UCID-20091

Thermal Analysis of NNWSI Conceptual Waste Package Designs

W. Stein
J. N. Hockman
W. C. O'Neal

April 1984

HYDROLOGY DOCUMENT NUMBER 566

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Thermal Analysis of NNWSI Conceptual Waste Package Designs*

W. Stein, J. N. Hockman, and W. C. O'Neal
Lawrence Livermore National Laboratory
Livermore, CA 94550

Abstract

Lawrence Livermore National Laboratory is involved in the design and testing of high level nuclear waste packages. Many of the aspects of waste package design and testing (e.g., corrosion and leaching) depend in part on the temperature history of the emplaced packages. This report discusses thermal modeling and analysis of various emplaced waste package conceptual designs including the models used, the assumptions and approximations made, and the results obtained.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

TABLE OF CONTENTS

Abstract i
Table of Contents. ii
List of Tables iii
List of Figures. iv
Summary. 1
Introduction 2
Need for Thermal Analysis. 2
Discussion 3
Vertically Emplaced Canisters. 5
Horizontally Emplaced Canisters. 8
Horizontally Emplaced Boxed Fuel Canisters 11
Fire Test Calculations 12
Thermal Modeling of Waste Package In-Situ Tests. 13
Material Properties. 14
Decay Heat Generation. 15
Results. 16
Conclusions. 17
Recommendations for Future Work. 18
References 19

List of Tables

Table 1 Significant Input Parameters and Output Results for 10 Year Old Waste Thermal Analysis 21

Table 2 Borehole Wall Temperature History Boundary Condition 24

Table 3 Material Properties 25

Table 4 Normalized Decay Heat Curve for DHLW 30

Table 5 Normalized Decay Heat Curve for CHLW 31

Table 6 Normalized Decay Heat Curve for BWR Spent Fuel for Cases 10, 11, & 12 32

Table 7 Normalized Decay Heat Curve for PWR Spent Fuel for Cases 18, 19, 21-23 33

Table 8 Normalized Decay Heat Curve for PWR Spent Fuel for Cases 13-17, and 20 34

List of Figures

Figure 1: Reference drift and borehole geometry for vertical emplacement. 35

Figure 2: Reference vertical emplacement drift and borehole geometry. 36

Figure 3: Reference drift and borehole geometry for horizontal emplacement of spent fuel. 37

Figure 4: Reference drift and borehole geometry for horizontal emplacement of DHLW and CHLW. 38

Figure 5: Reference access drift geometry for horizontal emplacement. 39

Figure 6: Vertically emplaced PWR spent fuel canister with 14 radial heat conducting fins separating the consolidated rods. 40

Figure 7: A portion of the finite element mesh for the axisymmetric model used in the thermal analysis of a vertically emplaced CHLW package. The 2D mesh is rotated 360 degrees about the y-y axis to produce the axisymmetric model shown on the far left. 41

Figure 8: Vertically emplaced CHLW waste package for Cases 5 - 9. 42

Figure 9: CHLW package dimensions as modeled for TACO2D analysis, Cases 5 - 9. 43

Figure 10: Dimensions of vertically emplaced CHLW axisymmetric model, Cases 5 - 9. 44

Figure 11: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 5. 45

Figure 12: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 6. 46

Figure 13: Temperature histories of waste package components and host rock for vertically emplaced CHLW with loose crushed tuff packing, Case 7. 47

Figure 14: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 8. 48

Figure 15: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 9. 49

Figure 16: Vertically emplaced BWR spent fuel waste package, Cases 10 -12. 50

Figure 17: BWR spent fuel package dimensions as modeled for TACO2D analysis, Cases 10 - 12. 51

Figure 18: Dimensions of vertically emplaced BWR spent fuel axisymmetric model, Cases 10 -12. 52

Figure 19: Selected temperature histories for vertically emplaced BWR spent fuel, Case 10. 53

Figure 20: Temperature histories of waste package components and host rock for vertically emplaced BWR spent fuel, Case 11. 54

Figure 21: Temperature histories of waste package components and host rock for vertically emplaced BWR spent fuel, Case 12. 55

Figure 22: The finite element mesh of the infinite cylinder model used for the thermal analysis of horizontally emplaced PWR spent fuel with 24 fins, packing and a borehole liner. 56

Figure 23: PWR spent fuel nuclear waste package for Cases 13 - 21. 57

Figure 24: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 13. 58

Figure 25: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 14. 59

Figure 26: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 15. 60

Figure 27: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 16. 61

Figure 28: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Cases 17 and 18. 62

Figure 29: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 20. 63

Figure 30: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 21. 64

Figure 31: One fourteenth cross section of waste package finite element mesh for use in TACO2D analysis of Case 19. 65

Figure 32: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with six internal fins, Case 13. 66

Figure 33: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with six internal fins and 15 cm of compressed tuff packing, Case 14. 67

Figure 34: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with 15 cm of compressed tuff packing, Case 15. 68

Figure 35: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with six internal fins, Case 16. 69

Figure 36: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with twelve internal fins, Case 17. 70

Figure 37: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with twelve internal fins, Case 18. 71

Figure 38: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with fourteen internal fins, Case 19. 72

Figure 39: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with 24 internal fins, 15 cm compressed tuff backfill, Case 20. 73

Figure 40: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with twelve internal fins, 15 cm compressed tuff backfill, Case 21. 74

Figure 41: Overpacked DHLW package for Cases 1 - 3. 75

Figure 42: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 1. 76

Figure 43: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Cases 2 and 3. 77

Figure 44: Temperature histories of waste package components and host rock for horizontally emplaced DHLW, Case 1. 78

Figure 45: Temperature histories of waste package components and host rock for horizontally emplaced DHLW, Case 2. 79

Figure 46: Temperature histories of waste package components and host rock for horizontally emplaced DHLW, Case 3. 80

Figure 47: Overpacked CHLW package, Case 4. 81

Figure 48: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 4. 82

Figure 49: Temperature histories of waste package components and host rock for horizontally emplaced CHLW, Case 4. 83

Figure 50: PWR spent fuel nuclear waste package, Case 2. 84

Figure 51: Model for calculating temperatures inside borehole. 85

Figure 52: Model for calculating borehole wall temperature. 86

Figure 53: Temperature histories of waste package components and host rock for horizontally emplaced pre-consolidated (boxed) PWR spent fuel, Case 21. 87

Figure 54: Temperature histories of waste package components and host rock for horizontally emplaced unconsolidated intact PWR spent fuel, Case 22. 88

Figure 55: 2D axisymmetrical model used for the fire test simulation. 89

Figure 56: Selected temperature histories for the computer simulated fire test of a BWR spent fuel package (initial power of 3.42 kW). 90

Figure 57: Temperature histories of host rock due to a 3.3 kW heater placed in a 30.5 cm (12 inch) borehole. 91

Figure 58: Temperature histories of host rock due to a 3.3 kW heater placed in a 50 cm borehole. 92

Figure 59: Reference Waste Package Design. For defense high-level waste and commercial high-level waste, the reference design consists of 304L pour canisters with no overpacks and no packing. For spent fuel, the reference design canister is one cm thick 304L with no overpack and no packing. The reference emplacement configuration is vertical emplacement beneath drift floors. 93

Summary

Lawrence Livermore National Laboratory is involved in the design and testing of high level nuclear waste packages as part of the U.S. Department of Energy's Civilian Radioactive Waste Management Program and the Nevada Nuclear Waste Storage Investigations (NNWSI) project.

A number of waste package conceptual designs have been developed for the disposal of spent fuel and high level wastes in tuff in the unsaturated zone at Yucca Mountain located at the Nevada Test Site. In the reference repository designs, the waste packages are emplaced several hundred meters below ground level, either vertically in the floor of access tunnels (reference) or, alternatively in horizontal boreholes extending from the sidewalls. The package generally consists of the waste form placed in a stainless steel canister which in turn may be surrounded by a metallic overpack and a carbon steel borehole liner. Waste forms considered included defense high level waste (DHLW), commercial high level waste (CHLW), and spent fuel from boiling water reactors (BWR) and pressurized water reactors (PWR).

Many aspects of the waste package function require knowledge of the temperature history of the waste package components and environs over time periods up to 1000 years. Preliminary thermal analyses of several package design concepts and the near field host rock have been made using the TACO2D two dimensional finite element computer code.

Package design concepts were evaluated with variations in package dimensions, decay heat, package spacing, internal fin arrangements and overpack arrangements. In general peak waste temperatures are reached in several years after emplacement and peak temperature in tuff within several meters of the package is reached in less than 50 years. The peak temperatures of the reference waste package conceptual designs do not exceed the adopted thermal limitations of the waste forms.

This report summarizes a suite of case studies performed in support of the conceptual design development, documents the techniques and assumptions adopted for these preliminary analyses, and recommends future work which will be necessary to support the evolution of more definitive designs. In

particular, it is recognized that detailed three dimensional modeling of internal package components and the near field environs will be necessary and more careful treatment of heat dissipation mechanisms should also be employed.

Introduction

The Nevada Nuclear Waste Storage Investigations (NNWSI) is part of the U.S. Department of Energy's Civilian Radioactive Waste Management (CRWM) Program. The Waste Package task of the NNWSI Project is working towards the development of multibarriered packages for the disposal of spent fuel and high-level waste in tuff in the unsaturated zone at Yucca Mountain located at the Nevada Test Site (NTS). Lawrence Livermore National Laboratory (LLNL) is responsible for the design, modeling and testing of the waste forms and barriers leading to the final waste package designs and specifications. The final engineered barrier system design may be composed of a waste form, canister, overpack, borehole liner, packing and the near field host rock, or some combination thereof. This report addresses thermal analysis of several waste package design concepts in the candidate repository host rock.

Need for Thermal Analysis

Many aspects of waste package design and testing depend in part on the temperature environment to which the emplaced packages will be exposed. Information produced by thermal analysis is needed for the following reasons.

- To demonstrate that designs will not exceed maximum temperature criteria for the various waste forms: 773 K (500°C) for DHLW glass, 673 K (400°C) for CHLW glass, and 623 K (350°C) for Spent Fuel;

- To provide projected temperature histories for materials selection;

- To assist in the verification of the performance analysis code, WAPPA [1];*

* (WAPPA is a one-dimensional code designed to calculate the corrosion and leaching of the various waste package components and to calculate the eventual breaching and the release rate to the repository. WAPPA consists of five process submodels including the radiation, thermal, mechanical and leach submodels.)

- To provide temperature boundary conditions for the performance analysis code;
- To provide the temperature environment for transportation, handling, storage and retrieval analyses;
- To calculate approximate time periods of steam/water contact with waste package;
- To provide temperature histories for corrosion testing;
- To provide temperature histories for waste form release rate testing;
- To provide temperature histories and boundary conditions for very near field steam/air/water porous flow calculations;
- To provide the temperature field for thermal stress analysis of waste packages and very near field host rock;
- To predict temperatures which would occur in canister fire tests.

Discussion

Waste package designs have been developed for two basic emplacement configurations: 1) the reference vertical emplacement of individual packages in holes drilled vertically in the floor of drifts (tunnels), and 2) the alternative horizontal emplacement of multiple packages in much longer holes drilled horizontally from drifts. The horizontal holes have a carbon steel liner to keep the hole open during emplacement and maintain capability for retrieval operations. Vertical holes may not require a liner.

The waste package designs accommodate three basic types of high level waste: DHLW, CHLW and Spent Fuel. Both DHLW and CHLW are in the form of glass which has been poured into a stainless steel pour canister. The alternative designs consist of placing the pour canisters inside overpacks which are designed to be the primary containment barrier.

There are two types of spent fuel rods, pressurized water reactor and boiling water reactor, with a number of different lengths for each. The canister designs for these waste forms consist of consolidating the rods into a canister or accommodating pre-consolidated "boxed" fuel rods. Alternative spent fuel (SF) designs employ the use of a backfill which is designed to reduce the release rate after the overpack has corroded through. The present preferred backfill design employs an outer "container" of backfill, approximately 15 cm thick, consisting of either crushed and pressed tuff, or crushed and pressed tuff containing 15% iron bearing smectite clay as a binder. The backfill may be prepackaged in a metal container.

Areal Power Density

For each possible arrangement of wastes in the repository, an areal power density, APD, was calculated and tabulated in Table 1. This power density represents the total repository decay heat generated by the wastes at the time of emplacement divided by the repository size in acres. Arrangements and basic dimensions of the various repository designs are given in reference 2 and shown in figures 1-5. The APD for horizontal and vertical boreholes is calculated as:

Horizontal Emplacement

$$APD = \frac{4047 \left[\frac{m^2}{Acre}\right] (200m - EDS) \times P \times \left\{1 + \frac{ADC - 2ADS}{BS}\right\}}{L \times (PS + ADC) \times 1/2 \times EDC}$$

Vertical Emplacement

$$APD = \frac{4047 \left[\frac{m^2}{Acre}\right] \times P \times \left\{1 + \frac{ADC - 2ADS}{BS}\right\}}{(PS + ADC) \times EDC}$$

ADC ≡ Access Drift Spacing [m]

ADS ≡ Access drift to borehole standoff [m]

EDC ≡ Emplacement drift spacing [m]

EDS ≡ Waste to emplacement drift standoff [m]

BS ≡ Borehole spacing [m]

P ≡ Average power per package [kW/pkg]

PS ≡ Panel spacing [m]

L ≡ Package length [m/pkg]

We are using TACO2D [3], a two-dimensional implicit finite element code to analyze the package designs. TACO2D requires temperature dependent material properties data, a mesh representing the physical geometry and the time dependent thermal loading of the waste form as input. Code output consists of temperature histories at all nodes of the mesh. Results obtained with TACO2D have shown good agreement with the results from other one- and two-dimensional codes (e.g., WAPPA).

Vertically Emplaced Canisters

Thermal calculations have been made for both CHLW and BWR consolidated spent fuel for vertical emplacement. Figure 6 shows a typical vertically emplaced PWR spent fuel canister. This particular design employs a heat conducting space frame separating the consolidated spent fuel rods into fourteen distinct compartments. The radial portions of the space frame serve as heat conducting fins which act to lower the peak fuel temperature.

The vertical emplacement scheme allows for packages to be emplaced in boreholes drilled vertically in the access drift floor. It is difficult to accurately model vertically emplaced waste in two dimensions but even more difficult to model the packages in three dimensions. For analyses of conceptual designs, we elected to use a 2D axisymmetric model modified from the standard cylindrical shape to an hour-glass shaped model. Figure 7 shows the mesh used for the analysis of a CHLW canister vertically emplaced in a repository. The smaller of the two radii shown represents the distance defined by one-half the package pitch. The larger radius represents the radius of a circle whose area is the same as that of the rectangle defined by the drift pitch and the package pitch.

This allows a package to see the thermal effects of adjacent packages at a time much sooner (and more conservatively) than would be experienced had the cylindrical axisymmetric model been used. Similarly, far field effects are preserved since the same amount of rock is available as a heat sink. The heat

flux which would in reality discharge into the host rock between drifts in a horizontal direction is forced by the model to flow in a vertical path with the total volume of tuff available as a heat sink in the far field being identical in either case. Also, at the 50 year point the numerical analysis was interrupted and the air properties in the equivalent drift volume were replaced with properties for crushed tuff. The analysis is then completed out to 1000 years. It should be noted that LLNL is mainly concerned with the waste package so that accuracy in temperature distributions within the near-field is the first priority.

The use of the 2D axisymmetric model results in two additional modeling approximations. The access drift is forced into the shape of a solid cylinder with the radius representing the radius of a circle whose area is equal the area of a rectangle (plan view) defined by the drift width and package pitch. When modeling spent fuel, the internal heat conducting fins which normally run axially through the waste are modeled horizontally. The vertical spacing between fins was made approximately equal to the spacing between fins in the horizontal real case. We have not yet fully evaluated the inaccuracy resulting from these two approximations (see p 18, Recommendations for Future Work).

Aside from the modeling approximations, a number of other assumptions and approximations, which apply also to horizontally emplaced canisters, have been made which are thought to have a minimal effect on the accuracy of the results. Forced convection (ventilation) in the drifts was not modeled and could have a significant effect on waste package temperatures.

- The thermal properties of dry air were used for gaps inside the outermost containment barrier.

- The thermal properties of dry air were used for gaps between the outermost containment barrier and the surrounding tuff up to a temperature of 373 K (100°C) at which time the properties of 100% steam were used.

- Heats of vaporization and recondensation of water in rock, and fluid transport were not included in the analyses, however, changes in the thermal conductivity and specific heat due to fluid phase changes in the rock were considered.

- No initial geological temperature gradient in the tuff was used. An initial value of 302 K (29°C) was used throughout the rock with the exception that a constant boundary condition of 295 K (22°C) was used to represent the earth's surface 350 m above the repository. In addition, for the runs modeling vertically emplaced waste a constant temperature boundary condition of 309 K (36°C) was used to represent a plane 350 m below the repository. Calculations showed that effect on the waste package of not including the thermal gradient in the rock was negligible.

- An initial temperature of 373 K (100°C) was assumed for each waste package at emplacement.

- The boiling point of water was assumed to be 373 K (100°C) although estimates show the true boiling point to be near 368 K (95°C) when altitude and impurity effects are considered.

- Generally, all air gaps and spaces (including the access drift) include the effects of conduction, natural convection and thermal radiation by means of a temperature dependent equivalent thermal conductivity. This approach has been successfully used by others [4,5] In some analyses thermal radiation was modeled directly without using an equivalent conductivity (Case 22 and 23, Table 1).

  The equivalent conductivity, K_e is calculated by:

$$K_e = K + K(0.11)(GrPr)^{0.29} + \frac{\sigma(T_1^4 - T_2^4)(r_2 - r_1)}{\{\frac{1}{\varepsilon_1} + \frac{r_1}{r_2}(\frac{1}{\varepsilon_2} - 1)\}(T_1 - T_2)}$$

where the three right-hand side terms represent the material conductivity due to conduction, convection and radiation [16]. The conductivity was input into the computer calculations in the form of a table with conductivity a function of temperature.

- All materials (including the consolidated spent fuel rod assemblies) were assumed to be isotropic.

Five different cases, cases 5-9 of Table 1, of vertically emplaced CHLW were analyzed (Figure 8 shows a drawing of the package). The package has an initial package power of 2210 watts and a canister outer diameter of 32.0 cm. Figure 9 shows canister and waste form dimensions and Figure 10 shows the vertical hour glass model dimensions for the five cases.

Figures 11 - 15 show the time history plots of temperatures at various points in the CHLW package and environs. Table 1 lists the key calculational results as well as significant dimensions of the packages.

Three different cases, cases 10-12 of Table 1, for vertically emplaced BWR spent fuel were analyzed. Figure 16 shows a drawing of the BWR package and each case has a package power of 3420 watts, canister diameter of 57 cm, borehole diameter of 67.2 cm and a drift pitch of 30.5 m. Package pitch, however, varies with values at 9.1, 6.1, and 4.6 meters. Figures 17 and 18 show the modeled canister and hour glass model dimensions.

Figures 19, 20 and 21 show the time history plots of temperatures at various points in the BWR package and environs. Table 1 lists the key calculational results as well as significant package dimensions.

Horizontally Emplaced Canisters

In the horizontal emplacement mode, horizontal boreholes of lengths near 180 m are bored at predetermined spacings perpendicular to the access drifts. A 2D model oriented perpendicular to the axis of a borehole of infinite length was used to model this emplacement mode. This is a reasonable approximation since the ratio of borehole diameter to borehole length is about 200. The

accuracy of results produced by this model are better for packages emplaced near the center of the borehole where end effects do not play a significant role until very late times. For conservatism, current designs are based on the "hottest" package. Figure 22 shows the finite element mesh and model used for a typical thermal analysis of a horizontally emplaced PWR spent fuel package with twenty-four internal heat conducting fins.

In the horizontal configuration, packages are placed end to end in the boreholes. However, even when canisters are touching, space does exist in the borehole volume that does not contain waste (e.g., pintles, partially filled canisters). To account for this in the 2D infinite cylinder model, a combination of two computer runs were used. The first run assumed an infinite cylinder of fully loaded waste (with a power density equal to the actual waste) with no allowance for gaps and partially filled canisters. The second run was identical to the first with the exception of a lower power density to allow for the gaps between canisters where there is no waste. The temperature drop across the waste form and canister from the first run was then superimposed onto the temperature history of the borehole wall from the second run. This super position technique is necessary to approach 3D accuracy using the more efficient 2D code.

Nine different cases, cases 13-21 of Table 1, of horizontally emplaced PWR spent fuel were analyzed. Each canister contains consolidated fuel separated internally by fins similar to those shown in Figure 6. As tabulated in Table 1, various package power levels were analyzed as well as designs varying the number of fins and other significant dimensions. For each case, Figure 23 shows a drawing of the PWR spent fuel package. Figures 24-30 show a quarter cross-section for each PWR horizontally emplaced package, except for case 19, from the canister centerline to the borehole wall. Each case contains six PWR fuel assemblies, except for cases 19 and 21, with seven and four assemblies, respectively.

Case 18 differs from the above PWR cases in that the canister analyzed has a power of 3300 watts, which is higher than the average power, 3050 watts, of the canisters in the borehole. This canister represents the peak expected power that a canister in the borehole may have. The superposition technique

described above is still applied here. The first run modeled an infinite cylinder of fully loaded waste (with a power density based on 3300 watt waste) with no allowance for gaps and partially filled canisters. The second run was similar to the first with the exception of a lower power density that allows for gaps and partially filled canisters and that is based on an average powered canister.

Case 19 is calculated differently from the other above PWR cases. The canister contains 14 carbon steel heat conducting fins with each resulting pie-shaped compartment containing one-half of a fuel assembly. Only a 1/7 portion is modeled as shown in Figure 31. At the borehole wall of Figure 31 a temperature boundary condition was imposed. This temperature boundary condition was calculated by assuming a package heat flux applied at the borehole wall and calculating the temperature history in the surroundings and at the borehole wall. The flux applied was based on 3560 watts which represents the average power of the canisters in the borehole. Table 2 gives the time dependent temperature condition calculated. This case also differs in that the canister has a power of 3850 watts which is higher than the average power of the canisters in the borehole.

Figures 32-40 show the time history of temperature at various locations for the nine PWR spent fuel cases calculated. Table 1 shows significant dimensions and results applicable to each case.

Three different cases, cases 1-3 of Table 1, of horizontally emplaced DHLW packages were analyzed. In each case the package pitch was 3.5 m and the package inside the borehole consisted of DHLW, a canister, overpack material and a liner. Figure 41 shows a drawing of the package and Figures 42 and 43 show a quarter section of the modeled packages. Figures 44-46 show the time history of temperature at various locations for the three DHLW cases. Table 1 shows significant dimensions, data and results applicable to each case.

One case for a horizontally emplaced CHLW package was analyzed. Figure 47 shows a drawing of the package. Package power was 2210 watts and the package consisted of the CHLW, a canister, overpack and liner. Table 1 gives pertinent dimensions and key calculational results for this case, case 4.

Figure 48 shows a quarter section of the modeled package and Figure 49 shows a temperature history of various points in the package and environs.

Horizontally Emplaced Boxed Fuel Canisters

Thermal calculations were made for wastes consisting of pre-consolidated boxed spent fuel from a pressurized water reactor. Three boxes of fuel (6 assemblies) are placed in a canister which is placed end-to-end in long horizontal boreholes at a depth of 400 meters with 52 meter spacing between boreholes, resulting in an areal power density of 40.6 kW/acre. The canister has a 68 cm outside diameter and a 1 cm wall thickness of 304 type stainless steel. Canister length is 4.5 meters. Figure 50 shows a drawing of the package. The canisters are placed in an 84 cm diameter horizontal borehole lined with a 76 cm inside diameter carbon steel liner which has a 1 cm wall thickness. The surrounding material is tuff. Saturated air is assumed in the gap between the borehole wall and the liner. Dry air is assumed between the liner and canister and helium is contained inside the canister.

The PWR spent fuel is 10 years out of the reactor core with a decay power of 1.1 kW per consolidated box and for three boxes resulting in a power of 3.3 kW per canister. This power represents the highest power expected for a PWR canister. As Figure 51 shows, the boxes are 21.42 cm square, [6], and are surrounded by a 1 cm thick carbon steel space frame. The fuel length is 3.89 m.

When fuel is first emplaced in the borehole, the canister and internals are assumed to be at 100°C. Initial temperatures outside of the canister from 400 m below the borehole up to the surface are at 29°C. A surface boundary temperature of 22°C is imposed at time of emplacement. The 22°C boundary condition also is applied to the repository 400 m below the borehole in this model.

The calculations were made in two stages. In stage one a boundary flux is applied to the inner wall of the borehole and temperature profiles throughout the tuff are calculated including the borehole wall temperature. The flux represents the heat generated by the spent fuel. A flux based on 3.05 kW initial spent fuel power was used with this heat flux applied over a 4.5 m

length of borehole. 3.05 kW is the average power of the canisters in the borehole. Because of symmetry only a quarter section of the problem needed modeling. Figure 52 shows a sketch of this. In stage two we model the package inside the borehole with a power of 3300 watts and apply a borehole wall temperature boundary condition calculated in stage one above. The 3300 watts represents the expected peak power of a package in the borehole. Symmetry along the borehole axis exists as well as above and below a horizontal plane through the borehole axis. Figure 51 shows this model.

Calculations from the time of emplacement up to 1000 years were made and are shown in Figure 53. Table 1, case 22 shows the key dimensions and results for this case.

Another case, case 23, was analyzed that is similar to the above boxed case with the exception that the package power in the stage two calculation is one-half that of the above case, or 1650 watts. This problem represents a case where one package containing unconsolidated fuel is placed in a borehole containing consolidated fuel at an average power of 3.05 kW per package.

Figure 54 shows the time history of temperatures at various locations in the package and environs. Table 1 shows significant dimensions and calculational results for this case.

Fire Test Calculations

Regulation 10 CFR 71 governing the transport of radioactive materials requires a fire test of the transportation cask containing the canister to verify that the canister has sufficient strength such that canister breach due to internal overpressure will not occur in the event of a fire of 800°C and 30 minute duration.

A computer-simulated fire test analysis was performed on a canister (without cask) containing BWR spent fuel (see Figures 16 and 17). BWR spent fuel was chosen for the analysis over the other waste forms under consideration since it has the highest thermal loading (3.42 kW/pkg). An

800°C constant temperature boundary condition was applied to the outer surface of the canister for a period of 30 minutes.

The model geometry is shown in Figure 55. Note the internal heat conducting fins which run horizontally through the waste. In reality these fins would run in a vertical direction as they also serve to contain the rods in separate intact fuel assemblies. However, in order to model the problem in the less complex axisymmetric mode (i.e., 2D versus 3D), the fins were again input in the horizontal direction. Each of the air spaces shown allowed for thermal radiation, convection and conduction by means of an equivalent thermal conductivity.

To accurately analyze the problem the initial temperatures (before the fire test) throughout the canister have to be known. In order to accomplish this, the problem was first run with a natural convection boundary condition of 5 W/m^2°C coupled with thermal radiation to a blackbody at 22°C. The problem was run until a steady state condition resulted. The temperatures of the package were then input as the initial temperatures for the simulated fire test with the new 800°C constant temperature boundary condition applied.

