MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES
3 4456 0356254 3

Y/OWI/TM-37

Cy. 2

AREAL THERMAL LOADING RECOMMENDATIONS FOR NUCLEAR WASTE REPOSITORIES IN SALT

J. E. Russell

ORNL TECHNICAL INFORMATION DIVISION
Y-12 TECHNICAL LIBRARY
Document Reference Section
LOAN COPY ONLY
Do NOT transfer this document to any other person. If you want others to see it, attach their names, return the document, and the Library will arrange the loan as requested.
UCN-1624
(3 5-60)

June 1979

UNION CARBIDE
OFFICE OF WASTE ISOLATION
OAK RIDGE, TENNESSEE

prepared for the U.S. DEPARTMENT OF ENERGY *under*
U.S. GOVERNMENT *Contract W-7405 eng 26*

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or 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.

Y/OWI/TM-37

AREAL THERMAL LOADING RECOMMENDATIONS FOR NUCLEAR WASTE REPOSITORIES IN SALT

J. E. Russell*

*Formerly a staff member of the Office of Waste Isolation and ORNL. Present address: Department of Petroleum Engineering, Texas A&M University, College Station, Texas 77843.

prepared for the
Department of Energy
under U.S. Government Contract No. W-7405-eng-26

Office of Waste Isolation
Union Carbide Corporation-Nuclear Division
Oak Ridge, Tennessee 37830

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0356254 3

CONTENTS

Page

ACKNOWLEDGMENTS v

SUMMARY 1

1. INTRODUCTION 2
   1.1 Scope and Objective 2
   1.2 Background. 2
   1.3 Significance of Thermal Loading 3
   1.4 Rock-Mass Disturbance Due to Mining 3
   1.5 Rock-Mass Disturbance Due to Imposed Thermal Loading. . . 4
   1.6 Control of Thermal Loading. 4

2. ASSUMPTIONS AND METHODS OF ANALYSIS. 5
   2.1 Reference Repository. 5
   2.2 Tentative Performance Limits Related to Thermal Loading 5
      2.2.1 Very near field parameters (canister scale). . . . 5
      2.2.2 Near-field parameters (room scale) 9
      2.2.3 Far-field parameters (regional scale). 9
   2.3 Methods of Analysis 10

3. AREAL THERMAL LOADING DENSITY RECOMMENDATIONS. 11
   3.1 Background. 11
   3.2 Comparision of Numerical Simulation Results with Tentative Performance Limits. 12
      3.2.1 Very near field results. 12
      3.2.2 Near-field results 17
      3.2.3 Far-field results. 23
   3.3 Recommendations for Areal Thermal Loading 31

4. REFERENCES 33

5. APPENDIXES 35
   5.1 Appendix A. 37
   5.2 Appendix B. 45

ACKNOWLEDGMENTS

Work on this report was initiated during 1977 and continued in 1978 while the author was a Project Manager for rock mechanics in the Office of Waste Isolation, operated for the Department of Energy under Contract No. W-7405-eng-26. The report has been completed under Consulting Agreement E514-00700 with the Office of Nuclear Waste Isolation, Battelle Project Management Division. This report synthesizes aspects of the work of several participants in the National Waste Terminal Storage Program and reflects the results of many helpful discussions with personnel in the Geologic Disposal Technology Program at Oak Ridge National Laboratory. In particular, the author would like to acknowledge H. C. Claiborne, G. H. Jenks, and W. C. McClain of the Chemical Technology Division.

AREAL THERMAL LOADING RECOMMENDATIONS FOR NUCLEAR WASTE REPOSITORIES IN SALT

J. E. Russell

SUMMARY

The objective of this report is to establish a wider understanding of the background and rationale behind the areal thermal loading recommendations for generic studies, including conceptual designs, of nuclear waste repositories in salt. This objective has been accomplished by (1) defining a reference repository; (2) proposing a set of tentative performance limits for the response of a well-sited generic repository; (3) discussing and documenting the background of the tentative performance limits; and (4) demonstrating that the reference repository can meet the proposed performance limits at the recommended thermal loadings by comparing the results of numerical studies on conservative models within the performance limits.

Throughout the report, it is emphasized that final recommendations for performance limits and areal thermal loading cannot be made before a site is selected. For a given site, the tentative performance limits may have to be modified and additional limits imposed. Such modifications in performance limits may be reflected in different areal thermal loadings than those given herein.

In addition, field, laboratory, and numerical simulation work relevant to nuclear waste repositories in rock salt is continuing and may provide justification for altering the tentative performance limits and/or the thermal loading recommendations.

Within the state of existing technology, a well-sited repository utilizing the appropriate recommended thermal loading will apparently satisfy the tentative performance limits. The final appropriate performance limits are almost certain to be site specific and should be determined prior to final design.

1. INTRODUCTION

1.1 Scope and Objective

Some confusion has existed relative to the origin of recommended thermal loadings for nuclear waste repositories in salt. The purpose of this document is to establish a wider understanding of the history of the recommended thermal loadings in salt for both high-level waste (HLW) from fresh UO_2-fueled, light-water reactors (LWR) with no recycle and spent unreprocessed fuel (SURF) from LWRs. Aspects of the current recommendations that need further study are identified. Finally, an interim set of design thermal-loading recommendations are given that have a common rationale of satisfying performance limits within our current state of knowledge. These recommendations are made on a generic rather than a site-specific basis.

1.2 Background

The disposal of radioactive nuclear wastes in deep, land-based, conventionally mined, room-and-pillar repositories in salt has been studied for the past 20 years. Rock salt was originally recommended for repositories because of its naturally dry state, plastic nature, relatively high thermal conductivity, abundance, and occurrence in stable basins at practical mining depths. In addition, rock salt may be mined economically using modern mechanized equipment. The ultimate objective of a repository is to effectively isolate radioactive nuclides from the biosphere until they decay to innocuous levels.

Several types of waste have been considered for disposal in underground repositories. In this report, only heat-generating wastes will be considered. For purposes of rock mechanics and heat transfer calculations, the waste and emplacement configuration may be characterized by the following: (1) the type of waste and, hence, its thermal decay characteristics; (2) the age of the waste at burial; (3) the areal thermal loading density generally given in kW/acre, but which can be readily converted to equivalent metric tons of heavy metal (MTHM) reactor fuel per acre; (4) the thermal power in each hole at the time of

emplacement; (5) the geometric configuration; and (6) rock and other material properties.

The area thermal loading used in conceptual repository designs has been identified as one of the most significant design parameters. This can be seen by considering two major disturbances to an originally stable rock mass that result from the development of an underground nuclear waste repository. These are the excavation of the repository itself and the imposed heat loading.

1.3 Significance of Thermal Loading

The thermal loading of a repository is intimately related to safety during the operational phase, long-term safety, and economics. During the operational phase, rock temperatures influence (1) the stability of the mine rooms and emplacement holes, which should remain open and stable for safety and ready retrievability; (2) the kinetics of corrosion and other chemical processes; (3) working temperatures for men and equipment; and (4) ventilation requirements. With respect to long-term safety, rock-mass-temperature increases resulting from the thermal loading cause the rock to expand upward; this could cause fracturing in overlying strata, increased permeability, changes in ground water flow and temperature, changes in surface drainage, and possibly have some effect on the local biota due to slightly increased mean soil temperature.

The significance of the thermal loading also relates to excavation costs as well as the total real estate required to store a given quantity of waste. If the waste can be stored more densely, the amount of excavation and real estate required can be minimized.

1.4 Rock-Mass Disturbance Due to Mining

Salt has been mined underground for centuries and, consequently, a great deal of empirical knowledge exists on salt mine design. Some of the factors influencing the design of salt mines include: (1) the local geology, in particular, the presence of clay bands or other materials interbedded with the salt mass; (2) the local hydrology, especially the

number and capacity of aquifers that may overlie and underlie the salt beds; (3) the depth of the mining horizon, which is directly related to the premining stress field; and (4) mine geometry effects, which include the areal extraction ratio, pillar width-to-height ratio, and barrier pillars.

1.5 Rock-Mass Disturbance Due to Imposed Thermal Loading

In contrast to our knowledge of mining salt, there has been comparatively little experience on the effects of imposed thermal loading. Project Salt Vault (PSV)[1] provided the first demonstration of the effects of imposed thermal loading on a salt mine. Both electrical heaters and radioactive sources were used during this experiment. Heater tests are now underway at the Avery Island, Louisiana salt dome where the response of salt in the immediate vicinity of electrical heaters is being monitored. In addition, data from the Avery Island test will indicate any differences in response that might be anticipated between bedded salt and domal salt.

1.6 Control of Thermal Loading

Several means are available for controlling thermal loadings per canister and per acre in a repository. The thermal loading imposed on the rock mass may be controlled by varying the age of the SURF at burial, the number of assemblies per canister, and the number of canisters per acre. In the case of HLW, the thermal power can be controlled by diluting of the HLW as well as aging it before burial, and by varying the number of canisters per acre. The spacing of HLW or SURF canisters and the room-and-pillar configuration control the thermal power per acre and can be conservatively designed to meet virtually any reasonable thermomechanical performance criteria in a properly sited repository. A tentative set of performance criteria are presented in this report.

The response of the rock mass to the thermal loading depends both on the areal thermal power density at burial and on the thermal decay characteristics of the SURF or HLW. The SURF thermal power decays much more slowly than the HLW and, consequently, the long-term far-field

effects become much more important in the case of SURF disposal than in the case of HLW disposal.

2. ASSUMPTIONS AND METHODS OF ANALYSIS

2.1 Reference Repository

Several assumptions must be made relative to the configuration (e.g., size, shape, depth) of the repository before areal thermal loading recommendations can be established. Collectively, these assumptions are referred to as the reference case and are presented in Table 1. These reference case assumptions are based on experience from PSV,[1] preconceptual designs,[2] and the ongoing conceptual designs by Kaiser Engineers for SURF in bedded salt and Stearns-Roger Engineering Company (SRENCO) for HLW in domal salt.

Although many other assumptions could have been made for the reference case, the objective at the conceptual design stage is to make assumptions and evaluate alternatives that will lead to a workable, safe repository.

2.2 Tentative Performance Limits Related to Thermal Loading

Tentative performance limits related to thermal loading have been set in order to determine whether a proposed design would lead to a repository that would perform satisfactorily. These limits, involving three geometric scales, are summarized in Table 2 and are considered tentative because they must be reevaluated on a site-by-site basis. Also, these limits are subject to change as more data are developed.

Background information on the selection of the performance limits of Table 2 follows.

2.2.1 Very near field parameters (canister scale)

The response of the rock and components in the very near field is almost independent of repository depth. Although thermal conductivity of salt decreases with increasing temperature and temperature increases with depth due to the natural geothermal gradient, peak temperatures are expected to occur in about tens of years for depths of interest.

