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THERMAL OPERATIONS CONDITIONS
IN A
NATIONAL WASTE TERMINAL STORAGE FACILITY

PREPARED FOR THE
OFFICE OF WASTE ISOLATION

OPERATED BY
UNION CARBIDE NUCLEAR DIVISION
FOR THE
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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PREPARED BY
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EXECUTIVE SUMMARY

A number of studies have been made of the long and short term temperature distributions for a geologic waste isolation facility in bedded salt.¹ These studies have examined a wide range of geometrical arrangements, canister and waste characteristics, thermal properties, etc. resulting in a general understanding of the thermal effects to be expected.

The goals of the present study were to investigate the temperature profiles over 30 years for a specific design of a waste storage pilot plant and, in particular, to examine the thermal effects due to ventilation of the storage rooms.

The approach used in this study has been to make three-dimensional calculations for a unit cell in the center of the facility using boundary conditions to account for the rest. The unit cell calculations were then extrapolated to provide results for the entire ventilated array. The calculations were made using two different heat-conduction codes, HEATING5 and TRUMP, which presently reside on the UCND computers; and the solutions were thoroughly checked for consistency and accuracy.

The results for the unit cell calculations show that the ventilation has a dramatic effect on the temperatures throughout the vicinity of the facility and that these effects are strongly dependent upon the temperature of the ventilating air and upon the heat transfer rates into the room from the floor, ceiling, and walls. In a calculation for waste canisters with an initial heat generation rate of 51 kW (158 kW/acre), for an air temperature of 74°F and for a convective heat transfer coefficient of 0.6 BTU/(hr-ft²-°F), after the first 5 years about 65% of the total heat produced to that time is removed by the ventilating air and after 30 years approximately 88% of the

heat produced is removed. The floor temperatures of the ventilated room depend strongly upon the air temperature and the heat transfer coefficient although there is little dependence upon the initial ambient temperatures for the system.

Ventilation results for the entire storage room show that for 70°F inlet air and for a convective heat transfer coefficient of 0.67 BTU/(hr-ft²-°F), maximum floor temperatures can be controlled at approximately 100°F if an air flow rate of approximately 50,000 cfm per storage room is maintained throughout the entire facility.

Calculations for a 2-dimensional representation of the facility show excellent agreement with the 3-dimensional calculations for distances larger than 5 feet from waste canisters. This result is due to the large thermal conductivity of salt and cannot be extrapolated to other formations. Parametric studies for the unventilated 2-dimensional case show that storage room temperatures depend sensitively upon the thermal conductivity of the surrounding medium and detailed treatment of radiation in the room.

These calculations are limited in that the parameters governing the heat transfer into the room are not well established. There is a strong dependence of the resulting temperature profiles in the salt and in the rooms upon these coefficients. Another limitation is that the unit cell calculations assume that all unit cells in the facility have the same thermal behavior. Thus temperature profiles due to the ventilation of only one or a few storage rooms cannot be extracted.

¹R.D. Cheverton and W.D. Turner, Thermal Analysis of National Radioactive Waste Repository: Progress through June 1971, ORNL-4726, 1971.

R.D. Cheverton and W.D. Turner, Thermal Analysis of National Radioactive Waste Repository: Progress through 1972, ORNL-4789, 1972.

H.C. Claiborne, Thermal Analysis of a Fuel Cladding Repository Pilot Plant in Salt, ORNL/TM-5221

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1. INTRODUCTION

Some of the major technical questions associated with the burial of radioactive high-level wastes in geologic formations are related to the thermal environments generated by the waste and the impact of this dissipated heat on the surrounding environment. The design of a high level waste storage facility must be such that the temperature variations that occur do not adversely affect operating personnel and equipment.

The objective of this investigation was to assist OWI by determining the thermal environment that would be experienced by personnel and equipment in a waste storage facility in salt. Particular emphasis was placed on determining the maximum floor and air temperatures with and without ventilation in the first 30 years after waste emplacement. The assumed facility design (described in Section 2) differs somewhat from those previously analyzed and reported, but many of the previous parametric surveys are useful for comparison.