Figure 56 shows the results of the TACO2D fire test simulation. The upper curve shows the temperature history of a typical node located in the air space directly above the fuel rods. The maximum temperature reached in 30 minutes was 787°C. The middle curve represents the top of a typical Zircaloy clad fuel rod. The top of the fuel rod reaches a temperature near 705°C in 30 minutes. The lower curve represents the temperature history of the node at which the highest initial temperature occurred. As can be observed the geometric center of the fuel rod bundle was not affected in the relatively short time of the fire test. The calculated temperatures were used in design and structural analyses of the canister [7].

Thermal Modeling of Waste Package In-Situ Tests

Waste Package In-Situ Tests are planned for the NNWSI exploratory shaft that include placing an electrical heater in a cylindrical borehole drilled into tuff material surroundings. The calculations were made using the ICARUS [8] computer code and verified using the TACO2D [3] code.

The problem was modeled in one dimensional cylindrical coordinates with a heat flux applied at the borehole surface and conduction heat transfer into an infinite tuff medium. Two borehole sizes were considered: a 30.5 cm (12 inch) diameter hole and a 50 cm (19.7 inch) diameter hole. In each case heater power (equal to that of a PWR spent fuel canister) was 3.3 kW. The flux at the borehole surface, for use in the calculations, was calculated based on 3.3 kW power distributed over a borehole surface area based on the borehole diameter (30.5 cm or 50 cm) and a length of 4.5 meters. The 4.5 meter dimension represents the reference length of PWR spent fuel canisters emplaced in a horizontal borehole. Initial tuff temperature was 29°C.

Calculations were performed to determine the time required to heat a point, one meter from the borehole surface, to 100°C. At that time the heater is turned off until the borehole surface temperature drops back down to 100°C (from a temperature above 200°C). When the borehole surface temperature reaches 100°C the heater is turned on again.

Figures 57 and 58 give temperature (°C) versus time (seconds) plots for the borehole wall and a point one meter out from the borehole wall for the 30.5 cm and 50 cm boreholes respectively. The figures generally show that it requires over two months to heat a point one meter out from the borehole to 100°C and then after shutoff of the heater it requires approximately one week to cool the borehole wall back to 100°C.

Material Properties

TACO2D requires three properties for every material included in the design in order to complete the calculations. The material properties are density, ρ, specific heat, Cp, and thermal conductivity, K. Before the properties could be researched, however, a number of assumptions and comments concerning the modeling of the problem were necessary:

(1) Dry air (air 1) is assumed to exist between the canister and the overpack.
(2) The density and specific heat for dry air are assumed constant.

(3) 100% humid air (air 2) at atmospheric pressure exists between the overpack and the surrounding tuff up to a temperature of 100°C at which time the atmosphere is assumed to be 100% steam (i.e., any air which may in reality exist is not taken into account). Note: The thermal conductivities for dry air were used in place of humid air values due to a lack of information over the range of temperatures of interest.

(4) The steam is assumed to be pure and consequently its material properties will not show any variation due to whatever may be present in the local groundwater.

(5) Liquid films are recognized to most likely exist up to 100°C on the outside of the overpack as well as on the tuff borehole wall, but the thermal effects of such cases are not considered in the model.

(6) Any effect that nuclear radiation has on the thermal properties of the system materials is not reflected in the data.

(7) The value of thermal conductivity of tuff is taken as constant with temperature for 80% saturated conditions up to 100°C. For the temperature regime beyond 100°C a lower constant value representing the dehydrated condition is used.

(8) Similar assumptions as listed above in item (7) were made for specific heat.

(9) The wastes and the tuff are modeled as isotropic materials.

(10) The convection process associated with the change of phase of a fluid is not taken into account.

(11) When the host rock cools below 100°C, thermal values for 80% saturated tuff are immediately in effect even though it will take many years for the rock to resaturate.

Table 3 lists the material properties used in the thermal analyses.

Decay Heat Generation

Heat generated by DHLW, CHLW, boiling water reactor and pressurized water reactor spent fuel wastes are given in Tables 4-8. The heat generated is given in normalized form with full power (1.0) being generated at time of emplacement. The waste heat generated at time of emplacement is based on 10 year old fuel.

Results

Figures show typical temperature history curves for the different waste forms under specific emplaced conditions. Refer also to Table 1 for a summary of all the significant input and output parameters for the thermal analyses completed to date.

Special attention should be paid to the two sets of analyses completed which gave the thermal effects of the introduction of packing into the design. The first analysis, case 14, encorporated compressed crushed tuff packing 15 cm thick on the radius (k = 0.97 [W/mK]) around horizontally emplaced canisters containing PWR spent fuel. The results showed that with no packing the peak fuel temperature was about 615 K (342°C) but when packing was included the peak fuel temperature was 652 K (379°C) which is above the design limit of 623 K (350°C) for spent fuel.

The second set of analyses (cases 6 and 7) modeled vertically emplaced canisters containing CHLW with and without 14.5 cm of loose crushed tuff packing (k = 0.185 [W/mK] for T < 372 K and k = 0.114 [W/mK] for T > 373 K). The peak centerline temperature for the analysis without the packing was 568 K (295°C). With packing included in the model the peak centerline temperature was near 1123 K (850°C) which is well above the design limit of 673 K (400°C) for CHLW.

Any reasonable amount of packing necessitates redesign of the reference spent fuel canisters to avoid raising the peak fuel temperature above allowable limits. Further analysis showed that a canister containing only four PWR spent fuel rod assemblies (case 21) would be required to satisfy the temperature limit. The thermal penalty of such a design would result in 50% more packages with the additional cost of larger boreholes, packing assemblies and additional handling required per assembly.

Furthermore, an analysis of a horizontally emplaced PWR spent fuel canister with six radial internal heat conducting fins (case 16) can be compared with an analysis of an identically emplaced canister but with twelve fins (case 17). Results show that doubling the number of fins reduces the

peak waste temperature by about 16 K. This may or may not be a significant amount depending on how close the peak temperature of the spent fuel is to the design limit of 623 K (350°C) after uncertainty studies are conducted.

Calculated waste package temperatures for all of the reference and alternative designs are within the temperature limits imposed to avoid waste-form degradation. In the canister design for consolidated spent fuel, the same diameter canister (65 cm) will accomodate up to 18 BWR assemblies (3.42 kW) and 7 PWR assemblies (3.56 kW). For the alternative SF canister with packing, it is necessary to reduce the number of assemblies to 4 PWR (2.0 kW) to avoid exceeding the 350°C limit. The 68 cm canister containing 6 PWR assemblies of pre-consolidated (boxed) spent fuel has a peak temperature of 335°C. Figure 59 shows current reference designs.

Interpretation of the results of thermal analyses shown in Table 1 show that the reference package designs for CHLW and DHLW when emplaced in the reference repository geometry (vertical emplacement) are well below waste form temperature limits. In fact, both CHLW and DHLW canisters could be emplaced at higher areal power density without exceeding temperature limits. The analysis also shows that, depending on detailed configurations and fuel loadings, the reference design spent fuel canisters can be emplaced in the reference repository and not exceed waste form temperature limits.

Conclusions

- The reference designs for SF, CHLW and DHLW have peak fuel temperatures below the design temperature limits.

- A significant thermal penalty may result if a packing is introduced into the waste package design. This effect is highly dependent on the material properties of the particular packing used. To stay within the temperature limits when packing is used, a lower heat output per package (implying more and smaller packages) will be required.

- The use of 6 heat transfer fins in a spent fuel canister with packing reduces the peak temperature by about 70°C.

- Doubling the number of heat transfer fins (from 6 fins to 12) in spent fuel canisters results in the further reduction of the peak fuel temperature by about 16°C.

- Results from the WAPPA thermal submodel compare quite favorably with results from the thermal analyses reported here. The WAPPA thermal submodel predicted temperatures a maximum of 7% higher than the results from TACO2D.

Recommendations for Future Work

Before the conceptual design process is completed, a number of additional analyses will have to be done. Perhaps the most significant of these would be some form of uncertainty analysis. Questions as to the accuracy of the results remain with respect to the two-dimensional modeling of a three-dimensional canister/repository and including possible end effects not considered where boreholes of finite length are modeled as having infinite length. Once the number of conceptual designs is reduced then three-dimensional finite element analysis could be utilized in a more economical way (both time and money) so as to answer some of these questions.

Some preliminary uncertainty studies have already been performed on calculated borehole temperatures for vertically emplaced spent fuel to determine the accuracy of the two dimensional TACO2D calculations compared to three dimensional analyses. It was determined in an extreme case that a two dimensional analysis resulted in a peak borehole temperatures 50°C higher than a three dimensional analysis. To rectify this differential, it is recommended that for vertical emplacement cases (with close borehole spacing) the borehole wall temperature history be recalculated using the three dimensioal code TACO3D. The TACO2D model for the package inside the borehole should then be recalculated using the new wall boundary condition.

In addition, some uncertainty is involved in the choice of material properties used in the calculations. This is due in part to uncertainties in the experimentally measured tuff properties and in part to assumptions concerning air, water and steam behavior near emplaced canisters. Parameter

studies may be used to bound the effects of some of these material property uncertainties.

Other parameter studies should be conducted so that cost effectiveness is reflected in the final designs. Thermal analyses including additional variation in areal power density and canister diameter, are examples of potential studies which, when completed, could influence final designs.

Lastly, the TACO codes should be completely documented using methods acceptable to regulatory agencies [9].

References

1. INTERA, WAPPA: A Waste Package Performance Assessment Model, Prepared by Arthur D. Little, Inc., Draft- ONWI/82/E512-02900/CD-05 (1982).

2. Scully, L. W., Reference Waste Emplacement Geometries, Keystone 6310-83-1, Sandia National Laboratories, Albuquerque, New Mexico, 17 June 1983.

3. Burns, Patrick J., TACO2D - A Finite Element Heat Transfer Code, Lawrence Livermore National Laboratory, Livermore, Ca, UCID-17980, Rev. 2 (January 1982).

4. Davis, B. W., Convection and Thermal Radiation Analytical Models Applicable to a Nuclear Waste Repository Room, Lawrence Livermore National Laboratory, Livermore, Ca, UCID-18103 (January 1979).

5. Southwest Engineering Enterprise, Preliminary Assessment of the Thermal Effects of an Annular Air Space Surrounding an Emplaced Nuclear Waste Canister, Sulphur Springs, Texas, UCRL 15014 (April 1979).

6. Schornhorst, J. R., et al, Conceptual Waste Package Designs for Disposal of Nuclear Waste in Tuff, Westinghouse Electric Corporation AESD, Pittsburgh, PA, ONWI-439 (April 1983).

7. O'Neal, W. C., et al. Nuclear Waste Package Design for the Vadose Zone in Tuff, UCRL-89830, February 1984.

8. Sutton, S. B., Icarus - A Multi-Option Generalized One Dimensional Heat Transfer Code, UCIR-1125 Rev 1 (to be published), Lawrence Livermore National Laboratory, Livermore, CA.

9. Silling, S. A., Final Technical Position on Documentation of Computer Codes for High-Level Waste Management, U.S. Nuclear Regulatory Commission, NUREG-0856, (June 1983).

10. Baxter, R. G., "Description of DWPF Reference Waste Form and Canister," DP-1606 Rev. 1, DuPont, August 1983.

11. "Military Standardization Handbook," MIL-HDBK-5C, September 15, 1976.

12. "Handbook of Tables for Applied Engineering Science," 2nd Edition, CRC Press, 1976.

13. "Structural Alloys Handbook," Vol. 1, Battelle Columbus Laboratories, 1982 Edition.

14. Johnstone, J. K., Peters, R. R., and Gnirk, T. F., Unit Evaluation at Yucca Mountain, Nevada Test Site: Summary Report and Recommendation, SAN83-0372, 1984.

15. Nimic, F. B., Price, R. H., and Schwartz, B. M., Bulk Thermal and Medium Properties of the Topopah Spring Member of the Paintbrush Tuff, Yucca Mountain, Nevada, Sandia National Laboratories.

16. Holman, J. P., Heat Transfer, McGraw Hill Book Co., 4th Edition.

TABLE 1 Significant Input Parameters and Output Results for 10 Year Old Waste Thermal Analyses

	DHLW			CHLW					
Case Number	1	2	3	4	5	6	7	8	9
Directory Number	D50H0.38B	D69H0.56A	D69H0.68A	C50H2.21A	C50V2.21B	C50V2.21C	C50V2.21D	C75V2.21A	C100V2.21A
Emplacement Mode	H	H	H	H	V	V	V	V	V
Areal Power Density [kW/acre]	41.5	56.8	57.3	44.9	42.6	42.6	42.6	63.6	84.5
Package Power at Burial [W]	380	556	680	2210	2210	2210	2210	2210	2210
Canister diam [cm], material	61 SST	81 SST	81 SST	32.4 SST	32.0 SST	32.0 SST	32.0 SST	32.0 SST	32.0 SST
Overpack diam [cm], material	66 SST	86.1 SST	86.1 SST	37.5 SST	-	-	-	-	-
Borehole liner diam [cm] material	72.4 CS	92.4 CS	92.4 CS	43.8 CS	-	-	-	-	-
Packing outer diam [cm], material	-	-	-	-	-	-	61.0 LCT	-	-
Borehole diam [cm]	81.3	101.6	101.6	54.0	42.2	61.0	61.0	42.2	42.2
Borehole pitch [m]	8.8	9.4	11.5	44.0	-	-	-	-	-
Package pitch [m]	3.5	3.5	3.5	4.0	5.9	5.9	5.9	3.91	2.94
Drift pitch [m]	-	-	-	-	30.5	30.5	30.5	30.5	30.5
Number of internal fins, material	-	-	-	-	-	-	-	-	-
Model	IC	IC	IC	IC	AS	AS	AS	AS	AS
Temperature Limit [°C]	500	500	500	400	400	400	400	400	400
Peak waste temp [°C], time [yrs.]	121 17.5	154 30	165 17.5	333 2.0	330 1.0	293 1.0	849 0.5	355 1.5	391 2.0
Waste temp at 300 yrs [°C]	62	78	73	101	92	88	115	114	139
Waste temp at 1000 yrs [°C]	44	54	50	59	60	59	63	74	87
Peak borehole temp [°C], time [yrs.]	101 35	136 35	135 30	206 4.2	220 2.5	193 2.5	178 3.5	256 3.5	304 7.0
Peak temperature ∿ 1 m from borehole surface [°C]	96	129	127	145	124	121	118	171	235

Abbreviations:

H = Horizontal
V = Vertical
SST = 304L Stainless Steel
CS = Carbon Steel
LCT = Loose Crushed Tuff (K = 0.15 [W/mK], estimated)
IC = 2D Infinite Cylinder
AS = 2D axisymmetric

TABLE 1 Significant Input Parameters and Output Results for the 10 Year Old Waste Thermal Analyses

	BWR			PWR								
Case Number	10	11	12	13	14	15	16	17	18	19	20	21
Directory Number	B50V3.42A	B75V3.42A	B99V3.42A	P56H3.3A	P56H3.3B	P56H3.3C	P57H3.3C	P57H3.3B	P115H3.05A	P57H3.56A	P57H3.3A	P57H2.2A
Emplacement Mode	V	V	V	H	H	H	H	H	H	H	H	H
Areal Power Density [kW/acre]	43.0	63.7	84.5	43.2	43.2	43.2	43.6	43.6	82.5	43.8	43.6	42.0
Package Power at Burial [W]	3420	3420	3420	3300	3300	3300	3300	3300	3050	3560**	3300	2200+
Canister diam [cm], material	57.0 SST	57.0 SST	57.0 SST	45.0 SST	45.0 SST	45.0 SST	50.0 SST	50.0 SST	50.0 SST	65.0 SST	50.0 SST	40.0 SST
Overpack diam [cm], material	-	-	-	-	-	-	-	-	-	-	-	-
Borehole liner diam [cm] material	-	-	-	51.4 CS	86.4 CS	86.4 CS	62.2 CS	62.2 CS	62.2 CS	76.2 CS	86.0 CS	76.4 CS
Packing outer diam [cm], material	-	-	-	-	80.1 CCT1	80.1 CCT1	-	-	-	-	82.4 CCT1	72.5 CCT2
Borehole diam [cm]	67.2	67.2	67.2	61.0	96.5	96.5	69.0	69.0	69.0	86.4	92.8	81.3
Borehole pitch [m]	-	-	-	48.9	48.9	48.9	52.0	52.0	24.0	56.3	52.0	34.7
Package pitch [m]	9.1	6.1	4.6	4.8	4.8	4.8	4.5	4.5	4.5	4.5	4.5	4.5
Drift pitch [m]	30.5	30.5	30.5	-	-	-	-	-	-	-	-	-
Number of internal fins, material	9*	9*	9*	6 SST	6 SST	-	6 CS	12 CS	12 CS	14 CS	24 CS	12 CS
Model	AS	AS	AS	IC	IC	IC	IC	IC	IC	IC	IC	IC
Temperature Limit [°C]	350	350	350	350	350	350	350	350	350	350	350	350
Peak waste temp [°C], time [yrs.]	336 2.0	357 4.0	394 9.0	342 2.5	379 2.0	449 2.5	343 3.0	327 3.0	345 13.0	330 5.0	374 2.5	326 3.0
Waste temp at 300 yrs [°C]	159	197	240	148	155	185	153	144	231	152	156	152
Waste temp at 1000 yrs [°C]	115	147	184	109	111	129	109	105	180	107	112	108
Peak borehole temp [°C], time [yrs.]	220 7.0	264 12.0	321 16.0	237 4.0	215 7.0	223 7.5	252 4.0	246 3.5	300 27.0	278 8.0	242 7.0	188 12.0
Peak temperature ∿ 1 m from borehole surface [°C]	142	195	258	170	158	167	175	175	252	202	178	147

* = modeled with 17 horizontal fins with the equivalent volume as the reference vertically finned canister with 9 fins.
** = 7 fuel assemblies instead of six.
\+ = 4 fuel assemblies instead of six.

Abbreviations:

H = Horizontal	CCT1 = Compressed Crushed Tuff (K = 0.97 [W/mK], estimated)
V = Vertical	CCT2 = Compressed Crushed Tuff (K = 0.65 [W/mK], measured)
SST = 304L Stainless Steel	IC = 2D Infinite Cylinder
CS = Carbon Steel	AS = 2D axisymmetric

TABLE 1 Significant Input Parameters and Output Results for the 10 Year Old Waste Thermal Analyses

	PWR	
Case Number	22	23
Directory Number	P50H3.3A	P50H1.65A
Emplacement Mode	H	H
Areal Power Density [kW/acre]	40.6	40.6
Package Power at Burial [W]	3300*	1650**
Canister diam [cm], material	68.0 SST	68.0 SST
Overpack diam [cm], material	-	-
Borehole liner diam [cm] material	76.0 CS	76.0 CS
Packing outer diam [cm], material	-	-
Borehole diam [cm]	84.0	84.0
Borehole pitch [m]	52.0	52.0
Package pitch [m]	4.5	4.5
Drift pitch [m]	-	-
Number of internal fins, material	-	-
Model	IC	IC
Temperature Limit [°C]	350	350
Peak waste temp [°C], time [yrs.]	335 3.4	295 5.0
Waste temp at 300 yrs [°C]	161	147
Waste temp at 1000 yrs [°C]	112	105
Peak borehole temp [°C], time [yrs.]	244 7.5	244 7.5
Peak temperature ∿ 1 m from borehole surface [°C]	180	180

* = Boxed consolidated PWR spent fuel. Three boxes per canister.
** = Boxed unconsolidated PWR spent fuel. Three boxes per canister.

Abbreviations:
H = Horizontal
SST = 304L Stainless Steel
CS = Carbon Steel
IC = 2D Infinite Cylinder

TABLE 2

Borehole Wall Temperature History Boundary Condition

Time [years]	Temp [°C]
0.0	100
1.0	235
3.0	266
5.0	275
8.0	278
10.0	276
15.0	268
20.0	258
25.0	249
30.0	240
40.0	223
50.0	208
60.0	197
70.0	187
80.0	179
100.0	168
125.0	157
150.0	151
175.0	147
200.0	143
250.0	139
300.0	136
400.0	129
500.0	124
600.0	119
800.0	109
1000.0	101

TABLE 3 MATERIAL PROPERTIES

DHLW — **REFERENCE**

ρ = 2740 [kg/m^3] — [10, p. 37]

T [°C]	Cp [$\frac{J}{Kg\ °C}$]	[10, p. 36]
0	778.2	
100	991.6	
200	1133.9	
300	1238.5	
400	1313.8	

T [°C]	K [$\frac{J}{yr \cdot m \cdot °C}$]	[10, p. 39]
0	2.670×10^7	
100	3.064×10^7	
200	3.459×10^7	
300	3.854×10^7	
400	4.248×10^7	

SST304L

ρ = 7916.5 [kg/m^3] [4, p. 2-187]

T [°C]	Cp [$\frac{J}{kg°C}$]	[11, p. 2-188]
0.0	460.6	
315.6	544.3	
537.7	586.2	

T [°C]	K [$\frac{J}{yr \cdot m \cdot °C}$]	[11, p. 2-188]
0.0	4.91×10^8	
315.6	6.14×10^8	
537.7	7.10×10^8	

TABLE 3 (cont)

CHLW [6, pg 71]

$\rho = 3100\ [kg/m^3]$

$Cp = 750\ \left[\frac{J}{kg\ °C}\right]$

T [°C]	K $\left[\frac{J}{yr \cdot m \cdot °C}\right]$
0°C	2.52×10^7
500°C	4.10×10^7

BWR and PWR SPENT FUEL [6]

$\rho = 2000\ [kg/m^3]$

$Cp = 2640\ \left[\frac{J}{kg\ °C}\right]$

T [°C]	K $\left[\frac{J}{yr \cdot m \cdot °C}\right]$
50	2.210×10^6
100	2.838×10^6
150	4.100×10^6
200	5.992×10^6
250	8.200×10^6
300	1.104×10^7
350	1.451×10^7
400	1.829×10^7
450	2.302×10^7
500	2.630×10^7

TABLE 3 (cont)

AIR1 - DRY AIR [12, pp. 11-12]

$\rho = 1.197$ [kg/m^3]

$Cp = 1006.0 \left[\frac{J}{kg\ °C}\right]$

T [°C]	K $\left[\frac{J}{yr \cdot m \cdot °C}\right]$
1.85	7.66×10^5
46.85	8.76×10^5
96.85	9.93×10^5
166.85	1.15×10^6
266.85	1.35×10^6
526.85	1.82×10^6

A537-A steel - CARBON STEEL

$\rho = 7861.1$ [kg/m^3] [13, p. 1]

T [°C]	Cp $\left[\frac{J}{kg°C}\right]$
29.0	485.7
100.0	485.7
150.0	519.2
500.0	519.2

$K = 1.61 \times 10^9 \left[\frac{J}{yr \cdot m \cdot °C}\right]$

AIR2 - AIR/STEAM

	T [°C]	ρ [kg/m^3]	
	25	1.147	[12, p. 11]
Air 2	40	1.045	"
	55	0.909	"
	100	0.590	[12, p. 33]
STEAM	150	0.516	"
	200	0.460	"
	300	0.379	"
	400	0.322	"

TABLE 3 (cont)

AIR2 - AIR/STEAM (Cont.)

	T [°C]	Cp $[\frac{J}{kg\ °C}]$	
AIR2	0	1008	[12, p. 11]
	99	1008	"
STEAM	100	1990	[12, p. 26]
	400	1990	"

	T [°C]	K $[\frac{J}{yr \cdot m \cdot °C}]$	
	26.85	8.275×10^5	[12, pp. 11-12] (dry air)
	46.85	8.761×10^5	"
AIR2	66.85	9.234×10^5	"
	96.85	9.934×10^5	"
	150.0	9.051×10^5	[12, p. 37] (steam)
	200.0	1.047×10^6	"
	250.0	1.205×10^6	"
STEAM	300.0	1.369×10^6	"
	350.0	1.545×10^6	"
	400.0	1.731×10^6	"

TUFF [14], [15]

$\rho = 2244.0\ [kg/m^3]$

T [°C]	Cp $[\frac{J}{kg\ °C}]$
0.0	971.4
99.0	971.4
100.0	689.0
400.0	689.0

T [°C]	K $[\frac{J}{yr \cdot m \cdot °C}]$
0.0	5.676×10^7
99.0	5.676×10^7
100.0	5.046×10^7
400.0	5.046×10^7

TABLE 3 (cont)

HELIUM [16]

ρ = 0.134 [kg/m^3]

Cp = 5180 $\left[\frac{J}{kg\ °C}\right]$

T [°C]	K $\left[\frac{J}{yr \cdot m \cdot °C}\right]$
29	6.5×10^6
100	7.3×10^6
200	8.2×10^6
300	9.2×10^6
400	1.0×10^7
500	1.1×10^7

COMPRESSED BACKFILL

ρ = 1700 [kg/m^3] (measured)

T [°C]	Cp $\left[\frac{J}{kg\ °C}\right]$
0	736.3
99	736.3
100	522.3
400	522.3

T [°C]	K $\left[\frac{J}{yr \cdot m \cdot °C}\right]$
0	3.15×10^7
99	3.15×10^7
100	2.97×10^7
400	2.97×10^7

TABLE 4

Normalized Decay Heat Curve for DHLW [10]

Time After Emplacement (Years)	Normalized Power
0.0	1.00
1.0	9.43×10^{-1}
2.0	8.30×10^{-1}
3.0	7.73×10^{-1}
4.0	7.54×10^{-1}
5.0	7.35×10^{-1}
15.0	5.64×10^{-1}
25.0	4.55×10^{-1}
35.0	3.58×10^{-1}
45.0	2.83×10^{-1}
55.0	2.45×10^{-1}
65.0	1.85×10^{-1}
75.0	1.51×10^{-1}
85.0	1.22×10^{-1}
95.0	1.04×10^{-1}
195.0	1.92×10^{-2}
295.0	7.92×10^{-3}
395.0	4.36×10^{-3}
495.0	2.83×10^{-3}
595.0	2.08×10^{-3}
695.0	1.89×10^{-3}
795.0	1.58×10^{-3}
895.0	1.42×10^{-3}
995.0	1.32×10^{-3}

TABLE 5

Normalized Decay Heat Curve for CHLW [6]

Time After Emplacement (Years)	Normalized Power
0	1.0
1	0.963
3	0.893
5	0.830
8	0.760
10	0.724
15	0.660
20	0.600
25	0.536
30	0.475
40	0.358
50	0.270
60	0.213
70	0.170
80	0.148
100	0.125
125	0.116
150	0.102
175	0.091
200	0.081
250	0.066
300	0.055
400	0.040
500	0.030
600	0.023
800	0.015
1000	0.010

TABLE 6

Normalized Decay Heat Curve for BWR Spent Fuel For Cases 10, 11 & 12

Time After Emplacement (Years)	Normalized Power
0	1.000
1	0.966
3	0.927
5	0.890
8	0.839
10	0.806
15	0.732
20	0.667
25	0.610
30	0.559
40	0.475
50	0.410
60	0.359
70	0.319
80	0.287
100	0.242
125	0.208
150	0.186
175	0.171
200	0.161
250	0.145
300	0.132
400	0.111
500	0.095
600	0.081
800	0.062
1000	0.048

TABLE 7

Normalized Decay Heat Curve for PWR Spent Fuel for Cases 18, 19, 21-23

Time After Emplacement (Years)	Normalized Power
0	1.000
1	0.9647
3	0.9245
5	0.8865
8	0.8330
10	0.7996
15	0.7234
20	0.6566
25	0.5979
30	0.5464
40	0.4614
50	0.3955
60	0.3444
80	0.2732
100	0.2289
150	0.1740
200	0.1494
250	0.1337
300	0.1214
400	0.1013
500	0.0854
800	0.0540
1000	0.0419

TABLE 8

Normalized Decay Heat Curve for PWR Spent Fuel for Cases 13-17, and 20 [6]

Time After Emplacement (Years)	Normalized Power
0	1.0
5	0.841
10	0.750
15	0.683
20	0.625
30	0.524
50	0.389
70	0.303
100	0.240
300	0.100
500	0.070
800	0.050
1000	0.045

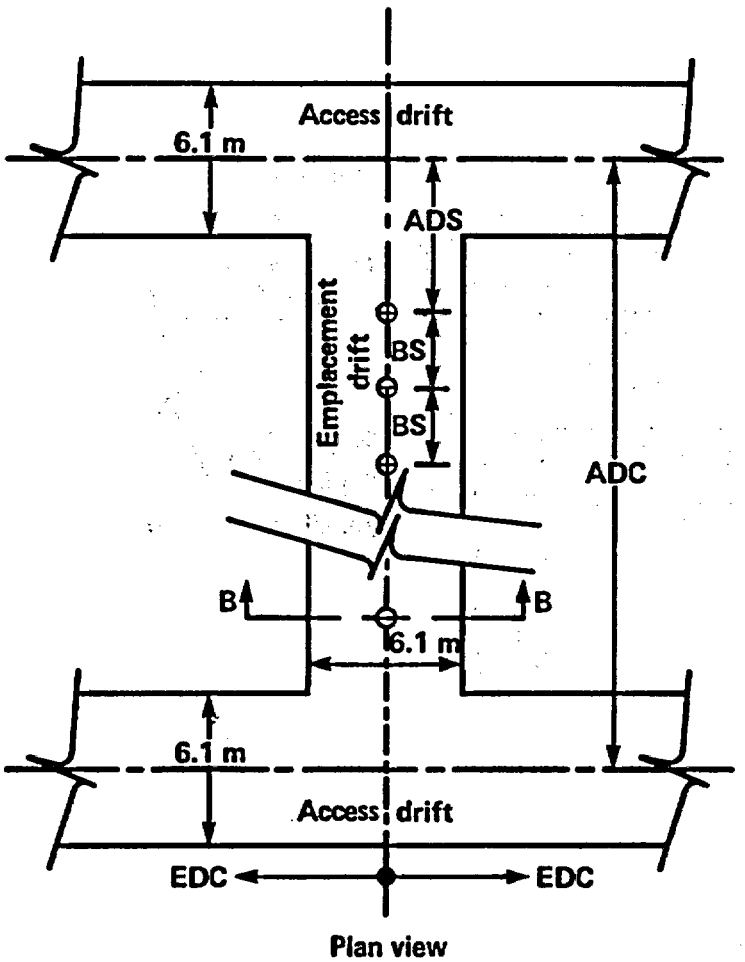


Figure 1: Reference drift and borehole geometry for vertical emplacement.

