\text{C}}$$

$$k = 0.09 \text{ Btu/hr-ft-}^\circ\text{F} = 1.55 \times 10^{-3} \text{ W/cm-}^\circ\text{C}$$

6. Aluminum

The top and bottom aluminum plates were assumed to have the following properties:

$$\rho = 1.69 \text{ lbm/ft}^3 = 2.71 \text{ gm/cm}^3$$

$$C_p = 0.208 \text{ Btu/lbm-}^\circ\text{F} = 2.35 \times 10^{-4} \frac{\text{W-hr}}{\text{gm-}^\circ\text{C}}$$

$$k = 118 \text{ Btu/hr-ft-}^\circ\text{F} = 2.042 \text{ W/cm-}^\circ\text{C}$$

C. Steady State Comparisons

1. Q = 1,000 W:

The first set of numerical-comparisons reported here correspond to a steady state heat input of $Q = 1,000 \text{ W}$ (day 87 and following).

First, it is necessary to calculate the convective and radiative coefficients. For that purpose, the ambient temperature* is assumed to be $T_{amb} = 15^{\circ}\text{C}$ (60°F). The measured surface temperature is $T_s = 55^{\circ}\text{C} = 131^{\circ}\text{F}$, resulting in a mean film temperature of $T_m = 95^{\circ}\text{F}$. Based upon a vertical surface length of $L = 3.28$ ft, $\Delta T = 71^{\circ}\text{F}$, and $\rho^2 g \beta / \mu^2 = 1.76 \times 10^8 / ^{\circ}\text{F} \cdot \text{ft}^3$ at a film temperature of 95°F , the Grashof number is

$$\text{Gr} = 4.4 \times 10^9$$

which is just over the turbulent limit. Since most of the surface will be subjected to laminar flow, the laminar correlation, Eq. (5), is used. The resulting convective coefficient is

$$h_c = 3.53 \text{ W/m}^2 \cdot ^{\circ}\text{C}$$

The radiative coefficient is determined from Eq. (7) using $\epsilon = 0.9$ (for painted surface at a temperature less than 200°F) and $\sigma = 0.1713 \times 10^{-8} \text{ Btu/hr} \cdot \text{ft}^2 \cdot ^{\circ}\text{R}^4$. The coefficient becomes

$$h_r = 6.026 \text{ W/m}^2 \cdot ^{\circ}\text{C}$$

The combined heat transfer coefficient is then $h = h_c + h_r = 9.565 \text{ W/m}^2 \cdot ^{\circ}\text{C}$.

As described in Section VI, on April 7 (day 87), 1977, vermiculite insulation was placed about the top and bottom of the salt block and fixtures and power was reduced to 1,000 W and held at this level until April 14. As mentioned earlier, the reason for modification of the experimental fixture was for simplification of the numerical model. Thus more than ample time was available for the temperature profile to reach steady state.**

* Unfortunately, no attempt was made to maintain constant room-temperature at any time during the test, resulting in a variable heat sink temperature.

**Steady state was normally reached overnight.

A direct comparison of measured and computed temperatures is presented in Table V. The first column gives the approximate vertical location of the particular thermocouple. The second column identifies the particular thermocouple (compare with Figures 6 and 7 for specific location). The next column is the recorded temperature while the fourth column indicates the computed temperature. In the last column, the percent error is indicated. With few exceptions, agreement is quite good considering the complexity of the model. The largest discrepancy generally was at the outside wall.

The steady state temperature profile is plotted in Figure 12 for two vertical levels in the salt block: at midheight of the heater and at the bottom of the heater. The solid and broken lines identify the computed profiles at the two locations, whereas the circular and square points denote experimental thermocouple data. The midheight radial profile is seen to lie within 10% of the measured data on the average.

TABLE V
COMPARISON OF MEASURED AND COMPUTED TEMPERATURES
Q = 1,000 W (INSULATED ENDS)

	<u>Thermocouple No.</u>	<u>Measured Temperature (°C)</u>	<u>Calculated Temperature (°C)</u>	<u>Percent Difference</u>
Midheight	4	234.9	248.1	4.7
	25	123.2	135.0	9.5
	20	88.4	92.8	4.9
	15	66.1	62.4	5.5
	10	56.4	48.9	13.2
Top of Heater	23	95.1	113.3	19.1
	18	78.4	84.1	7.1
	13	63.9	60.7	5.0
	9	56.4	48.4	14.1
Bottom of Heater	26	97.1	112.9	16.2
	21	77.0	81.7	6.1
	16	62.2	58.5	5.9
	11	53.8	46.6	13.3
Top Plate	58	60.1	-68.0	13.1
	59	56.4	-68.0	14.4

Figure 12. Steady State Temperature Profile Comparison: $Q = 1000$ watts.