Table 1. Reference repository design parameters

Parameter	Assumed value
Host rock	Bedded or domal salt (undisturbed by man and geologically stable)
Repository size	2000 acres underground on a single level
Repository shape	Square or rectangular
Repository depth	2000 ft
Mine configuration	Long rooms and rib pillars
Burial configuration	One or more rows of vertical emplacement holes drilled in the floor of each room
Mining method	Continuous mining machine with rubber-tire and/or conveyor-belt haulage
Waste haulage	Rubber-tire transporters
Retrievability period	5 years for HLW and SURF in disposal mode; 25 years for SURF in storage mode
Age of waste at burial	10 years for HLW and SURF
Backfill material	Crushed salt placed to a density as high as practically achievable
Canister size	HLW: ∿1-ft-ID cylinder; 10 ft long (active length = 8 ft); Net waste volume = 6.28 ft^3/canister SURF: 14-in.-OD cylinder; 16 ft long
HLW density	1-MTHM fuel equiv/3 ft^3 of HLW
Thermal decay characteristics of HLW and SURF	See Appendix A

Table 2. Tentative performance limits

	Limit
Very near field parameters, canister scale	
Decrepitation temp	Salt 260-320°C
HLW temp	
Glass	500°C
Calcine	700°C
Sintered glass ceramic	800°C
SURF temp	200°C
HLW canister temp	375°C
Moisture content of salt (temp and temp gradient result in brine migration)	No limit established
Near-field parameters, room scale	
Room closure at end of retrievability period	10-15% of original room height
Far-field parameters, regional scale	
Uplift over repository	4 to 5 ft max
Temp rise at surface	<1°F
Temp rise in aquifers	<10°F and ALARA

Decrepitation temperatures for salt, 260 to 320°C. Laboratory tests[1] indicated that unconfined rock-salt samples from several locations began to decrepitate (disaggregate) in the 260 to 320°C range, but samples from other locations show no decrepitation when heated to 400°C. Decrepitation is undesirable because it reduces thermal conductivity of the salt in the vicinity of a waste package and could lead to undesirable higher temperatures in the container and waste. In the case of bedded salt, decrepitation may release brine, which is also undesirable.

HLW temperature for glass, 500°C. Typical borosilicate waste glasses have a transition temperature of about 500°C, with a slightly higher softening temperature. Migration of heavy, separate phases in the glass might occur above the softening temperature. Significant increases in cracking and in leach rates have been observed in test glasses heated for a few months in the range 500 to 800°C. Additional information is available for solid waste temperatures of glass, calcine, and sintered glass ceramic.[3,4]

SURF temperature, 200°C. The surfaces of Zircaloy hulls might become very reactive during storage within a sealed canister due to degradation of the protective oxide film, which will occur during heating in the absence of an oxidant. Additional work is needed to arrive at firmer estimates of reasonable temperature limits for spent fuel.[3]

HLW canister temperature, 375°C. Austenitic stainless steel, probably 304L, used in HLW canisters undergoes changes in structure during long-term exposure in air at temperatures in the range 400 to 900°C. The observed effect is an increased susceptibility to stress cracking when it is subsequently exposed to aqueous solutions.[3]

Moisture content of salt with no established limit. Brine inclusions in rock salt tend to migrate when subjected to a temperature gradient with velocities that also depend on temperature. Natural rock salt contains moisture that may range to 1% by volume. Brine migration into waste emplacement holes may cause more rapid deterioration of sleeves and canisters with an accompanying release of gases, including hydrogen gas. Moisture content in rock-salt samples measured to date do not seem to cause any unmanageable difficulties.[5,6]

2.2.2 Near-field parameters (room scale)

Rooms must be accessible at the end of the retrievability period to allow safe entry for the removal of canisters with the same equipment used to emplace them. Calculated room closures of less than the limit imply that the repository will generally remain structurally stable throughout the retrieval period, although some local failure controlled by local rock conditions not accounted for in the analysis may occur.

In addition to thermal loading, the closure of rooms in a salt repository will depend on the depth of the repository; this relates directly to stress and mine-geometry parameters such as the percent extraction of salt and pillar width-to-height ratios. Room closure calculations appear to be relatively insensitive to stratigraphy provided that the salt near the burial horizon is at least hundreds of feet thick.

2.2.3 Far-field parameters (regional scale)

Calculations of far-field, long-term effects are sensitive to the assumed depth of the repository as well as the geologic section assumed, the waste type, the thermal power emplaced per acre, and the age of the waste at burial. Consequently, it is imperative that far-field studies be made for each proposed site before site-specific performance limits are set.

Uplift over repository, 4 to 5 ft max. Uplift over the repository centerline was chosen as a measure of the far-field structural consequences of repository thermal loading. The 4- to 5-ft-max uplift, neglecting subsidence, is based on the assumption that rock-mass movements caused by uplift may be no worse than movements caused by subsidence over mines in sedimentary rocks, which is sometimes more than twice the stated limit. Far-field effects are currently being studied to determine whether 4 to 5 ft of uplift is reasonable. This tentative limit may change as more information is developed. In any case, this limit must be reevaluated for each site so that the effects of rock-mass movement on the hydrological regime and long-term safety may be assessed.

Temperature rise at the surface, <1°F. Temperature rise at the surface has been limited to avoid undesirable effects on the biota. This limit must also be reevaluated for each site.[7]

Temperature rise in aquifers, <10°F and ALARA. Temperature rise in aquifers has been limited because the flow velocity could conceivably carry the higher-temperature water outside the repository area. In addition, temperature rise and temperature gradients can influence ground-water flow patterns and, in the worst case, may provide a transport mechanism to return nuclides to the biosphere. This limit is currently under study and must be reevaluated for each site, with consideration given to flow rate, salinity, ultimate use of the water, and geochemistry, including dissolution, transport, and subsequent precipitation of minerals. Ultimately, this limit may prove to be overly conservative for many sites. Permissible temperature rises of 15 and 50°F for stagnant aquifers 100 and 300 ft deep, respectively, have also been proposed.[7]

2.3 Methods of Analysis

Relatively little experience exists on the effects of imposed thermal loading on a rock mass; therefore, we must rely on numerical models to investigate the effects of various configurations and power levels. The mechanical response of the rock mass to an imposed thermal loading, in addition to the usual isothermal stress loading, is being analyzed by several different techniques: the finite-element method,[8] the finite-difference method,[9] and the displacement-discontinuity method.[10] Each method of analysis incorporates a nonlinear creep law for salt. With the exception of the displacement-discontinuity method, which uses PSV results directly, the analysis techniques make use of laboratory-derived properties that predict the creep and strength behavior of the rock-salt mass. Predictions using computer codes involving these techniques are validated by comparing them with field data from PSV as well as other mines for which deformational data have been collected.[9,11]

The analysis for other rock types in the repository region is somewhat similar to that for salt with some important differences. These differences include the importance of features such as existing joints, contacts, and fractures in nonsalt rocks, the importance of

porosity, permeability, and ground-water flow through the repository area, and the relatively greater importance of strength than creep behavior. Although computer codes presently in use do not incorporate all of these features, progress is being made.

The finite-element and finite-difference codes are suitable for analysis of response in the very near field, near field, and far field. The displacement discontinuity method is useful for near- and far-field studies but is not suitable for very near field analysis. Finite-element calculations are being made for the National Waste Terminal Storage Program (NWTS) by RE/SPEC Inc., of Rapid City, South Dakota. Science Applications, Inc., Oakland, California is making explicit finite-difference calculations, while the displacement-discontinuity method calculations are being performed at the University of Minnesota.

3. AREAL THERMAL LOADING DENSITY RECOMMENDATIONS

3.1 Background

Prior to 1977, the thermal loading recommendation for HLW repositories in rock salt was 150 to 158 kW/acre of 10-year-old waste. This recommendation was based on the excellent thermal analysis work of Cheverton and Turner.[12] Interim criteria, based on temperature alone, were used to arrive at the recommended thermal power loading. These thermal criteria were termed "interim" because they were based on preliminary, undocumented rock mechanics analyses of the Lyons, Kansas site.

In 1977 the interim temperature criteria[12] were replaced by the tentative performance limits given in Table 2. These limits focus attention on the maximum allowable response of individual components of the system. Theoretical and experimental methods can be used to evaluate how reasonable the performance limits are for a specific site. Numerical simulation of the entire system allows us to compare the performance of a proposed design with the performance limits. If any of the limits are exceeded, attention is focused on the controlling variable, and adjustments can be made in the design until all of the limits are satisfied.

It should be emphasized that the tentative performance limits given in this report are for generic studies useful in conceptual design. Some of the limits will probably change for specific sites, and these changes may be reflected in different thermal loadings than those recommended here for generic studies.

3.2 Comparison of Numerical Simulation Results with Tentative Performance Limits

3.2.1 Very near field results

These results are available[13] for maximum salt temperatures for a single row of 10-year-old PWR-SURF or HLW canisters in the configuration shown in Fig. 1. Maximum salt temperature increases for these two cases are shown in Fig. 2 and are summarized in Table 3. Table 3 also contains results obtained for 10-year-old PWR-SURF at 36 kW/acre (25-year retrieval case) with canisters in two rows and a pitch of 4 ft.[14] The maximum temperature rise calculated in this case is over twice that of the PWR-SURF temperature rise calculated in ref. 13; this is primarily caused by the presence of the second row of canisters in the room and the different assumptions used in the analyses. In any case, none of the calculated temperatures approach the tentative temperature limit of 260 to 320°C given in Table 2.

A relatively high degree of confidence can be placed in temperature calculations at this scale because the models, material properties, and computational techniques can be validated by comparison of computed results with in situ test results. This has been done for results from PSV.[1] Data from the Avery Island heater tests should be available in the near future for further validation of computed results.

With respect to HLW temperatures, tentative limits of 500°C for glass and 700°C for calcine are given in Table 2. The HLW temperature will depend on the properties of the glass or calcine, its thermal power density at burial, the size and shape of the waste container, the ambient salt temperature, and the heat transfer properties of the rock salt.

