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THERMAL ANALYSIS OF NATIONAL RADIOACTIVE WASTE REPOSITORY; BRIEF SUMMARY OF RESULTS OBTAINED THROUGH APRIL 1971

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ABSTRACT

At the proposed National Radioactive Waste Repository at Lyons, Kansas, solidified high-level waste will be placed in thick salt formations 1000 ft below the earth's surface. Heat release from the waste will result in temperature increases throughout the immediate geologic formations. The following several factors influence the permissible temperature rises: (1) thermal instability of the solidified waste; (2) migration of brine; (3) integrity of the mine during operation; (4) integrity of the overlying formations; (5) temperature in freshwater aquifers; (6) temperature of earth's surface; and (7) temperatures beyond the boundaries of the mine. Preliminary thermal calculations indicated the technical feasibility of the repository. More recent analyses have considered the repository in greater detail and have employed updated thermal property and stratigraphy data. The results indicate that all of the criteria can be satisfied, and that a heat load of about 130 kW per acre can be tolerated.

1. INTRODUCTION

Heat is generated in reprocessed reactor waste as a result of radioactive decay. After the solidified waste is buried in the mine, the heat from radioactive decay is dissipated in the salt and surrounding formations and eventually flows to the surface of the earth, where it is transferred to the atmosphere and flowing ground water. A consequence of the subsurface heat release is an increase in the temperature of the mined area and its environs. The temperatures gradually increase and then finally decrease since the heat generation rate in the waste is continuously decreasing. Eventually the heat source will decay to nothing, and the temperatures will return to normal. However, the time scale is thousands of years.

During the period of significant heat release, temperature limitations must be considered to assure mine operability and absolute confinement of the waste. Temperatures can be controlled by placing limitations on the amount of thermal power in waste containers and by varying the spacing between the containers. Factors which influence the allowable heat release rate include: (1) thermal instability of the solidified waste; (2) release

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and migration of brine contained in small cavities in the salt; (3) structural integrity of the mine during operation; (4) structural integrity of the overlying formations; (5) temperature rise in freshwater aquifers; (6) heating of the earth's surface; and (7) temperature increases beyond the boundaries of the mine. Different types of waste with regard to power density and decay rate will be buried in the salt. This report deals primarily with a type of waste referred to as the high level waste.

2. CHARACTERIZATION OF THE WASTE

There are basically two types of waste that must be considered in the thermal analysis. One is referred to as high level waste, which is concentrated reactor fission products and thus is a high gamma emitter. The other is alpha waste, which is primarily miscellaneous materials that have been contaminated with alpha emitters. Both wastes are made up of many different radioactive nuclides, and therefore their decay curves consist of sums of many exponential terms. At the time of burial the decay rate of the high level waste will be somewhat greater than that for the alpha waste, and thus temperatures associated with the former will peak sooner than those for the latter.

For the high level waste the volumetric heat generation rate in a particular concentrate at the time of waste burial will depend upon the fuel enrichment, the rate and degree of fuel burnup, and upon the length of time from reactor discharge to burial. A typical anticipated waste from a light water reactor will correspond to a burnup rate of 30 MW per metric ton and a total burnup of 33,000 MWd per metric ton. Also, 99.5% of the uranium and plutonium will be recovered during reprocessing of the fuel. This waste is presently referred to as the Diablo Canyon waste. Federal regulations restrict the time between fuel reprocessing and burial of the wastes to a maximum of 10 years, and there appears to be an economic advantage in deferring burial for that period of time. However, it is possible that wastes much younger than 10 years will be buried, and thus they must be considered in the thermal analysis.

The high level waste can also be characterized by the chemical and physical form of the solidified product. Oxides, glasses, powdered and solid products are among the variations being considered. Accompanying these variations are significant differences in thermal properties and maximum permissible storage temperatures.

3. CRITERIA RELATED TO THERMAL ANALYSIS

Criteria are required to facilitate interpretation of the thermal analysis results. These criteria are derived from studies that consider the effects of temperature increases on the seven factors mentioned in the introduction. As the calculations associated with the various studies are refined new criteria are fed back for use in the thermal analysis. A set of tentative criteria are listed below.

3.1 Waste Container Dimensions and Temperatures

The waste container dimensions have tentatively been specified as 10 ft long and 6 to 14 in. in diameter. The maximum permissible temperature of the waste is presently specified as the maximum temperature that existed during the waste solidification process. It appears that these temperatures will range between 1100 and 2000°F.

3.2 Mine Dimensions

Dimensions of the rooms, pillars, and corridors are dependent upon many factors in addition to thermal considerations. Eventually the dimensions will be optimized for safety and economics. For the present a reasonable set of dimensions appears to be as follows:

Room and corridor height = 15 ft,
Room, corridor, and pillar width = 30 ft,
Room length = 300 ft.

3.3 Location of Waste Containers

The waste containers must be at least 4 ft from the walls of the room (hole drilling and waste container loading restrictions), and the distance between the top of the can and the floor of the mine is tentatively specified as 8 ft.

3.4 Formation Temperatures

Previous thermal and rock mechanic studies indicate that in order to prevent excessive migration of brine to the containers, ensure stability of the mine during operations, and avoid undesirably high temperatures in adjoining formations and overlying fresh water aquifers, the salt temperatures at positions 8 in. from the can surface and midway between the containers should be no greater than 480 and 390°F, respectively.

4. THERMAL PROPERTIES OF THE GEOLOGIC FORMATION AND OF THE WASTE

The thermal properties of interest for the heat removal analysis are the thermal conductivity, k, and the diffusivity, $k/\rho \cdot c_p$. At the present time there is some uncertainty regarding these properties, particularly with regard to temperature dependence, anisotropy and radiation damage effects. Proposals have been made for obtaining more accurate information than exists, and some work is in progress. In the meantime, estimates of properties have been obtained from the literature, from preliminary experiments, and from data obtained in connection with test holes drilled at the Lyons site.

For many of the two-dimensional calculations the geologic formation is divided into five discrete regions: surface deposits, shale, salt-shale, a disc source imbedded in the salt-shale region, and another region of shale. With the exception of the source, the boundaries were defined by temperature profiles obtained from two test holes at the Lyons site.[1] These profiles are shown in Fig. 1. The thermal conductivities for each of the regions were calculated using the indicated temperature gradients and an estimated geothermal heat flux of 1.3×10^{-2} Btu/hr·ft². More recently the geothermal heat flux at the Lyons site has been estimated on the bases of experimental data[2] to be 2.0×10^{-2} Btu/hr·ft². Thus the thermal conductivities should be increased by about 50% for ambient temperature conditions. However, for most of the calculations discussed herein the lower values were used.