Previous thermal analyses of high level waste repositories in salt formations examined a wide range of geometric arrangements, canister sizes, thermal properties, ages of wastes, etc.^{2,3,4,5} The 1972 report concluded that the maximum permissible loading per gross acre for 10-year old waste was about 158 kW/acre at the time of burial, and that a 12 inch diameter canister could contain a maximum of approximately 5 kilowatts initial power.³ Preliminary calculations were reported for the removal of heat from rooms with ventilation air. It was concluded that the maximum temperature rise at the center of the floor would be in the neighborhood of 20°F, for an assumed convective heat transfer coefficient of 0.6 to 0.7 BTU/hr-ft²-°F and that approximately 40 percent of the waste heat was removed with the room ventilation air. Radiant heat transfer was not considered.

In this investigation a number of 2-dimensional and 3-dimensional simulations of the heat flow in a repository have been performed on the HEATING5 and TRUMP heat transfer codes. The representative repository constructs used in the simulations are described in Section 2 of this report, as well as the computational models and computer codes.

Results of the simulations are presented and discussed in Section 3. Comparisons are made between the recent results and those from previous analyses.

Finally, Section 4 contains a summary of study limitations, comparisons and conclusions.

2. SPECIFICATION OF THE PROBLEM

2.1 PHYSICAL DESCRIPTION

The high level solid waste considered in this study is stored deep below the surface of the earth in salt. The mined burial rooms are assumed to be situated at a depth of 2000 feet below the surface of the earth, and are shown schematically in Figures 2-1 and 2-2. A single room has an 18' x 18' cross-sectional area and is 558' in length.* For this facility 32 rooms are considered, each separated by a 60' rib pillar.

The geological medium immediately around the rooms and below is salt and the material above is a mixture of shale and salt. The relevant properties of these materials are given in Tables 2.1 and 2.2. The thermal conductivity of these media are expected to be important for the analysis and the upper region is assumed to be composed of layers, 80 percent salt and 20 percent shale, in order to account for the shale components of the salt bed in an approximate way.

The anisotropy in the upper region due to the presence of shale and due to the layering is neglected here. While this effect may be important for far-field effects above the room, it was felt that this approximation would be adequate for treatment of heat flow in the region of the room. A revision would be required if substantial amounts of shale were to be found immediately above the actual mined room.

The canisters are assumed to be buried under the floor, below the centerline axis of the room as in Figure 2-2. The receptacle for the waste canister is a 21" diameter hole 18' deep lined with a 2" carbon steel sleeve as in Figure 2-3. Inserted in this receptacle is a 10' stainless steel canister with carbon steel overpack and a 7' concrete thermal plug.

*This length is chosen in conjunction with the 78' separation between rooms to provide approximately 1 room and pillar per acre.

FIGURE 2-1 PARTIAL CONCEPTUAL LAYOUT OF HIGH-LEVEL WASTE STORAGE ROOMS

Fig. 2-2 WASTE STORAGE ROOM CONFIGURATION

Fig. 2-3 DETAILS OF WASTE RECEPTACLE AND CANISTER

TABLE 2.1

THERMAL PROPERTIES OF SOME MATERIALS

	DENSITY (lb/ft ³)	HEAT CAPACITY (BTU/lb-°F)	THERMAL CONDUCTIVITY (BTU/hr-ft ² -°F)
Air ^a	0.07	0.24	d
Stainless Steel 304L ^a	488	0.11	10.0
Carbon Steel ^a	490	0.11	25.0
Glass Waste ^b	200	0.22	0.58
Salt ^c	135	0.22	d
80% Salt - 20% Shale Mix	138	0.216	d
Concrete	144	0.20	0.54

a) Ref. 6

b) Ref. 11

c) Ref. 3

d) See Table 2.2

TABLE 2.2

THERMAL CONDUCTIVITY (BTU/hr-ft-°F)

<u>T(°F)</u>	<u>Salt</u> ^a	80% Salt - 20% <u>Shale Mixture</u> ^a	<u>Air</u> ^b
32	3.53	2.29	0.014
122	2.90	2.06	0.016
212	2.43	1.85	0.018
302	2.08	1.68	0.019
392	1.80	1.53	0.021
482	1.60	1.41	0.023
572	1.44	1.31	0.024
662	1.33	1.23	0.026
752	1.20	1.14	0.028

a) See Ref. 3

b) See Ref. 6

TABLE 2.3^a

TRANSIENT THERMAL POWER OF TYPICAL WASTE RESULTING
FROM THE REPROCESSING OF LIGHT WATER REACTOR FUEL

Reprocessing, 90 days after reactor shutdown

<u>Time, t (years)</u> ^b	<u>P(t)/P₀</u>
0	1.0
2	0.917
5	0.845
7	0.800
10	0.737
12	0.697
15	0.638
20	0.576
30	0.450
40	0.351

a) See Ref. 2

b) t is considered to be zero ten years after fuel has been discharged from reactor.