Table 4 contains upper-bound conservative estimates of maximum centerline temperatures for HLW as obtained in Appendix B. The conservative maximum HLW temperature estimates are comfortably less than the

Fig. 1. Three-dimensional unit-cell model for a PWR spent-fuel (SF) assembly or high-level waste canister.[13]

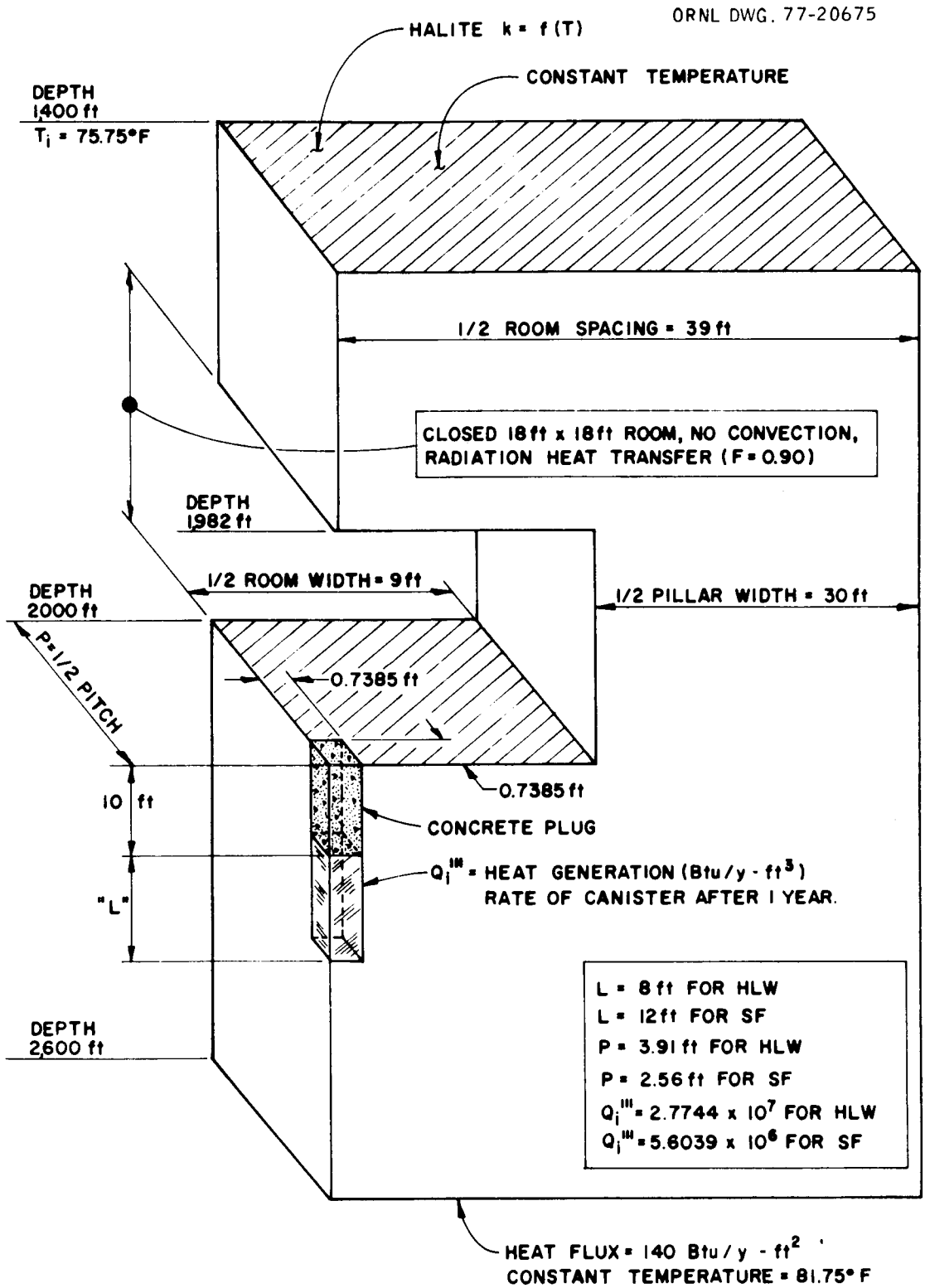


Fig. 2. Comparison of maximum temperature increases in salt as functions of time in the three-dimensional unit-cell models for spent fuel (SF) stored at 60 kW/acre and HLW stored at 150 kW/acre.[13]

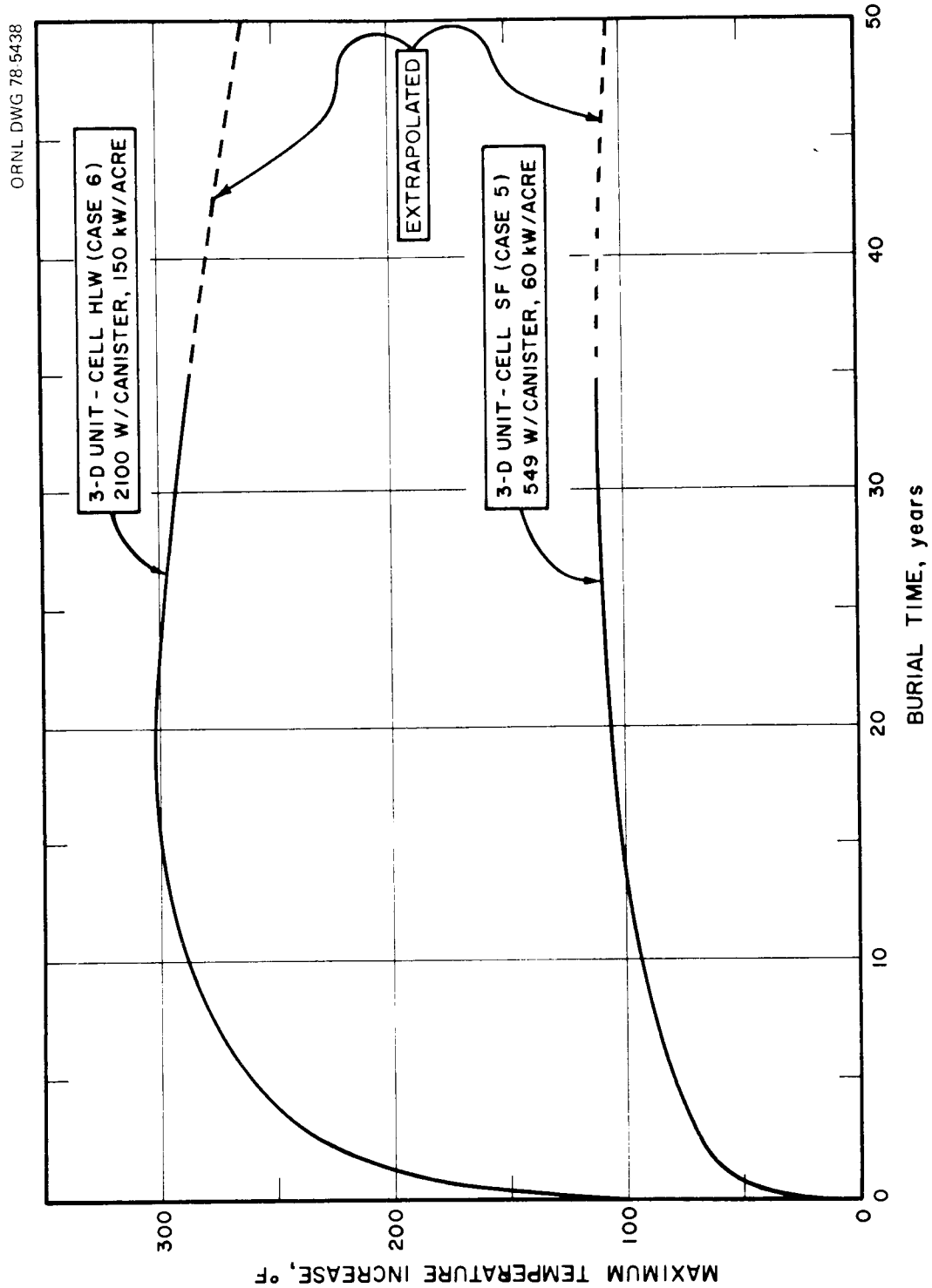


Table 3. Maximum salt temperatures for three different repository configurations

Type waste	Power density (kW/acre)	Power/can (kW)	Maximum temp rise (°C)	Maximum temp (°C)	Approximate time of maximum (years)	Pitch (ft)	Ref.
HLW-UO_2	150	2.1	127	171	20	7.82	13
PWR-SURF	60	0.549	43.3	87.2	30	5.12	13
PWR-SURF	36	0.549	106	135	5	4[a]	14

[a]Two rows of canisters per room spaced 5.5 ft apart.

Table 4. Estimates of maximum HLW temperatures from Appendix B

HLW waste type	Maximum centerline temp[a] (°C)	Maximum allowable canister temp (°C)	Thermal conductivity of waste Btu/hr - ft - °F	Ref.
Glass	435	375	0.66, $\bar{T}$ = 405°C	4
Calcine	534	375	0.25	12

[a]Thermal power assumed to be 2.1 kW/canister for a 1-ft-ID canister with an active length of 8 ft.

tentative temperature limits given in Table 2. For these limits, it is apparent that the HLW thermal loading limit for the reference repository in rock salt is not controlled by either the resulting very near field temperatures of the waste or by its container for canister spacings under consideration.

A maximum temperature of 200°C for the spent fuel element and 500°C for PuO_2 are recommended for SURF.[3] Preliminary temperature calculations are available for a 10-year-old PWR assembly within a canister within an overpack of 17.5 in. OD, and an open hole of 24 in. diam.[15] Center-pin temperature estimates vary with time and depend on emissivities assumed for the canister, overpack, and salt. Estimated peak temperatures occur approximately 1 year after burial and range from 155°C for moderate emissivities of 0.6, 0.6, and 0.9 for the canister, overpack, and salt, respectively, to 198°C when relatively low emissivities of 0.3 are used for three surfaces. These calculations should be repeated and documented.

Independent temperature calculations for SURF have been made by Kaiser Engineers. These calculations also indicate that the SURF temperature maximum will be within the tentative limit given in Table 2. Therefore, it is unlikely that the thermal loading of the reference repository for 10-year-old SURF will be controlled by the pin temperature.

With respect to moisture content of the salt, no discussion of the effects of different amounts of brine in different temperature and temperature gradient fields will be included in this report because no

tentative limit has been set. Preliminary estimates have been made,[5] and work is continuing on brine migration and the effects of different brine contents on the thermal, mechanical, and chemical properties of rock salt.

3.2.2 Near-field results

These results are obtained using finite-element, finite-difference, and displacement-discontinuity computer codes to calculate rock mechanics response at room scale. A great deal of effort has been expended over the past decade to assess the stability of the underground caverns in rock salt after the emplacement of the heat-generating waste canisters, because preliminary estimates of very near field temperatures indicated that they probably would not be a problem.

The following information is required to calculate the response of the salt mass:

1. the geometry of the room and pillar configuration;
2. transient temperature field results for the thermal loading and geometry under consideration;
3. a sufficiently accurate material or constitutive law for rock salt, and
4. a computer code capable of incorporating (1) through (3) above with Newton's second law and the strain-displacement relations to calculate the desired stress and displacement fields needed to judge the stability of the underground cavities.