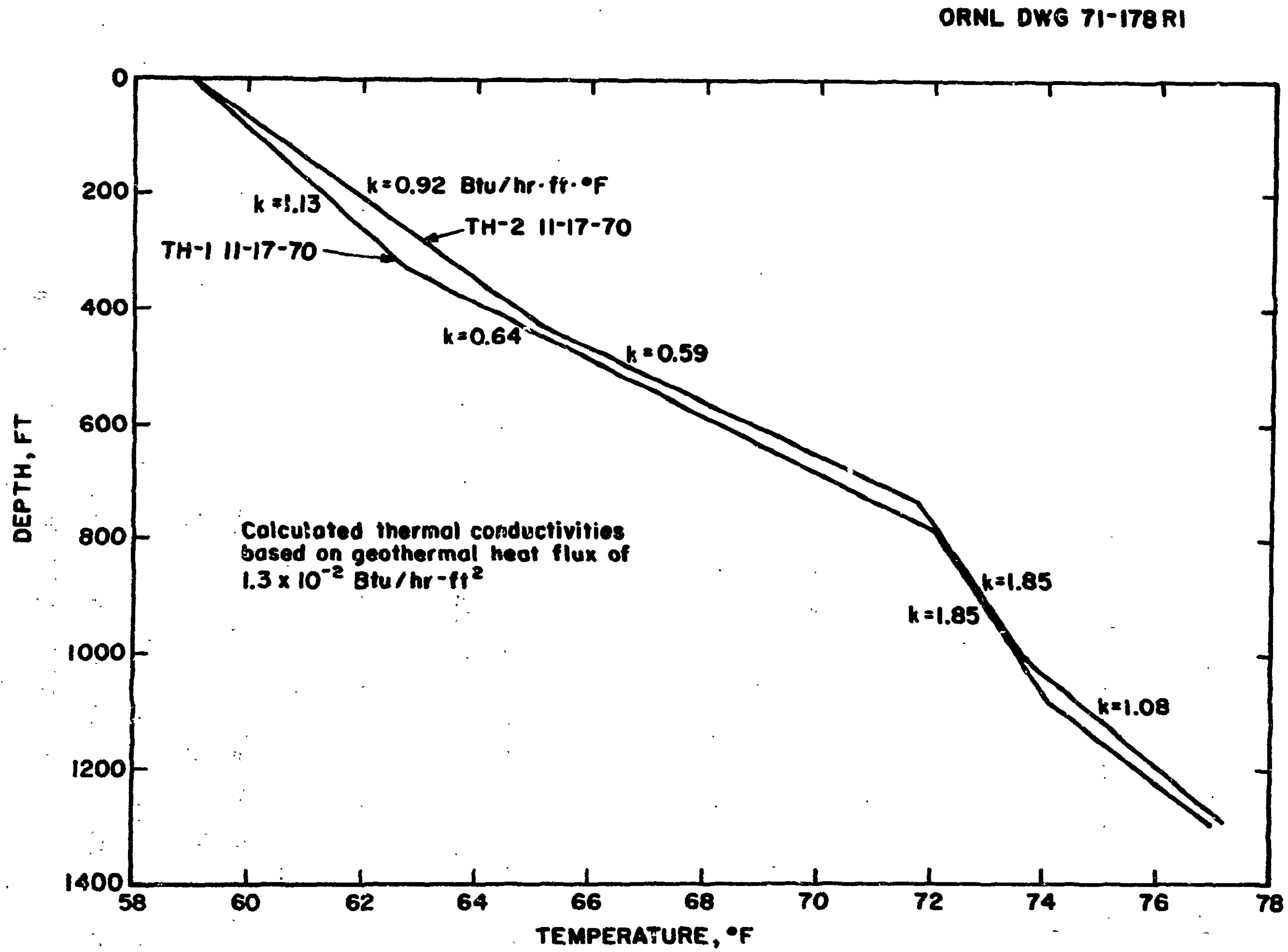

Fig. 1. Temperatures Measured in Two Test Holes at Lyons, Kansas.

The detailed nature of the three-dimensional and some of the two-dimensional problems requires the use of thermal properties for pure shale, pure salt, crushed salt, and the solidified waste. Salt and shale properties were taken from the literature and properties for typical crushed salt and for a particular solidified waste were determined experimentally. In regions where the formation consisted of many narrow laminations of salt and shale the materials were homogenized and the effective thermal conductivity calculated assuming series resistances. For a few cases anisotropy was included by using different conductivities for the vertical and horizontal directions. The ratios of the two values were determined from preliminary experimental data.[3]

The temperature dependence in salt was included in some calculations by considering region-and-time-averaged temperatures throughout the transient calculation. In a few other calculations the temperature dependence was reevaluated at several positions in time.

Significant experimental data are not yet available concerning radiation-induced variations in thermal properties. However, estimates of the effects, which are restricted to the solidified waste and a small area of salt surrounding the waste, indicate no serious thermal restrictions attributed to the radiation effects.

5. CALCULATIONAL TECHNIQUES AND MODELS

The thermal analysis of the repository requires solution of the heat conduction equation for a very complicated geometry and combination of materials. For a problem of this type it is desirable to use finite difference numerical analysis in conjunction with a large and fast computer. Furthermore, the calculational models must be selected with care so as not to overtax the computer and yet provide accurate results. To obtain local temperatures in the burial area of the mine a three-dimensional model is used that considers a unit cell of the mine as shown in Fig. 2. The cell contains room, pillar and waste container detail and extends to a few hundred feet above and below the room

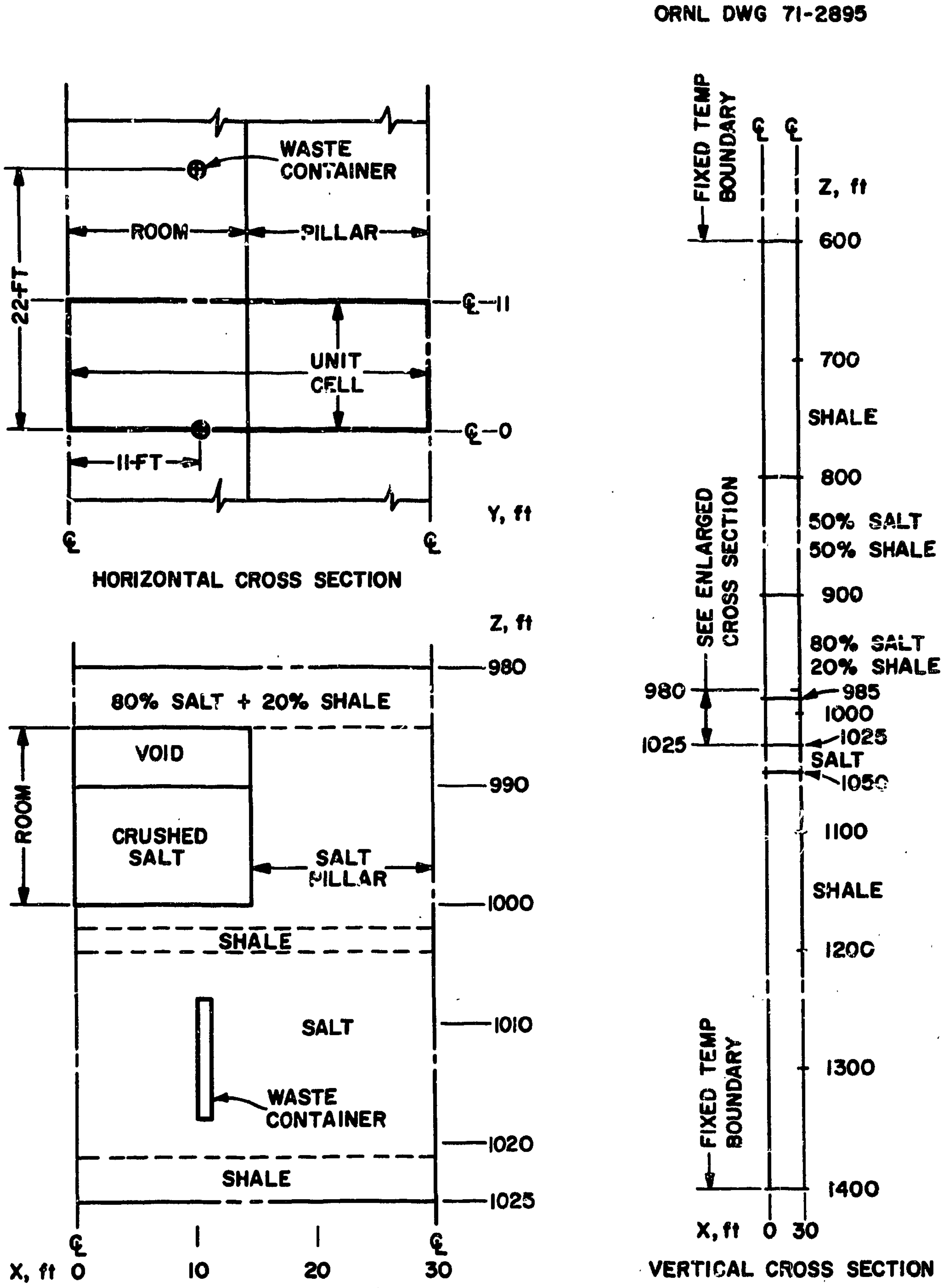

Fig. 2. Three-Dimensional Model of a Unit Cell of the High Level Mine.

floor level. Temperatures in this area peak in about 50 years, and the calculations are restricted accordingly. Nearly the same model can be constructed in two dimensions as shown in Fig. 3. Since a two-dimensional model requires less computer time, greater physical detail and longer periods of time from time of burial can be considered.