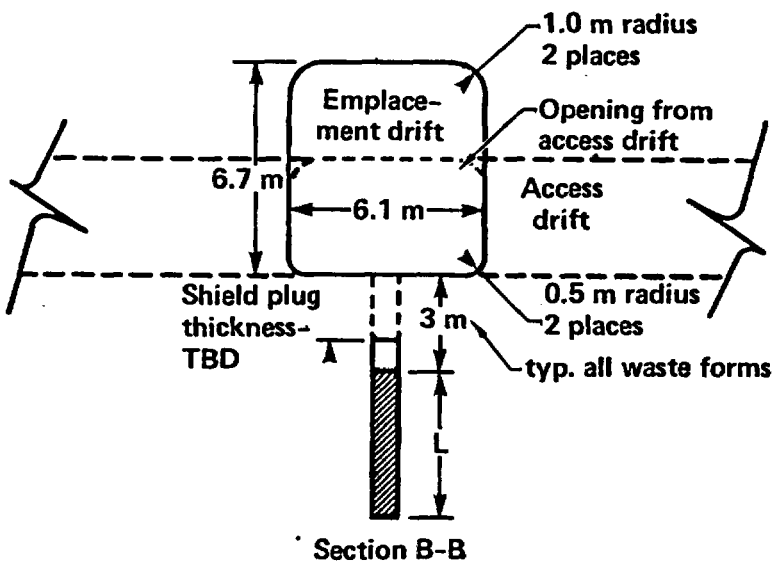


Figure 2: Reference vertical emplacement drift and borehole geometry.

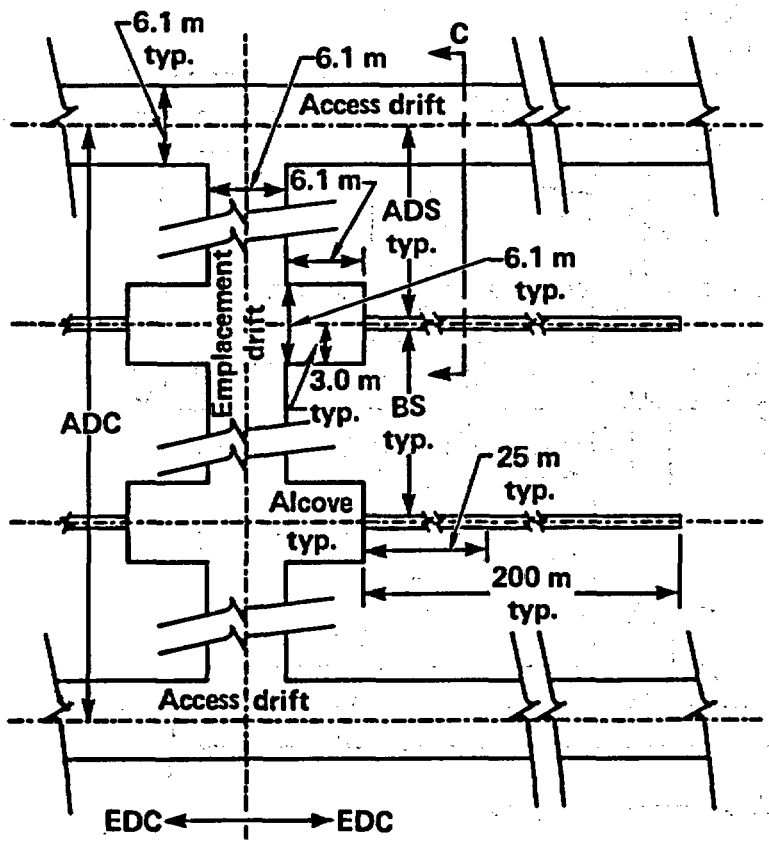


Figure 3: Reference drift and borehole geometry for horizontal emplacement of spent fuel.

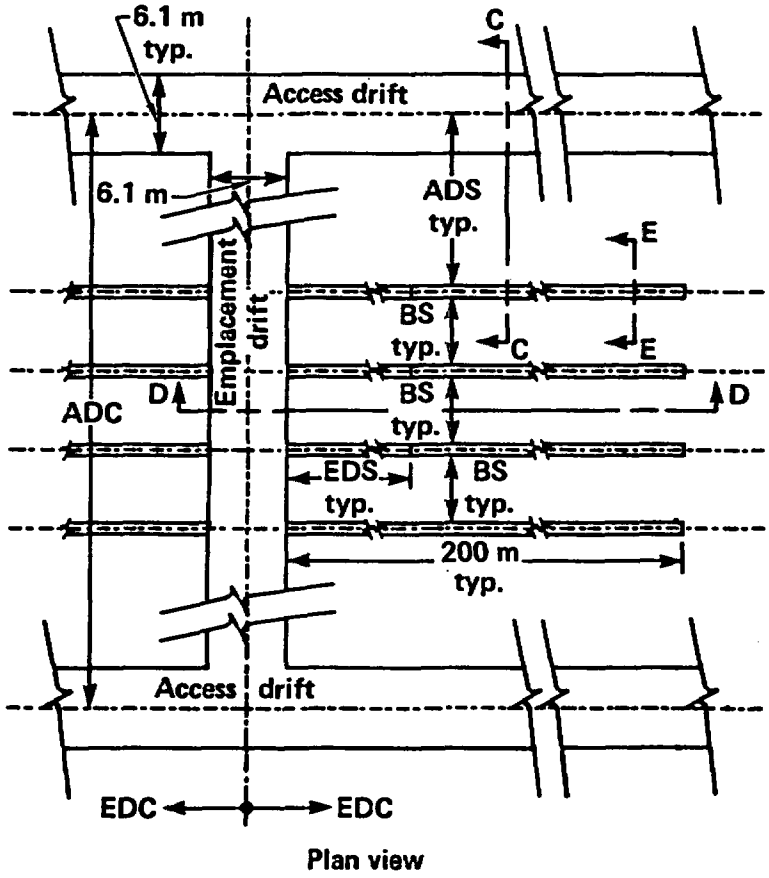
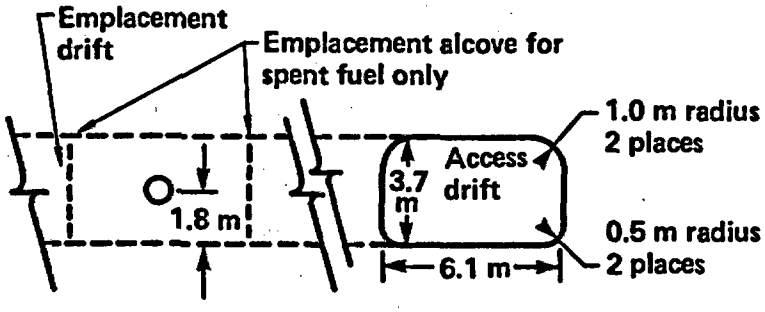


Figure 4: Reference drift and borehole geometry for horizontal emplacement of DHLW and CHLW.



Note:
Parallel access drift for adjacent panel with emplacement drifts running to the right is located ~30 m (100') to the right (℄ to ℄).

Section C-C

Figure 5: Reference access drift geometry for horizontal emplacement.

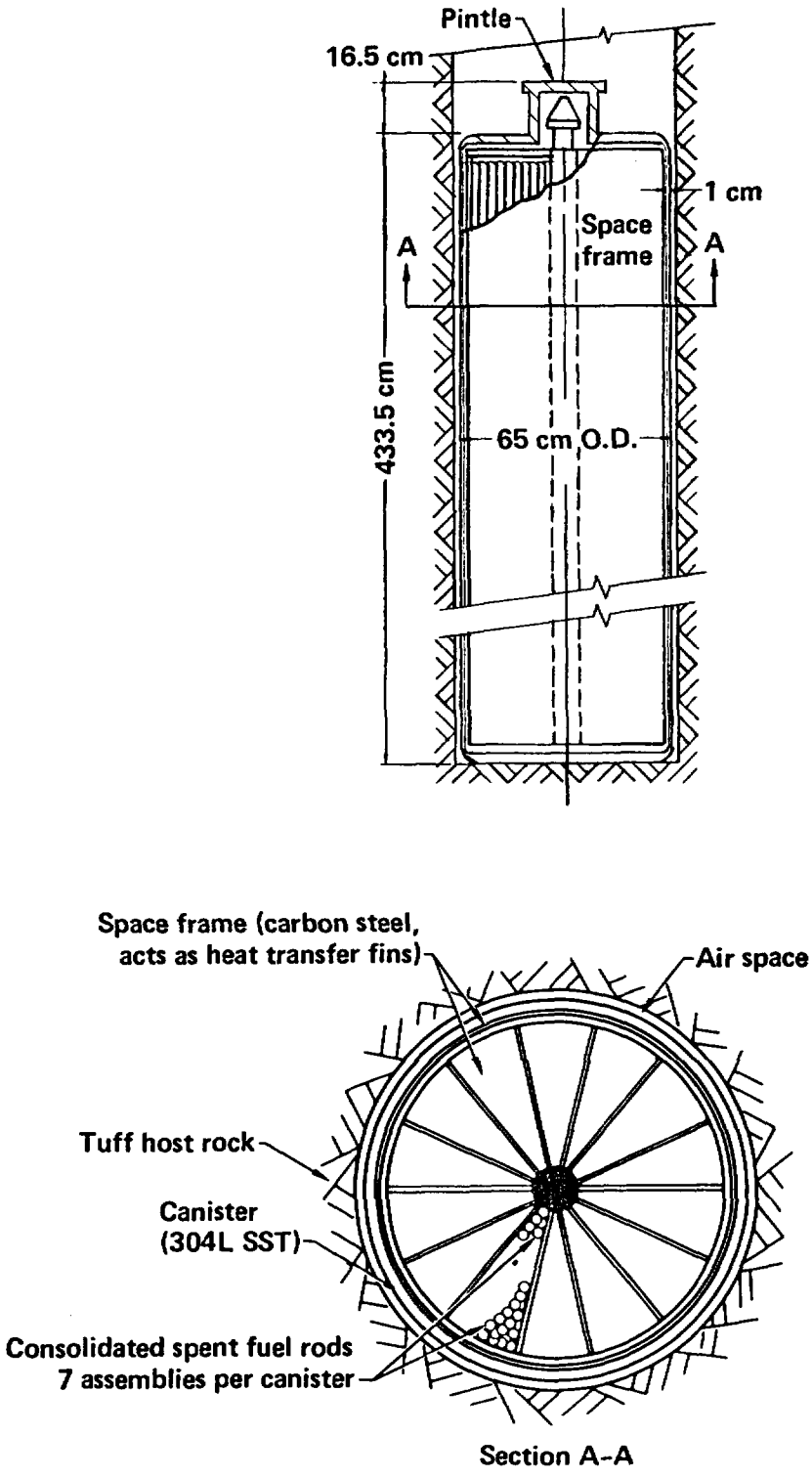


Figure 6: Vertically emplaced PWR spent fuel canister with 14 radial heat conducting fins separating the consolidated rods.

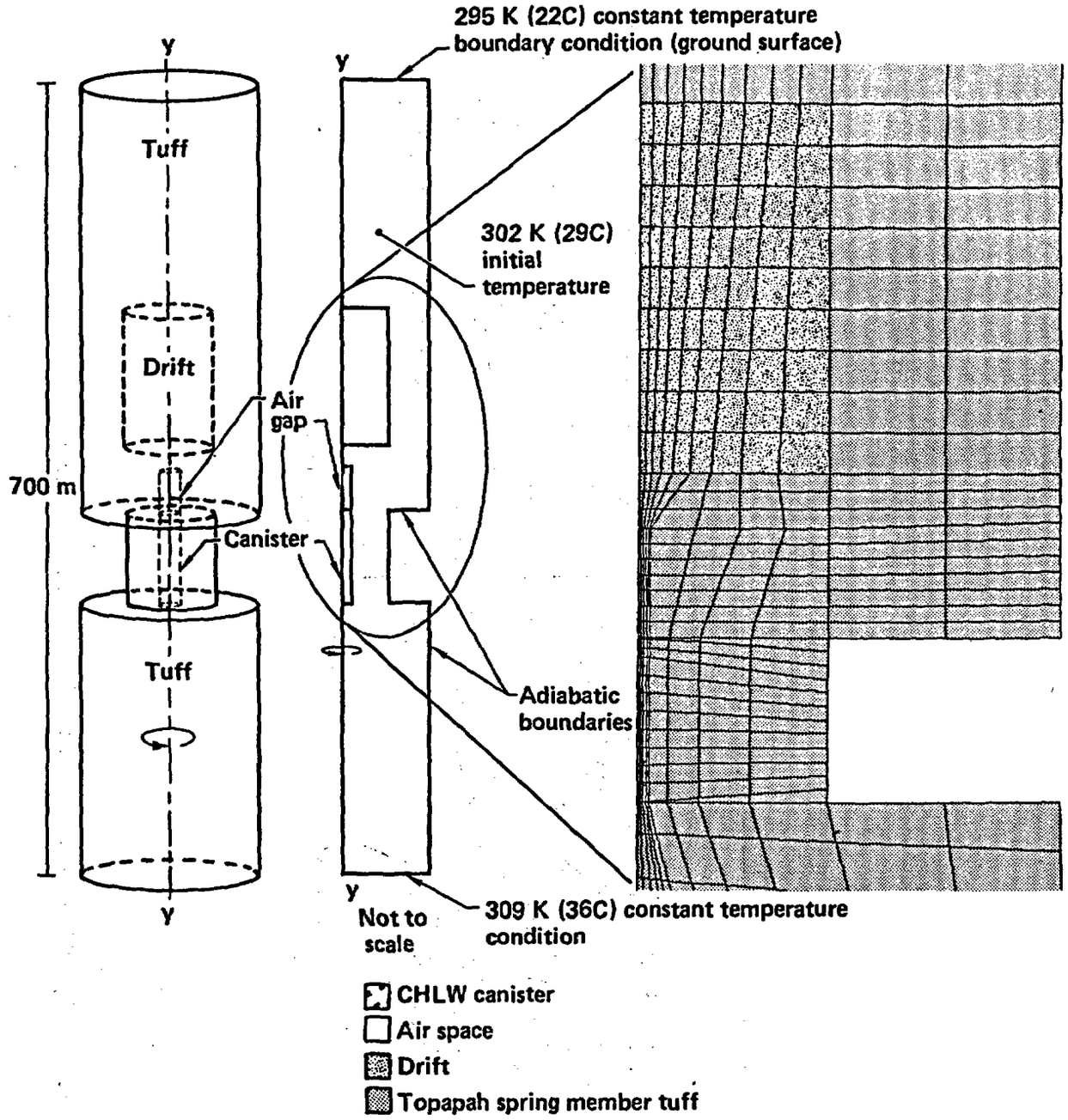


Figure 7: A portion of the finite element mesh for the axisymmetric model used in the thermal analysis of a vertically emplaced CHLW package. The 2D mesh is rotated 360 degrees about the y-y axis to produce the axisymmetric model shown on the far left.

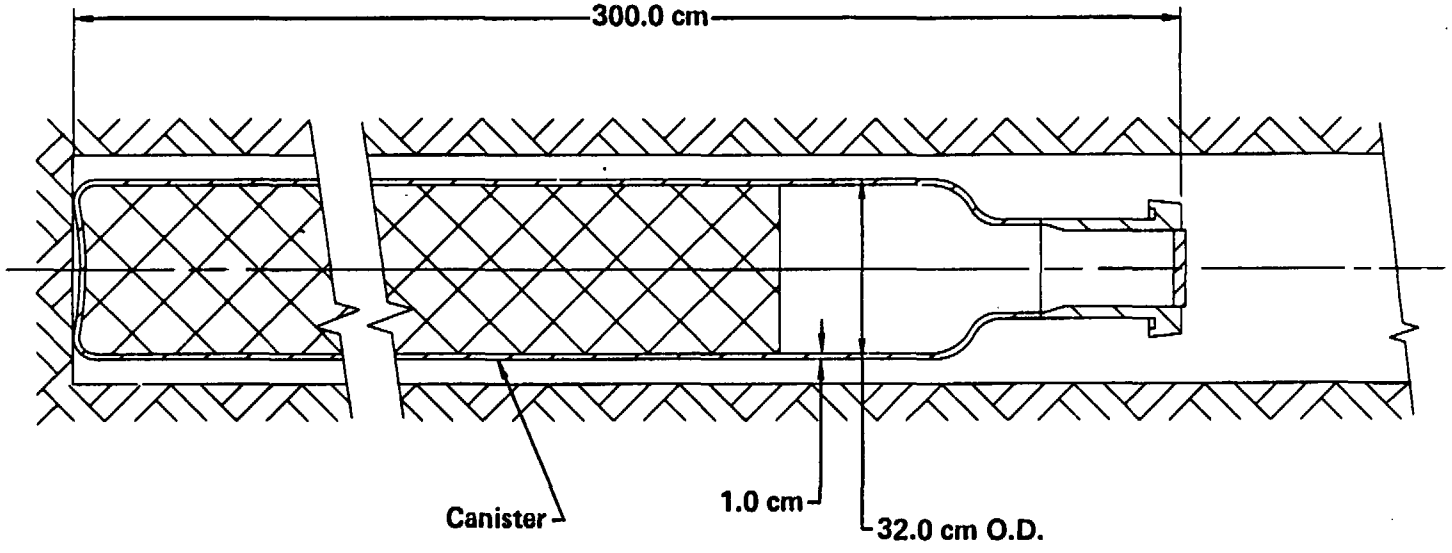


Figure 8: Vertically emplaced CHLW waste package for Cases 5 - 9.

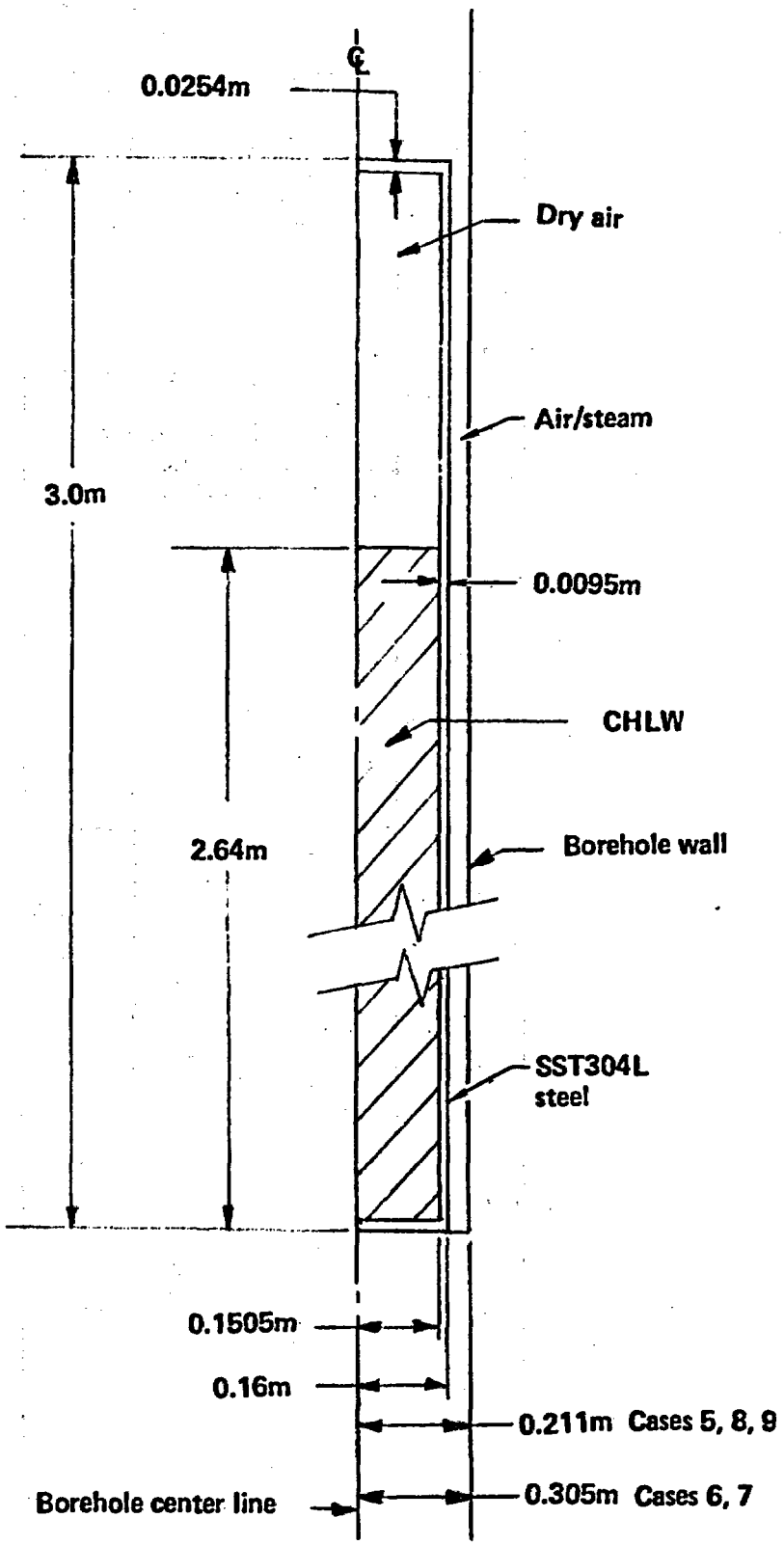


Figure 9: CHLW package dimensions as modeled for TACO2D analysis, Cases 5 - 9.

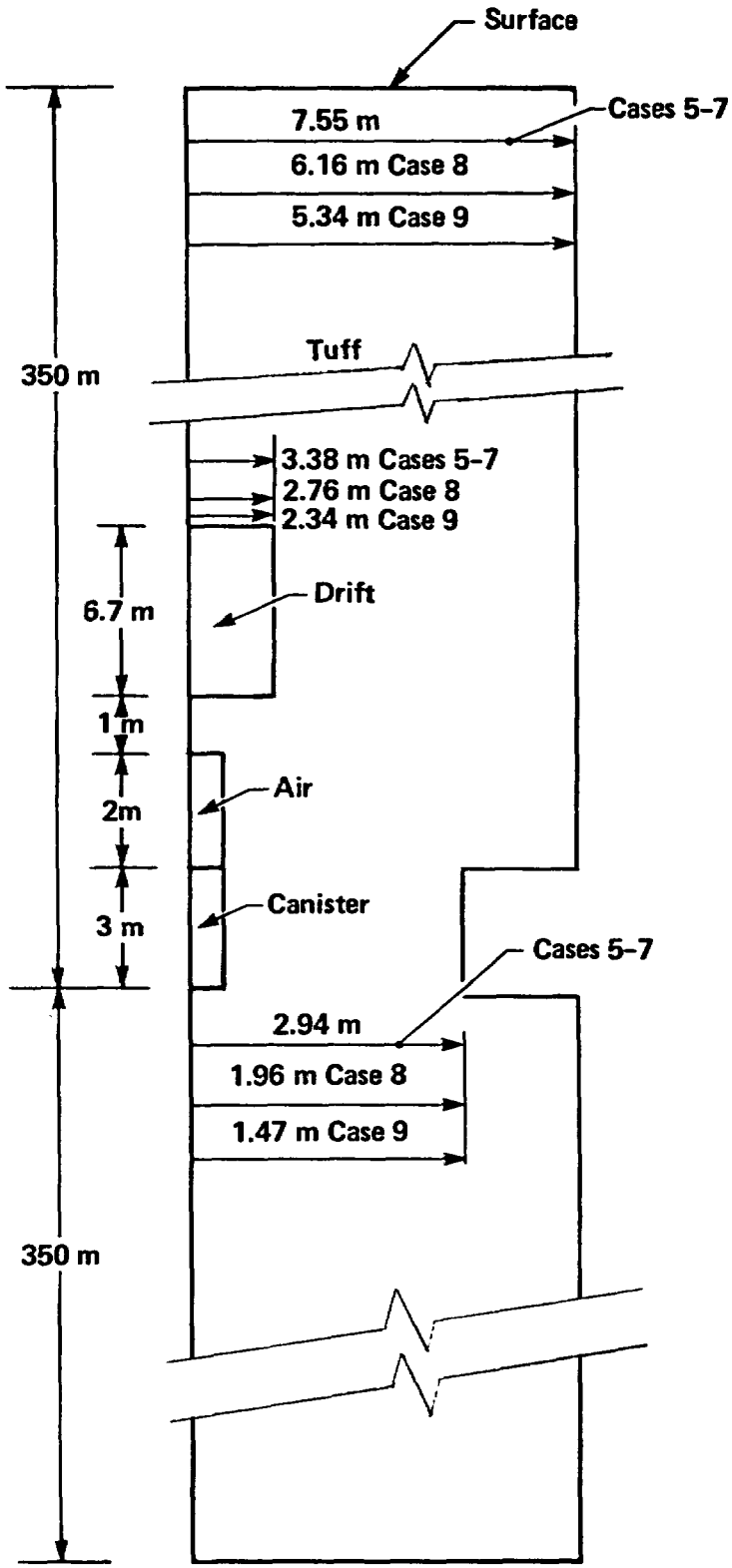


Figure 10: Dimensions of vertically emplaced CHLW axisymmetric model, Cases 5 - 9.