All of the near-field analyses performed to date have assumed that the salt-rock mass will behave as a homogeneous, isotropic continuum. In general, this assumption is reasonable; however, at any particular location within a repository, the stability of a room may be controlled by local geologic features such as clay stringers within the salt-rock mass and deviations of the material properties from the mean values used in analysis. Consequently, the value of the near-field analyses lies in guiding us to the configurations that should be most stable rather than giving the detailed stress and deformation fields at every location in the repository.

A typical finite-element mesh is shown in Fig. 3.[16] This two-dimensional model, in which one-half of a room-and-pillar unit are represented, is typical of analyses performed in the near field to assess room stability. Fig. 6 represents centerline room closure as a function of pillar height-to-width ratio for three thermal loadings and three repository depths.[16] Note that the pillar height is held constant; therefore, the height-to-width ratios of 1:3, 1:4, and 1:5 imply local areal extraction ratios of 25%, 20%, and 16.7% respectively. The results presented in Fig. 4 are for 10-year-old PWR-SURF in the 25-year retrievable storage configuration. These results clearly demonstrate the dominant influence of repository depth and the lesser influences of areal thermal loading and pillar height-to-width ratios (areal extraction ratios) on room closure after 25 years. Curves analogous to those shown in Fig. 4 are presented for earlier times in ref. 16.

Results such as those in Fig. 4 provide guidance for site selection (structural stability during the operational phase is relatively sensitive to repository depth) and for repository designers who will choose values of thermal loading and repository geometry. Sufficient flexibility exists to meet performance limits such as those given in Table 2.

As further evidence of flexibility in design, the results shown in Fig. 5 indicate that reducing the extraction ratio while holding the thermal power loading per acre and depth constant may actually decrease the stability of the room due to the higher local temperatures. This is contrary to what would be expected in a mine without heat sources and leads to the conclusion that, for local stability, an optimum extraction ratio exists for a particular depth and thermal loading.

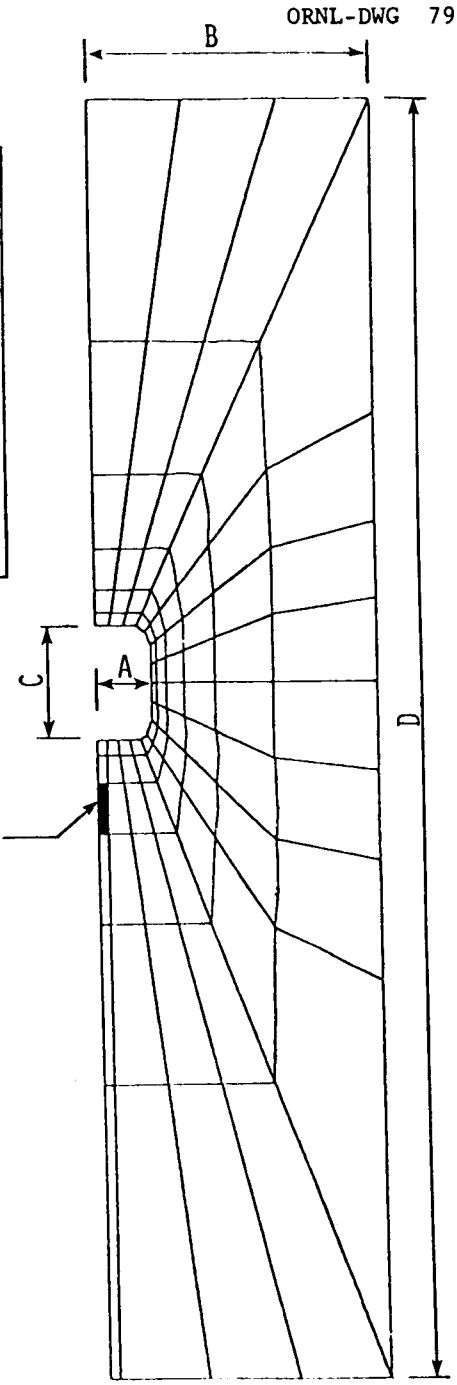
Centerline room closure has been chosen as a key indicator of room stability because it incorporates pillar shortening, roof sag, and floor bulging subject to the assumption that the salt mass remains a continuum. To demonstrate that this is a reasonable assumption, consider Fig. 6, which shows the displacement of the periphery of the room at 25 years for three thermal loadings of a repository at 2000 ft.

The strip-model configuration used in these calculations is conservative, because it implies that rooms and pillars continue to infinity on both sides of the modeled room and pillar, and that all of the heat

Fig. 3. Finite-element mesh describing the four models used in the mine stability study.[16]

ORNL-DWG 79-11634

MODEL	DIMENSIONS (FEET)			
	A	B	C	D
1	8.75	35.8	18.0	200.0
2	8.75	44.8	18.0	200.0
3	8.75	52.5	18.0	200.0
4	8.75	87.5	18.0	200.0



$$\text{EXTRACTION RATIO} = \frac{A}{B}$$

$$\text{PILLAR HEIGHT-TO-WIDTH RATIO} = \frac{C}{2(B-A)}$$

Fig. 4. Comparisons of roof-floor closure vs pillar height-to-width ratio for combinations of thermal load and repository depth at 25 years.[16]

ORNL-DWG 79-11633

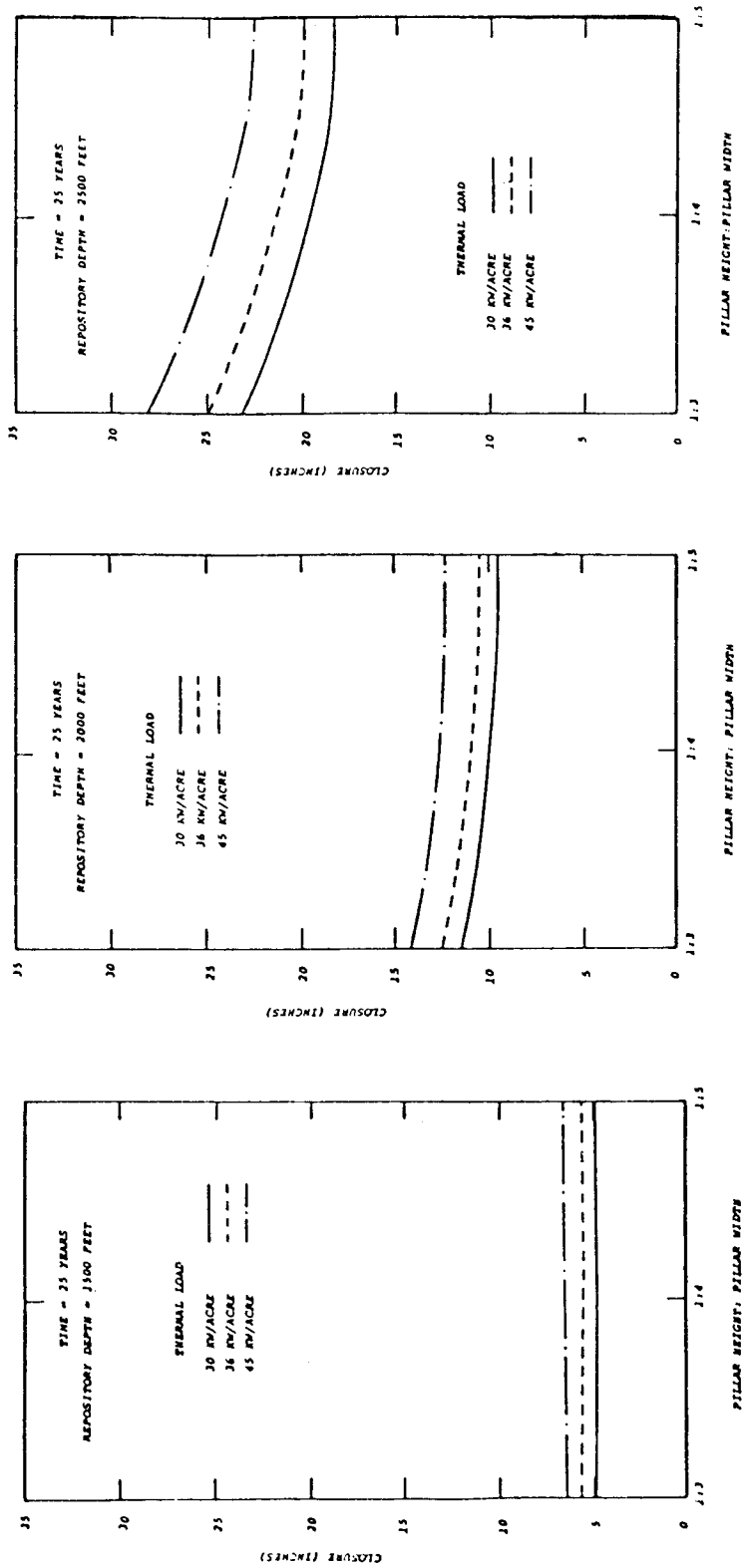


Fig. 5. Comparison of room closure for various extraction ratios to determine an optimum extraction ratio.[16]