TABLE 2.4 GEOTHERMAL GRADIENT^a

<u>Distance below surface of Earth (ft)</u>	<u>Ambient Temperature (°F)</u>
0	59.0
400	63.0
710	72.5
1100	74.0
3500	124.0

a) See Ref. 2

Figure 2-4 INITIAL TEMPERATURE PROFILE FOR 5 KW CANISTER
PLACED IN RECEPTACLE

Figure 2-5 3-DIMENSIONAL UNIT CELL

The actual volume of high level waste is assumed to be uniformly distributed through a cylindrical volume 8' long by 1' diameter. The thermal properties of these materials and the waste material are included in Table 2.1. The canisters are assumed to contain 10-year old waste when placed in the repository. A single canister is assumed to generate 5.096 kW of power at placement and the relative heat generation rate thereafter is in Table 2.3. The initial temperature profile of the canister is given in Figure 2-4.

The ambient temperatures of the geological formation are provided in Table 2.4. With this assumed geothermal gradient, the initial ambient temperature in the storage rooms is roughly 93°F.

2.2 COMPUTATIONAL MODEL

A schematic of a 3-dimensional (3D) unit cell for calculations is shown in Figure 2-5. The geological medium for this unit cell consists of a homogeneous block of salt(80%)/shale(20%) from 1500 below the earth's surface to 1982 feet below the surface and a block of pure salt from 1982 feet to 2500 feet below the surface. The upper and lower boundaries are sufficiently far from the 2000 foot level that for the first 30 years they have no impact on temperatures in the vicinity of the room. The length of the unit cell is controlled by the pitch between canisters (chosen to be 18 feet for 5.1 kW canisters). The width is given by the sum of the room half width (9 feet) and pillar half width (30 feet). The room consists of an 18 ft. x 18 ft. x 9 ft. tunnel in the center of the unit cell with the floor of the room being at the 2000 ft. level. The waste is located 10 ft. below the center of the room floor.

Assuming symmetry about the tunnel axis, the model actually employs a half-unit-cell with an adiabatic boundary condition at the plane which bisects the unit cell. For cases where

ventilation is not considered, insulating boundary conditions are assumed for the vertical planes defining the ends of the unit cell and bisecting the pillar. Hence this unit cell is probably a reasonable representation of a central section of one of the rooms somewhere near the middle of the array for the static case. Even for the ventilated case this unit cell will be useful if the induced temperature gradient due to the air cooling is small.

The initial temperature distribution of the unit cell is given by the ambient temperature of the formation except that the waste material is initially specified to be 350°F. The geothermal temperatures are maintained at the upper and lower boundaries of the unit cell.

For ease in handling the problem the waste canister is treated as a parallelepiped rather than a cylinder. This approximation should only affect the heat flow near the heat source and Cheverton and Turner³ pointed out that the error introduced is less than 3% as long as the volumetric heat generation rate is given correctly. In this case the initial rate for a 5kW canister is

$$\dot{q} = \frac{5.1 \text{ kW} \times 3414 \text{ BTU/kW-hr}}{8 \text{ ft}^3} = 2176 \text{ BTU/hr-ft}^3.$$

Another approximation is to neglect the steel sleeve, overpack and canister wall. Claiborne⁷ has suggested that this approximation will lead to little error in the temperatures in the room⁴ and several preliminary calculations support this assertion. In addition, details of the waste material itself, other than the heat generation rate, appear to have little bearing on the temperatures in the room.