For temperatures outside the immediate burial area and extending to the earth's surface, hundreds of feet below the mine level and well beyond the edge of the mine a cylindrical-geometry two-dimensional model, as shown in Fig. 4, is used. The model does not include mine detail, but rather considers a homogenized source zone. This simplification of mine detail is justified for the intent of the calculation and permits the consideration of very long times after burial. This feature is necessary since up to several thousand years are required for temperatures to peak at positions quite some distance from the heat source.

By synthesis techniques the various two- and three-dimensional models provide a consistent set of temperatures throughout the entire repository.

The accuracy of the calculations is continually checked by conventional means and can generally be increased at the expense of computer time. In future studies more complex models will be used. For these models it may be necessary to use a more sophisticated method for solving the heat conduction equation to achieve the same required degree of accuracy. Improved methods are already under development and will be applied when required. At the present time a modified version of the classical explicit procedure is being used. One of the more sophisticated techniques under development is the alternating direction implicit method.

An important means for checking on the accuracy of the overall numerical analysis is an independent study. Such an effort is under way on a small scale and will be amplified in the near future.

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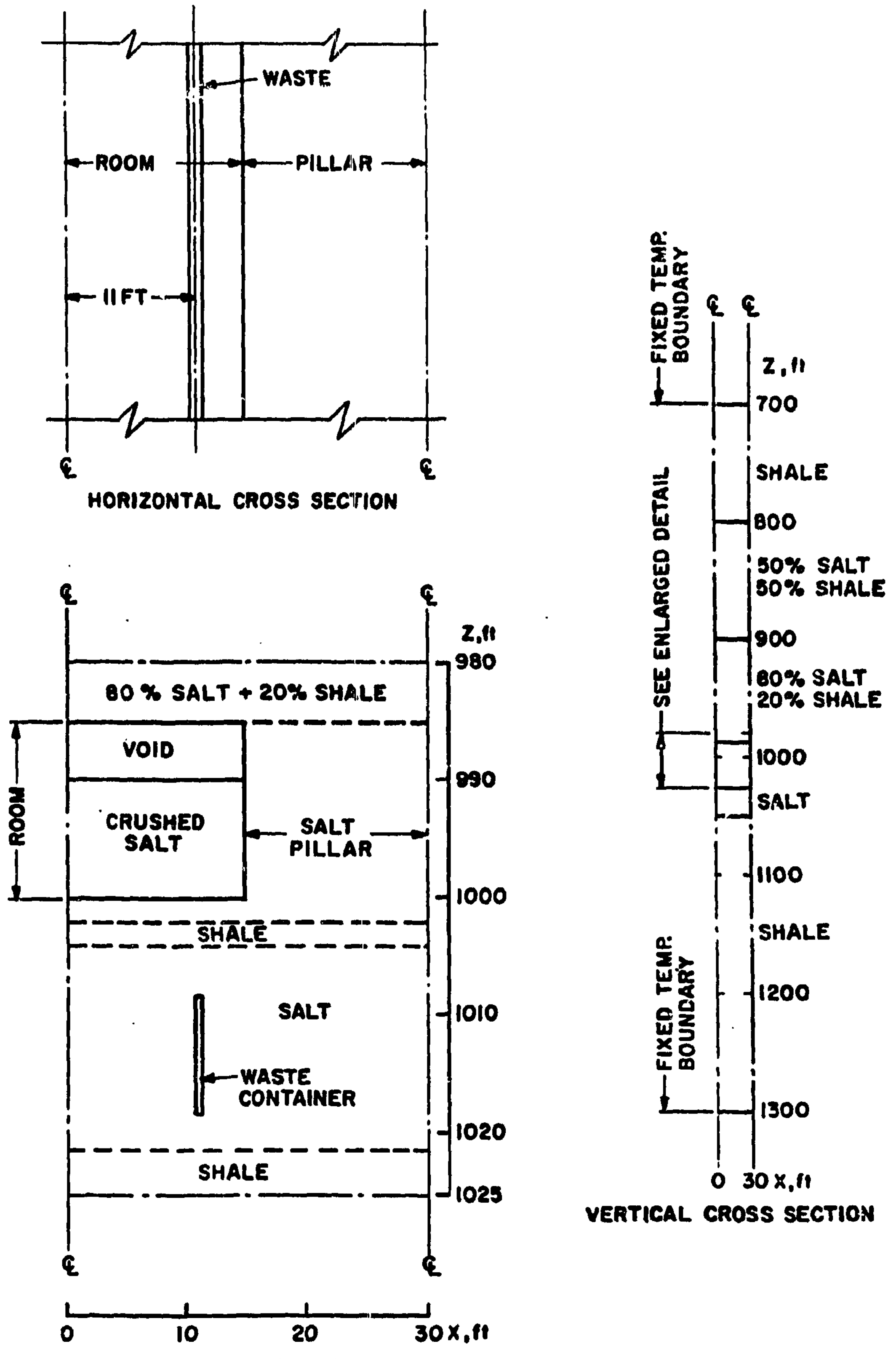

Fig. 3. Two-Dimensional XZ Model of a Unit Cell of the High Level Mine.

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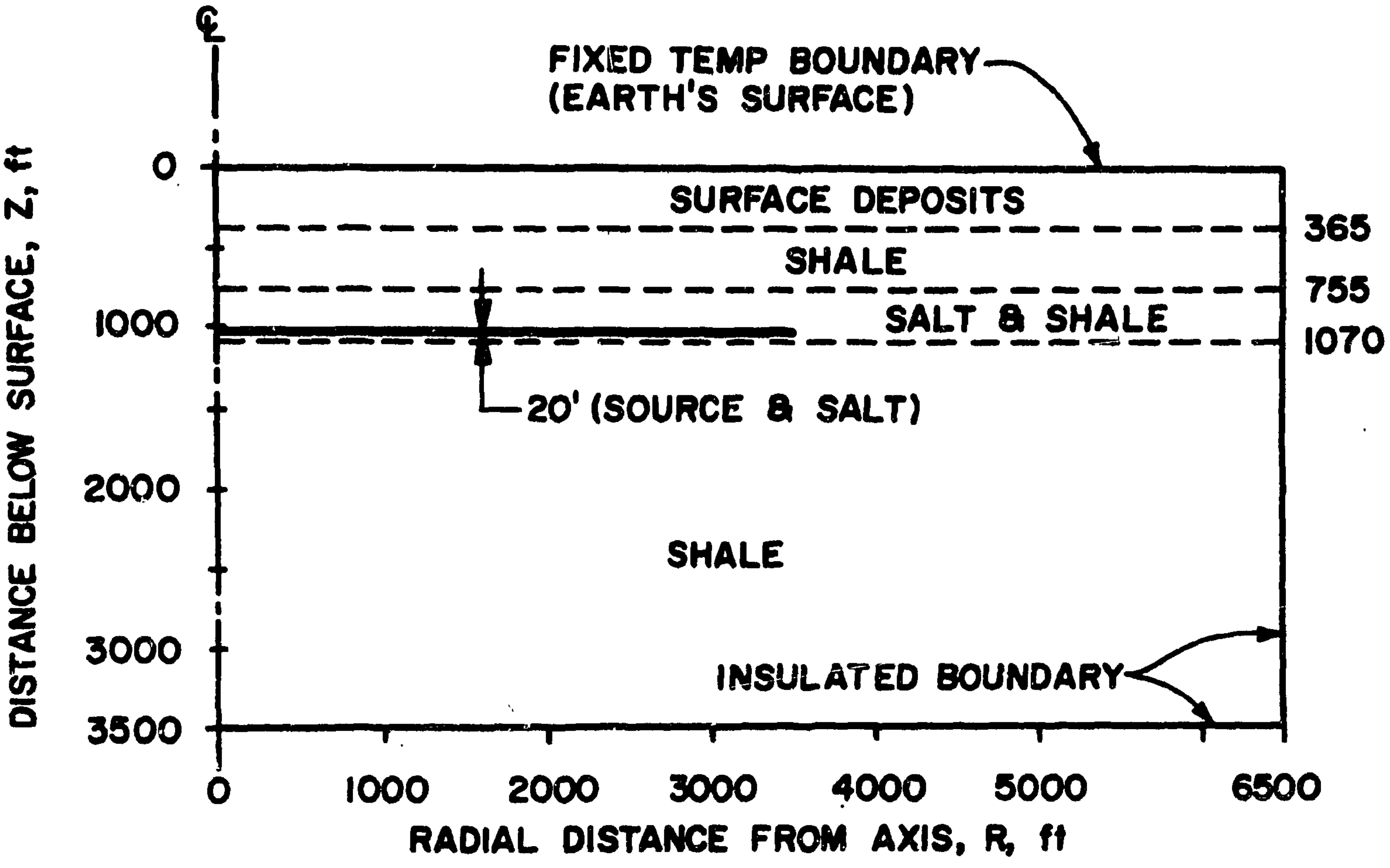

Fig. 4. Two-Dimensional Cylindrical Model of the High Level Mine.