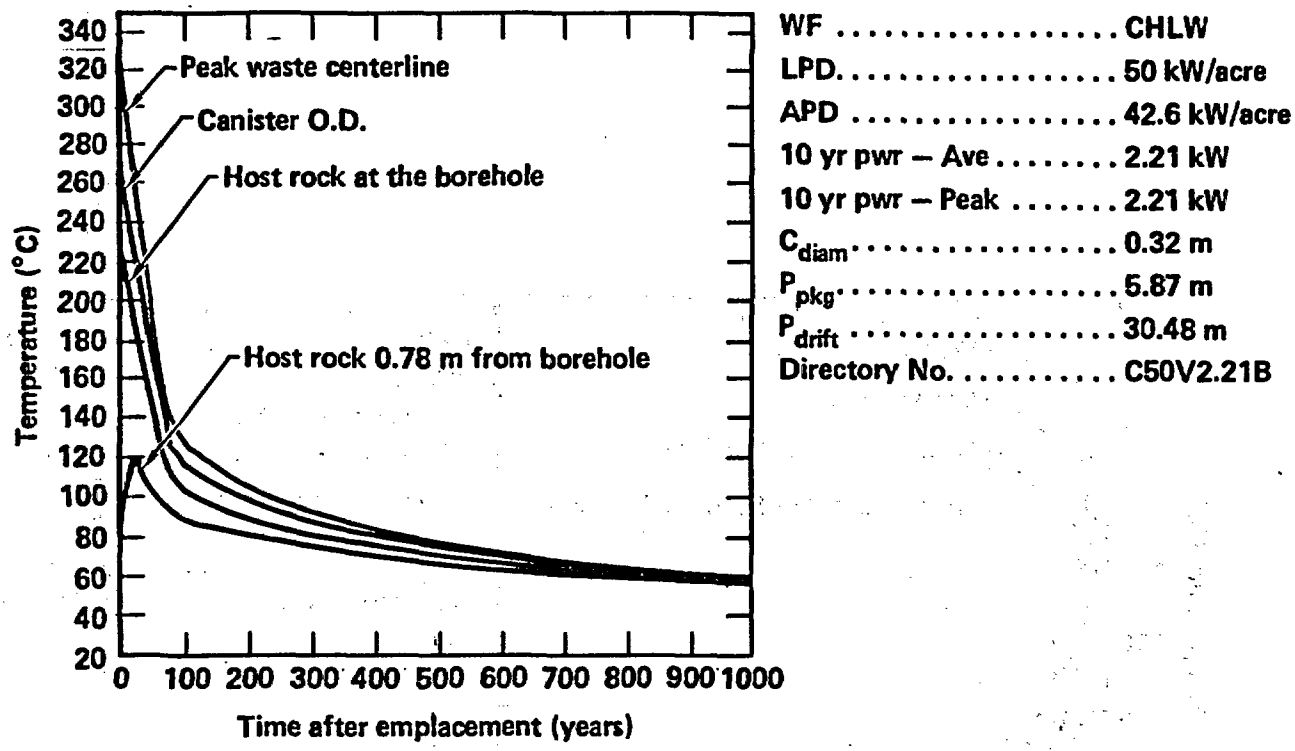


Figure 11: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 5.

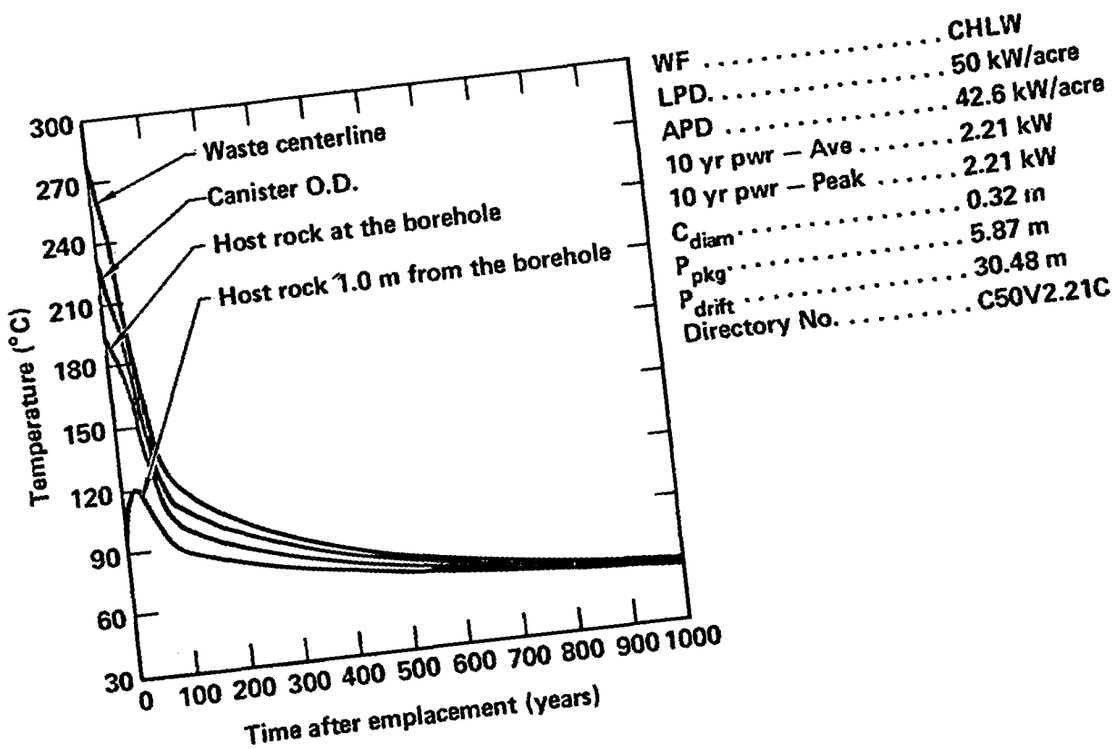
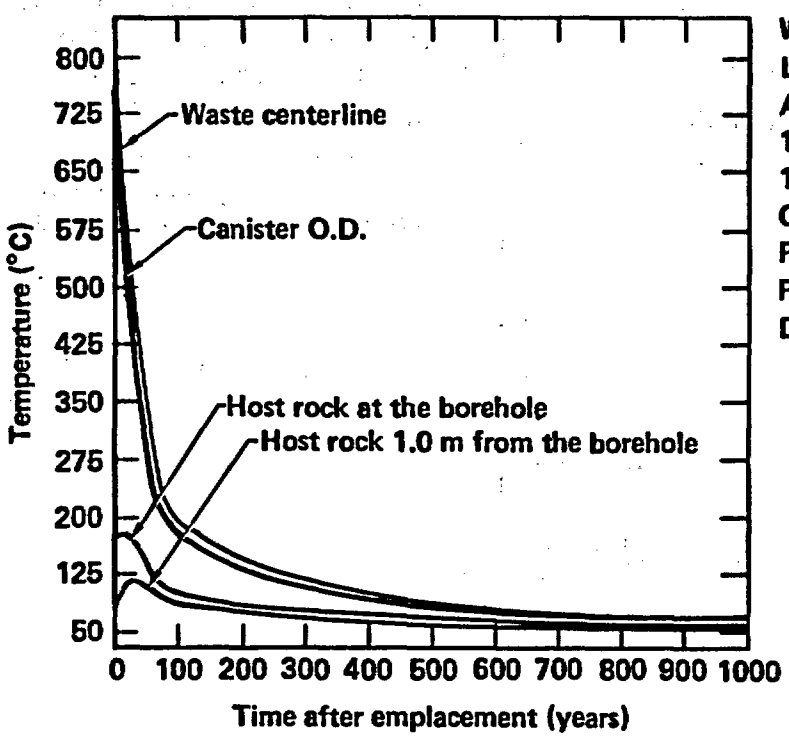


Figure 12: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 6.



WF	CHLW
LPD	50 kW/acre
APD	42.6 kW/acre
10 yr pwr – Ave	2.21 kW
10 yr pwr – Peak	2.21 kW
C_{diam}	0.32 m
P_{pkg}	5.87 m
P_{drift}	30.48 m
Directory No.	C50V2.21D

Figure 13: Temperature histories of waste package components and host rock for vertically emplaced CHLW with loose crushed tuff packing, Case 7.

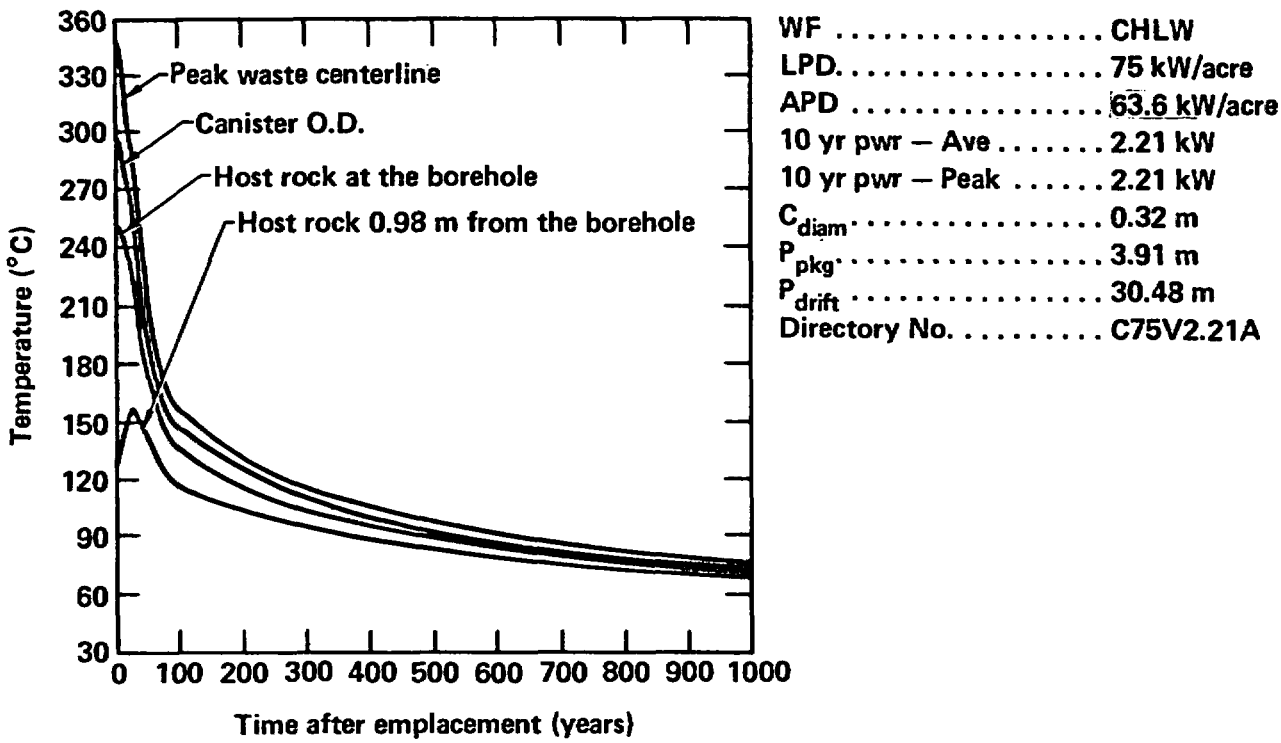


Figure 14: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 8.

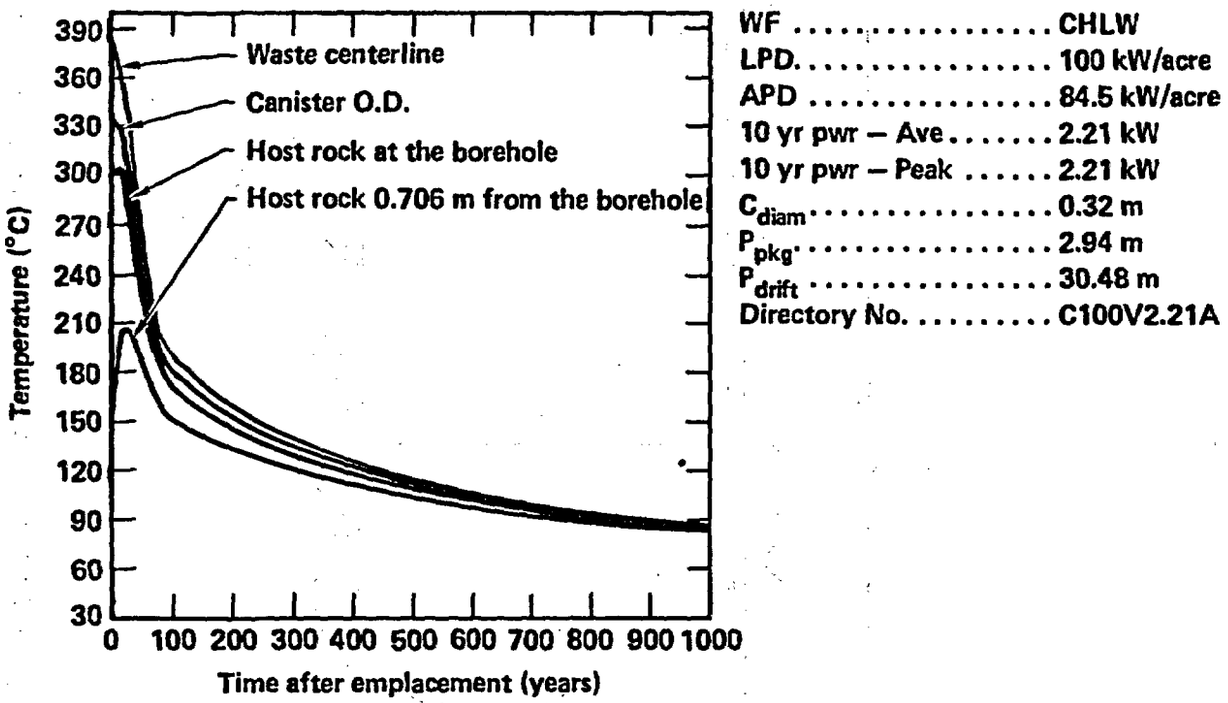


Figure 15: Temperature histories of waste package components and host rock for vertically emplaced CHLW, Case 9.

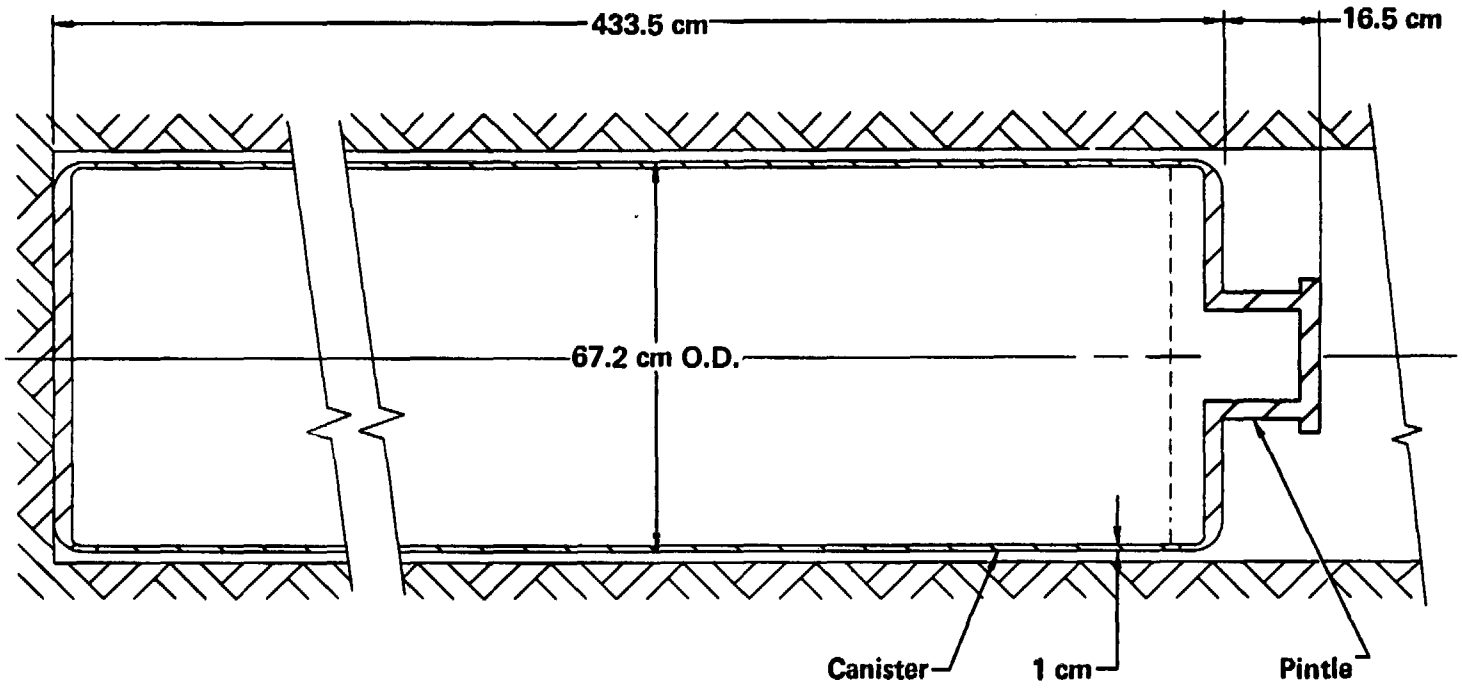


Figure 16: Vertically emplaced BWR spent fuel waste package, Cases 10 -12.

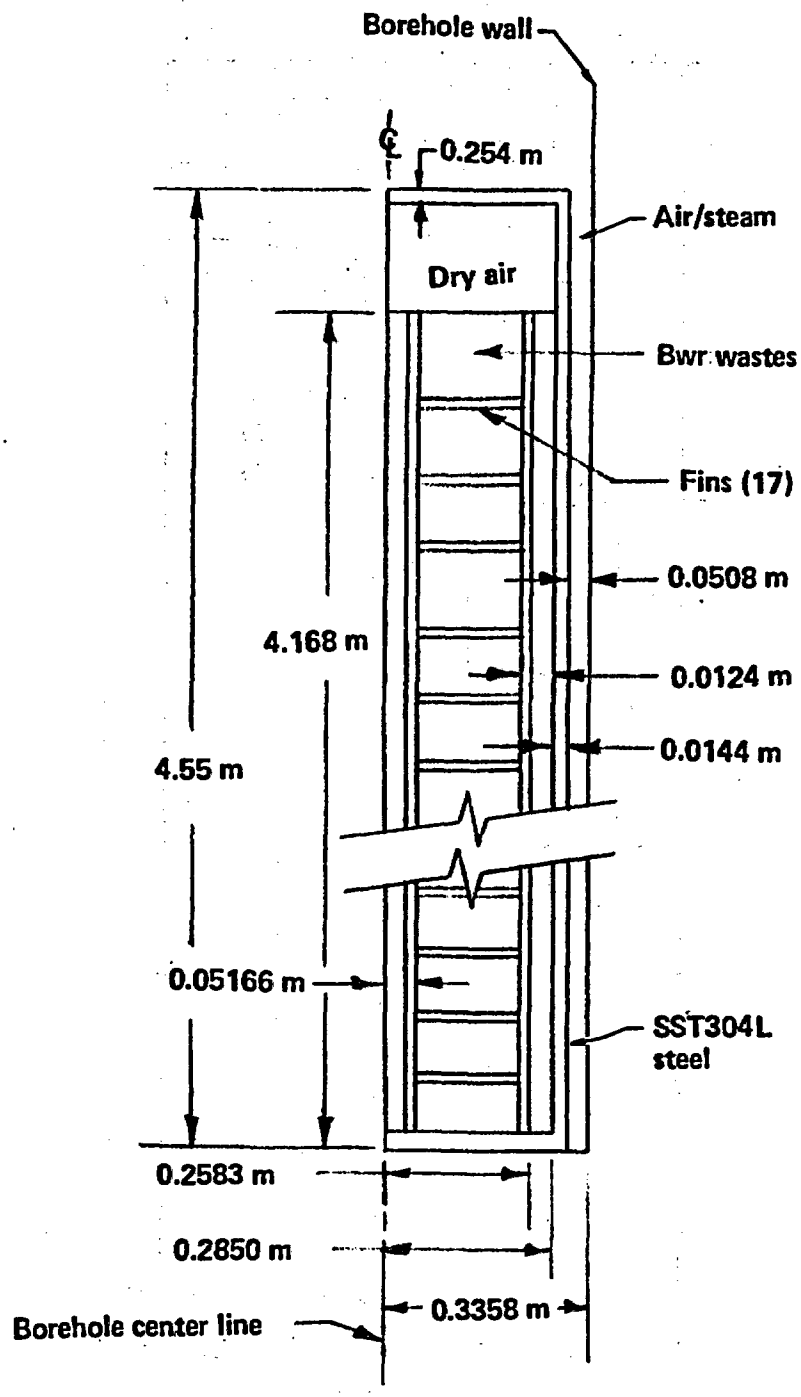


Figure 17: BWR spent fuel package dimensions as modeled for TACO2D analysis, Cases 10 - 12.

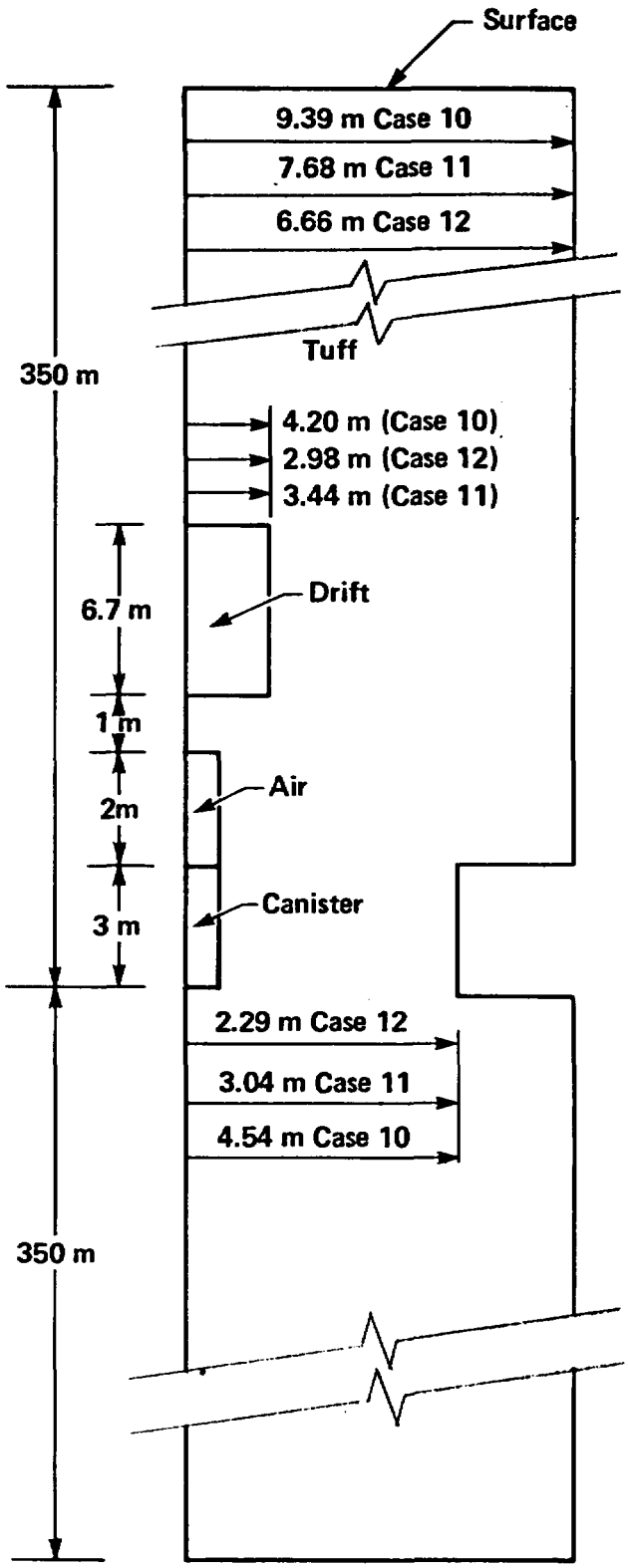


Figure 18: Dimensions of vertically emplaced BWR spent fuel axisymmetric model, Cases 10 -12.

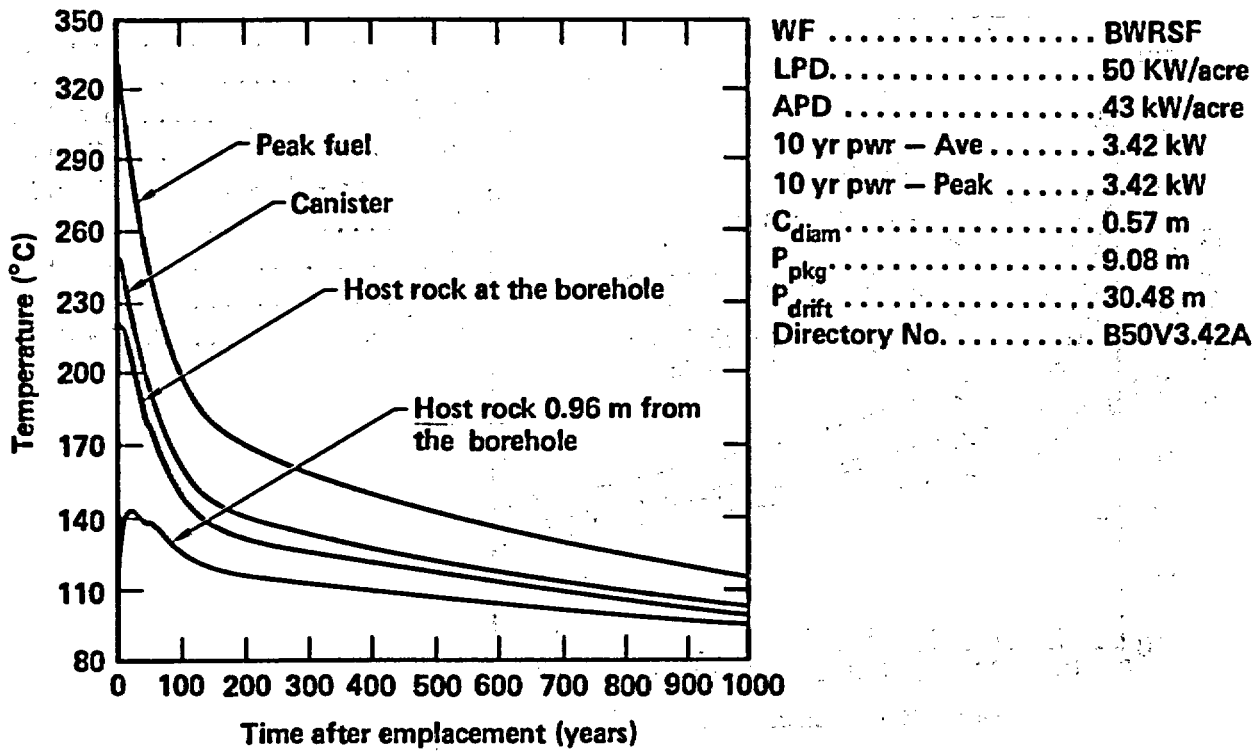


Figure 19: Selected temperature histories for vertically emplaced BWR spent fuel, Case 10.