2. Q = 525 W

An additional comparison of steady state temperature profiles both computed and recorded is made at the 525 W heater output level. This power was reached on April 18, 1977, following reduction of power from the 1,000 W level. The experimental configuration is identical to the 1,000 W case, i.e., vermiculite insulation was still in place on the ends of the cylinder.

Again, the ambient temperature is taken as 15°C. The surface temperature is of course lower, $T_s = 42.3^\circ\text{C}$. Based upon laminar flow, the convection coefficient (Eq. 6) is calculated as

$$h_c = 3.220 \text{ W/m}^2\text{-}^\circ\text{C}$$

The radiation coefficient is again found using Eq. (7) to be

$$h_r = 5.6482 \text{ W/m}^2\text{-}^\circ\text{C}$$

resulting in a combined heat transfer coefficient of

$$h = 8.868 \text{ W/m}^2\text{-}^\circ\text{C}$$

A comparison at this lower power level is shown in Table VI using the same format as Table V. Further, theoretical and experimental profiles are plotted in Figure 13 for this 525 W power level using the same format as Figure 12. Results were as good or better than the 1,000-watt comparison.*

* Based upon comparison of Figures 12 and 13. Note that percentage errors as calculated in Tables V and VI can be somewhat misleading, they were based upon 0°C rather than 0 K.

TABLE VI

**COMPARISON OF MEASURED AND COMPUTED TEMPERATURES
Q = 525 W (INSULATED ENDS)**

	<u>Thermocouple No.</u>	<u>Measured Temperature (°C)</u>	<u>Calculated Temperature (°C)</u>	<u>Percent Difference</u>
Midheight	4	133.1	131.3	1.3
	25	73.8	76.8	4.0
	20	87.9	88.2	2.9
	15	47.9	41.0	14.4
	10	42.3	34.1	19.3
Top of Heater	23	61.5	66.0	7.3
	18	53.5	51.8	3.1
	13	47.0	40.1	14.6
	9	42.4	33.8	20.2
Bottom of Heater	26	61.2	66.0	7.8
	21	52.1	50.7	2.6
	16	45.5	39.0	14.2
	11	40.8	33.0	19.1
Top Plate	58	44.5	~43-44	3.3
	59	44.2	~43-44	3.3

Figure 13. Steady State Temperature Profile Comparison: $Q = 525$ watts.

3. Uninsulated Correlations at 225, 525, 750, and 1,200 W

Based upon the success of the experimental-numerical steady state correlations performed above on the vermiculite insulated container, an attempt was then made to go back to the data generated during the earlier days of the Salt Block I test and develop further correlations with numerical predictions.

Since the earlier data were generated without adequate insulation on the ends, it was necessary to account for both convective and radiative losses at these locations. In the following four "uninsulated" correlations (performed at "steady state" power levels of 225, 525, 750, and 1200 W, respectively) the radiation losses were handled in a method analogous to those described above, except that an emissivity of $\epsilon = 0.3$ was used for top and bottom surfaces ($\epsilon = 0.8$ still being used for the lateral vertical surface of the cylinder). In addition, convection from lower and upper surfaces is included using the equations in Section VII B. Calculations of the respective radiation and convection coefficients is straightforward and analogous to calculations in the insulated correlation sections above. The calculations are omitted here for brevity.

The first comparison (225 W) is presented in Table VII. Arrangement of this table is similar to Tables V and VI, except that a little more detail is included. In particular, the range in recorded temperatures for the given thermocouple is indicated. Since the $Q = 225$ W was held "constant" for day 4 through day 6, the temperature range indicated only applies to day 6 by which time any significant transients would have died out.

Inspection of Table VII, column 3, reveals that such temperature variations are within one degree on day 6. Such minor fluctuations are caused by small variations in air sink temperature (ambient temperature of room was uncontrolled), and changes in convection coefficient due to air flow in room (say when a door was opened).