ORNL-DWG 79-11637

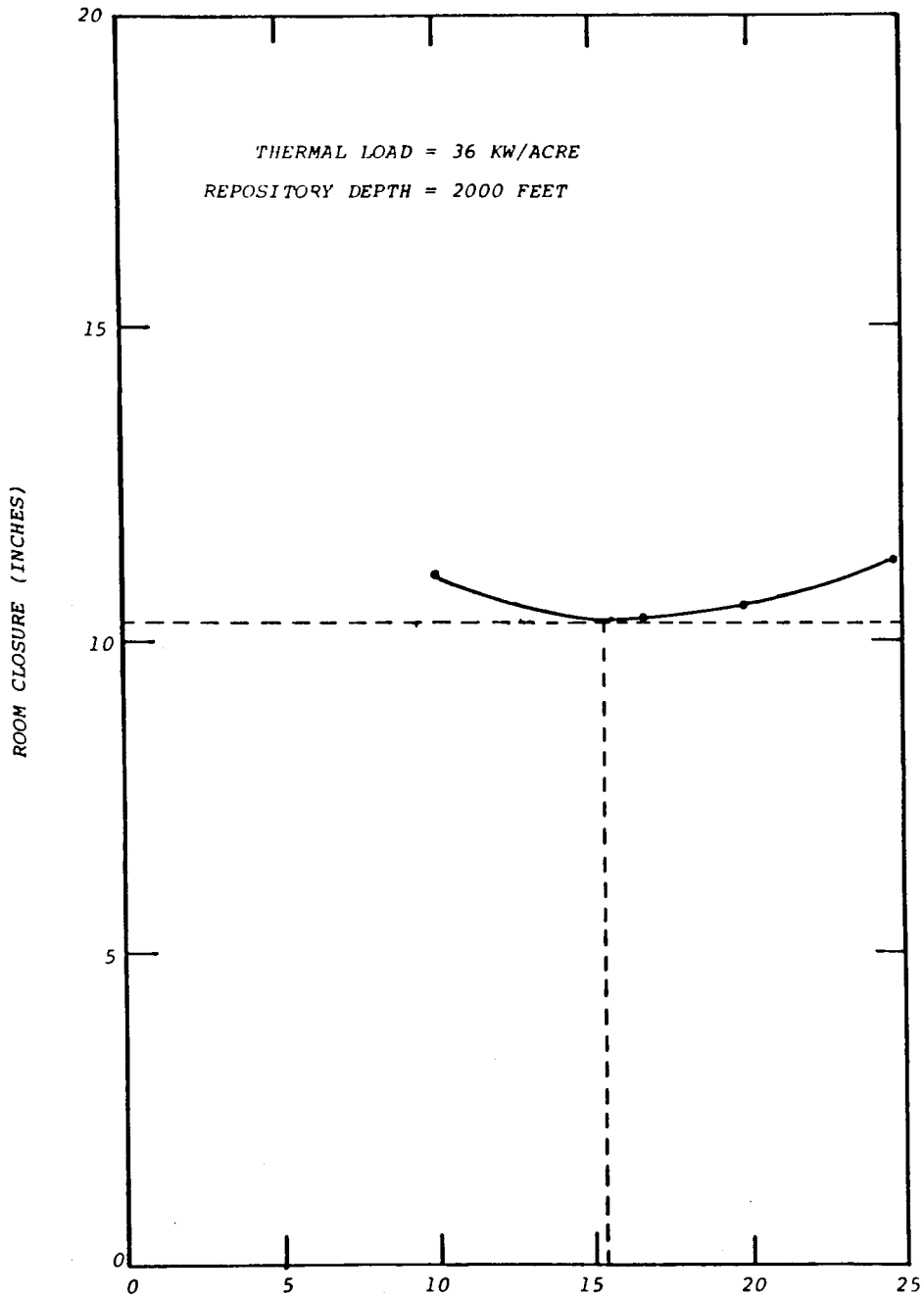
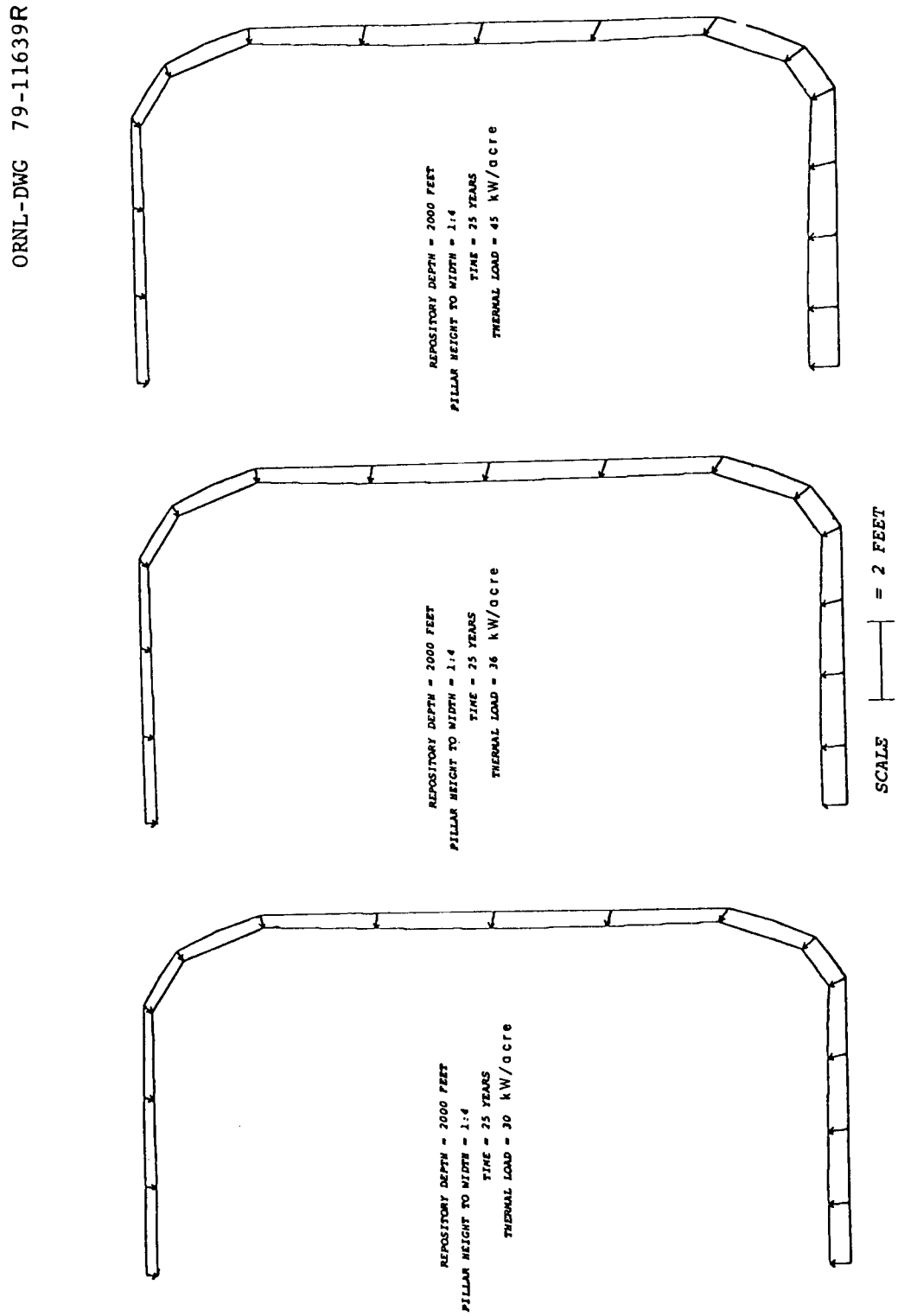


Fig. 6. Vector displacements of the roof, rib, and floor of mine cavity for a 2000-ft-deep repository at a 1:4 pillar height-to-width ratio for various thermal loads at 25 years.[16]



sources are implaced simultaneously and are at full strength at the same time. In addition, the beneficial influence of heat removal by ventilation is neglected. Some heat removal by ventilation is certain to occur as long as the room is open and being ventilated. This is likely to be the period of highest thermal power output, which makes results obtained while neglecting this influence conservative.

Two-dimensional analyses such as those above are reasonable approximations near the center of the relatively long (hundreds of feet) burial rooms being planned. However, such 2-D analyses are not adequate to assess the stability of intersections that occur in all of the designs being considered. Consequently, an effort is currently underway at Science Applications, Inc., Oakland, California to evaluate a 3-D version of the explicit finite-difference code STEALTH by comparing it with PSV results.

The displacement-discontinuity computer codes developed at the University of Minnesota are useful for studying repository stability on a somewhat larger scale and with different room-and-pillar configurations. Figure 7 shows room closure vs time for extraction ratios of 20 and 25% per cent at depths of 1500 and 2000 ft, assuming a regular array of rooms and pillars, using the 2-D code SALT 2.[17] Figure 8 shows the stabilizing influence on room closure of including periodic barrier pillars while holding the extraction ratio constant at 20%. The analyses shown in Figs. 7 and 8 are for rooms that are 36 ft wide and 25 ft high. Even though such large and less-stable rooms are not now being considered, the configuration shown in Fig. 8 does satisfy the near-field room closure limit of Table 2; however, the comparable regular extraction case shown in Fig. 7 does not satisfy the limit. This example illustrates how mine geometry can be varied to increase the near-field stability of the repository.

The displacement-discontinuity method can also be used to study three-dimensional aspects of near-field stability. Due to the large size of the problem, less detail can be included in the 3-D analyses.

3.2.3 Far-field results

These results are available in refs. 17-19. In ref. 18, the model

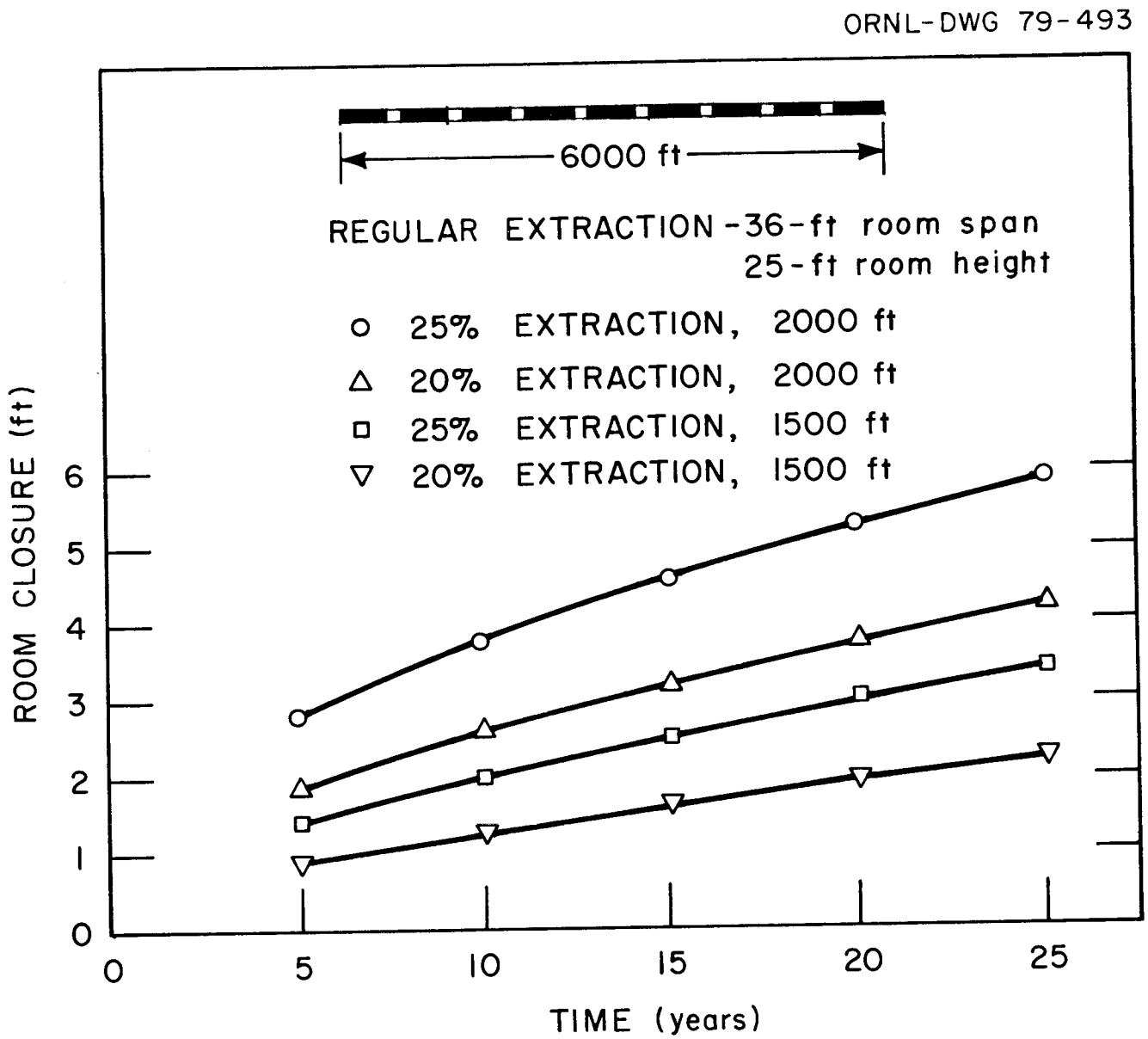


Fig. 7. Room closure with regular extraction.[17]