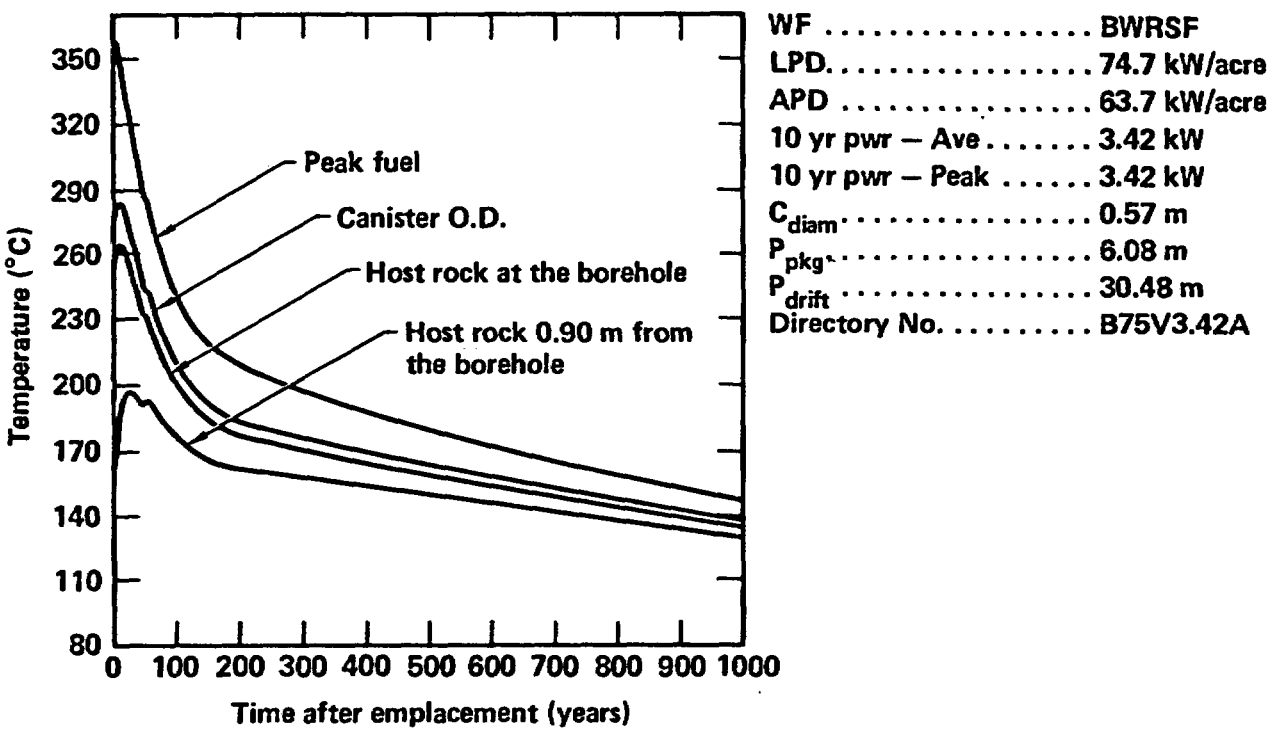
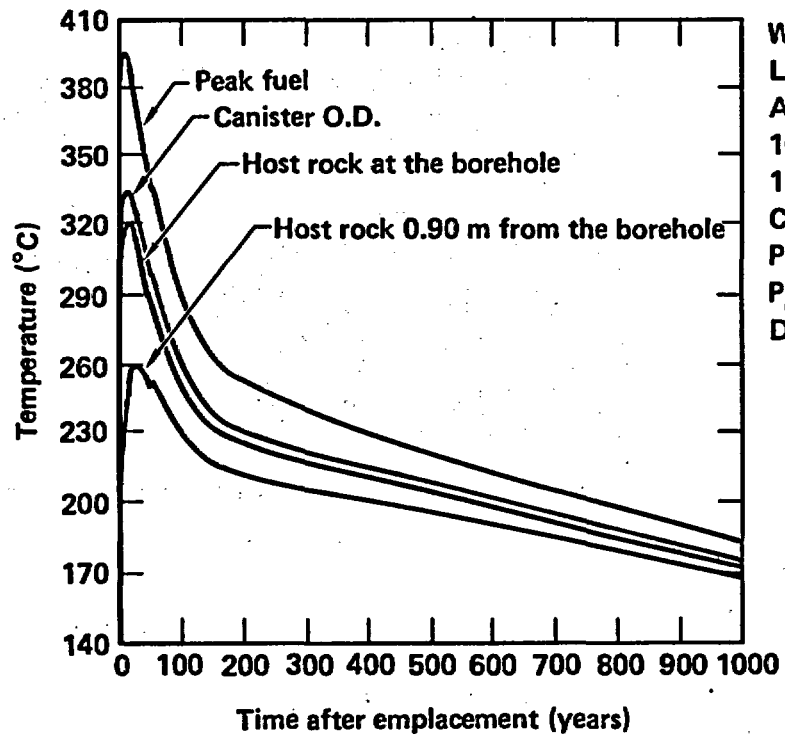


Figure 20: Temperature histories of waste package components and host rock for vertically emplaced BWR spent fuel, Case 11.



WF ..... BWR•SF
LPD..... 99.4 kW/acre
APD ..... 84.5 kW/acre
10 yr pwr – Ave ..... 3.42 kW
10 yr pwr – Peak ..... 3.42 kW
C_{diam} ..... 0.57 m
P_{pkg} ..... 4.57 m
P_{drift} ..... 30.48 m
Directory No. B99V3.42A

Figure 21: Temperature histories of waste package components and host rock for vertically emplaced BWR spent fuel, Case 12.

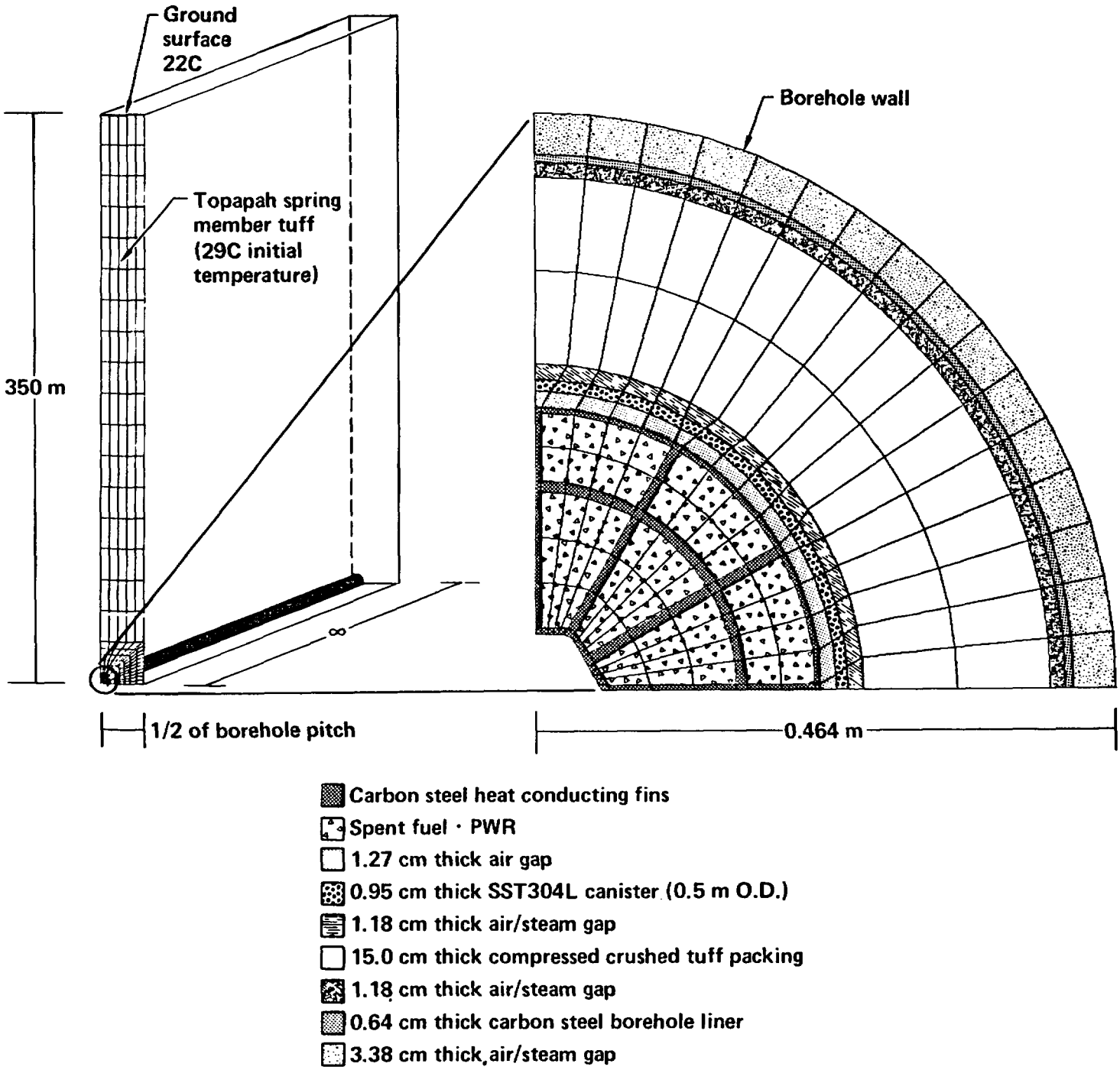


Figure 22: The finite element mesh of the infinite cylinder model used for the thermal analysis of horizontally emplaced PWR spent fuel with 24 fins, packing and a borehole liner.

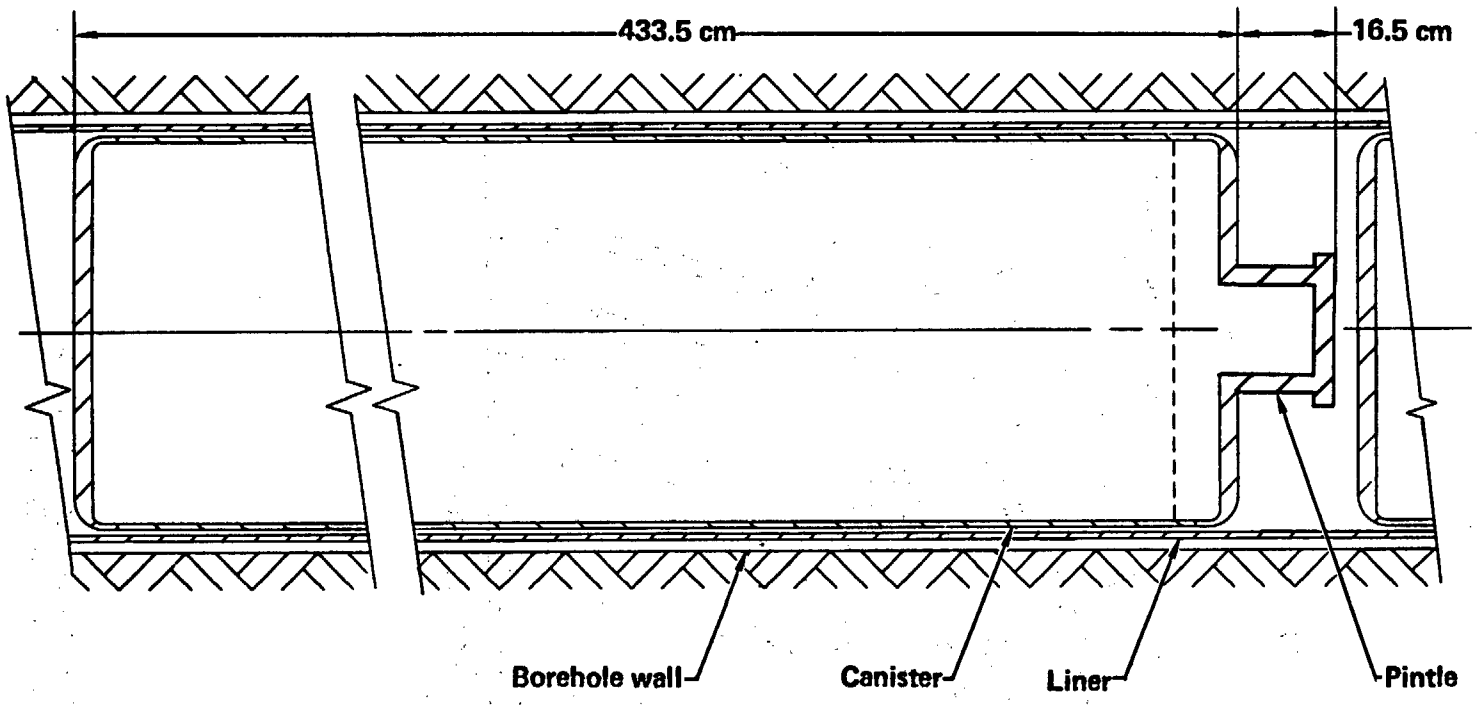


Figure 23: PWR spent fuel nuclear waste package for Cases 13 - 21.

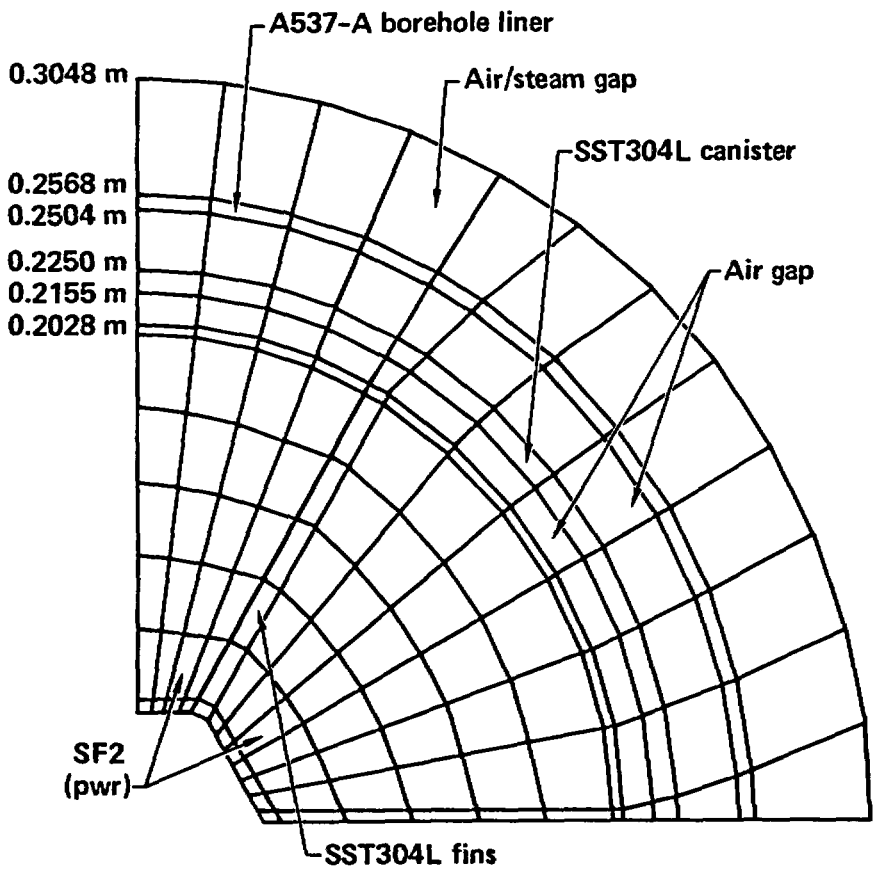


Figure 24: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 13.

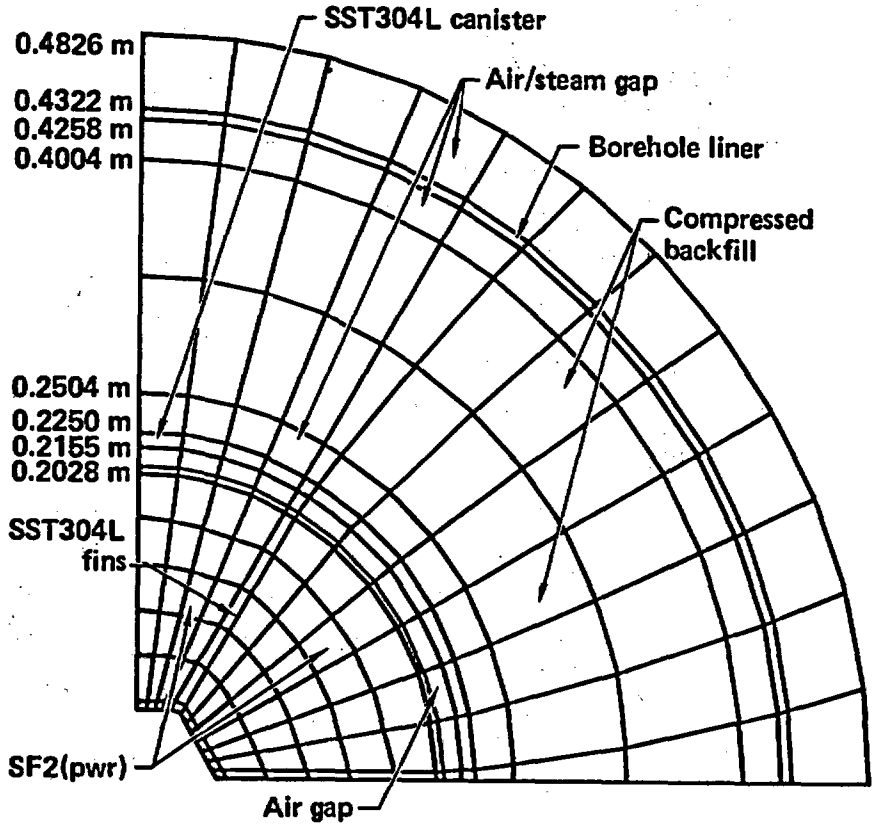


Figure 25: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 14.

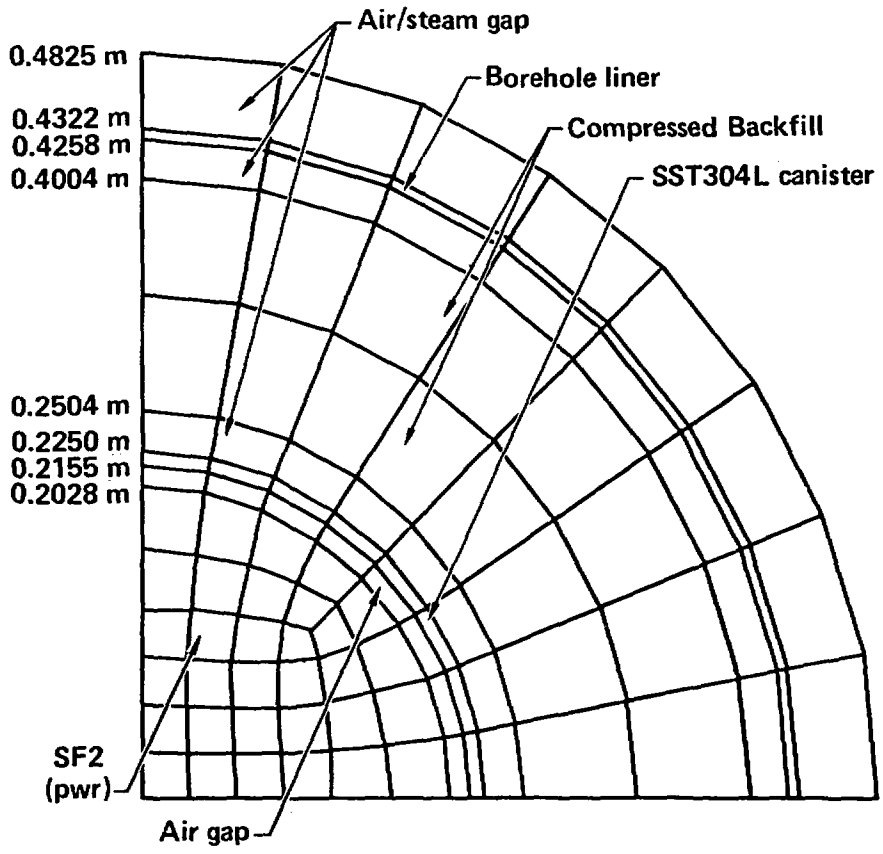


Figure 26: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 15.

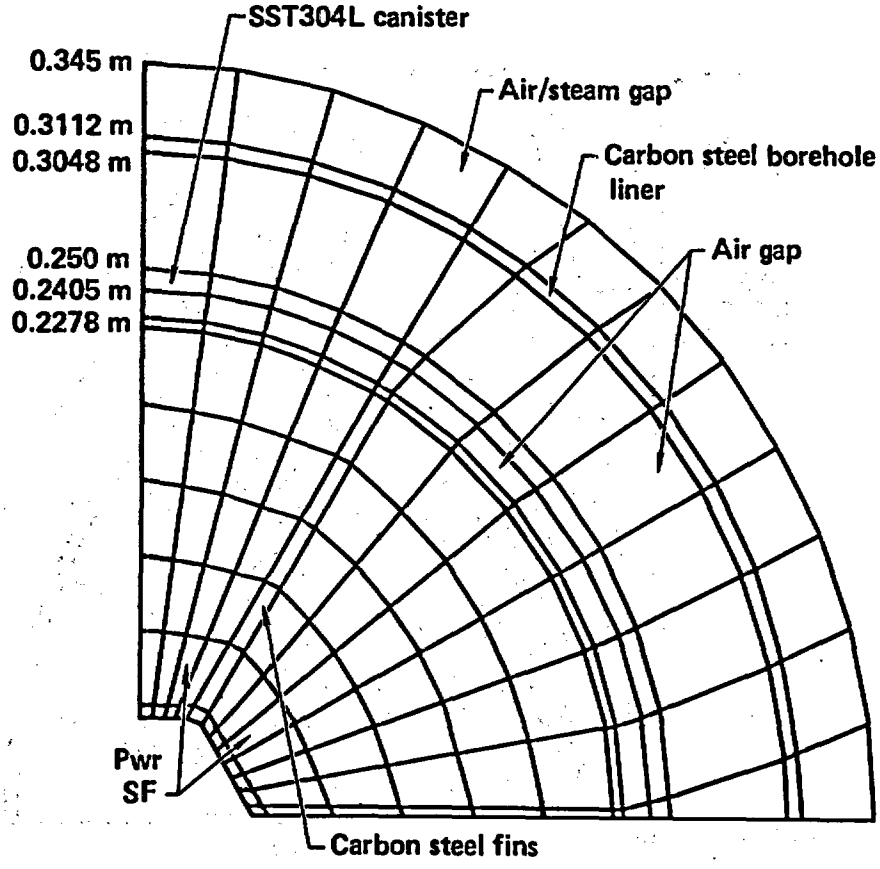


Figure 27: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 16.

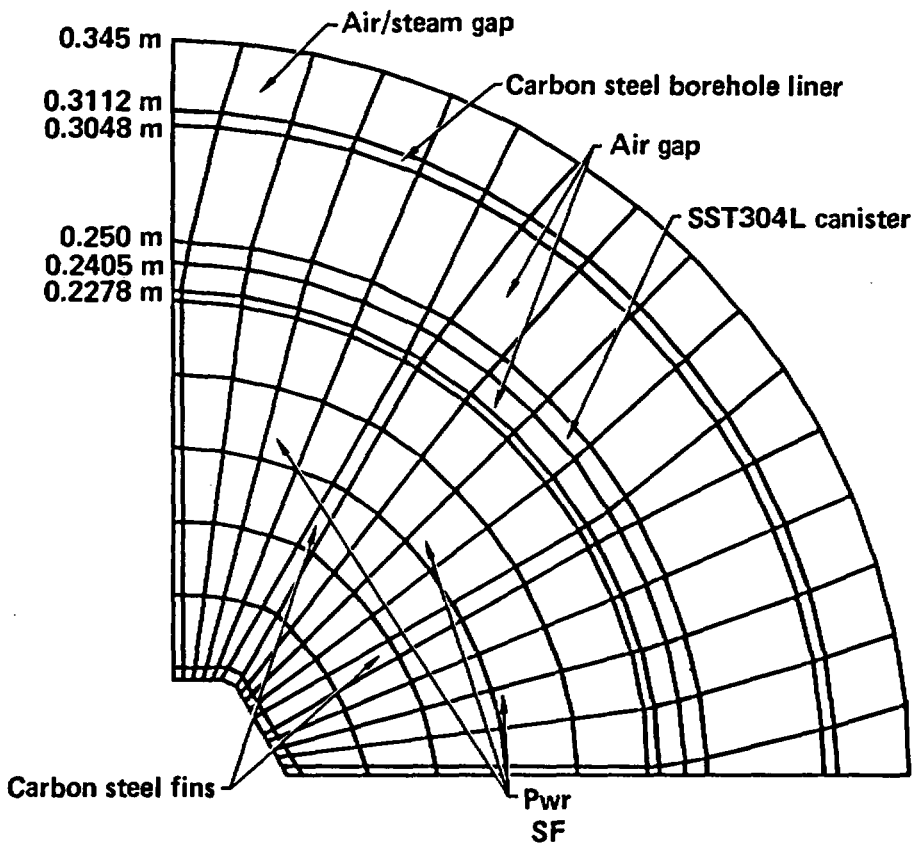


Figure 28: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Cases 17 and 18.

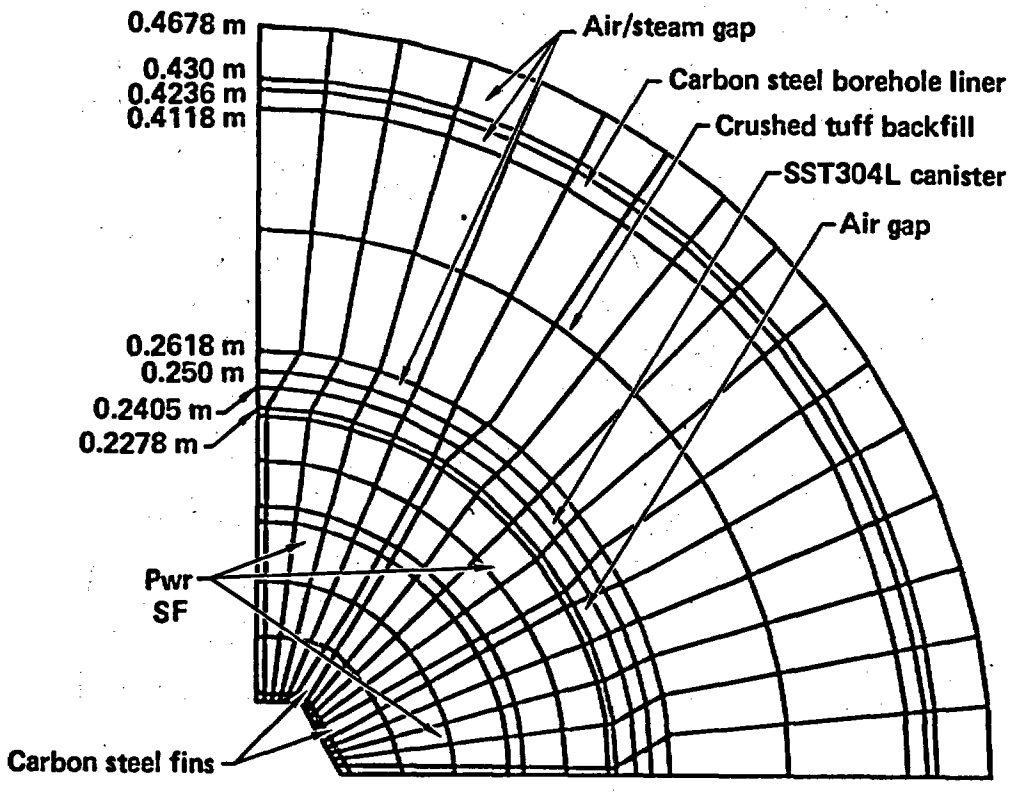


Figure 29: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 20.