TABLE VII

COMPARISON OF MEASURED AND COMPUTED TEMPERATURES:
Q = 225 W (UNINSULATED)

General Location	Thermocouple No.	Temp. Range Measured °C	Mean Temp. Measured °C	Temperature Computed °C	Absolute Difference °C	Percent Difference
Midheight of Heater	4	67.3-67.9	67.6	63.9	3.7	5.5
	25	39.7-40.1	39.9	40.5	0.6	1.5
	15	30.3-30.5	30.4	26.5	3.9	12.8
	10	28.2-28.6	28.4	23.9	4.5	15.8
Top of Heater	23	35.9-36.3	36.1	35.5	0.6	1.7
	18	32.3-32.6	32.4	29.9	2.5	7.7
	13	29.9-30.2	30.0	25.5	4.5	15.0
	9	28.1-28.5	28.3	23.2	5.1	18.0
Bottom of Heater	26	34.8-35.2	35.0	36.1	1.1	3.1
	21	31.4-31.8	31.6	30.0	1.6	5.1
	16	28.9-29.3	29.1	25.5	3.6	12.3
	11	27.4-27.8	27.6	23.2	4.4	15.9
Top Plate	59	26.8-27.3	27.0	23.6	3.4	12.6

*Based upon average experimental reading.

Figure 14. Steady State Temperature Profile Comparison: $Q = 225$ watts.

TABLE VIII
COMPARISON OF MEASURED AND COMPUTED TEMPERATURES:
Q = 525 W
(Day 10)

<u>General Location</u>	<u>Thermocouple No.</u>	<u>Temp. Range Measured °C</u>	<u>Mean Temp. Measured °C</u>	<u>Temperature Computed °C</u>	<u>Absolute Difference °C</u>	<u>Percent Difference</u>
Midheight of Heater	4	128.1-129.4	128.7	127.1	1.6	1.2
	25	63.1-64.1	63.6	72.9	9.3	14.6
	20	48.0-48.7	48.4	52.9	4.5	9.3
	15	37.9-38.7	38.3	38.7	0.4	1.0
	10	33.9-35.0	34.4	32.5	1.9	5.5
Top of Heater	23	51.2-52.1	51.7	60.4	8.7	16.8
	18	42.9-43.7	43.3	46.8	3.5	8.0
	13	36.2-37.2	36.7	36.2	0.5	1.4
	9	32.8-34.2	33.5	31.0	2.5	7.5
Bottom of Heater	26	51.7-52.6	52.2	61.9	9.7	18.6
	21	42.8-43.5	43.2	47.1	3.9	9.0
	16	35.9-36.7	36.3	36.2	0.1	0.3
	11	32.5-33.7	33.1	31.0	2.1	6.3
Top Plate	58	29.0-31.0	30.0	32.0	2.0	6.7
	59	29.0-30.9	30.0	31.7	1.7	5.7

Figure 15. Steady State Temperature Profile Comparison: $Q = 525$ watts.

The next comparison is at a heater output of 750 W, which was reached on day 22 at 0900 hr. The range in values of recorded temperature, shown in Table IX, is based on maxima and minima recorded from 8 p.m. that evening through 8 a.m. the following morning, again in an attempt to compare steady state readings with corresponding steady state predictions.

As at lower power levels, predictions are somewhat low at the $r = 5$ in. locations, although agreement at the heater wall as well as at the other radial positions are excellent. For visualization purposes, experimental and numerical steady state temperature profiles are plotted in Figure 16 as a function of radius at elevations corresponding to heater midheight and bottom.

The final comparison is at maximum heater power (1,280 W), again still in the "uninsulated" configuration, that is, the vermiculite skirt has not yet been added to each end of the cylinder. This power level was maintained for days 46 to 48 of the test.

Both experimental as well as numerical temperature ranges and values, respectively, are presented in Table X. Again, to assure steady state conditions, the indicated experimental temperature ranges are based upon day 48. As Table X illustrates, correlations at the heater wall at this high power level are excellent (thermocouple No. 4), whereas those temperature values recorded at 5-in. radius (No. 25, No. 23, and No. 26) are disturbingly off as has been observed at all power levels. Correlations at other radial locations can best be described as good to excellent.

Finally, "midheight" and "bottom" profiles are as shown in Figure 17 for this 1,280 W situation. It is readily seen that predictions are inadequate at the 5-in. radial position, although at least satisfactory elsewhere.