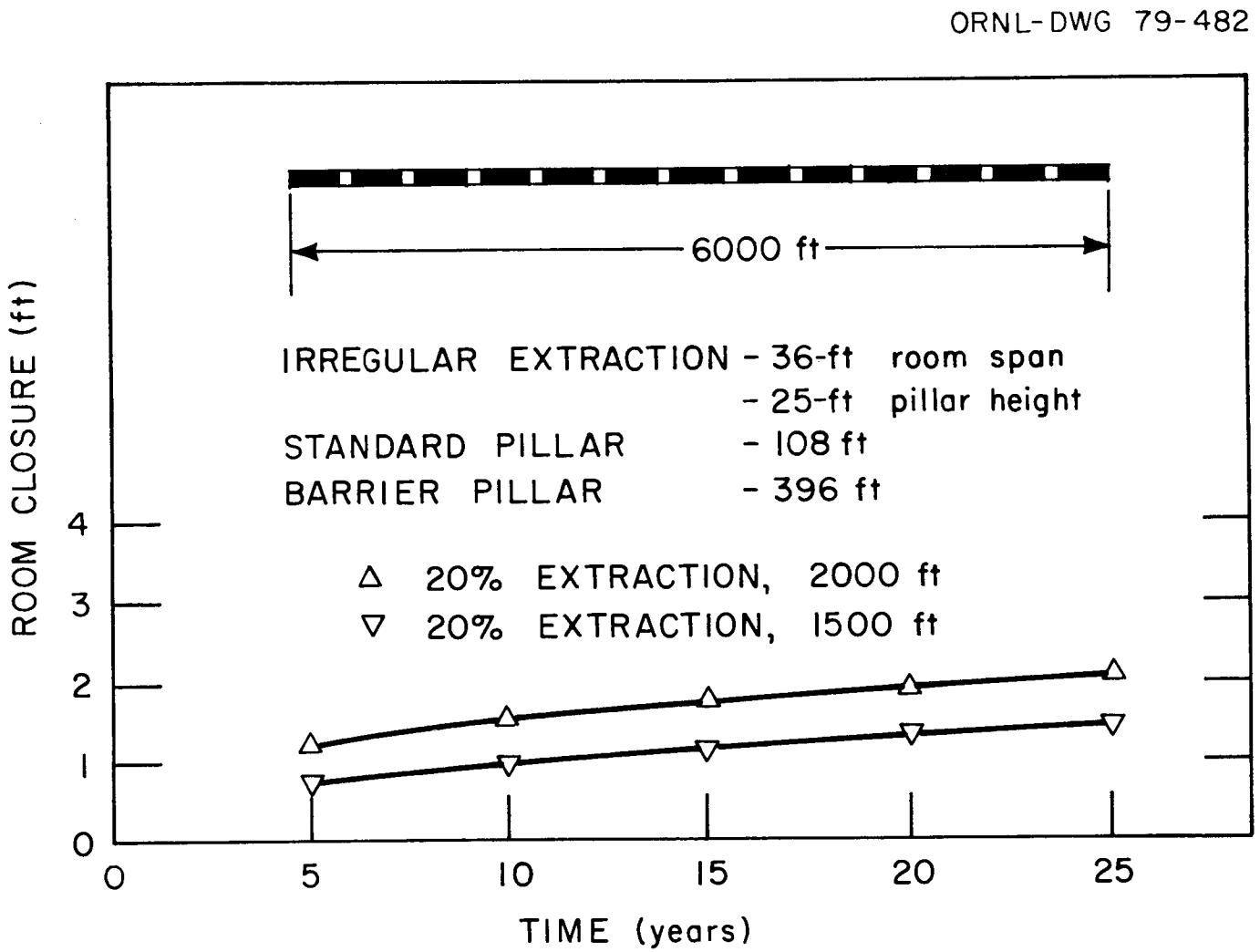


Fig. 8. Room closure with irregular extraction.[17]

consisted of a right-circular cylinder with a 10,000-ft radius for a representative bedded-salt case, and a 16,000-ft radius for the domal-salt case. The top of the model was the surface of the earth, and the lower surface was assumed to be a horizontal plane at a depth of 10,000 ft. The repository burial level was modeled as a homogenized heat-generating disk with a radius of 3500 ft at a depth of 2000 ft. A fictitious geologic section was used and representative thermal and elastic properties were assigned to each rock type. Axially symmetric finite-element models were prepared for the bedded- and domal-salt cases. Temperature distributions, displacements, and stresses were then determined using finite-element heat transfer and thermoelastic computer codes for various areal thermal loadings.[18]

Figure 9 shows typical vertical temperature profiles through the centerline of the repository for 75 kW/acre of 10-year-old SURF at various times. Repository plane temperatures are shown in Fig. 10 for the same case and indicate that the temperature rise is primarily directly above the repository, particularly at earlier times. This indicates that the heat transfer is mostly vertical in single-level repositories of large areal extent.

Heating a large mass of rock in the model results in a doming of the surface over the repository. Vertical movement upward of a point on the centerline of the repository at the surface of the earth is shown in Fig. 11 as a function of time. The results, shown in Fig. 11, indicate that the uplift for the 10-year-old HLW case peaks at approximately 150 years and approximately 50 in., which is within the limit of 4 to 5 ft given in Table 2. For the 10-year-old SURF case, the results indicate that all of the SURF displacements peak at about 1000 years, and 75 kW/acre will not meet the uplift limit. Consequently, the thermal loading recommendation for 10-year-old SURF is 60 kW/acre if all of the repository area (including ventilation ways, haulage ways, etc.) is used as area in the calculation, rather than just the room-and-pillar storage area, as is done in the near-field calculations.

Different models and computational methods were used in refs. 19 and 20, but the basic results discussed in ref. 18 are confirmed.

Fig. 9. Bedded-salt repository model centerline temperatures for spent fuel, assuming a gross thermal loading of 75 kW/acre.[18]

ORNL-DWG 79-11635

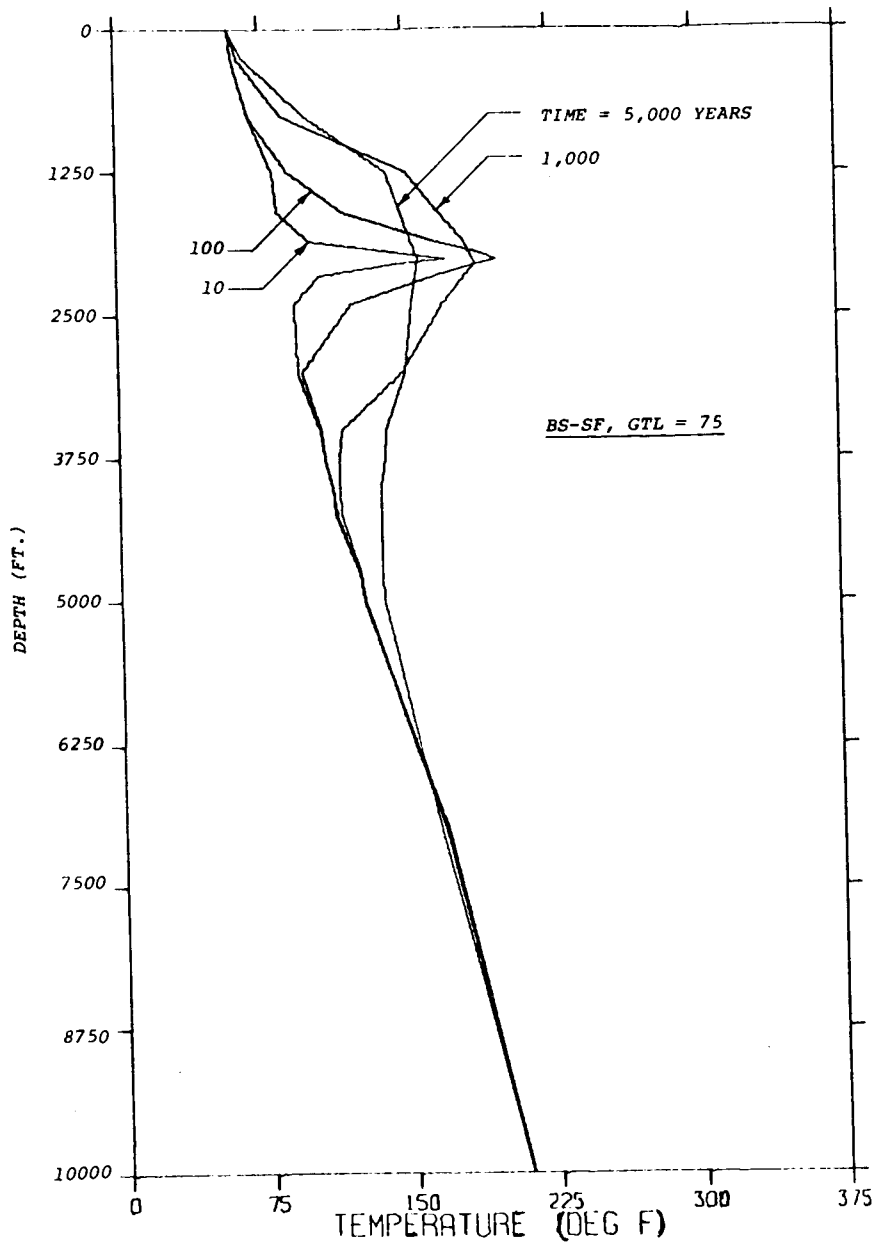


Fig. 10. Repository midplane temperature for the bedded salt repository model for spent fuel, assuming a gross thermal loading of 75 kW/acre.[18]