Radiant heat transfer between floor and ceiling of the storage room is included with an emissivity of $\epsilon = 0.9$. For many purposes it is desirable to make computations with a 2-dimensional (2D) model which is shown in Figure 2-6. This model is equivalent to a 3-dimensional model when the heat source is homogeneously distributed down the length of the room. The power density in this case is:

$$\dot{q} = \frac{(5.1 \text{ kW})(3414 \text{ BTU/kW-hr})}{(8 \text{ ft})(1 \text{ ft})(18 \text{ ft})} = 121 \text{ BTU/hr-ft}^3.$$

For these values, this amounts to power generated in a 558' room of 31 unit cells equal to 158 kW/acre. Although the 2D model may not represent realistically the temperature distributions in the neighborhood of the waste, temperature distributions for the salt should be adequately described.

2.3 COMPUTER CODES

The calculations have been made using the heat transfer codes TRUMP and HEATING5. Both codes treat the conduction with one of several finite differencing schemes and both can utilize sophisticated implicit approaches to treat the transient problem.

The codes are different in a number of ways, including treatment of individual nodes and certain boundary conditions, as well as in the methods of solution, and agreement between them provides an independent check on the reliability of the solutions. Each code has advantages. For example the treatment of new cases and the necessary input is much simpler with HEATING5. TRUMP is able to treat ventilation explicitly by means of a mass transfer mechanism while HEATING5 can only solve this problem in an approximate manner. However for cases where the characteristic times associated with air transit are much smaller than the time constants associated with the heating of the air, the latter approximations become very good. Both codes are available on the UCND computers and are described in more detail in references 8 and 9.

Fig. 2-6 TWO DIMENSIONAL NODAL MODEL

Prior to the calculations, mesh spacing and convergence of the codes and heat balances at many node points were examined to check the consistencies of the results. Reduction of the mesh spacing by factors of 3 or more in the regions of steepest gradients changes the resulting absolute temperatures in the region of interest by less than 2°F. For a similar spacing in the 3D case the same result was found. Time steps were restricted to assume operation in a stable region. It is believed that the solutions to each code are accurate to within 10% although perfect agreement between the codes has not yet been achieved on anything but the simplest one dimensional models.

3. STORAGE ROOM TEMPERATURE DISTRIBUTIONS

3.1 THREE DIMENSIONAL CALCULATIONS

The basic model employed for the three dimensional calculations consists of the unit cell described in Section 2 (see Figure 2-5). In this section results are presented for temperature profiles over time for the unit cell caused by the placement of a 5.1 kW canister with the room continuously ventilated by air of various velocities and inlet air temperatures. Particular emphasis is placed on the environment that will impact personnel and equipment operating in the room during the first 30 years after placement of the waste. It should be remembered that these calculations represent a situation for an array of unit cells which are all heated and ventilated in the same way. The results presented include bulk salt temperatures, then more detailed storage room profiles which are then extrapolated to give approximate results for the entire 558 foot room. The induced temperature gradient due to the air flow rate is small enough to produce small temperature variations throughout the unit cell although the cumulative effect for the entire room (31 unit cells) is significant.

Since the relationship between the velocity of the ventilating air and the corresponding convective heat transfer coefficient is not well understood for ducts with cross sections as large as for this room (18' x 18'), the results are presented for a range of convective heat transfer coefficients (0.2 to 0.6 BTU/hr-ft²-°F).

3.1.1 Bulk Salt Temperatures Profiles - Unit Cell

The ventilation of the room has a significant impact on the temperature levels reached throughout the unit cell. For the case of continuous ventilation, peak temperatures in the vicinity of the room and waste are reached at about five years. Figures 3-1 and 3-2 are graphical presentations of the 5-year isotherms in two planes intersecting the waste parallel to the room axis and perpendicular to it, respectively. These figures are for ventilation conditions of 74°F constant air temperature and a convective heat transfer coefficient of 0.6 BTU/hr-ft²-°F.

The conductivity of the salt is large enough and the thermal sink due to the ventilation is important enough that isotherms quickly smooth out as they move away from the heat source. The temperature gradients in the mid-waste region are very steep - on the order of 225°F/ft - while 10 feet above the waste there is only about a four degree variation over the entire length of the unit cell. The floor temperatures themselves will be discussed in more detail in the next subsection.

- Approximately 65% of the heat generated in the first 5 years is removed by the ventilation air by this time for $h_c = 0.6$ and about 88% is removed after 30 years. Dramatic visualization of the impact of this large heat sink is presented in Figure 3-3 which gives the temperature versus depth profile near the intersection of the two planes discussed above. Note that the material forming the roof of the room never reaches temperatures above 100°F.