TABLE IX
COMPARISON OF MEASURED AND COMPUTED TEMPERATURES
Q = 750 W (UNINSULATED)

General Location	Thermocouple No.	Temp. Range Measured °C	Mean Temp. Measured °C	Temperature Computed °C	Absolute Difference °C	Percent Difference
Midheight of Heater	4	181.2-183.6	182.4	177.6	4.8	2.6
	25	87.7-88.8	88.3	97.6	9.3	10.5
	20	64.0-64.6	64.3	68.1	3.8	5.9
	15	48.7-49.4	49.0	47.3	1.7	3.4
	10	42.9-43.7	43.3	38.3	5.0	11.5
Top of Heater	23	67.8-68.8	68.3	79.4	11.1	16.3
	18	55.9-56.5	56.2	59.2	3.0	5.3
	13	45.9-46.7	46.3	43.8	2.5	5.4
	9	41.2-42.1	41.6	36.3	5.3	12.7
Bottom of Heater	26	70.7-71.4	71.1	81.5	10.4	14.6
	21	56.7-57.2	57.0	59.6	2.6	4.6
	16	46.1-46.6	46.3	43.8	2.5	5.4
	11	41.0-42.0	41.5	36.2	5.3	12.8
Top Plate	58	35.8-37.3	36.7	37.8	1.1	3.0
	59	35.7-37.2	36.5	37.3	0.8	2.2

Figure 16. Steady State Temperature Profile Comparison: $Q = 750$ watts.

TABLE X

COMPARISON OF MEASURED AND COMPUTED TEMPERATURES
 $Q = 1,280 \text{ W (UNINSULATED)}$

General Location	Thermocouple No.	Temperature Range Measured °C	Mean Temperature Measured °C	Temperature Computed °C	Absolute Difference °C	Percent Difference
Midheight of Heater	4	286.4-288.6	287.5	290.8	3.3	1.1
	25	140.3-141.9	141.1	158.7	17.6	12.5
	20	93.4-94.9	94.2	104.3	10.1	10.7
	15	64.6-65.7	65.2	66.8	1.6	2.4
	10	54.4-55.8	55.1	51.0	4.1	7.4
Top of Heater	23	97.7-99.2	98.5	125.3	26.8	27.2
	18	76.6-78.1	77.4	88.4	11.0	14.2
	13	59.0-60.2	59.6	60.8	1.2	2.0
	9	51.3-52.9	52.1	47.6	4.5	8.6
Bottom of Heater	26	106.2-107.7	107.0	128.1	21.1	19.7
	21	79.7-80.9	80.3	88.5	8.2	10.2
	16	60.3-61.3	60.8	60.6	0.2	0.3
	11	51.2-52.6	51.9	47.4	4.5	8.7
Top Plate	58	40.7-43.8	42.3	50.2	7.9	18.7
	59	40.3-43.3	41.8	49.3	7.5	17.9

Figure 17. Steady State Temperature Profile Comparison: $Q = 1280$ watts.

D. Transient Comparisons

For transient experimental comparisons, the first 2 days of the Salt Block I experiment were selected. First, the input values are here calculated, followed by the results.

Over the first 2 days of the experiment, the outside surface temperature rose from approximately 18 to 24°C. With a constant ambient temperature of 18°C assumed, the maximum convective heat transfer coefficient is (for assumed laminar flow)

$$h_c = 2.218 \text{ W/m}^2\text{-}^\circ\text{C} .$$

Radiation is neglected due to the low temperature.

Power input was varied the same as in the experiment. Resulting experimental-numerical comparisons are as shown in Figures 18 and 19 for day 1 and day 2, respectively, at four radial locations at midheight of the heater. The comparison of numerical and experimental curves is quite reasonable for these 2 days. The largest errors are seen to be near the heater during the first day and at the first thermocouple (in the salt) during the second day. The first error is attributable to poor knowledge of the crushed salt conductivity. The second error is similar to that observed in the steady state comparisons. Recall that at the first radial salt thermocouple location, experimental values were consistently lower than theory.

E. Discussion of Discrepancies

While both steady state thermal profiles and transient temperature-time histories as recorded generally show very satisfactory agreement with predictions computed using the COYOTE finite element program, there nevertheless do exist some discrepancies that are worth brief comment.