6. TYPICAL RESULTS OF ANALYSIS

Eventually the thermal analysis must consider all reasonable types of waste with regard to type of material, waste container size, initial power level, age, etc. The intent will be to minimize the total cost of solidifying, packaging, shipment, and burial, while achieving the required degree of safety. Thus far calculations have been made primarily for the purpose of demonstrating feasibility and examining the sensitivity of the results to variations in the calculational models, stratigraphy, thermal properties, and solidified waste characteristics. The results indicate that some distance from the local burial area the temperatures in the geologic formations are essentially independent of room, pillar, and waste detail, and even reasonable variations in thermal properties and stratigraphy, provided that the temperature criteria in the burial area are met. The important independent variable is the average initial power density in the mine and thus the initial total power when considering a specific repository size. With regard to temperatures in and close to the waste containers there is a greater dependence on local detail. However, it appears that by varying room, pillar, and waste container dimensions, waste burial arrays, and initial power per container the criteria can always be satisfied. Thus, for the purpose of demonstrating feasibility it is sufficient here to report detailed results for a single but typical case and to discuss generally some of the more important perturbations.

The typical case considered burial of 10-year-old waste from reprocessing Diablo Canyon fuel. This case is further characterized by the dimensions and stratigraphy indicated in Figs. 2 and 4. In addition the waste container diameter was 6 in., and the solidified waste was a calcine-type, which tends to have relatively low thermal conductivity and relatively low permissible temperature. The corresponding three-dimensional model stratigraphy and backfill characteristics were selected so as to result in conservatively high temperatures in the local salt formation, but it was assumed that bedded salt was in contact with the waste container from the outset, a somewhat optimistic assumption. Thermal properties used in the two-dimensional (RZ) calculation were selected to give conservatively high temperatures at the earth's surface and in the aquifers. Furthermore it was assumed that all of the waste in the mine was identical and that it was all buried at the same time. Thermal property temperature dependence, anisotropy, and radiation damage effects were neglected for the base case, but have subsequently been considered.

For a particular set of dimensions and criteria the thermal analysis establishes a maximum permissible initial power level per waste package. The typical case considered herein can, according to the calculations, accommodate 2000 W per waste package and thus about 130 kW per acre. It is desired, although not necessary, to bury the equivalent of about 100 MW of waste in the particular repository. Thus about 800 acres would be required.

6.1 Temperature Distributions in Space and Time

In the following discussion of temperature variations reference is made to temperature changes relative to the original ambient values. The changes are nearly proportional to power level, thus permitting a convenient means for scaling. Temperatures per se can be obtained using the initial geologic formation ambient temperatures given in Fig. 5.

Temperatures in the waste package at the time of burial will actually be significantly higher than the mine ambient temperature. Upon insertion of the package and backfilling of the annular void with crushed salt the package temperature will drop very quickly to the values reported herein.

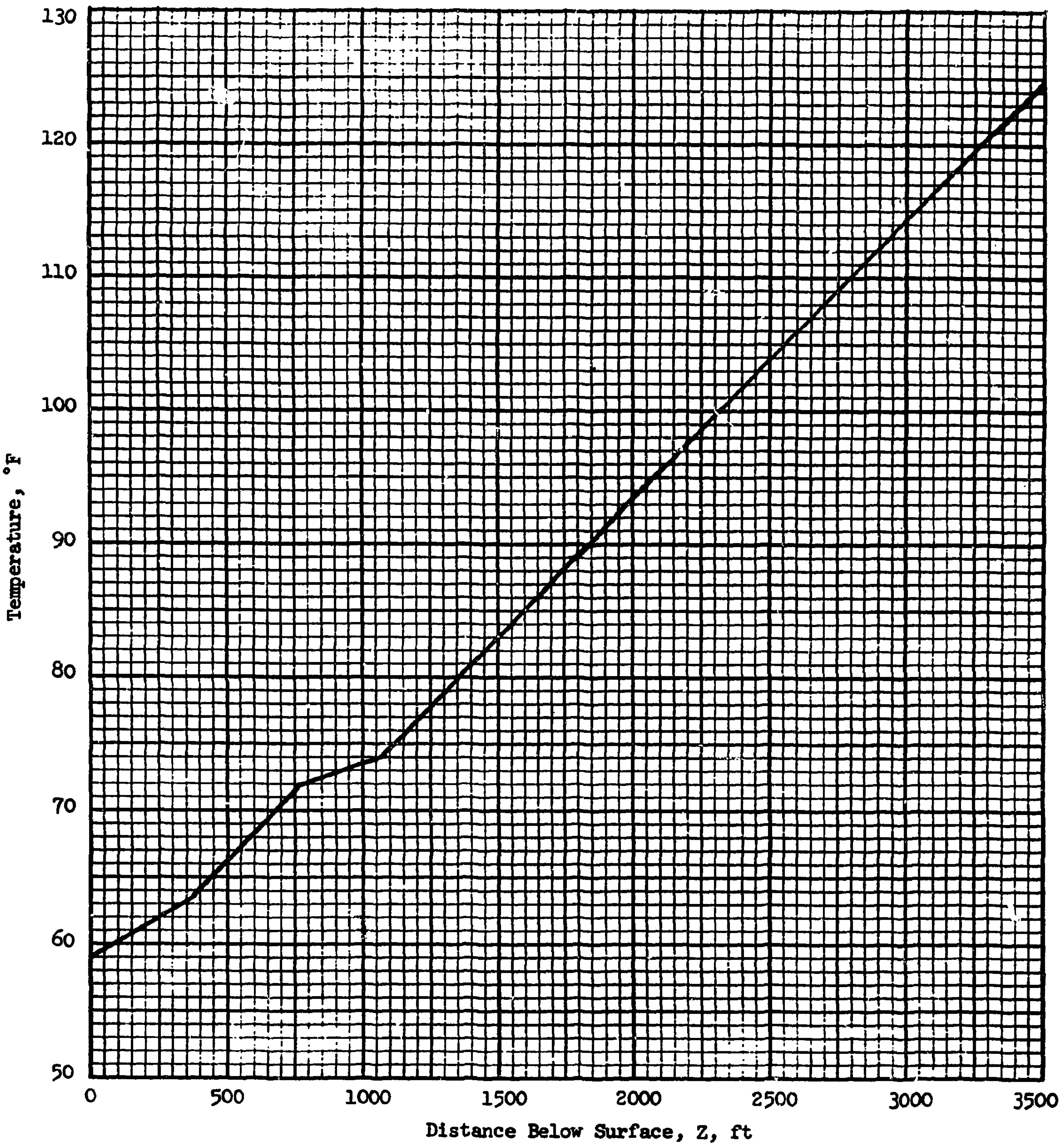

Fig. 5. Geologic Formation Temperatures Prior to Burial of Waste.

6.1.1 Temperatures In the Vicinity of the Mined Area

Figure 6 shows what the time behavior of the temperature rise is at various points of interest in the mined area close to the waste package. As indicated, the temperature at the center of the waste peaks in about 12 years, reaching a temperature rise of 540°F compared to a minimum limiting value of 1000°F. Eight inches from the edge of the container the temperature peaks in 30 years, and the corresponding temperature increase is 365°F compared to a limit of 410°F. Midway between the containers (center of the room) the temperature peaks at 40 years with a temperature rise of 328°F. This is essentially the same as the permissible value of 320°F.

Figure 7 depicts the mine in the XZ plane at Y = 0 and shows isotherms at 50 years, the approximate time at which temperatures in the pillar peak. As indicated, the average peak pillar temperature rise is about 250°F. In the Y direction through the pillar there is very little variation in temperature.