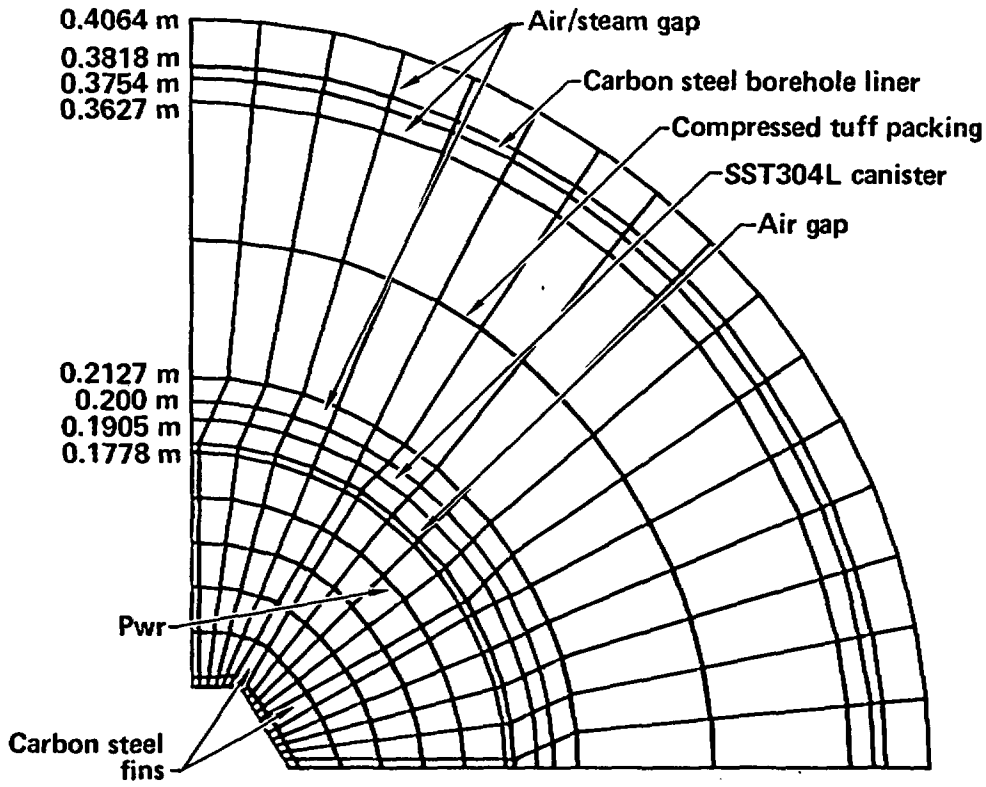


Figure 30: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 21.

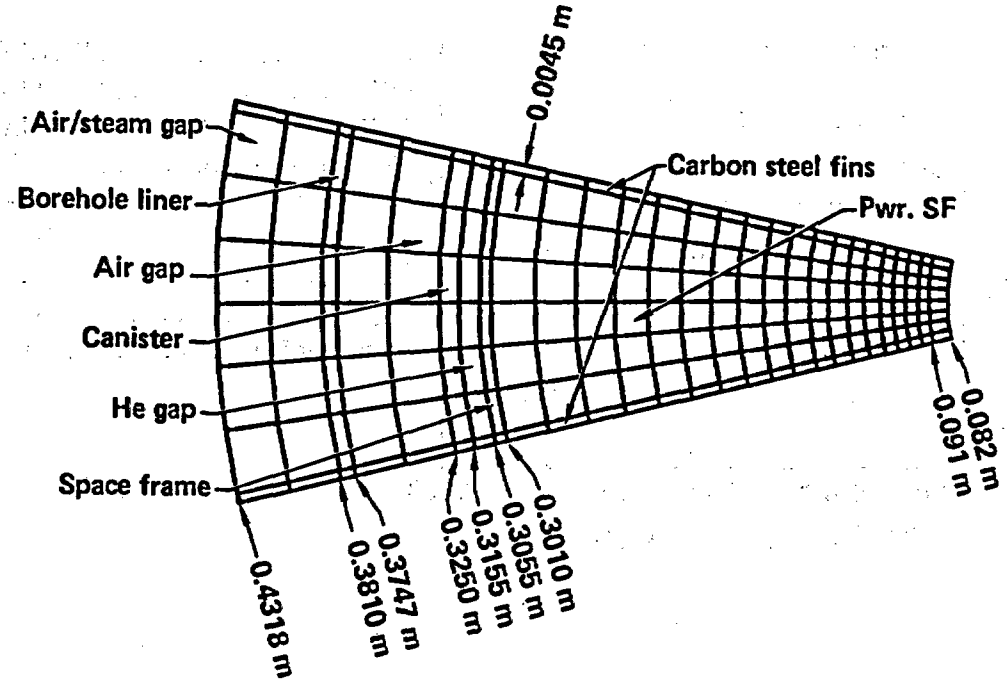


Figure 31: One fourteenth cross section of waste package finite element mesh for use in TACO2D analysis of Case 19.

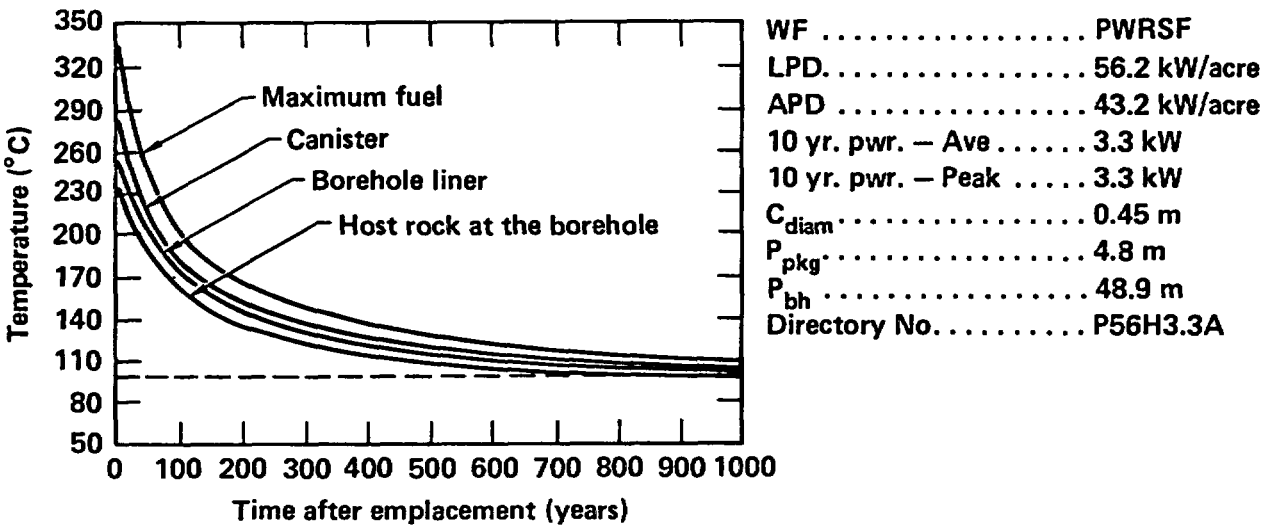


Figure 32: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with six internal fins, Case 13.

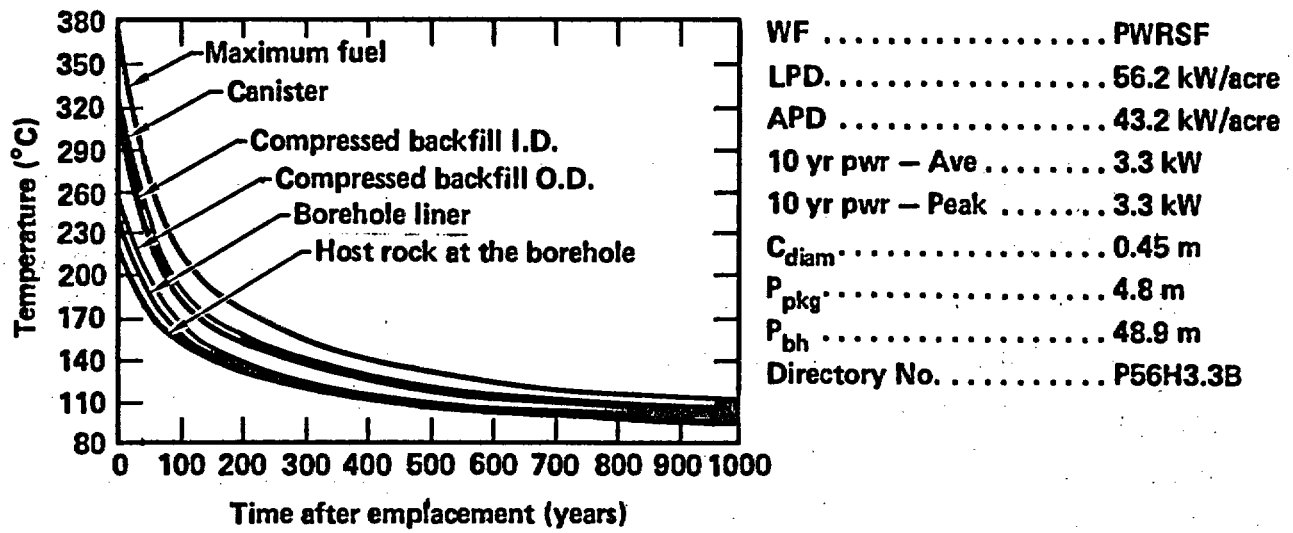


Figure 33: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with six internal fins and 15 cm of compressed tuff packing, Case 14.

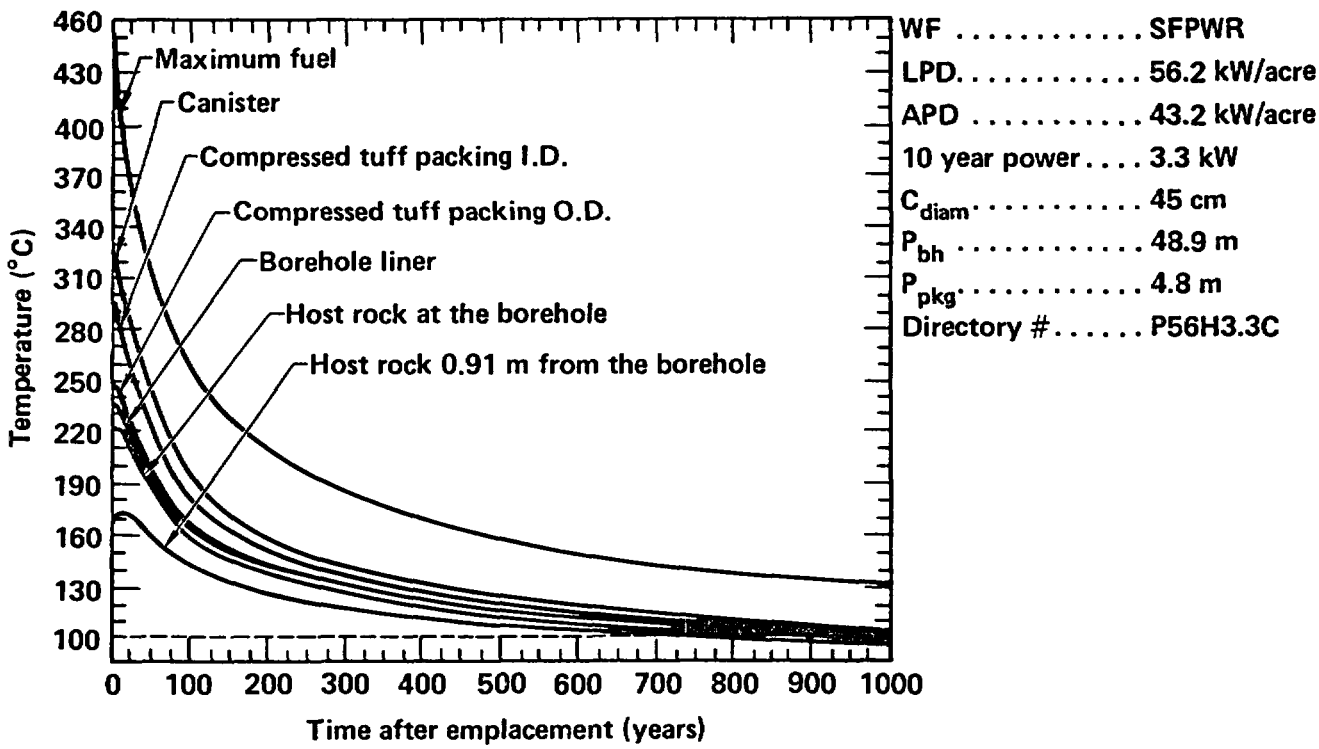


Figure 34: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with 15 cm of compressed tuff packing, Case 15.

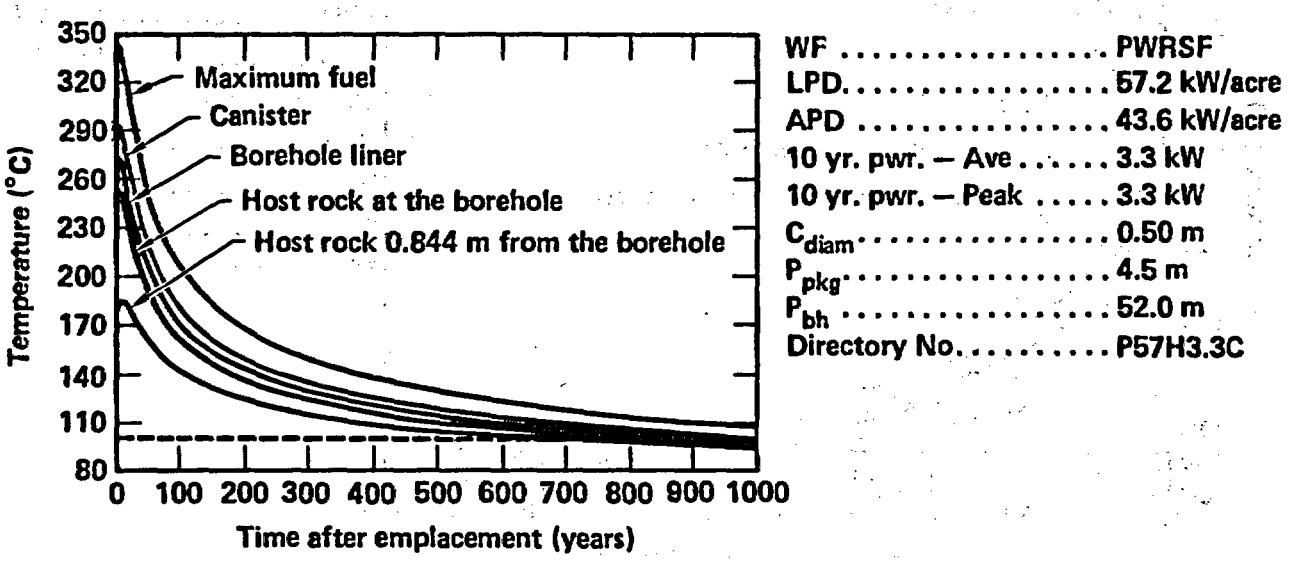


Figure 35: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with six internal fins, Case 16.

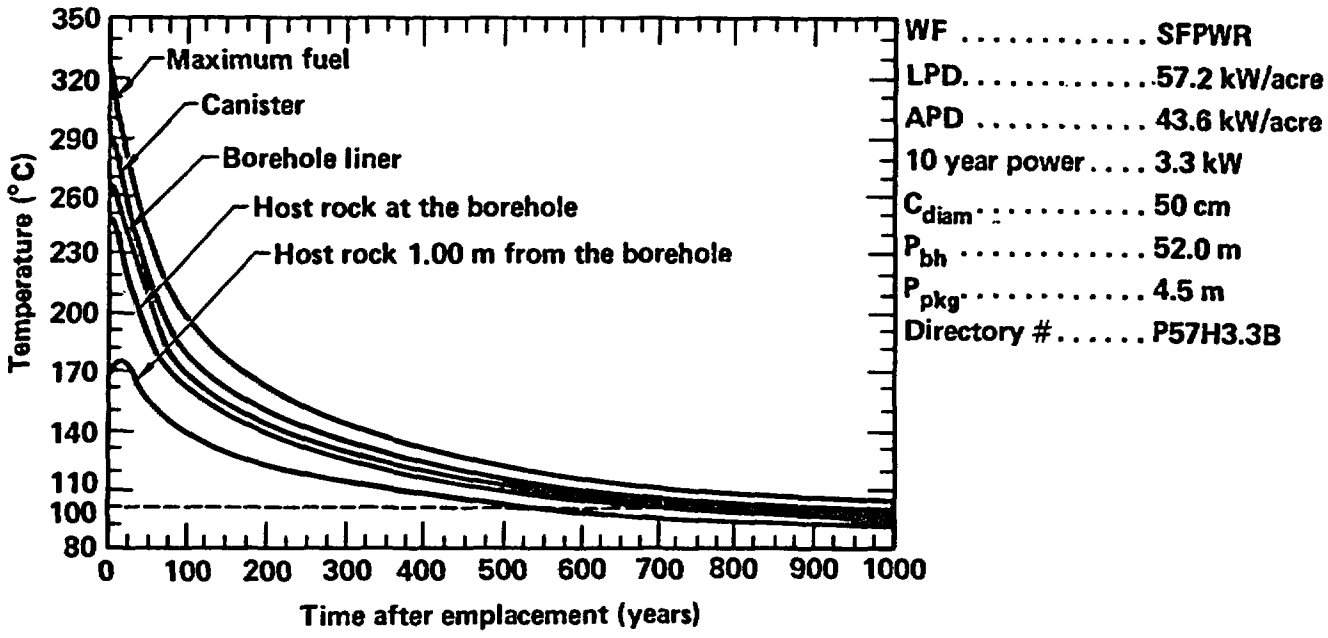


Figure 36: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with twelve internal fins, Case 17.

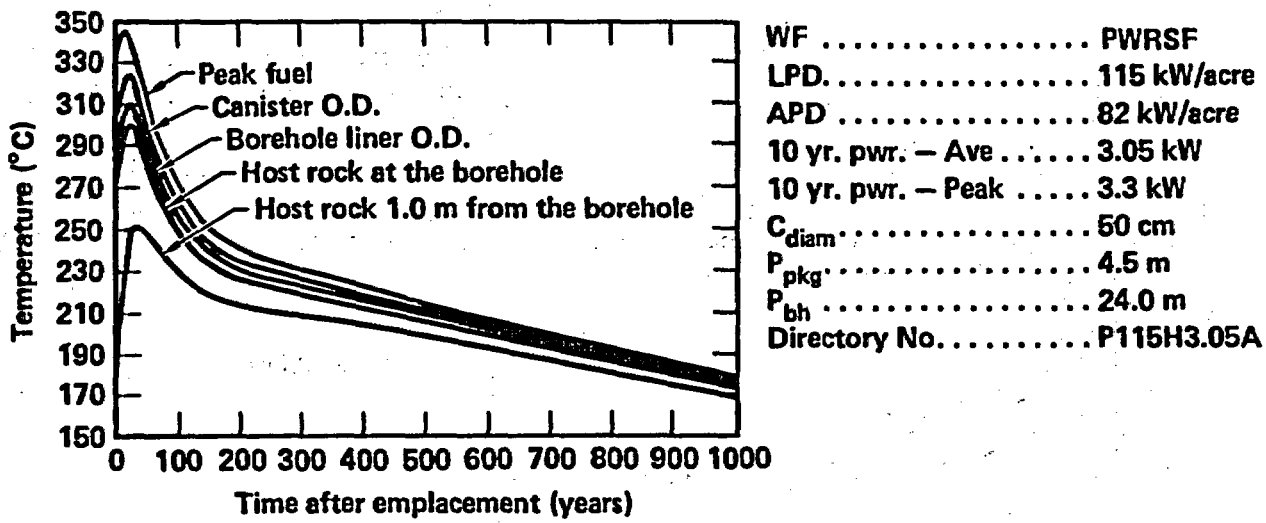


Figure 37: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with twelve internal fins, Case 18.

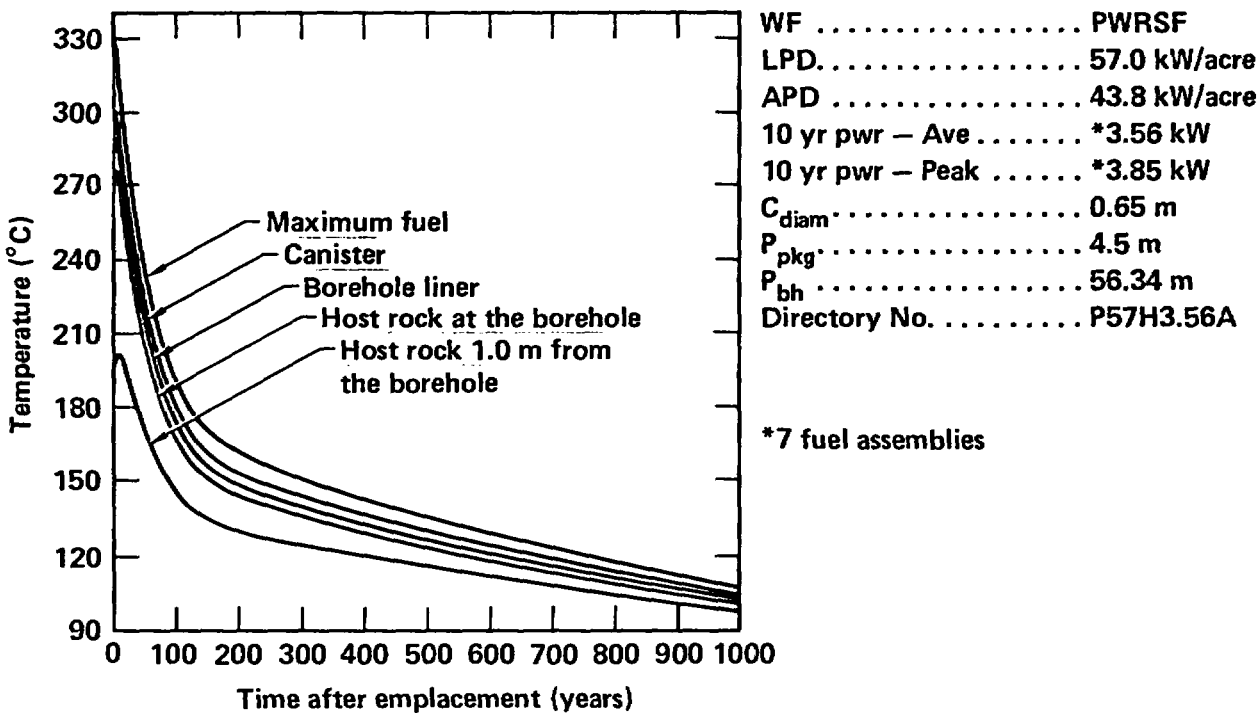


Figure 38: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with fourteen internal fins, Case 19.

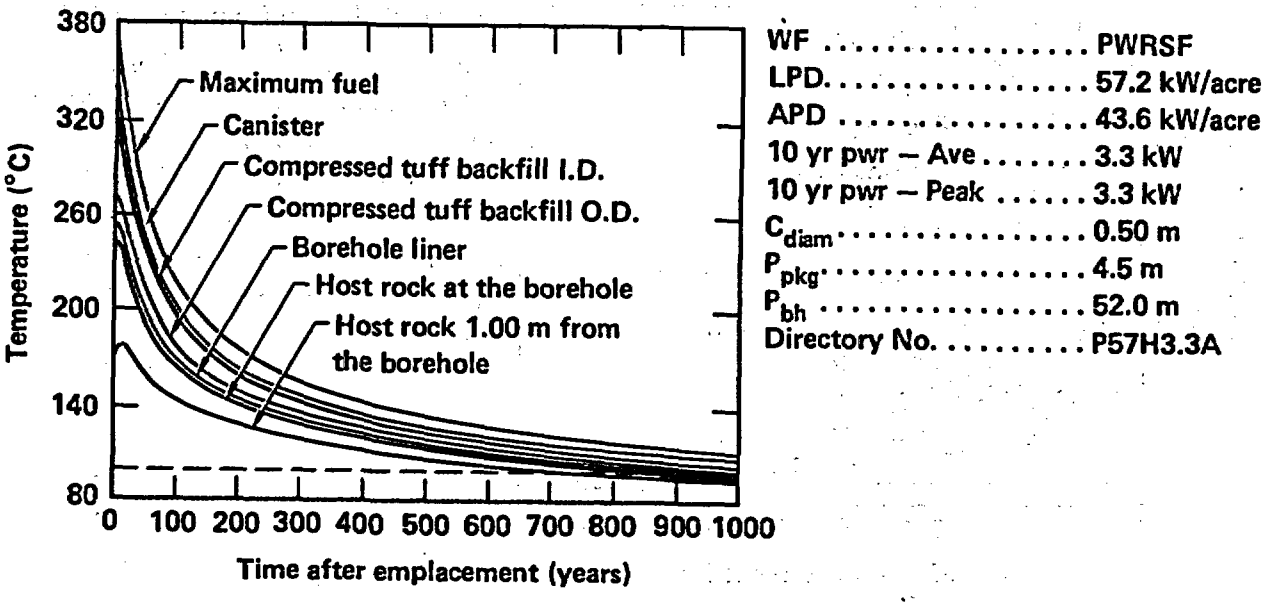


Figure 39: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with 24 internal fins, 15 cm compressed tuff backfill, Case 20.