Figure 18. Experimental-Numerical Comparisons of Temperature as a Function of Time at Four Radially Spaced Thermocouple Locations: Day 1.

Figure 19. Experimental-Numerical Comparisons of Temperature as a Function of Time at Four Radially Spaced Thermocouple Locations: Day 2.

Thermocouples located on a 5-in. radius from the center of the salt block have output consistently below numerical predictions. Consider Figure 10 presented earlier. This figure shows locations of thermocouple holes as well as the locations of holes used for corrosion coupons. It can be seen that the corrosion coupon holes are significantly larger than the thermocouple holes; in addition, the inner coupon hole is located in the near proximity of the two inner thermocouple holes 4 and 5 (containing thermocouples 25, 23, and 26, among others). It is believed that the inclusion caused a perturbation in the temperature field, leading to the discrepancies observed between theory and experiment.

It should be mentioned that subsequent to performing the heat transfer finite element calculations, some more recent physical properties of bedded salt were obtained that are not reflected in the correlations presented earlier in this section. The new rocksalt thermal conductivity data which were generated gave values substantially higher, as is shown in Figure 20. However, the earlier values (See Figure 3 and Table IV) were taken from the core of Salt Block I, while the later values were from another salt block in the same formation in the mine. Since the site specific Salt Block I values were utilized in the correlations presented herein, the best available salt properties (though not the latest reported values) were used and the basic conclusions of the Salt Block I are, of course, unchanged. The above differences still should be kept in mind.

Figure 20. Thermal Conductivity of a One Meter Cube of Rocksalt From Mississippi Chemical Company of S. E. New Mexico Potash Mine - Latest Data

SECTION IX

SUMMARY OF RESULTS AND CONCLUSIONS

The fundamental purpose of the Salt Block Test I, as stated earlier, was to provide data and information relating to the storage of radioactive wastes in salt. A number of specific objectives related to this underlying purpose have been accomplished.

1. A heat source has been developed, instrumented, and successfully demonstrated for the purpose of simulating an emplacement of high-level waste in salt (see Section VI).
2. Based upon the axisymmetry of the recorded temperature field in Salt Block I (see Section VI, Subsection D), as well as agreement with isotropic thermal calculations, evidence suggests that thermal conductivity of bedded salt may be isotropic.
3. Sauereisen cement and fine salt have been evaluated as backfilling materials (see Section VI, Subsection D). These materials were found to both yield identical thermocouple results.
4. The corrosion field in salt was investigated for a variety of different materials as part of Salt Block I (see Section VI, Subsection E). At least for this one experiment, results suggest that the corrosion problem in WIPP may not be very significant. However, additional experiments are recommended before any firm general conclusions are drawn.
5. Considerable experience has been gained in instrumenting bench scale samples of salt (see Section VI, Subsections A through D). It is believed that the instrumentation development undertaken in Salt Block I will prove valuable in later in-situ experiments.

6. Preliminary data on brine migration have been obtained (see Section VI, Subsection F) where results suggest that water migration in salt formations is a minor phenomenon, at least at the temperature ranges experienced in Salt Block I. Again, additional experiments are required before stronger conclusions can be drawn.

It should be further mentioned that a numerical model of the salt block was developed for predictions of both transient and steady state temperature profiles. These predictions agreed quite well with the experimentally recorded response of the salt block to a thermal input. In addition, the following specific conclusions were reached:

1. Temperature dependent conductivity values measured on small salt samples (and reported herein) adequately characterized large salt block conductivity.
2. Crushed salt conductivity was estimated by repeated numerical parameter variations and comparisons with experimental results to be in the range 0.35 to 0.50 W/m K. This range in values is roughly an order of magnitude below bedded salt values.
3. Based upon spatial extrapolation of validated numerical temperature profile predictions, the pretest target of 200 to 250°C maximum salt temperature was achieved.

The need to closely match numerical and experimental data in this test forced the experimental setup and numerical model to be critically evaluated especially with regard to control of the thermal boundary conditions. As a result of this evaluation, a number of points can be made to aid in future experimental designs.

1. The layers of asbestos in the original experiment design were inadequate to prevent heat loss from the horizontal surfaces and piping leads, making the numerical modeling somewhat

more difficult than anticipated. The experimental setup was eventually modified to eliminate this problem.