Fig. 3-1 ISOTHERMS FOR 3-D VENTILATION CALCULATIONS
VERTICAL PLANE ALONG THE ROOM AXIS
(5 YEARS)

Fig. 3-2 ISOTHERMS FOR 3-D VENTILATION CALCULATIONS
VERTICLE PLANE/PERPENDICULAR TO ROOM AXIS
(5YEARS)

Fig. 3-3 TEMPERATURE VS. DEPTH ALONG AXIS SHOWN
VENTILATED UNIT CELL

Further, the ventilated room suppresses temperatures in the pillar at room level and above sufficiently to maintain them at 130°F or less. A presentation of these pillar center line temperatures versus depth is given in Figure 3-4.

The comparison of the 5-year and 30-year curves in both Figures 3-3 and 3-4 demonstrates the expected smoothing of the thermal gradient in the salt repository as time progresses. After the peak the continuous ventilation and the decaying heat generation rate gradually decrease the temperatures in the vicinity of the room.

Further, a comparison of the 5-year temperature profiles in Figure 3-4 for convective heat transfer coefficients of 0.2 and 0.6 BTU/hr-ft²-°F indicates a small range of variation in maximum temperatures. The calculations indicate the salt temperatures for a convective heat transfer coefficient of 0.2 and 0.6 BTU/hr-ft²-°F. The 30-year temperatures for the lower value of convective heat transfer coefficient are about 10° to 20°F hotter than the higher value. The 30-year ($h_c = 0.2$) profile is indistinguishable from the 5-year ($h_c = 0.6$) profile down to about 2050 feet.

3.1.2 Storage Room Floor Temperatures - Unit Cell

As stated earlier, one of the major reasons for ventilation is to maintain a reasonable operating environment within the room. Of particular importance to this environment is the floor temperature experienced by vehicles and personnel. A time history of the peak floor temperatures within the unit cell for the period of 30 years is presented in Figure 3-5 for various values of the convective heat-transfer coefficient. The maximum floor temperature is reached after 4½, 5 and 5½ years of burial for convective heat transfer coefficients of 0.6, 0.4 and 0.2 BTU/hr-ft²-°F, respectively. The corresponding maximum

Fig. 3-4 TEMPERATURE VS. DEPTH AT PILLAR CENTER-LINE
VENTILATED UNIT CELL
($T_{AIR} = 74^\circ\text{F}$)

Fig. 3-5 PEAK FLOOR TEMPERATURE HISTORIES FOR VARIOUS
HEAT TRANSFER COEFFICIENTS
(UNIT CELL)

floor temperature variation along the floor of the unit cell is on the order of one degree. This is illustrated down the center of the unit cell in Figure 3-6. The physical phenomena which tend to equalize these floor temperatures include conduction of heat through the salt, radiant heat transfer between floor and ceiling and the impact of the large heat sink on the temperature gradients in the bulk salt surrounding the room. However, there is a large variation in floor temperature as a function of the convective heat transfer coefficients.

3.1.3 Storage Room Temperatures - Entire Room

Since the time constants for transfer of heat into the unit cell are of the order of hours while the characteristic time for removal of heat by ventilation is much smaller (1/200 hr for 1 ft/sec velocity), the cooling of the room does not depend directly on v although there can be an implicit dependence since the forced convection heat transfer coefficient generally is a function of velocity. However, extrapolation of the unit cell ventilation calculations to the entire 558' storage room requires that the flow rate of the ventilating air be made explicit. The relationship between h_c and v is not well known for this geometry. In the forced convection limit, Chapman¹ suggests a local correlation of the form

$$h_c = 0.39 v^{0.8} / X^{0.2} \quad \text{BTU}/(\text{hr-ft}^2\text{-}^\circ\text{F})$$

for turbulent flow past large, flat surfaces where X is the distance along the surface. In the natural convection limit McAdams¹³ finds a heat transfer coefficient for turbulent free convection off flat surfaces of the form

$$h_c = 0.20 (\Delta T)^{1/3} \quad \text{BTU}/(\text{hr-ft}^2\text{-}^\circ\text{F}).$$

Fig. 3-6 ROOM CENTER-LINE FLOOR TEMPERATURE,
3-D UNIT CELL
(T AIR = 74°F)

It is unlikely that either of these limits is strictly applicable. Moreover entrances effects and duct effects are not understood for this case and are neglected here. Nevertheless these relationships provide estimates of the desired extrapolation from the unit cell ventilation to ventilation for an entire storage room.