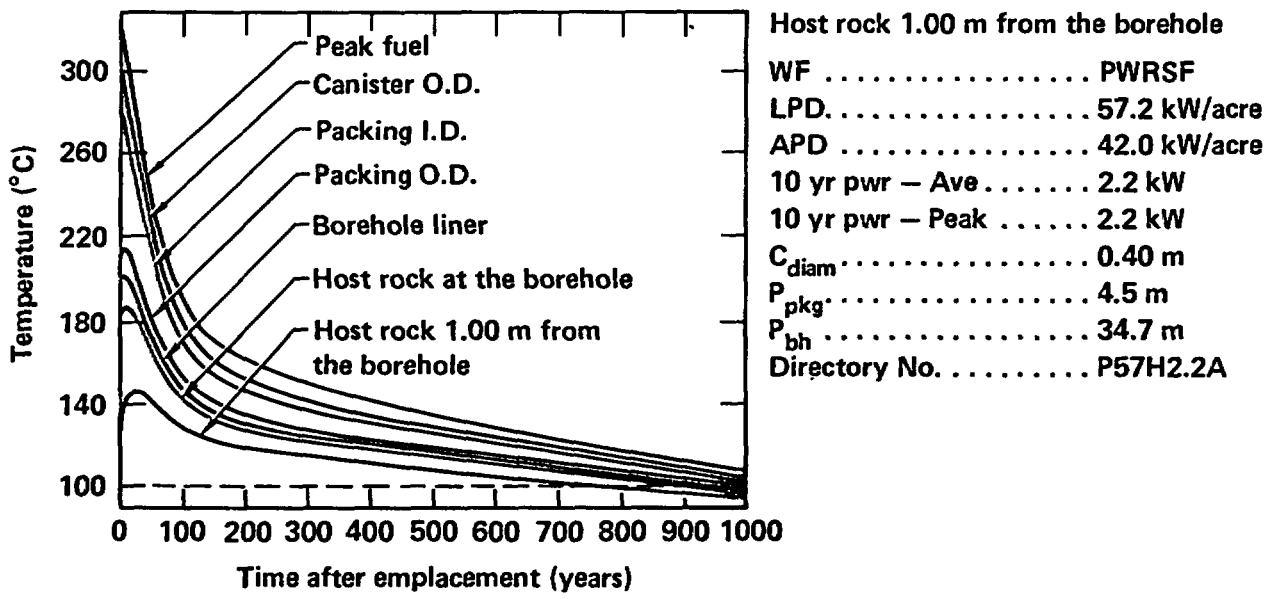


Figure 40: Temperature histories of waste package components and host rock for horizontally emplaced PWR spent fuel with twelve internal fins, 15 cm compressed tuff backfill, Case 21.

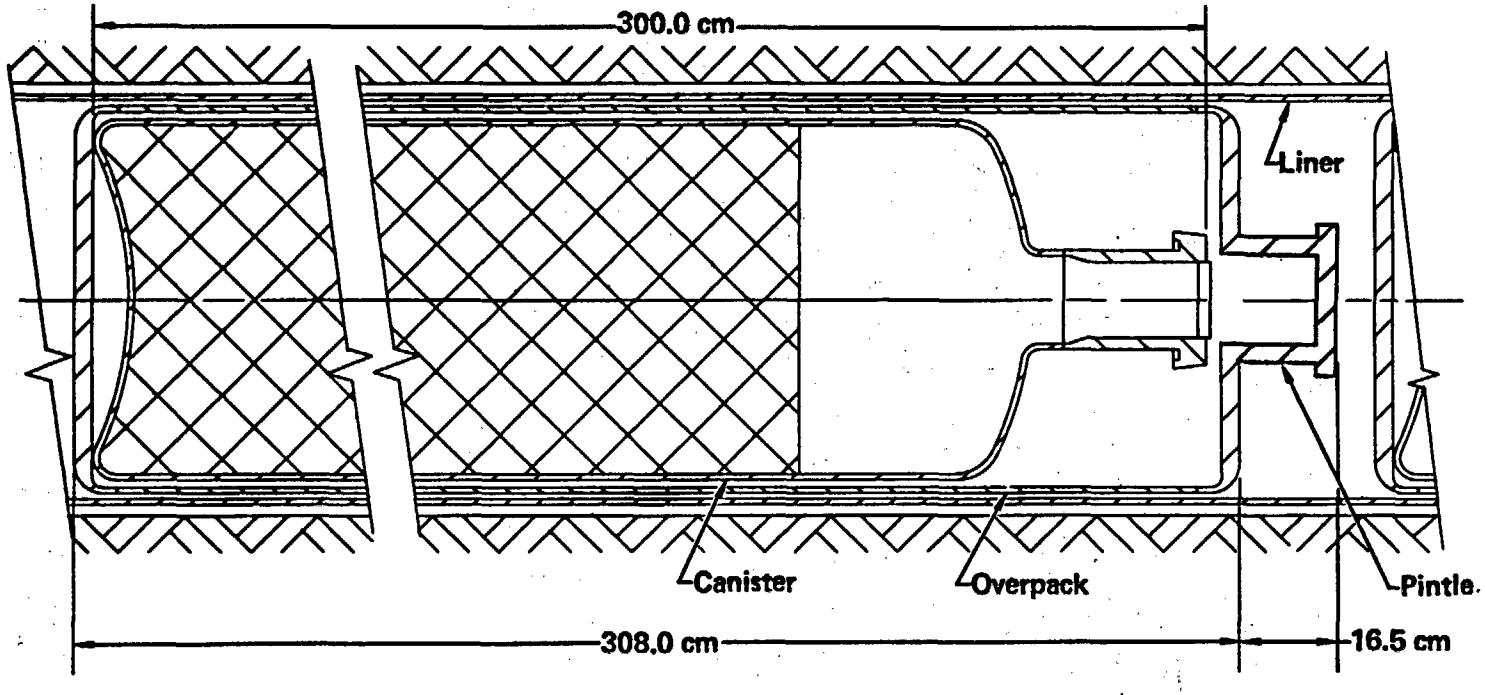


Figure 41: Overpacked DHLW package for Cases 1 - 3.

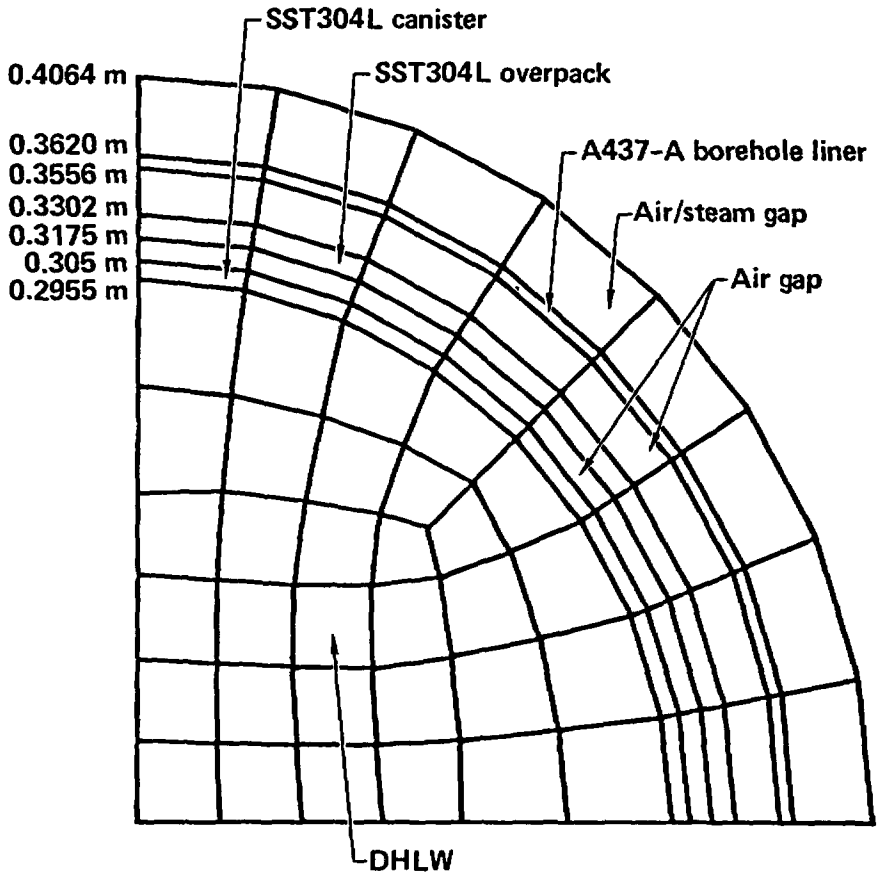


Figure 42: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 1.

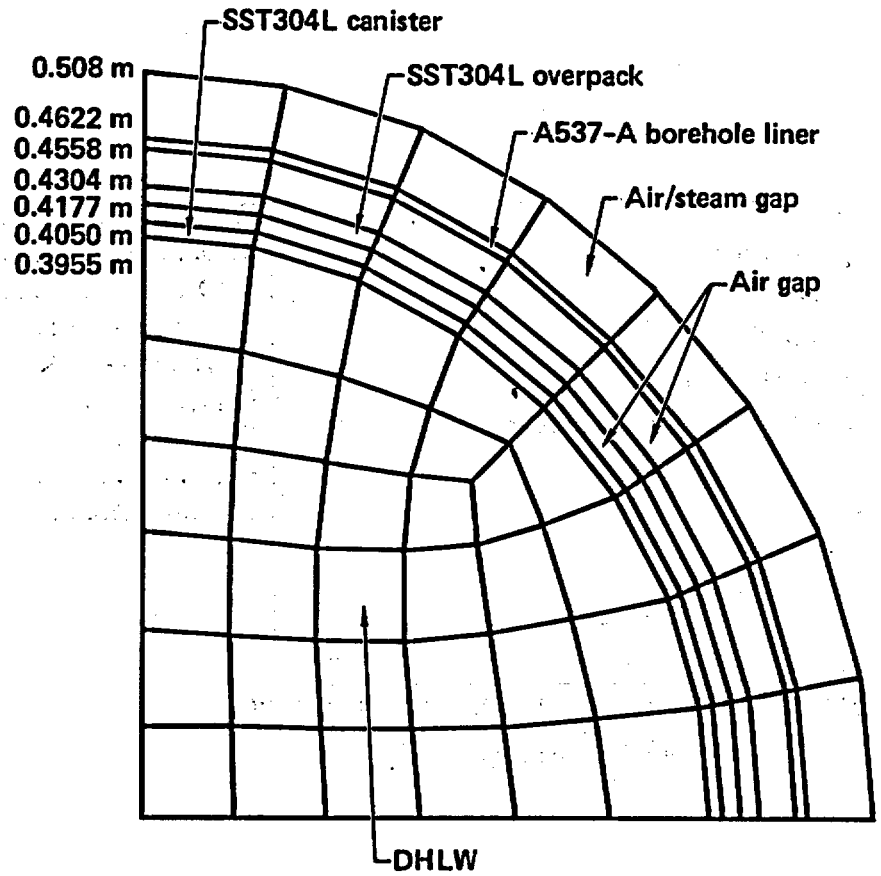


Figure 43: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Cases 2 and 3.

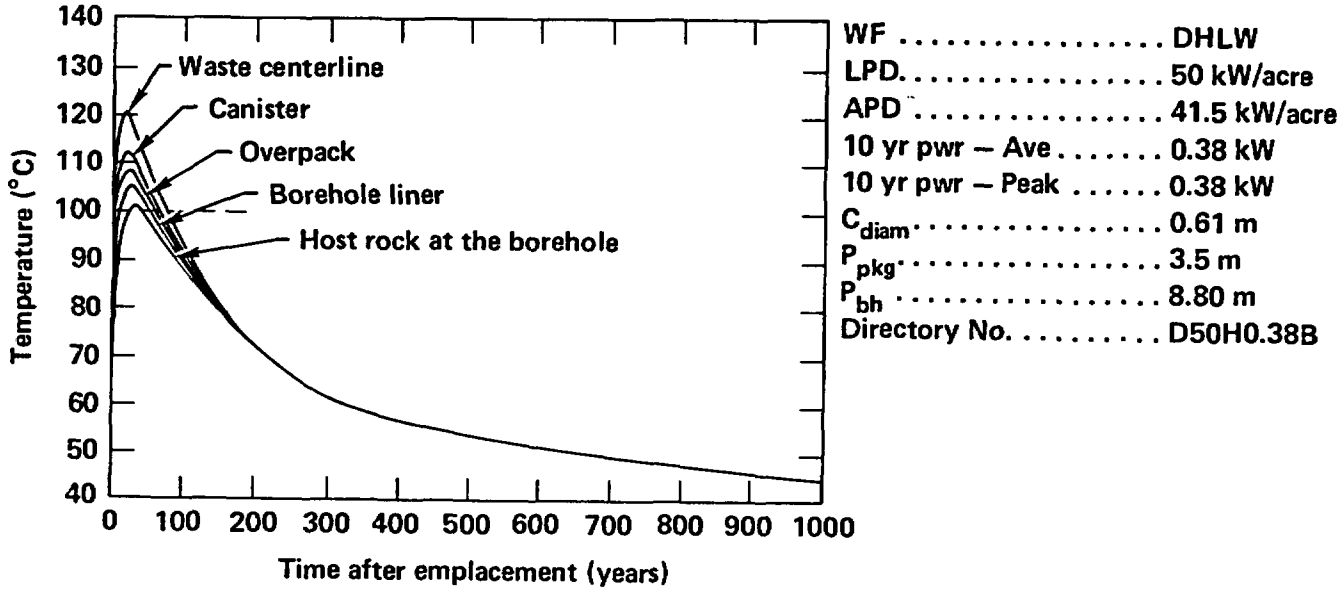


Figure 44: Temperature histories of waste package components and host rock for horizontally emplaced DHLW, Case 1.

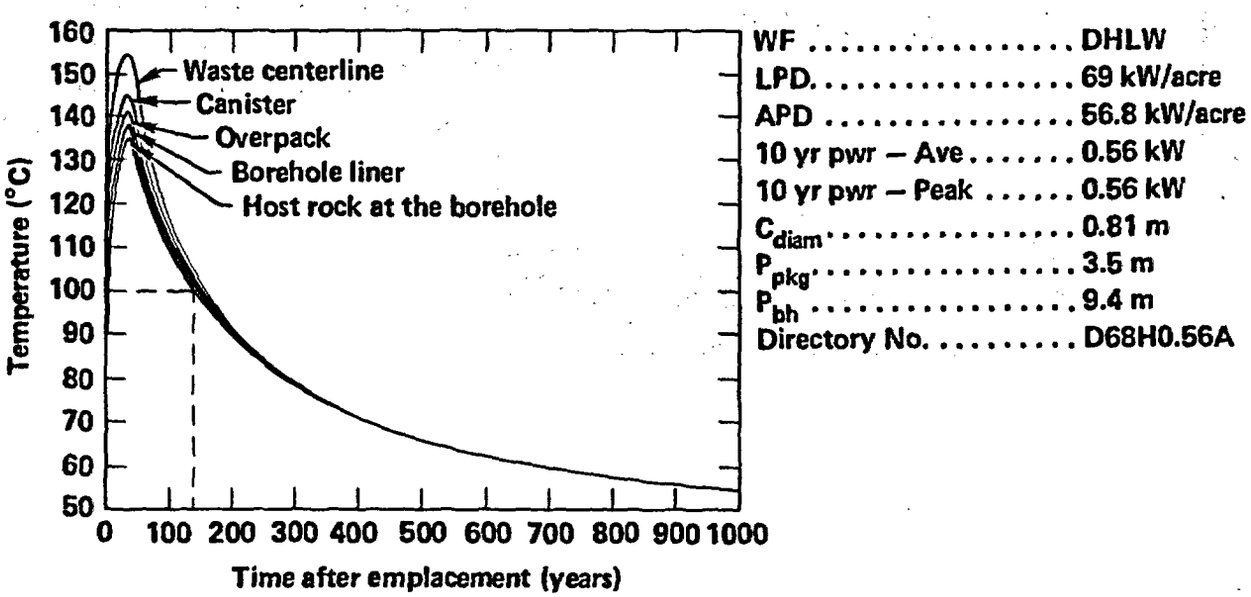
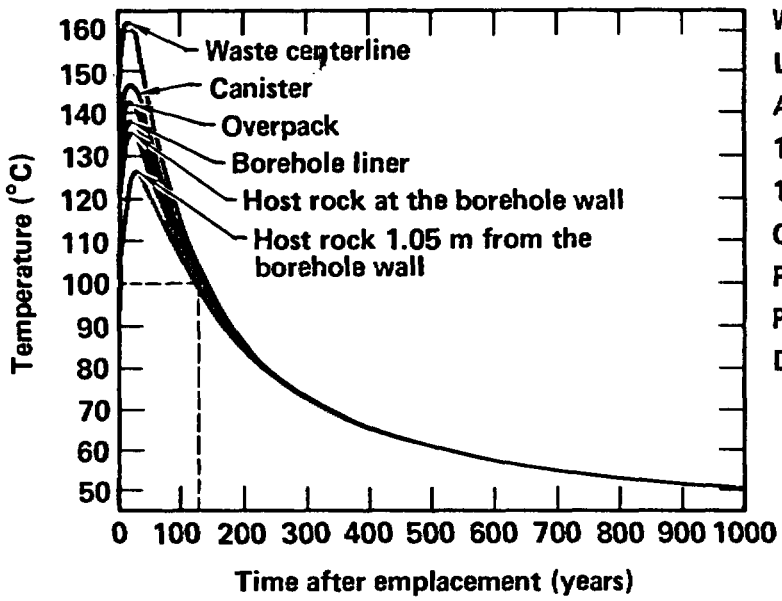


Figure 45: Temperature histories of waste package components and host rock for horizontally emplaced DHLW, Case 2.



WF	DHLW
LPD	69 kW/acre
APD	57.3 kW/acre
10 yr pwr – Ave	0.68 kW
10 yr pwr – Peak	0.68 kW
C_{diam}	0.81 m
P_{pkg}	3.5 m
P_{bh}	11.5 m
Directory No.	D69H0.68A

Figure 46: Temperature histories of waste package components and host rock for horizontally emplaced DHLW, Case 3.

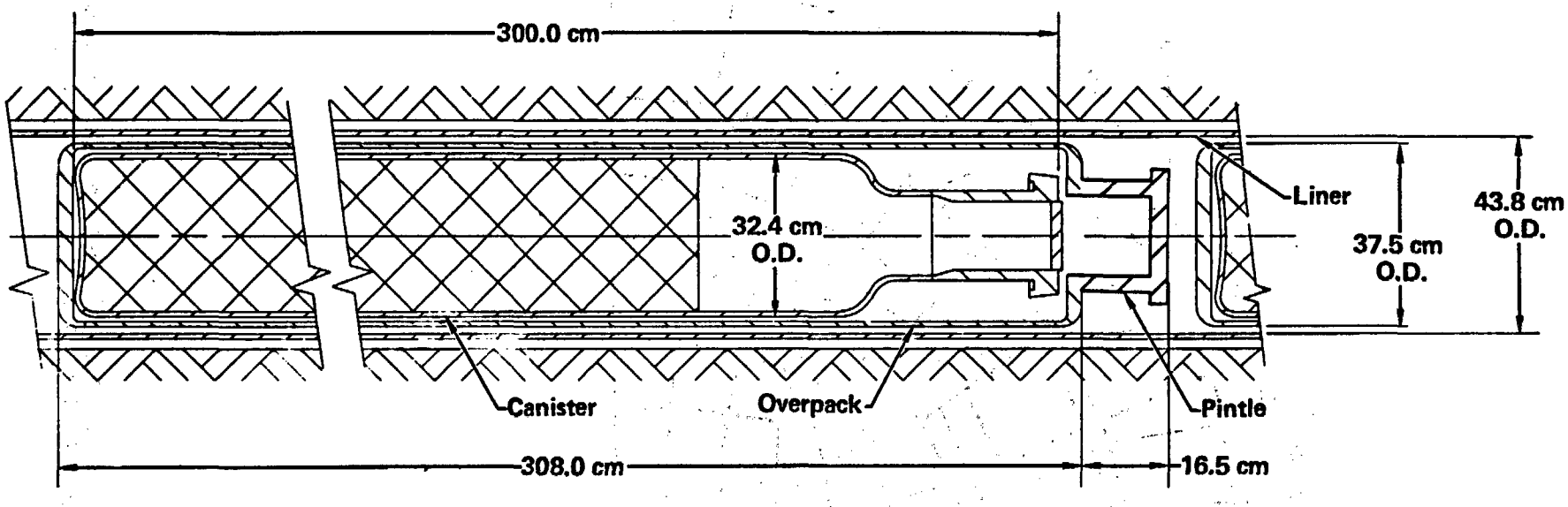


Figure 47: Overpacked CHLW package, Case 4.

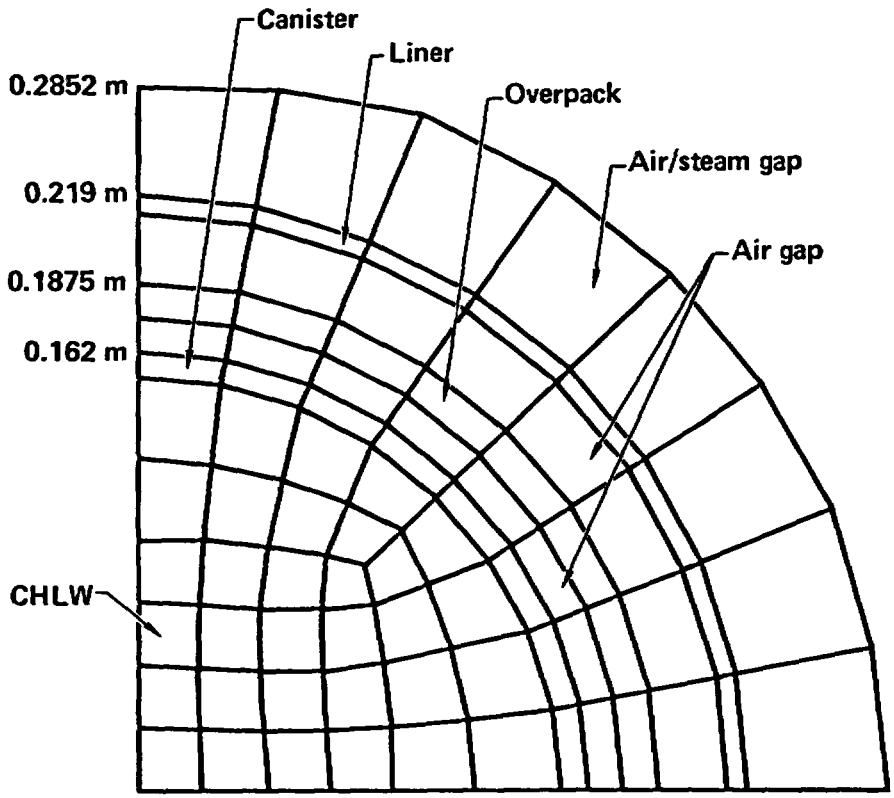


Figure 48: Quarter cross section of waste package finite element mesh for use in TACO2D analysis of Case 4.

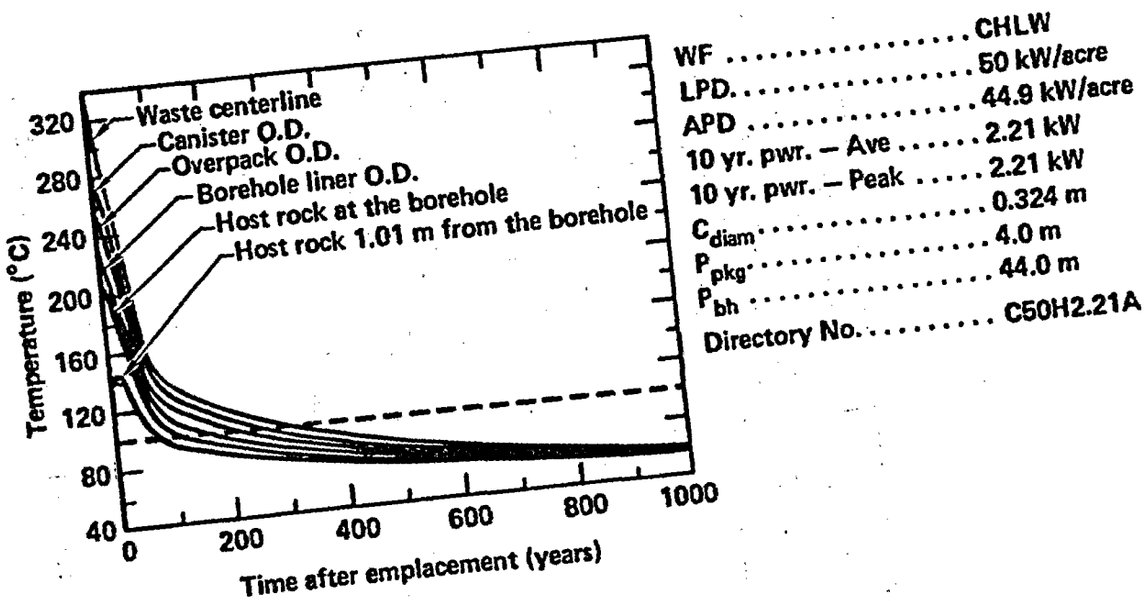


Figure 49: Temperature histories of waste package components and host rock for horizontally emplaced CHLW, Case 4.

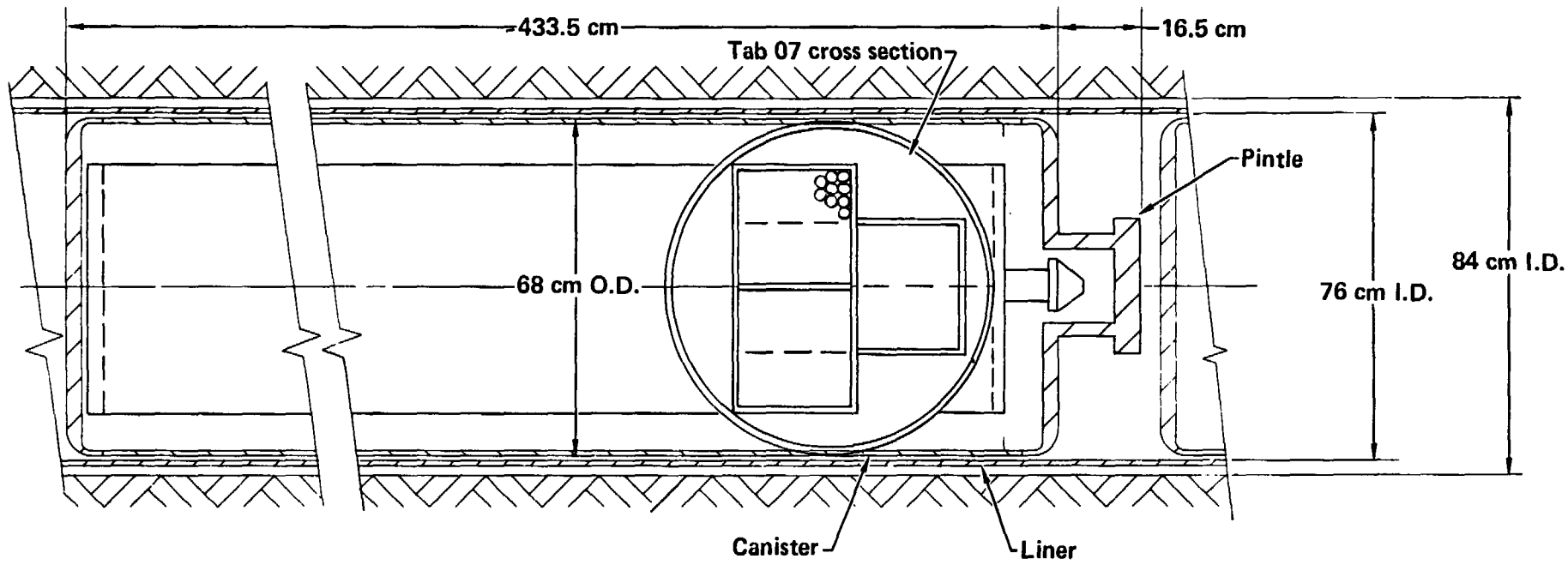


Figure 50: PWR spent fuel nuclear waste package, Case 2.