6.1.2 Temperatures Outside the Immediate Mine Area

Temperature increases outside the immediate mine area are shown in Figs. 8, 9, and 10. Each of these figures represents vertical temperature rise profiles extending from the surface of the earth to about 2500 ft below the waste container. Results of the analysis indicate that several years after the entire disposal area is full the radial temperature distributions above and below the mine area are essentially flat to within about 500 ft of the edge of the mine. Figure 8 shows the vertical temperature profiles for this area.

The peak temperature increases in the region containing freshwater aquifers (down to 300 ft below the surface) are in the range <1°F to 30°F, assuming that the aquifers are stagnant. Because of the very low heat flux in this region, only a small flow rate would be required to reduce the aquifer temperature rise to essentially nothing. It is observed that it takes 100 years for a perceptible temperature increase in a stagnant aquifer and 700 years to reach the peak.

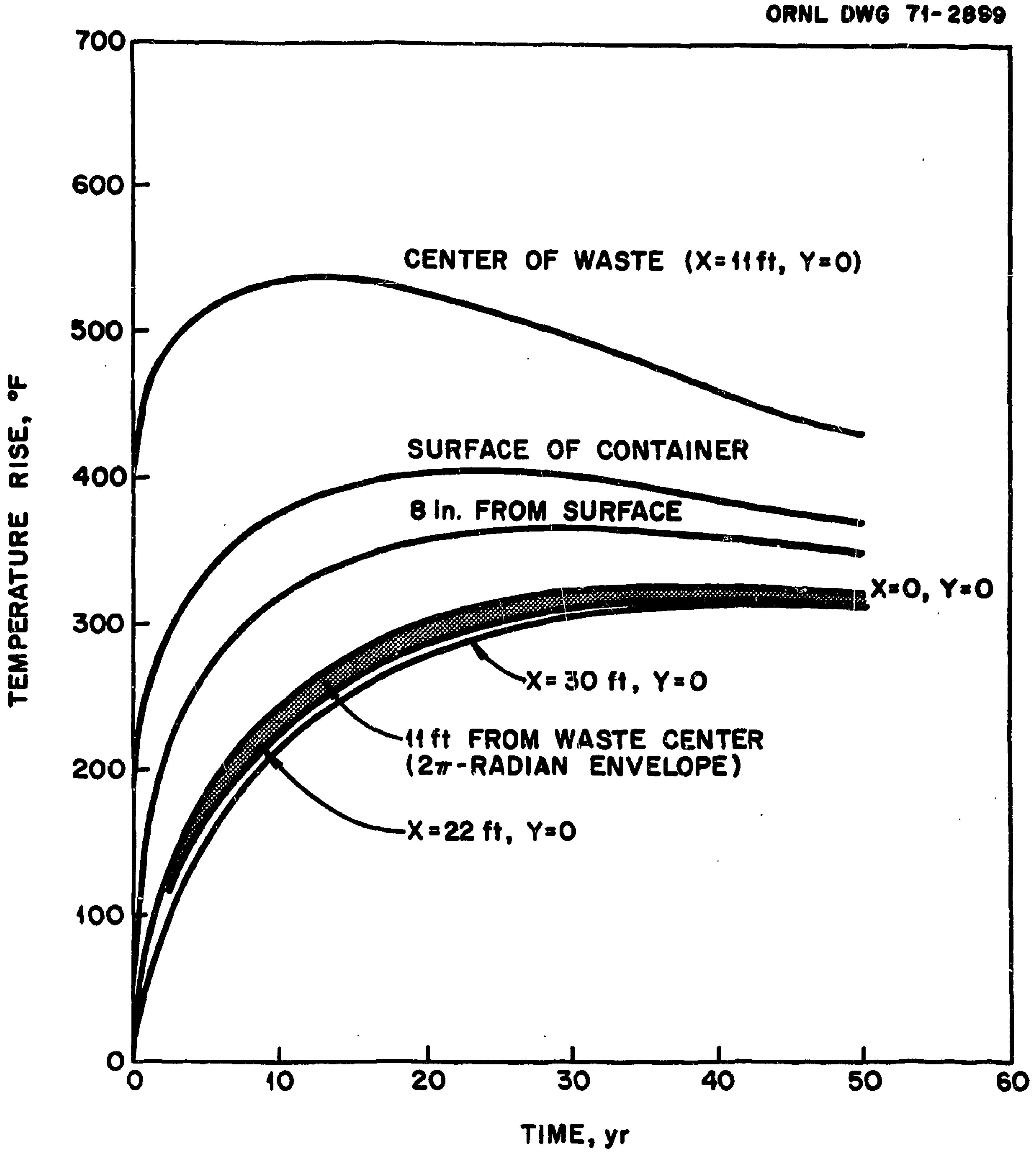

Fig. 6. Temperature Rise vs Time at Z = 1013 ft and X = 0 to 30 ft for 2000 W.

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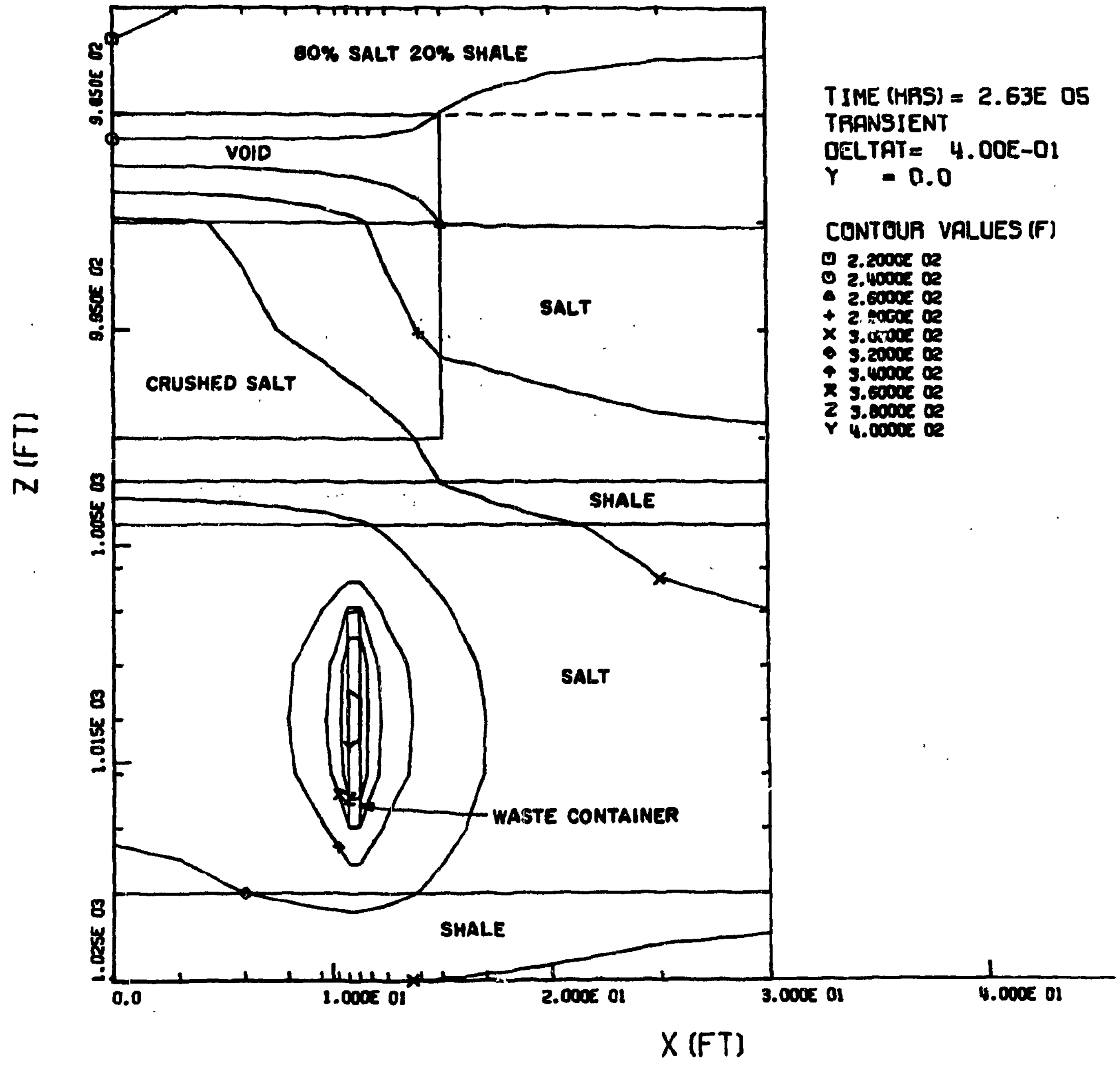

Fig. 7. Isotherms at 30 Years from Three-Dimensional Calculation with 10-Year-Old Waste and 2000 W.