Shown in Figures 3-7a and 3-7b are temperature ranges which can be expected throughout the entire storage room assuming a convective heat transfer coefficient of the form

$$h_c = 0.28 V^{0.8} \text{ BTU}/(\text{hr-ft}^2\text{-}^\circ\text{F}).$$

This relation reproduces the forced convection limit results for the flow rates shown and is somewhat smaller than natural convection limit in the region of interest. Figure 3-7a shows exhaust air temperatures for the room as a function of inlet air temperature for various flow rates. Figure 3-7b gives the range of floor temperatures which can be expected as a function of inlet air temperature. For example for a flow rate of 27,200 cubic feet per minute in the storage room ($h_c = 0.37$) the minimum floor temperature for 70°F inlet air is about 100°F and the maximum floor temperature is about 110°F . Figure 3-8 gives maximum air and floor temperatures as a function of air flow rate for 60°F inlet air temperature. In this case curves for both the natural convection and forced convection limits are shown. It is noted that floor temperatures can be held below 100°F if a flow rate of 30,000 cfm or more is maintained in each room in the facility.

3.2 TWO DIMENSIONAL CALCULATIONS

Prior to executing the 3-dimensional calculations reported in the previous subsection, analyses were performed using a 2-dimensional model of the repository. This technique was

Fig. 3-7a MAXIMUM AIR TEMPERATURES IN ROOM

Fig. 3-7b RANGES FOR FLOOR TEMPERATURES

Fig. 3-8 MAXIMUM TEMPERATURES
INLET AIR AT 60°F

employed to develop familiarization with the problem of using a simpler model and to generate results that could be compared directly with earlier results.^{2,3,4,5} However, comparison of the 2-dimensional model results with those from the 3-dimensional model indicates a number of regions for which the simpler model is valid.

The 2-dimensional (2D) model corresponds to a facility where the 155 kW heat source associated with one storage room is uniformly distributed along the length of the room. The 2D model also prohibits heat transfer along the axis of the room which is only approximately true for the real situation. Additional detail for the 2D model is given in Section 2.

3.2.1 Comparison with Three-Dimensional Results

Calculated points from the 2D model have been indicated on Figures 3-3 and 3-4, respectively. These results show the variation in repository temperature as a function of depth below the surface of the earth for lines that intersect the repository room and the pillar centerline, respectively. All 2D calculated points compare very well with 3D calculations except those that are within a few feet (≤ 5 feet) of the waste. Therefore, it appears that for the present geometry in a bedded salt formation a 2-dimensional model can be employed to investigate thermal environments at distances greater than a few feet from the high level waste canister.

Results presented in Subsection 3.1.2 indicates that floor temperature as a function of distance down the unit cell varies by only about one degree at the most; further, the 2-dimensional model agrees very well with the 3-dimensional floor temperatures (e.g. see Figure 3-3). Thus, the 2-dimensional model may be used to analyze room environments if an air temperature is used which takes into account the temperature rise associated with the distance traveled by the air through the tunnel prior to entering the cross section of interest.

3.2.2 Impact of Ventilation on Temperatures

Because of the agreement between 2D and 3D results generally, the conclusions for the 3D model with regard to ventilation necessarily apply here as well. Nevertheless it is fruitful to pursue explicit results in this case.

The 2-dimensional model has been executed both for ventilated storage rooms and for closed rooms. The impact of the ventilation on the salt throughout the facility is illustrated by comparing Figures 3-9 and 3-10, which present the rise above the ambient temperatures along the centerline of the pillar as a function of depth below the earth's surface for 1, 5, 10, 20, and 30 years after high level waste emplacement. Some caution should be expressed with regard to these figures. Due to the large ventilation heat sink, temperatures in the vicinity of the storage room are essentially independent of initial conditions and, thus, for the ventilated case, displays of temperature rise are somewhat less useful than displays of the temperatures themselves.