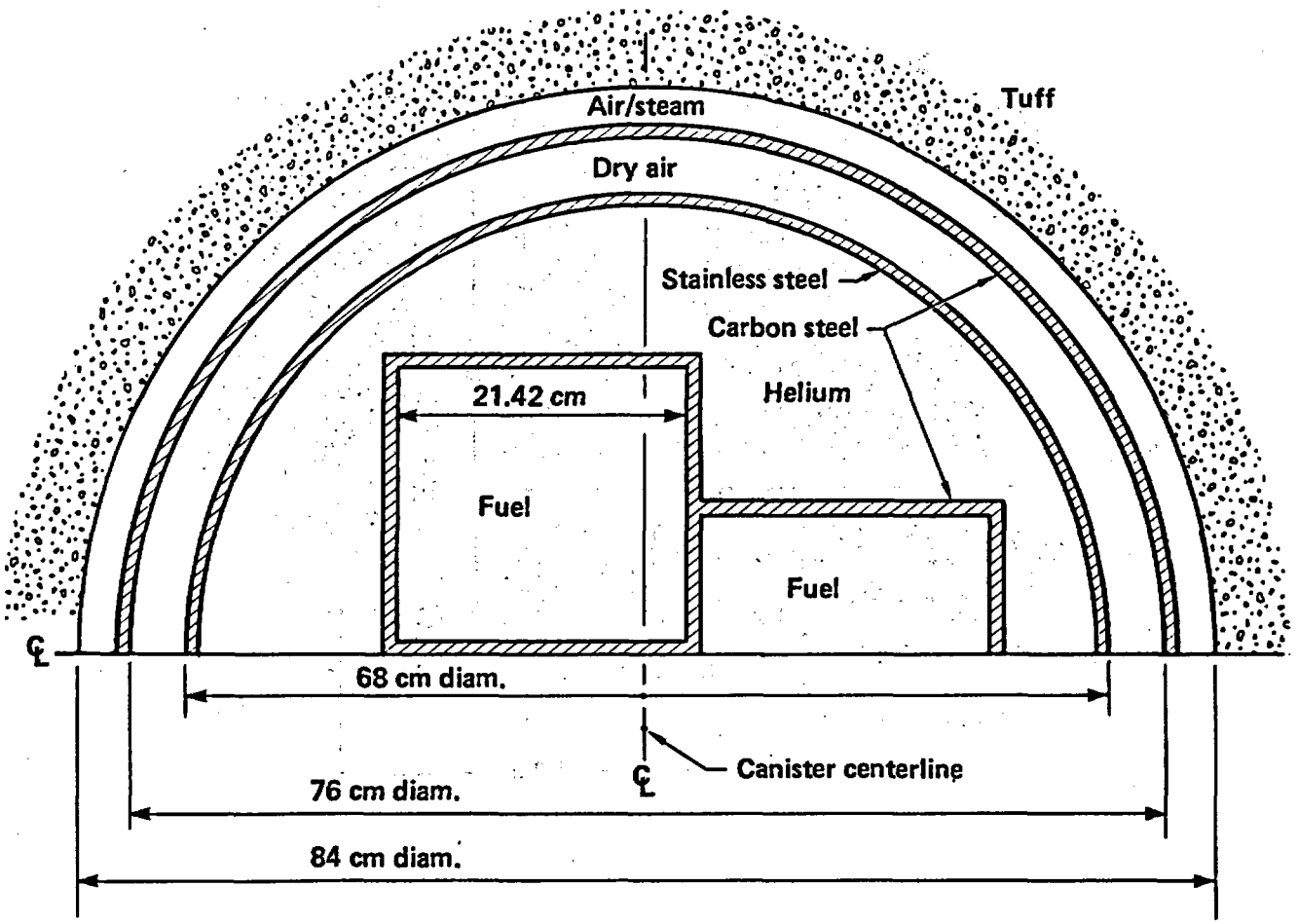


Figure 51: Model for calculating temperatures inside borehole.

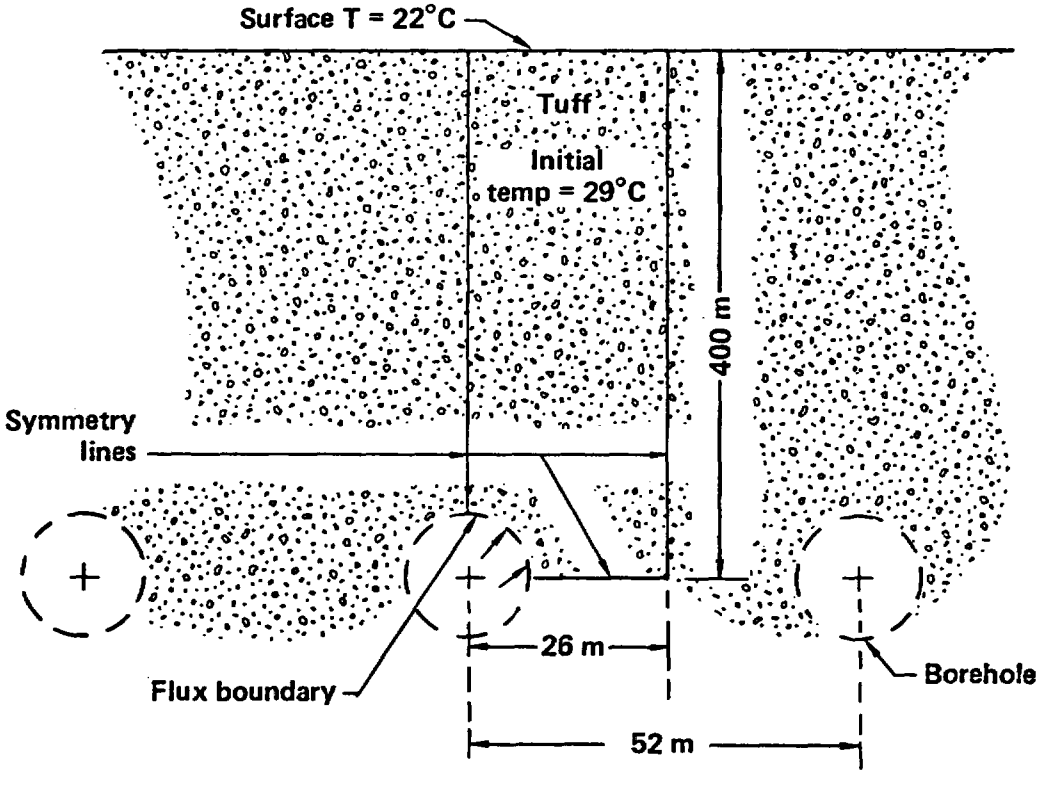


Figure 52: Model for calculating borehole wall temperature.

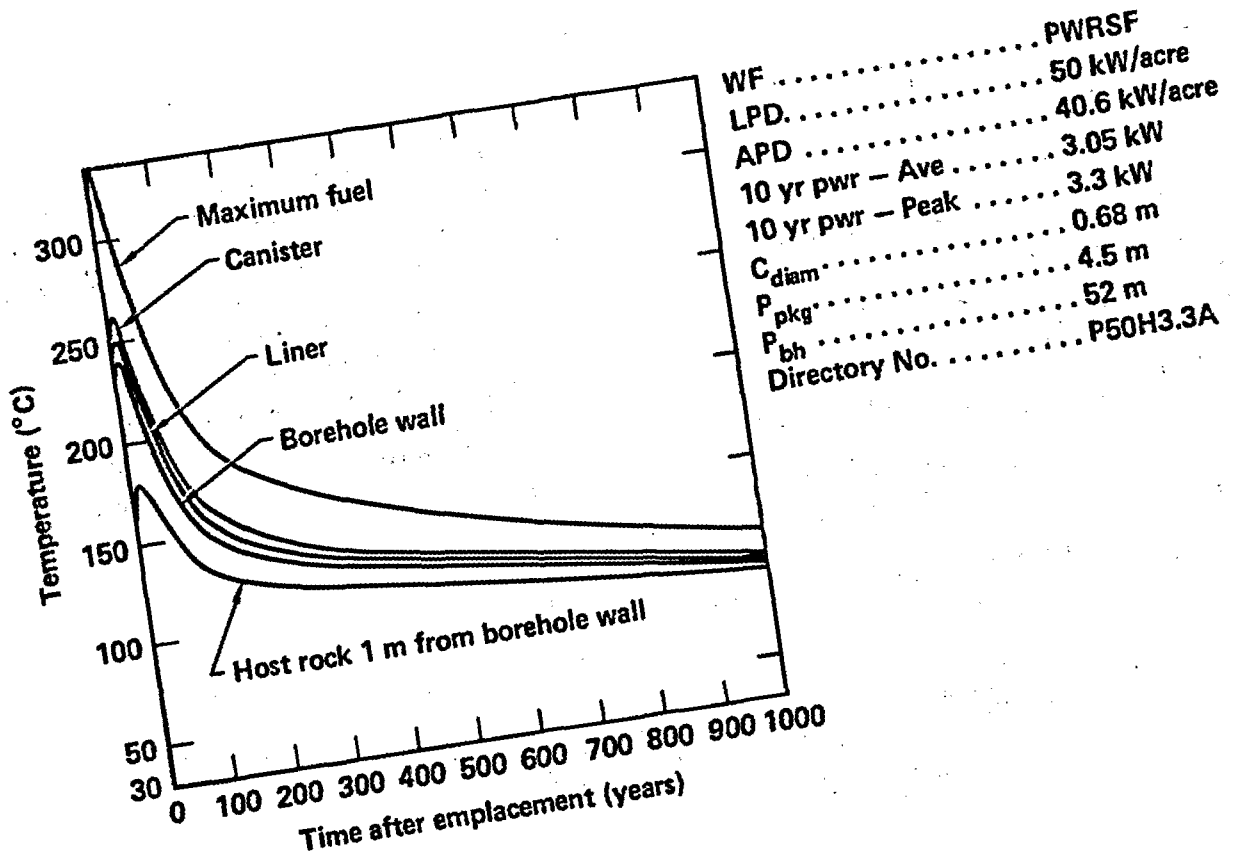


Figure 53: Temperature histories of waste package components and host rock for horizontally emplaced pre-consolidated (boxed) PWR spent fuel, Case 21.

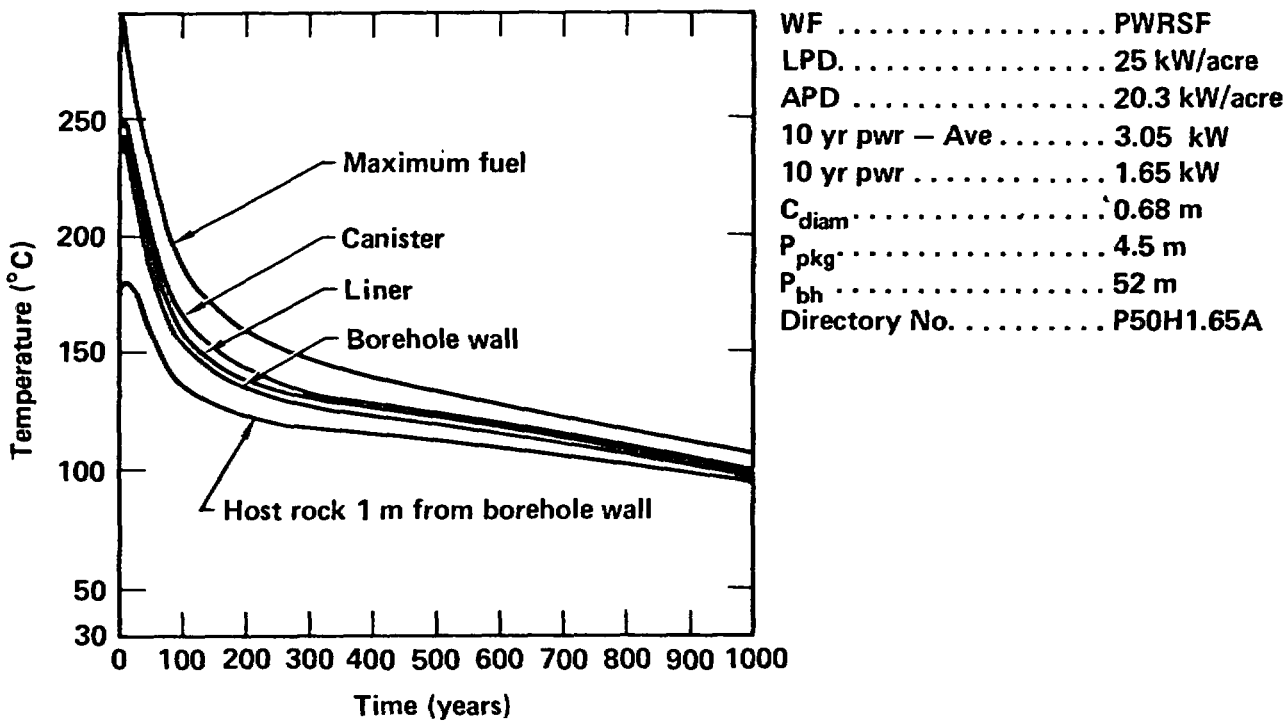


Figure 54: Temperature histories of waste package components and host rock for horizontally emplaced unconsolidatd intact PWR spent fuel, Case 22.

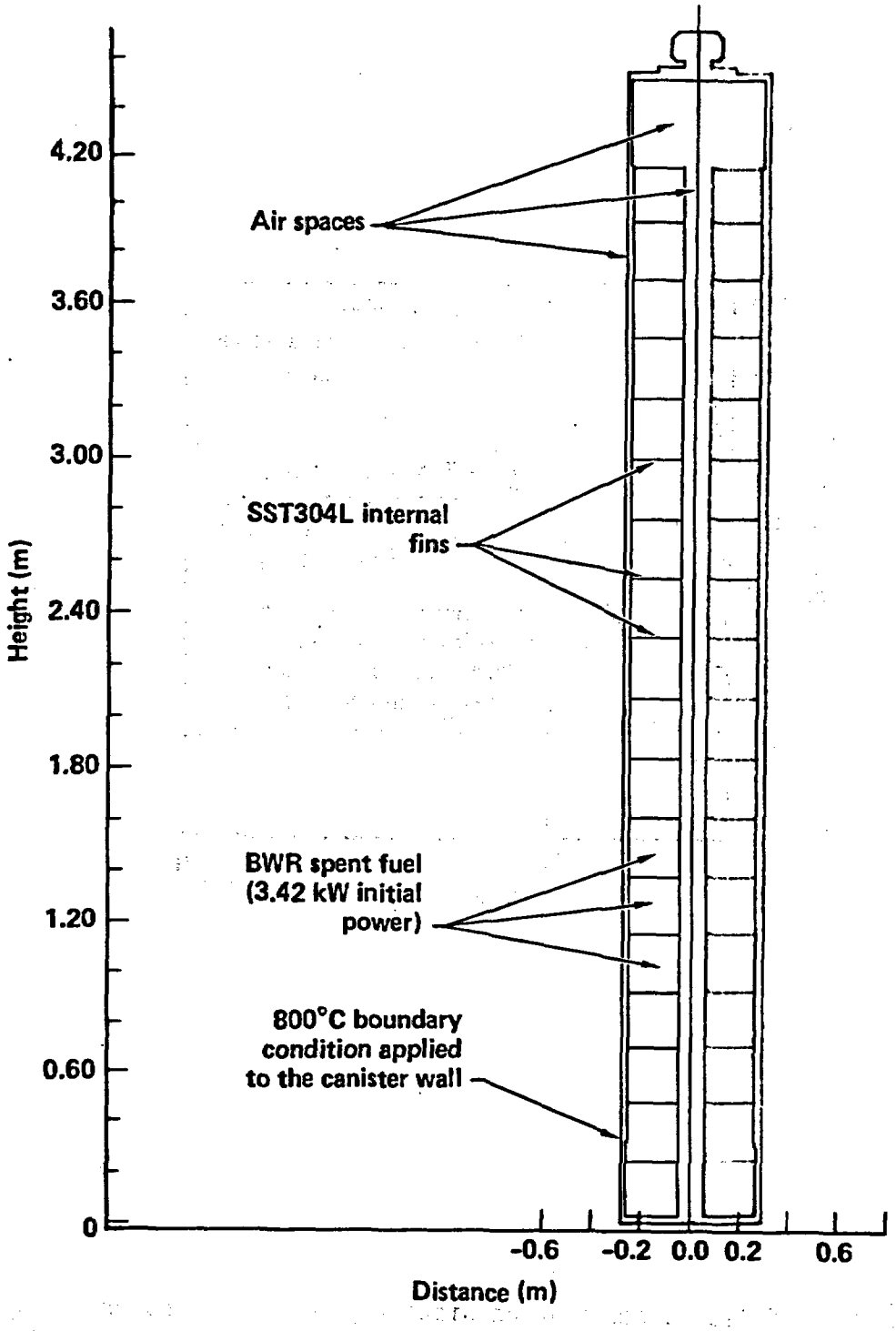


Figure 55: 2D axisymmetrical model used for the fire test simulation.

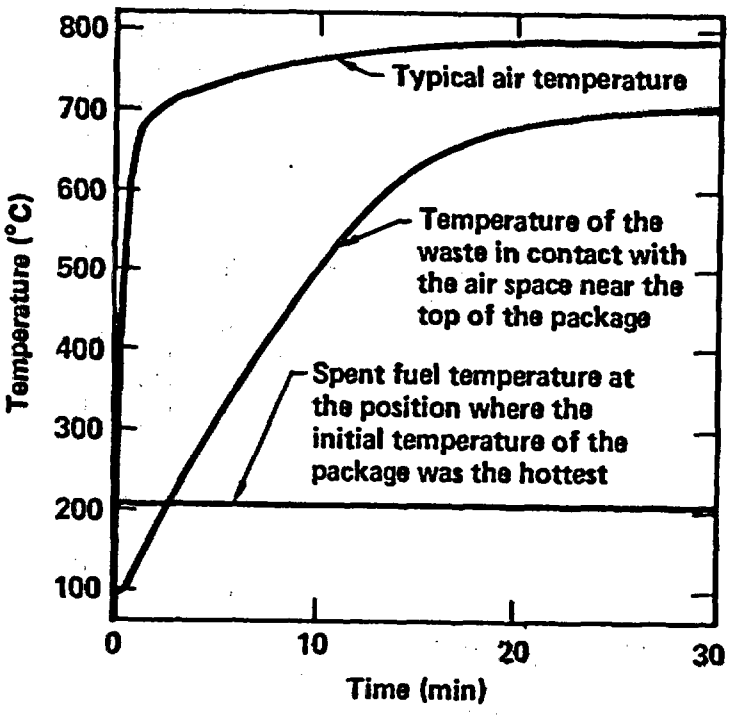


Figure 56: Selected temperature histories for the computer simulated fire test of a BWR spent fuel package (initial power of 3.42 kW).

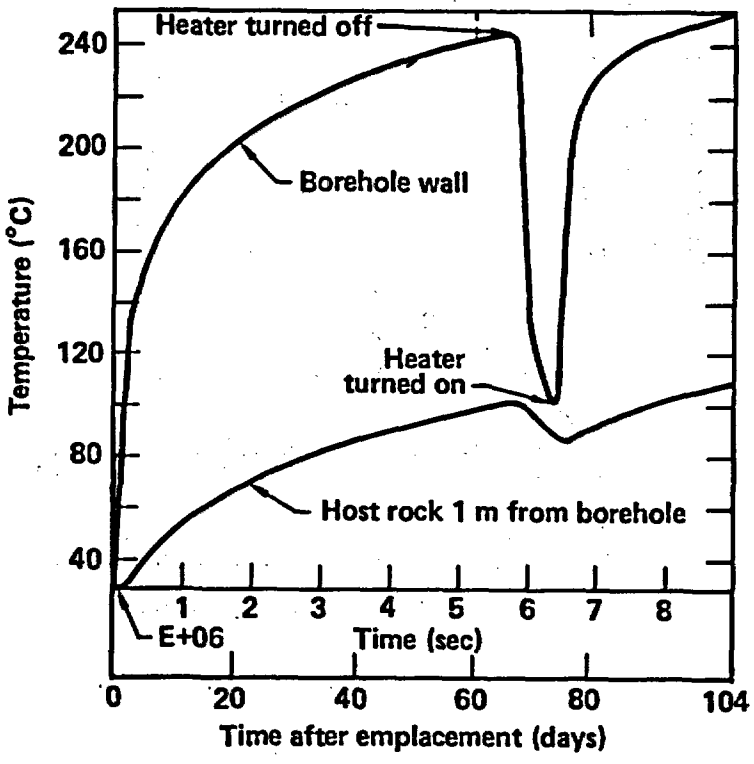


Figure 57: Temperature histories of host rock due to a 3.3 kW heater placed in a 30.5 cm (12 inch) borehole.

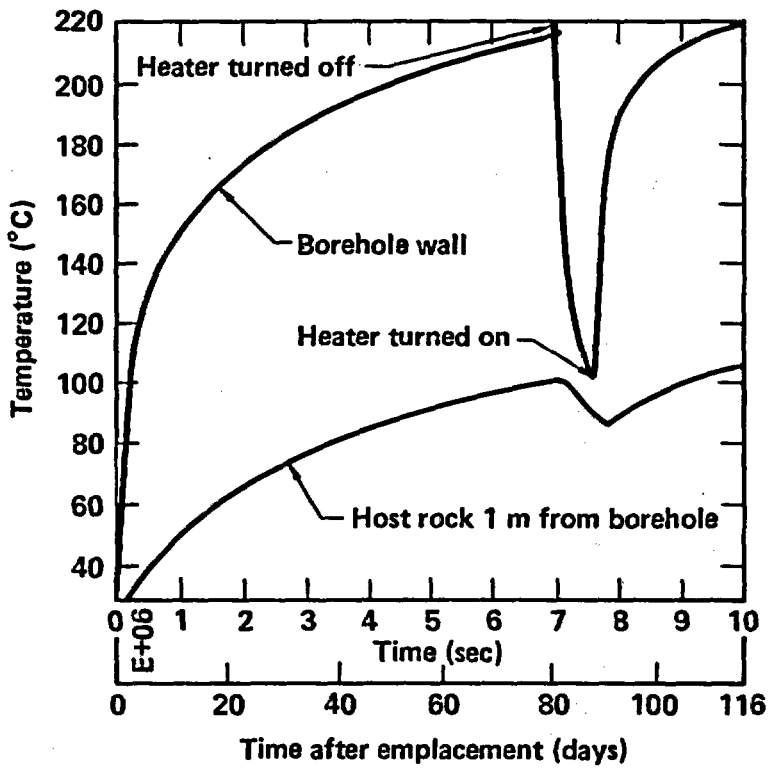
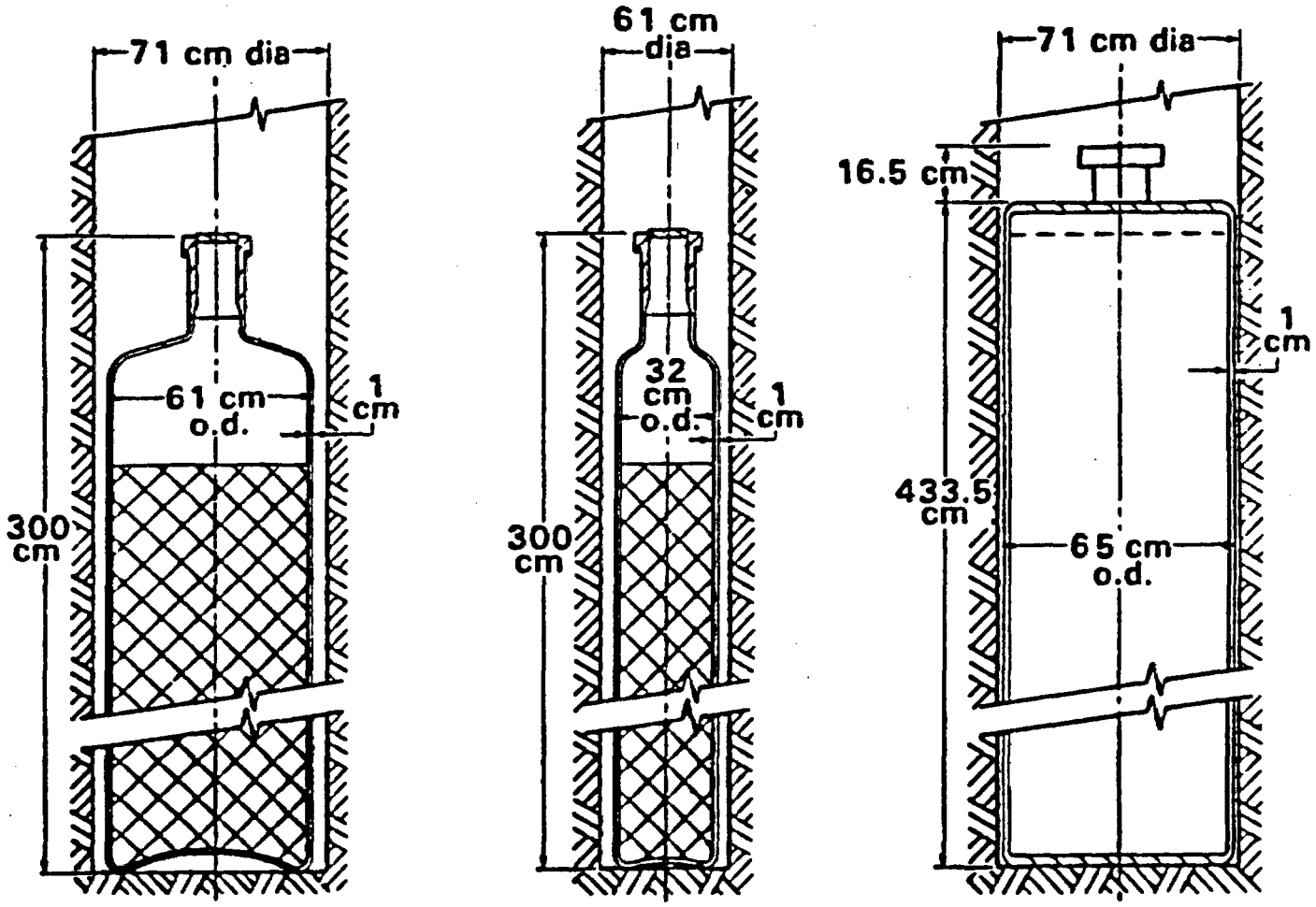


Figure 58: Temperature histories of host rock due to a 3.3 kW heater placed in a 50 cm borehole.



DHLW package emplaced in vertical borehole.

CHLW package emplaced in vertical borehole.

Spent fuel waste package emplaced in vertical borehole.

Fig. 59 Reference Waste Package Design. For defense high-level waste and commercial high-level waste, the reference design consists of 304L pour canisters with no overpacks and no packing. For spent fuel, the reference design canister is one cm thick 304L with no overpack and no packing. The reference emplacement configuration is vertical emplacement beneath drift floors.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government thereof, and shall not be used for advertising or product endorsement purposes.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $; Microfiche $4.50

Page Range	Domestic Price	Page Range	Domestic Price
001-025	$ 7.00	326-350	$ 26.50
026-050	8.50	351-375	28.00
051-075	10.00	376-400	29.50
076-100	11.50	401-426	31.00
101-125	13.00	427-450	32.50
126-150	14.50	451-475	34.00
151-175	16.00	476-500	35.50
176-200	17.50	501-525	37.00
201-225	19.00	526-550	38.50
226-250	20.50	551-575	40.00
251-275	22.00	576-600	41.50
276-300	23.50	601-up[1]	
301-325	25.00		

[1]Add 1.50 for each additional 25 page increment, or portion thereof from 601 pages up.

Technical Information Department • Lawrence Livermore National Laboratory
University of California • Livermore, California 94550