ORNL-DWG 79-11638

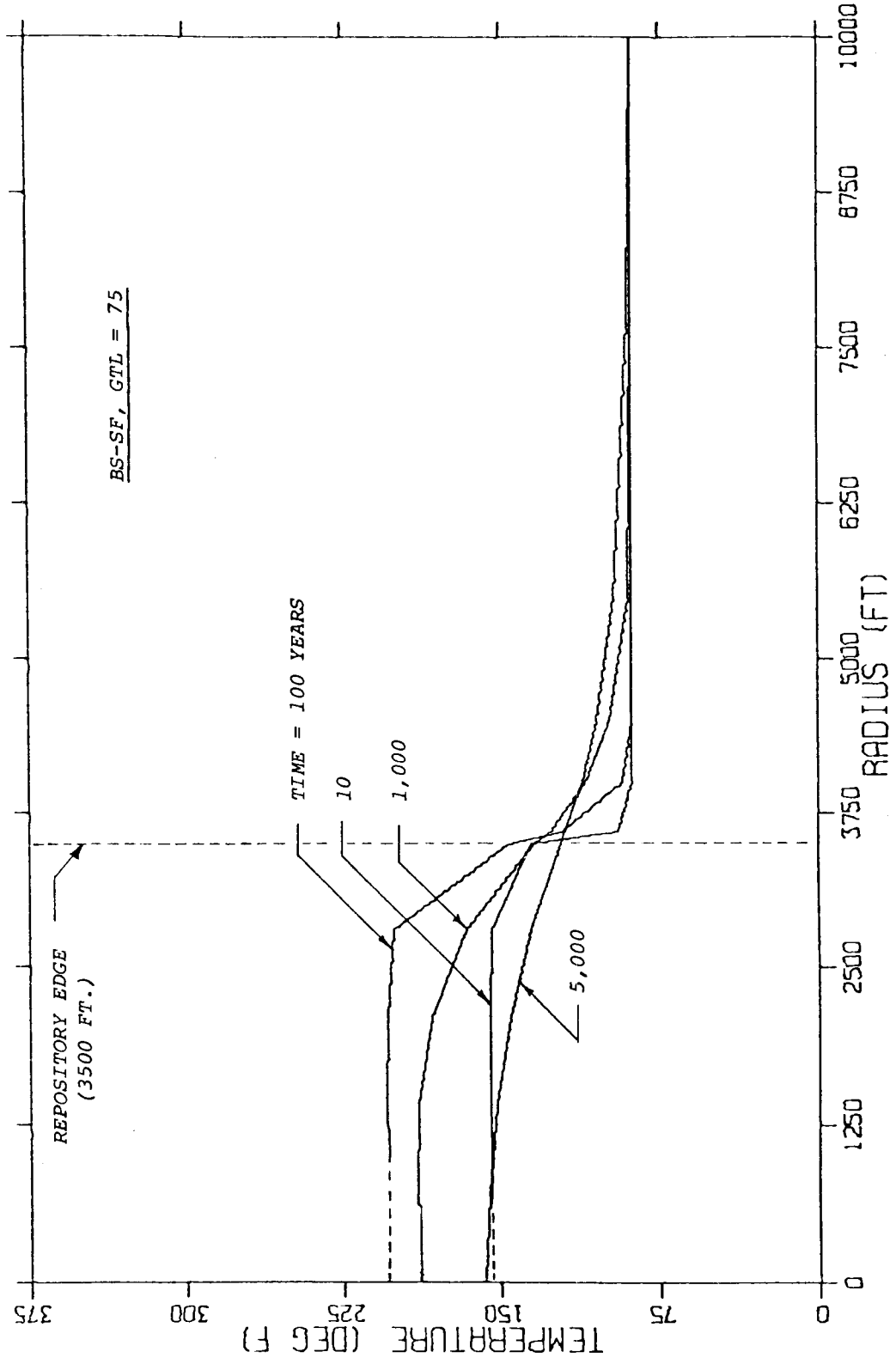
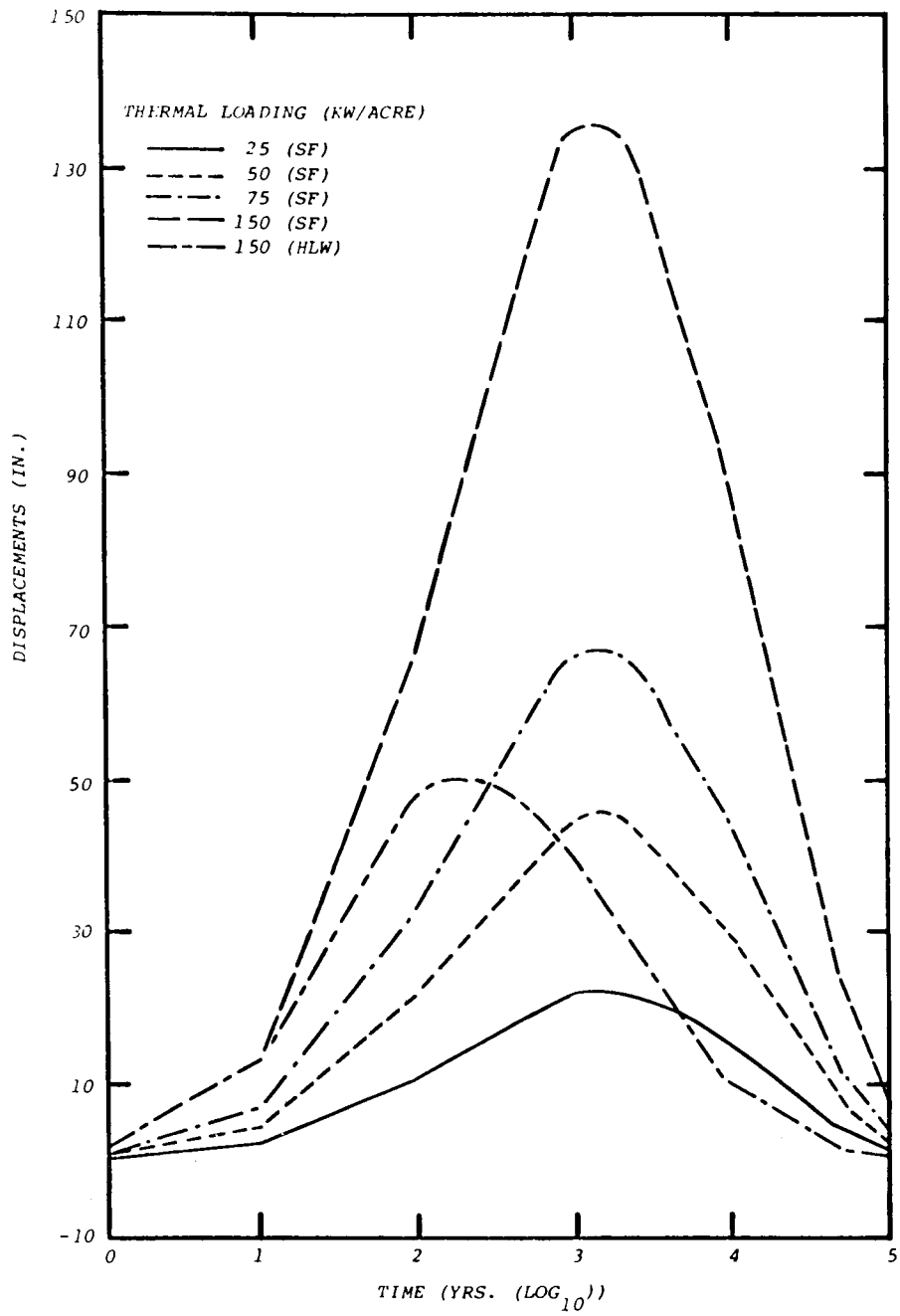


Fig. 11. Comparison of the vertical displacements of the surface at the centerline of the dome salt model for five thermal loading conditions.[18]

ORNL-DWG 79-11636



Studies are presently underway to evaluate the influence of repository depth and thickness of the salt unit on thermally driven ground movement.

The tentative performance limit for temperature rise at the surface is 1°F (Table 2). Reference 13 indicates the maximum temperature rise at the surface would not exceed 0.01°F for the reference repository with either HLW or SURF, thus the limit is easily satisfied.

The final, tentative limit considered in Table 2 requires that the temperature rise in aquifers at the site must be less than 10°F and as low as reasonably achievable. The temperature rise in an aquifer depends on several factors in addition to thermal loading. These include proximity to the burial horizon, flow rate in the portion of the aquifer in the immediate vicinity of the repository, etc. The temperature rise in aquifers and its consequences are questions that can be addressed in detail only for a specific site. For the purposes of this report, we can show that the proposed limit is probably achievable by assuming that as a conservative approximation, the aquifer temperature is equal to the calculated rock temperature.

Temperature rises in aquifers surrounding salt domes are of interest. Calculations reported in ref. 18 indicate that for SURF, temperature increases of approximately 7.5°F would occur at the edge of a dome with a radius of 8000 ft loaded at 50 kW/acre (approximately 9°F for 60 kW/acre). For the HLW case (150 kW/acre), the corresponding temperature increase is approximately 13°F but drops to 9°F within 500 ft of the edge of the dome. Consequently, even with a conservative analysis, the temperature rise in aquifers surrounding salt domes would apparently be about 10°F, and the limit seems to be reasonable.

In the case of a repository in bedded salt, the proximity of overlying or deeper aquifers to the burial horizon would be limited if it is again assumed that rock and aquifer temperatures are equivalent. For a SURF repository loaded at 50 kW/acre, the the temperature rise from the surface to a depth of approximately 600 ft would not exceed 10°F.[18] Therefore, this region could probably contain aquifers without violating the 10°F temperature-rise limit. This conclusion also holds for HLW at 150 kW/acre.

The calculated temperature increases for points below the burial horizon are greater than those above the horizon due to the geothermal gradient, the decrease in thermal conductivity of salt at higher temperature, and the boundary conditions. Therefore, for a SURF repository loaded at 50 kW/acre, a 10°F temperature rise may occur at depths of about 5000 ft.

It thus appears that a site with approximately the characteristics assumed in ref. 18 will meet the limit of 10°F temperature increases in aquifers if no aquifers occur between the depths of approximately 500 and 5000 ft. It should again be emphasized that limits must be set and calculations made for each site under consideration. The range of depths given above are for that example only and should not be used as a criterion in site selection.

3.3 Recommendations for Areal Thermal Loading

Based on the comparison of numerical simulation results of Sect. 3.2 with the tentative performance limits of Table 2, Table 5 gives thermal loading recommendations for generic studies. The factor(s) that appear to be controlling the recommended thermal-loading densities are also given in the table.