2. In designing the experiment, only free convective losses were assumed to be important for the rejection of heat from the vertical surfaces of the block. During the running of the experiment, it became evident that at the higher power levels, radiation was also a significant heat transfer mechanism. The unexpectedly high power requirements for the heater were mostly a result of the radiation losses.
3. There was no control on the ambient temperature conditions surrounding the experiment. This made modeling difficult since the thermal sink temperature could only be approximated.
4. A weak point in the numerical model was the representation of the resistance heater. In hindsight, it would have been of value to know the heat flux distribution along the heater wall. The addition of several heat flux gages to the instrumentation will remedy this problem.
5. A second weak point in the numerical model was the lack of material data for crushed salt. If crushed salt is to be used extensively for the backfilling of canisters, reliable property data are mandatory.

SECTION X

REFERENCES

1. Internal Sandia Memo from A. R. Sattler, 1141 and P. L. Nelson, 1142, to Distribution, "Experiments in Support of Bench Scale Experiments with Large Salt Blocks," December 7, 1976.
2. Internal Sandia Memo from R. V. Acton, 5842, to P. L. Nelson, 1142, "Thermal Conductivity of a Rock Salt Core in Support of Bench Scale Experiments on Large Salt Blocks," December 21, 1976.
3. Internal Sandia Memo from A. R. Sattler, 1141, and P. L. Nelson, 1142, to Distribution, "Operating Plan for Large Salt Block Heater Experiment #1," January 10, 1977.
4. Internal Sandia Memo from C. W. Cook, 1116, to L. R. Hill, 1141, "Observations of Instrumentation Performance During Salt Block I Test," May 17, 1977.
5. Internal Sandia Memo from D. K. Gartling, 1261, to Distribution, "Preliminary Report Salt Block Experiment #1 - Thermal Analysis," May 17, 1977.
6. Internal Sandia Memo from J. T. McIlmoyle, 1125, to Distribution, "Heated Salt Block Experiment," May 31, 1977.
7. Internal Sandia Memo from R. I. Ewing and M. P. Apodaca, 1112, to A. R. Sattler, 4512, "Water Loss from the Interior of Salt Block I Due to Heating Cycle Tests," November 13, 1978.
8. Omega Temperature Measurement Handbook, p. A-4.
9. D. K. Gartling, COYOTE--A Finite Element Computer Program for Nonlinear Heat Conduction Problems, SAND77-1332, Sandia Laboratories, Albuquerque, New Mexico, June 1978.
10. E. L. Wachspress, Iterative Solution of Elliptic Systems and Applications to the Neutron Diffusion Equations of Reactor Physics, Prentice-Hall, Inc., 1966, pp. 29-31.
11. W. H. McAdams, Heat Transmission, McGraw-Hill, New York, 1954, p. 173.
12. J. P. Holman, Heat Transfer, Third Edition, McGraw-Hill, New York, 1972, p. 219.
13. B. Gebhart, Heat Transfer, McGraw Hill, New York, 1961, pp. 122-123.

14. K. Kühn, Über die Wärmeleitfähigkeit von Salzgrus (Thermal Conductivity of Crushed Salt), Gesellschaft für Strahlenforschung mbH München, Institut für Tieflagerung Clausthal-Zellerfeld, West Germany, September 15, 1969 (Sandia Laboratories translation dated March 21, 1977).
15. R. D. Cheverton and W. D. Turner, Thermal Analysis of the National Radioactive Waste Repository: Progress Through June 1971, Oak Ridge National Laboratory, ORNL-4726, December 1971, p. 38.
16. Internal Sandia Memo from D. D. Dees, 5831, "Salt Block I Volatile Content Measurements," July 18, 1978.
17. J. J. Hohlfelder, Measurement of Water Lost from Heated Geologic Salt, SAND79-0462, Sandia Laboratories, Albuquerque, New Mexico, July 1979.

APPENDIX I

WATER LOSS DATA FROM SALT BLOCK I (PART I)

The first investigation was performed to provide further understanding of water loss during the Salt Block I experiment. The investigation, as described in Reference 7, is as follows:

The residual water content of selected salt samples was investigated by measuring the weight loss of each sample upon heating to 250°C. Samples were taken from two locations inside Salt Block I after its heating cycle tests were completed, and compared to samples of the same formation that had not been previously heated. The differences between these measurements were taken to be a measure of the water driven out of the samples as a result of the heating cycle tests on Salt Block I. The samples from the center zone of the Block, near the heater, were heated to about 140°C during the heating cycle tests and showed a water loss of $0.05 \pm .02$ weight percent of sample as a result of those tests. The samples taken from the outer zone of the Block, near its wall, were limited to less than 60°C during the Block tests and showed essentially no water loss as a result, with an upper limit of 0.02 weight percent.