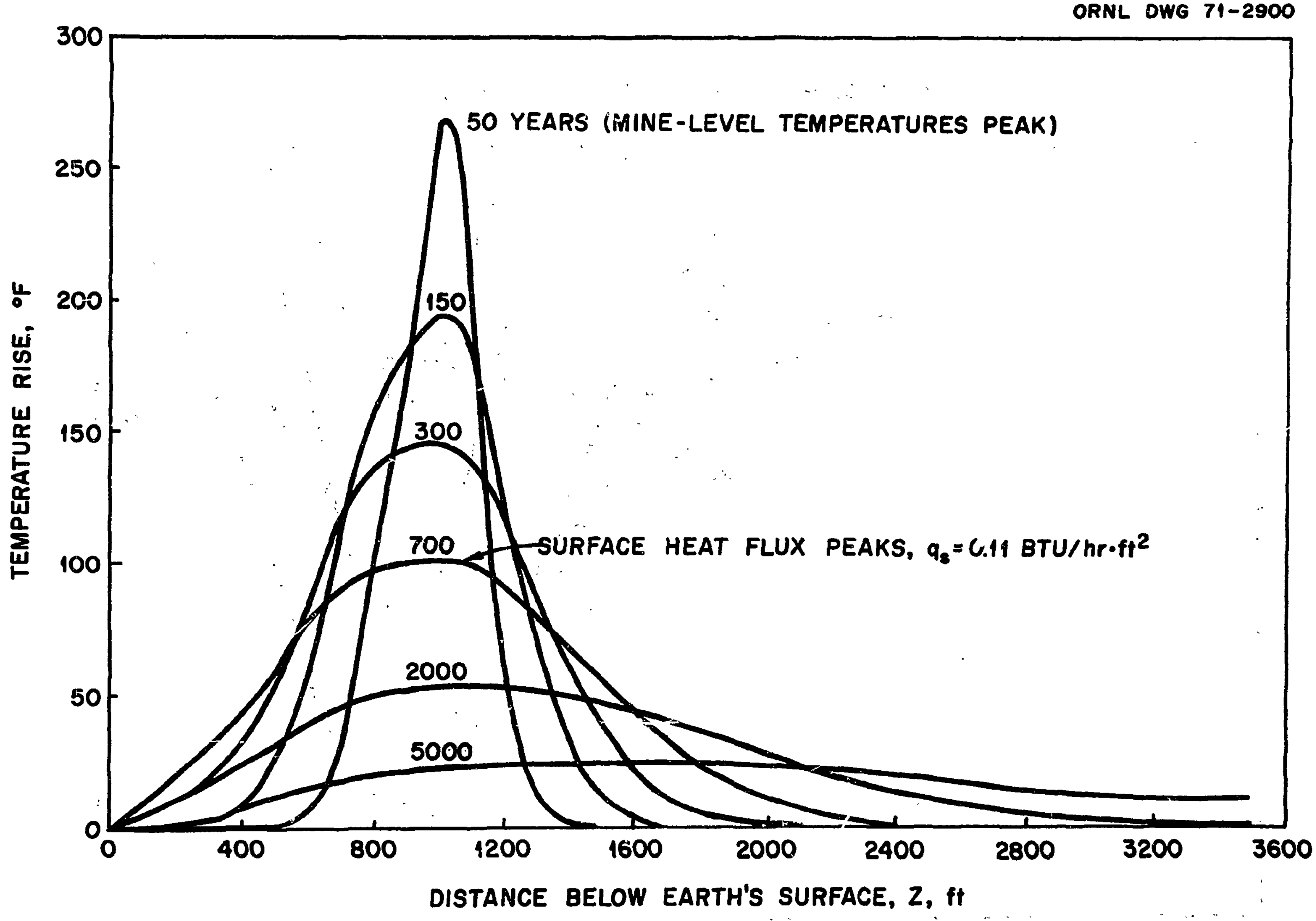

Fig. 8. Temperature-Rise Vertical Profiles at Center of Disposal Area (2000 W).

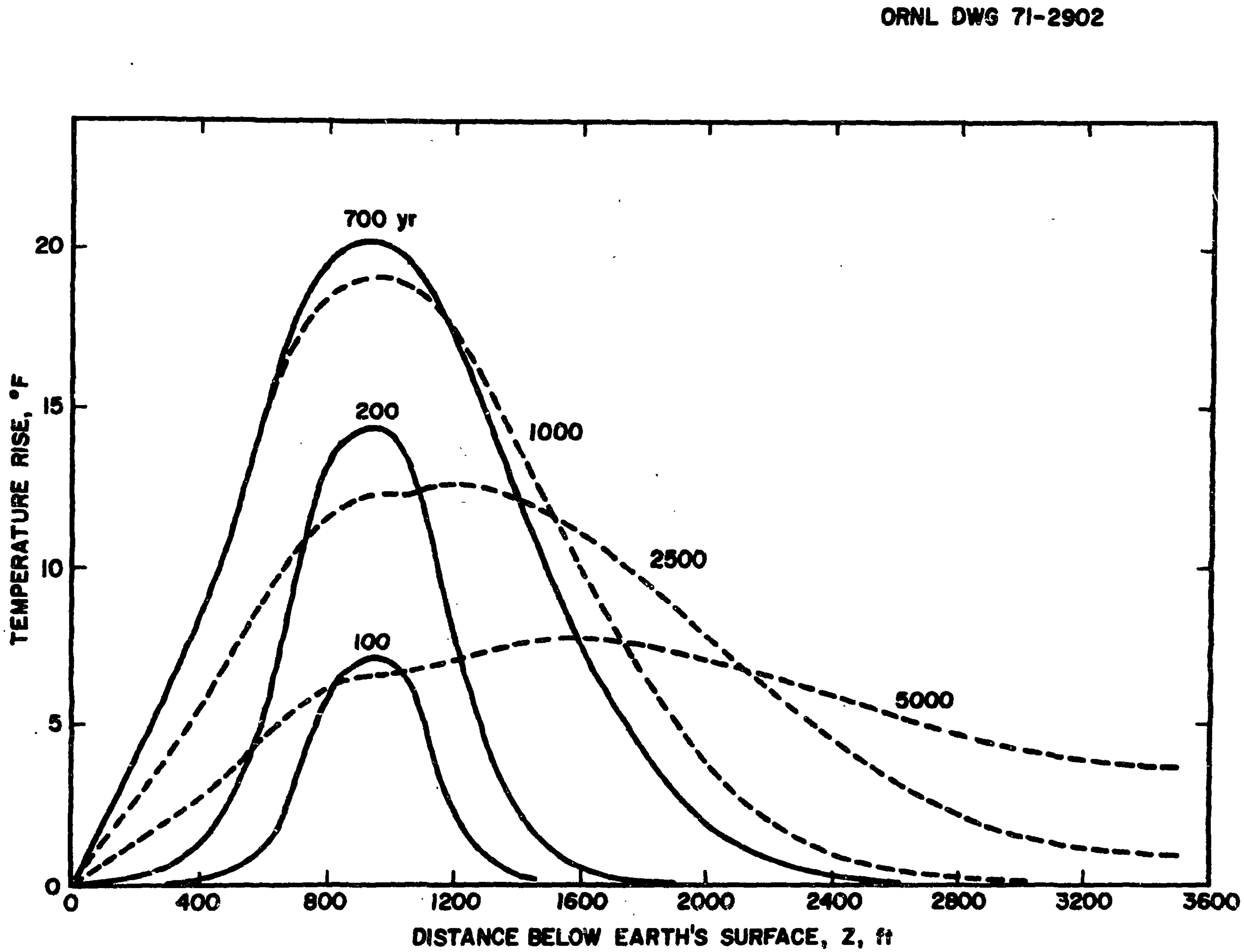

Fig. 9. Temperature-Rise Vertical Profile 500 ft Beyond Edge of Mine (2000 W).