A summary of the maximum pillar centerline temperatures as a function of time for the ventilated (85°F inlet air, $h_c = 0.6 \text{ BTU/hr-ft}^2\text{-}^{\circ}\text{F}$) and non-ventilated rooms is given in Table 3.1.

Table 3-1. Maximum Pillar Centerline Temperature

Time (Yrs)	Maximum Temperature	
	Ventilated	Non-ventilated
1	115	124
5	141	202
10	141	245
20	139	296
30	131	315

Fig. 3-9 TRANSIENT TEMPERATURE DISTRIBUTION
ALONG PILLAR CENTER—LINE.
2-D CASE WITH VENTILATION

Fig. 3-10 Transient Temperature Distribution Along Pillar Centerline. 2-D Case Without Ventilation.

The dramatic impact of ventilation on the bulk salt temperatures is illustrated by these results. The ventilated repository reaches a maximum pillar centerline temperature of about 140°F near the fifth year. This maximum temperature is maintained through about the twentieth year, when it begins to decline. On the other hand, the non-ventilated temperatures continue to increase throughout the entire thirty year period that was investigated, reaching a pillar centerline temperature of 315°F .

A similar dramatic impact on the storage room floor temperatures can be seen in Figure 3-11, which present the floor temperature as a function of time for ventilated and non-ventilated rooms. In this ventilated case the inlet air temperature was maintained at 85°F and the air velocity was assumed to be sufficient to generate a convective heat transfer coefficient (h_c) of $0.6 \text{ BTU/hr-ft}^2\text{-}^{\circ}\text{F}$. The ventilated room floor temperature reaches a maximum of about 106°F at about five years after waste burial. On the other hand, the non-ventilated room floor temperature continues to rise throughout the thirty year period, reaching a temperature of about 300°F .

3.2.3 Parametric Studies

Shown in Figure 3-12 are the results of 2D floor temperature calculations above the waste canister under various conditions. Calculations were made for the non-ventilated case, without radiative heat transfer in an infinite pure salt medium and are shown as Curve 1 in Figure 3-12. Curve 2 displays the effect of using a constant value of the salt conductivity, $K_s = 2.06 \text{ BTU/hr-ft-}^{\circ}\text{F}$ rather than the temperature dependent in Table 2.2. Curve 3 gives the result for $K_s = 2.06$, but explicitly including the steel sleeve around the waste. The effect of radiative heat transfer between ceiling and floor in the room for an emissivity of $\epsilon = 0.9$ is shown in Curves 4 and 5. The effect of describing the region above the room in terms

Fig. 3-11 COMPARISON OF PEAK FLOOR TEMPERATURES
(1976 DESIGN)

Fig. 3-12 FLOOR TEMPERATURE ABOVE CANISTER
2-D MODEL
NO VENTILATION

of an 80%-20% mixture of salt and shale is shown in Curve 6. Each of these changes produces temperature changes of 10-50°F in the room.

3.2.4 Comparison with Previous Analyses

The most complete previous analysis of the thermal effects of high level waste burial in a repository presented by Cheverton and Turner.^{2,3} In order to determine the impact that modifications to the repository design have had on the thermal environments predicted by them, comparisons are presented between the thermal environments computed for the present design (1976) and those computed for the design considered by Cheverton and Turner (1972). The difference between the the two designs are summarized in Table 3.2, and results are presented in Figures 3-13 and 3-14.

Figure 3-13 presents the temperature histories for the pillar at the floor level for the two designs under the condition of a non-ventilated repository. The diversity of the designs makes a quantitative comparison impossible; however, the shapes of the temperature histories are very similar and it can be stated that the environments generated by the 1976 design are less severe than those generated by the 1972 design.