After the heating cycle tests were completed on Salt Block I, it was cut in half, and cores 4 in. in diameter by 10 in. long were extracted at the locations marked "wall" and "center" in Figure 21. The cores were broken into small chunks and divided into samples weighing 20 to 40 grams each. Ten such samples were used from each location indicated by the cross-hatched region on the diagram. Unheated samples from the same formation and source as Salt Block I were measured as a baseline. Each sample was weighed to an accuracy better than one-tenth milligram, heated to $248^{\circ}\text{C} \pm 3^{\circ}\text{C}$ in a vented air oven for 100 hours, allowed to cool in a dessicator, and reweighed. The resulting percent weight loss averages and the observed standard deviation among the samples are shown below.

Figure 21. Section of Salt Block I Showing Locations of Sample Removal.

Experimental uncertainties were much smaller than the standard deviations. 250°C was the maximum safe temperature to avoid decrepitation of the salt samples. The samples were weighed at 72 and 100 cumulative hours of heating, and no significant weight changes were observed after 72 hours.

<u>Sample</u>	<u>% Weight Loss Upon Heating to 250°C</u>
Unheated	.12 ± .03
"Wall"	.12 ± .02
"Center"	.07 ± .01

Results were analyzed under the following assumptions:

- (1) the observed weight loss is due to water being driven out of the sample;
- (2) these samples all had the same initial water content (prior to heating); and
- (3) the differences in the measurements are due to the prior thermal history of the samples, i.e., the heating cycle tests of Salt Block I.

Since the "unheated" and "wall" samples produced the same percent weight loss in our tests, it is concluded that the salt formation near the outer wall was essentially unchanged in water content by the heating cycle tests on Salt Block I. The "center" samples showed a lower percent weight loss in our tests than the other samples. It is concluded that the difference in these values, $0.05 \pm .03$ weight percent, is a measure of the water lost by the salt formation in the vicinity of the central heater due to the heater cycle tests on Salt Block I.

For comparison, earlier work is reported in Reference 17 using a similar technique on samples of previously unheated salt from the same

formation. Figure 22 shows cumulative weight loss percentage for temperatures from 70°C to 300°C. The rapid increase in weight loss above 250°C and the increased standard deviation among the samples accompany the decrepitation phenomenon. The value of $.10 \pm .02$ weight percent at 250°C is in rough agreement with the present data. Also these comparison data indicate a value of about $.03 \pm .02$ weight percent for the difference between 60°C and 140°C samples, again in rough agreement with the value of $.05 \pm .02$ ("wall" -- "center") reported above. The conclusion from this earlier data is that at a fixed temperature, only a certain fraction of the total water content can be removed from the formation even after heating for several days. The implication of these results is that "water migration" in salt formation is a minor and easily measured phenomenon.

Figure 22. Percent Weight Loss as a Function of Temperature from Previously Unheated Salt Block I Samples.

APPENDIX II

WATER LOSS DATA FROM SALT BLOCK I (PART II)

The second set of measurements¹⁶ on Salt Block I directed toward detection of possible brine migration was obtained at higher temperatures as follows: tests were performed on three salt samples involving heating the samples in air at 500°C for 12 days. Each sample consisted of 40 grams of ground salt (particle size less than 2.4mm).

The first sample (1001) was prepared from a specimen of Salt Block I before the Salt Block I heater experiment was performed. The second sample (1002) was prepared from salt from the outer part of the block after the Heater Experiment. Finally, the third sample (1003) was taken from the center section of the Block after the Heater Experiment.

A weight percent volatiles (percent weight loss) was determined for the salt using procedures similar to those described in Appendix I. Results for the three samples are as follow:

<u>Sample</u>	<u>Weight Percent Loss</u>	<u>Notes</u>
1001	0.46 %	From Salt Block I before heating
1002	0.47 %	From outside of Salt Block I after heating
1003	0.53 %	From center of Salt Block I after heating