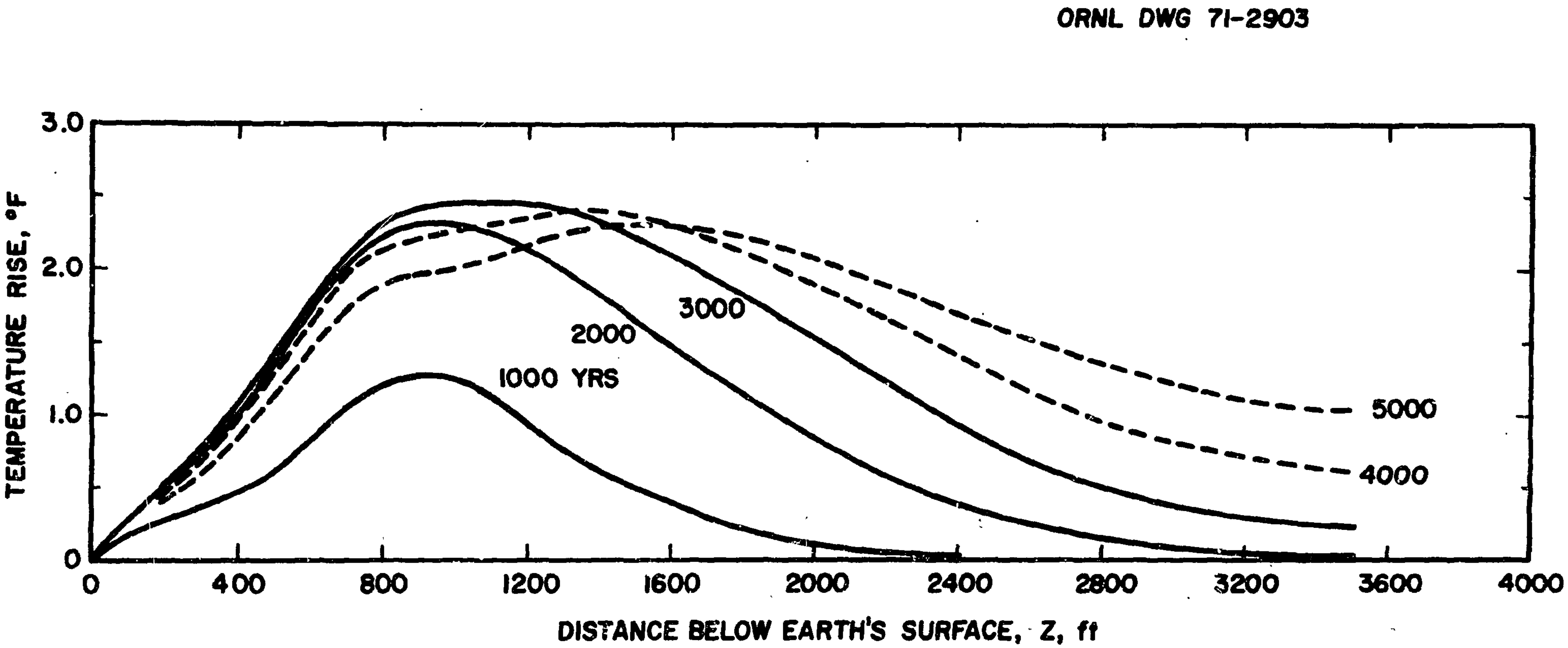

Fig. 10. Temperature-Rise Vertical Profile 1750 ft Beyond Edge of Mine (2000 W).

Figure 9 shows the vertical temperature profiles 500 ft from the edge of the mine. The shortest peak time is about 600 years, and the corresponding temperature rise is about 20°F. At 1750 ft from the edge of the mine (Fig. 10) the minimum peak time is about 3000 years and the corresponding temperature increase is 2.5°F.

Referring back to Fig. 8 it is observed that the surface heat flux peaks in about 700 years. Its value is estimated from the slope of the temperature curve to be 0.11 Btu/hr·ft^2. As indicated in Fig. 11, it takes about 100 years for a noticeable calculated addition, but after reaching its peak in 700 years it persists for hundreds of years. Figure 12 shows how the peak surface heat flux varies with radial distance from the center of the mine. A short distance (500 ft) beyond the edge of the mine the peak value is down by a factor of five.

The surface temperature rise associated with the added surface heat flux has been calculated to be about 0.1°F. It is of interest to note that the "waste" peak heat flux at the surface is about six times the geothermal heat flux (2.0×10^{-2} Btu/hr·ft^2) and about 1000 times less than the solar heat flux.

6.2 Sensitivity Study Results

Sensitivity studies have thus far considered perturbations in the following parameters: (1) shale layer thickness above and below the waste package (see Fig. 2), (2) room content (crushed salt and void, bedded salt and void, all bedded salt), (3) backfill around waste container, (4) mine loading sequence, and (5) thermal conductivity (temperature, anisotropy, radiation damage and general uncertainty effects).

The concern over the existence of shale layers close to the waste package is that they tend to insulate the enclosed region because of the low thermal conductivity of shale compared to that of salt. The layer thicknesses used for the typical case are considered to be maximums. Removal of one or both layers has little effect on the temperatures, the maximum change in the salt being only 9°F (2%).

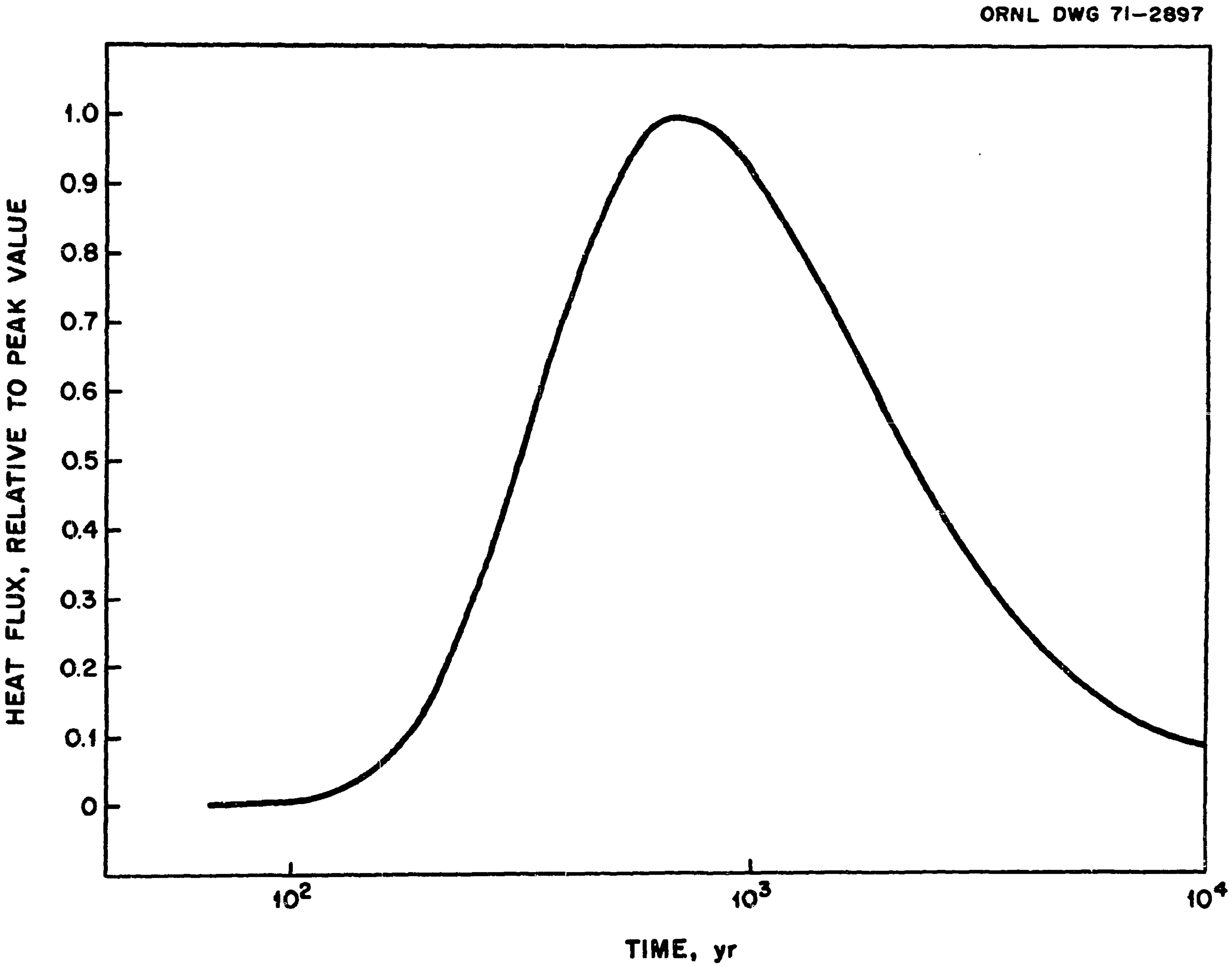

Fig. 11. Relative Surface Heat Flux Above the Center of the High Level Mine.