Floor temperature histories for various convective heat transfer coefficients (h_c) were presented in Reference 3 for an inlet air temperature of 74°F. These are compared with the floor temperature history generated for the 1976 design assuming $h_c = 0.6$ and an inlet air temperature of 85°F in Figure 3-14. As demonstrated in the previous subsection, the dominant factors associated with the floor temperature of a ventilated room are h_c and the inlet air temperature. Figure 3-7 shows that the floor temperature for a repository cell

Table 3.2 Parameters in 1972 Design
and 1976 Design

Parameter	1976 Design	1972 Design
Repository Room Size	18' x 18' x 558'	15' x 15' x 1000'
Pillar Width	60'	25'
Canister Power	5.1 kW	4.4 kW
Power generated/area of unit cell	$3.63 \times 10^{-3} \text{ kW/ft}^2$	$3.67 \times 10^{-3} \text{ kW/ft}^2$
Canister Pitch	18'	30'
Pillar Floor Level Below surface\	2000'	1000'

Fig. 3-13 COMPARISON OF NON-VENTILATED PILLAR TEMPERATURES

Fig. 3-14 COMPARISON OF PEAK FLOOR TEMPERATURES

with an inlet air temperature of 74°F and $h_c = 0.4$ should be on the order of 103°F , while that for an inlet air temperature of 85°F and $h_c = 0.6$ should be on the order of 106°F . A more detailed comparison is difficult since the ventilation calculations here explicitly included radiative heat transfer while those of Cheverton and Turner did not.¹² For the ventilation cases, radiant heat transfer may be approximately accounted for with a correction to the convective heat transfer coefficient of about $0.5 \text{ BTU/hr-ft}^2\text{-}^{\circ}\text{F}$.

4. SUMMARY AND CONCLUSIONS

The goals of the present study were to investigate the temperature profiles over 30 years for a specific design of waste storage pilot plant and, in particular, to examine the thermal effects due to ventilation of the storage rooms.

The approach used in this study has been to make 3-dimensional calculations for a unit cell in the center of the facility using boundary conditions to account for the rest. The unit cell calculations were then extrapolated to provide results for the entire ventilated array. The calculations were made using two different heat-conduction codes, HEATING5 and TRUMP, which presently reside on the UCND computers; and the solutions were thoroughly checked for consistency and accuracy.

The results for the unit cell calculations show that the ventilation has a dramatic effect on the temperatures throughout the vicinity of the facility and that these effects are strongly dependent upon the temperature of the ventilating air and upon the heat transfer rates into the room from the floor, ceiling and walls. In a calculation for waste canisters with an initial heat generation rate of 5.1 kW (158 kW/acre), for an air temperature of 74°F and for a convective heat transfer coefficient of

heat produced is removed. The floor temperatures of the ventilated room depend strongly upon the air temperature and the heat transfer coefficient although there is little dependence upon the initial ambient temperatures for the system.

Ventilation results for the entire storage room show that for 70°F inlet air and for a convective heat transfer coefficient of 0.6F BTU/(hr-ft²-°F), maximum floor temperatures can be controlled at approximately 70°F if an air flow rate of approximately 50,000 cfm per storage room is maintained throughout the entire facility.

Calculations for a 2-dimensional representation of the facility show excellent agreement with the 3-dimensional calculations for distances larger than 5 feet from waste canisters. This result is due to the large thermal conductivity of salt and cannot be extrapolated to other formations. Thus results due to more closely spaced canisters of lower power generation where an initial 158 kW is maintained are not likely to be different from those here.

Parametric studies for the unventilated 2-dimensional case show that storage room temperatures depend sensitively upon the thermal conductivity of the surrounding medium and detailed treatment of radiation in the room.

These calculations are limited in a number of ways. For example the parameters governing the heat transfer into the room are not well established. Since the resulting temperature profiles depend strongly upon these coefficients, the calculated temperatures have a resulting degree of uncertainty. Another limitation has been the use of unit cell model which assumes that all unit cells have the same behavior. Although this model is probably adequate for the static case, it provides results which may be too optimistic for the ventilated case. Temperature

profiles for the ventilation of only one or a few rooms cannot be extracted. The effect of heated, sealed rooms upon nearby ventilated rooms is not treated nor the effects of development of adjacent tunnels or other facilities.

A number of questions regarding the thermal operating conditions remain open. The ventilation effects are coupled with the properties and design of the system so that studies for other systems are of considerably interest. For example a reasonable change in storage room dimensions may improve the heat removal by ventilation. Changes in the design of the canister and canister well may also improve the operating conditions. Analysis should also be performed for other geological formations. For example in the non-ventilated case it is known that a lower thermal conductivity of the formation will induce large temperature increases in the vicinity of the waste canisters and storage rooms; however, for a well ventilated system sufficient heat might be removed through the ventilated room to maintain low temperatures in the storage rooms.