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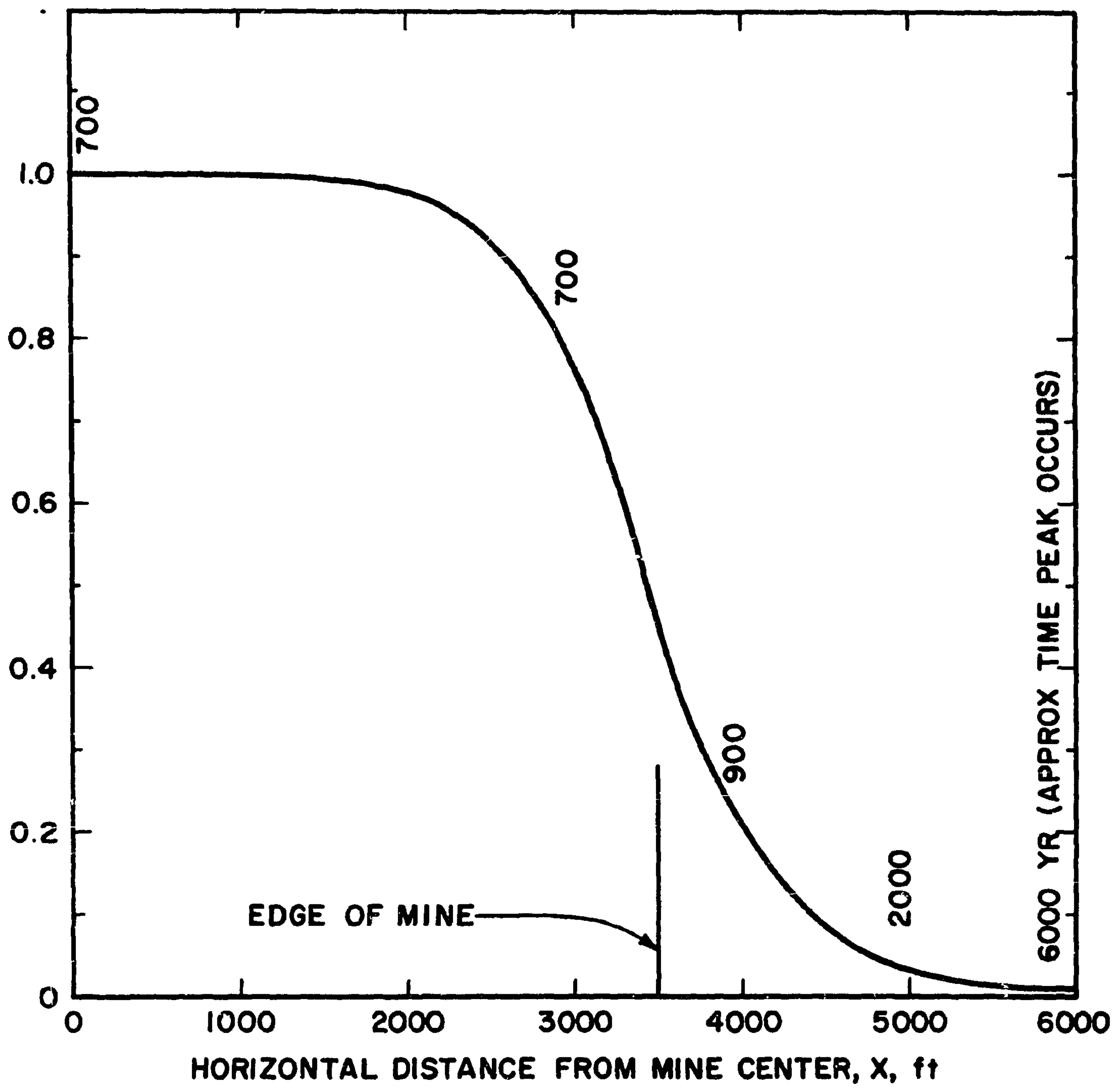

Fig. 12. Peak Surface Heat Flux as a Function of Horizontal Distance from Mine Center.

Variations in room content have a somewhat greater effect. The worst condition expected with regard to temperatures near the waste package is that used for the typical case. With time the void will be replaced with salt, and the crushed salt will recrystallize, improving the thermal conductivity substantially. If this condition existed from the outset, the peak temperature at the container surface would be about 30°F (8%) lower, and at the point of maximum positive difference, which is located a few feet above the pillar, the peak temperature would be about 14°F (6%) higher compared to the typical case.

When the waste package is placed in the salt, there will be an annular clearance around the container that must be backfilled with some reasonably good thermal conductor. Crushed salt has been proposed for that purpose, in which case the annulus thickness might be about 2 in. The thermal conductivity of typical crushed salt is much less than that of bedded salt. If the lower value persisted, the peak temperature rise in the waste would be about 870°F, and it would occur at about 5 years. This condition, although more severe, appears to be acceptable. Actually, based on experiments in the Lyons salt mine, it is expected that the crushed salt will revert to bedded salt within a few months as a result of temperature and pressure effects.[4] Under these conditions the waste temperature rise would peak even sooner but at a value less than 870°F.

A mine loading sequence was simulated in a two-dimensional (RZ) calculation by adding at two-year intervals for 26 years concentric equal-radial-width annuli to make up the disc source shown in Fig. 4. This accelerated loading-rate scheme resulted in very little difference in temperatures compared to the instantaneous loading scheme used in the typical case. Further loading sequence studies must be performed, but it appears that the anticipated sequences will not have a significant effect.

The thermal conductivities used in the typical-case two-dimensional (RZ) calculations and shown in Fig. 1 presumably should be increased by about 50%, based on the recent geothermal flux measurements. This was done in one calculation. Peak temperatures adjacent to and near the center of the disc source were 42°F (16%) less but occurred at about the same time. Away from the source the temperatures peaked sooner, but the percentage differences were smaller.

Thermal conductivity anisotropy in shale was included in a two-dimensional (RZ) calculation assuming that the ratio of horizontal to vertical thermal conductivity was 1.5. Based upon recent experiments[2] the ratio might be this high at 74°F, but at the higher temperatures that will exist the ratio is expected to be less.[5] The results of the calculation indicate a peak temperature rise of 3.3°F at a position 1750 ft from the edge of the mine as compared to 2.5°F without anisotropy. Temperatures close to the source and near the center of the mine all the way to the earth's surface were essentially the same. Thus, it appears that anisotropy effects are negligible.

Gamma radiation of salt presumably will reduce the thermal conductivity and perhaps by a significant amount. However, it is believed at this time that the brine migration through the irradiated salt will reduce the radiation damage by a large factor. Preliminary estimates indicate that the net change in thermal conductivity will not present a significant problem.

The thermal property temperature dependence for the materials in the geologic formation has been considered only by using time-averaged values or conservative extremes for specific regions. Computer programs are being modified to accommodate essentially continuous changes in properties in accordance with the time-wise variations in temperatures. However, based on the results of the sensitivity studies it is believed that temperature-rise variations associated with the thermal property time-dependence will be insignificant.

7. REFERENCES

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