Table 5. Recommended thermal loadings for generic studies in salt

Waste type	Age at burial (years)	Thermal load (kW/load)	Controlling factor	Area used in calculations	Retrievability period (years)
HLW[a]	10	150	Room closure, far-field effects	Room-and-pillar storage area	5
SURF[b]	10 (∿75 based on room-and-pillar storage area)	60	Far-field effects	Gross repository area including shaft pillars, ventilation drifts, haulage ways, etc.	
	10	36	Room closure	Room-and-pillar storage area	25

[a]High-level waste from UO_2 fueled reactors.

[b]Spent unreprocessed fuel; values given in this table are for PWR SURF.

4. REFERENCES

1. R. L. Bradshaw and W. C. McClain, (Eds.), Project Salt Vault: A Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines, ORNL-4555 (April 1971).

2. Parsons, Brinkerhoff, Quade, and Douglas, Inc., Waste Isolation Facility Description. Bedded Salt, Y/OWI/SUB-76/16506 (September 1976).

3. G. H. Jenks, Maximum Acceptable Temperatures of Wastes and Containers During Retrievable Geologic Storage, Y/OWI/TM-42 (August 1977).

4. J. E. Mendel et al., Annual Report on the Characteristics of High-Level Waste Glasses, BNWL-2252 (June 1977).

5. G. H. Jenks, personal communication to W. C. McClain, July 13, 1978.

6. G. H. Jenks, Radiolysis and Hydrolysis in Salt-Mine Brines, ORNL/TM-3717 (March 1972).

7. Science Applications, Inc., The Selection and Evaluation of Thermal Criteria for a Geologic Waste Isolation Facility in Salt, Y/OWI/SUB-76/07220 (September 1976).

8. G. D. Callahan, Documentation of the Thermo/Viscoelastic Code TEVCO, ORNL/SUB-4269/17 (September 1975).

9. Science Applications, Inc., A Simulation of the Thermomechanical Response of Project Salt Vault, Y/OWI/SUB-77/16519/1 (February 1977).

10. S. L. Crouch and W. C. McClain, Interim Report on Development of a Semi-Empirical Numerical Model for Simulating the Deformational Behavior of a High-Level Radioactive Waste Repository in Bedded Salt ORNL/TM-5462 (April 1978).

11. J. L. Ratigan and G. D. Callahan, Evaluation of the Predictive Capability of the Finite Element Method: II. Project Salt Vault - Thermo-Viscoelastic Simulation, Y/OWI/SUB-78/22303/11 (July 1978).

12. R. D. Cheverton and W. D. Turner, Thermal Analysis of the National Radioactive Waste Repository: Progress Through March 1972, ORNL-4789 (September 1972).

13. G. H. Llewellyn, Prediction of Temperature Increases in a Salt Repository Expected from the Storage of Spent Fuel or High-Level Waste, ORNL/ENG/TM-7 (April 1978).

14. M. Rath, Kaiser Engineers personal communication to Joe Busch, NWTS-1733 (January 4, 1978).

15. G. H. Jenks, personal communication, August 18, 1978.

16. R. A. Wagner, Parametric Study Involving Thermo/Viscoelastic Analyses of a Room and Pillar Configuration, ONWI/SUB-78/E520/02300/1 (November 1978).

17. C. M. St. John, Spent Fuel Repository Study - Short-Term Room Closure, Technical Letter Report No. 1, Office of Waste Isolation, (June 22, 1977).

18. G. D. Callahan and J. L. Ratigan, Thermoelastic Analysis of Spent Fuel Repositories in Bedded and Dome Salt, Y/OWI/SUB-77/22303/4 (May 1977).

19. Science Applications, Inc., The Thermomechanical Response of a One-Level Spent Fuel Nuclear Waste Repository, Y/OWI/SUB-78/16549/1 (March 1978).

20. C. M. St. John, Thermoelastic Analysis of Spent Fuel and High-Level Radioactive Waste Repositories in Salt - A Semi-Analytical Solution, Y/OWI/SUB-7118/1 (April 1977).

21. R. A. Kisner et al., Nuclear Waste Projections and Source-Term Data for FY 1977, Y/OWI/TM-34 (April 1978).

5. APPENDIXES

5.1 Appendix A. Waste Projection Data

UNION CARBIDE

INTERNAL CORRESPONDENCE

NUCLEAR DIVISION

POST OFFICE BOX Y, OAK RIDGE, TENNESSEE 37830

To (Name) J. E. Russell

Division

Location

Date February 15, 1978

Originating Dept.

Answering letter date

Copy to

A. L. Boch	S. C. Matthews
G. D. Brunton	L. L. McCauley
W. A. Burnett	W. C. McClain
H. C. Claiborne	J. M. Morrison
L. B. Cobb	H. N. Noritake
L. R. Dole	W. H. Pechin
P. D. Fairchild	A. S. Quist
W. A. Goldsmith	H. N. Rosenberg
G. H. Jenks	R. L. Shoup
R. K. Kibbe	C. S. Sims
R. B. Laughon	D. W. Turner
T. F. Lomenick	J. E. Vath
R. S. Lowrie	C. D. Zerby

Subject Waste Projection Data Memo 15

Attached are copies of the tables you requested. The decay heat generation rates (Watts/MTU) for HLW as a function of years after discharge are given in Table 1. The power from HLW (PWR and BWR) for both the full recycle (U, Pu recycle) and the no-recycle (fresh u cycle) cases are listed separately in columns one through four. Listed in the next two columns is the power from HLW having mixed fuel cycles (one part full recycle to three parts no-recycle) for PWR's and BWR's separately. In the last column is listed the HLW power from PWR's and BWR's mixed 2:1 having mixed fuel cycles (1:3).

The decay energy (Kw-Yr/MTU) for HLW as a function of years after discharge is given in Table 2. Column format is the same as Table 1 described above. The last column of both tables because of the inclusion of mixed fuel cycles is believed to be a better representation of the actual heat deposited to a repository than any of the standard fuel cycles taken individually (e.g. U, Pu recycle; U-only recycle; no-recycle) since different fuel cycles may coexist during the operating life of a repository.

The equilibrium burnup is assumed to be 33,000 MWD/MT for the PWR and 27,500 MWD/MT for the BWR. It is assumed that 99.5% of the U and Pu are removed during reprocessing. Reprocessing is assumed to occur one year after the fuel has been discharged from the reactor.

R. A. Kisner

RAK:eg

YEARS AFTER DISCHARGE	PWR POWER U,PU RECYCLE (WATTS/MT)	BWR POWER U,PU RECYCLE (WATTS/MT)	PWR POWER FRESH U CYCLE (WATTS/MT)	BWR POWER FRESH U CYCLE (WATTS/MT)	PWR POWER MOX (1:1)* (WATTS/MT)	BWR POWER MOX (1:3) (WATTS/MT)	PWR AND BWR IN A 2:1 RATIO MOX (1:1) (WATTS/MT)
1	1.536E 04	1.109E 04	1.027E 04	7.571E 03	1.154E 04	8.451E 03	1.052E 04
2	8.210E 03	6.012E 03	5.505E 03	4.117E 03	6.178E 03	4.596E 03	5.558E 03
3	5.446E 03	4.057E 03	3.457E 03	2.625E 03	1.954E 03	2.983E 03	1.634E 03
4	4.114E 03	3.112E 03	2.426E 03	1.869E 03	2.853E 03	2.140E 03	2.613E 03
5	3.429E 03	2.600E 03	1.868E 03	1.457E 03	2.257E 03	1.743E 03	2.047E 03
6	3.009E 03	2.293E 03	1.541E 03	1.216E 03	1.908E 03	1.484E 03	1.769E 03
7	2.735E 03	2.092E 03	1.337E 03	1.065E 03	1.697E 03	1.322E 03	1.566E 03
8	2.540E 03	1.948E 03	1.201E 03	0.428E 02	1.536E 03	1.209E 03	1.423E 03
9	2.392E 03	1.837E 03	1.106E 03	0.901E 02	1.426E 03	1.127E 03	1.327E 03
10	2.271E 03	1.747E 03	1.032E 03	0.352E 02	1.342E 03	1.063E 03	1.250E 03
11	2.169E 03	1.671E 03	9.751E 02	7.919E 02	1.274E 03	1.012E 03	1.187E 03
12	2.080E 03	1.604E 03	9.291E 02	7.564E 02	1.217E 03	9.583E 02	1.135E 03
13	2.000E 03	1.544E 03	8.905E 02	7.263E 02	1.168E 03	9.307E 02	1.090E 03
14	1.926E 03	1.489E 03	8.572E 02	7.002E 02	1.124E 03	9.074E 02	1.049E 03
15	1.859E 03	1.439E 03	8.277E 02	6.769E 02	1.086E 03	8.672E 02	1.013E 03
16	1.795E 03	1.391E 03	8.011E 02	6.558E 02	1.050E 03	8.396E 02	9.803E 02
17	1.735E 03	1.346E 03	7.768E 02	6.363E 02	1.016E 03	8.137E 02	9.495E 02
18	1.679E 03	1.303E 03	7.542E 02	6.182E 02	9.854E 02	7.894E 02	9.207E 02
19	1.625E 03	1.262E 03	7.330E 02	6.011E 02	9.560E 02	7.661E 02	8.934E 02
20	1.573E 03	1.224E 03	7.129E 02	5.849E 02	9.274E 02	7.437E 02	8.675E 02
21	1.524E 03	1.186E 03	6.938E 02	5.695E 02	9.013E 02	7.236E 02	8.427E 02
22	1.476E 03	1.151E 03	6.756E 02	5.547E 02	8.757E 02	7.038E 02	8.190E 02
23	1.431E 03	1.116E 03	6.580E 02	5.405E 02	8.513E 02	6.844E 02	7.962E 02
24	1.387E 03	1.083E 03	6.411E 02	5.267E 02	8.276E 02	6.655E 02	7.742E 02
25	1.345E 03	1.052E 03	6.248E 02	5.135E 02	8.048E 02	6.481E 02	7.531E 02
26	1.305E 03	1.021E 03	6.091E 02	5.004E 02	7.831E 02	6.307E 02	7.329E 02
27	1.266E 03	9.916E 02	5.938E 02	4.882E 02	7.618E 02	6.149E 02	7.131E 02
28	1.228E 03	9.632E 02	5.790E 02	4.762E 02	7.413E 02	5.979E 02	6.940E 02
29	1.192E 03	9.357E 02	5.646E 02	4.645E 02	7.214E 02	5.823E 02	6.755E 02
30	1.157E 03	9.093E 02	5.507E 02	4.531E 02	7.021E 02	5.671E 02	6.577E 02
31	1.123E 03	8.837E 02	5.372E 02	4.420E 02	6.836E 02	5.524E 02	6.403E 02
32	1.090E 03	8.590E 02	5.240E 02	4.313E 02	6.655E 02	5.382E 02	6.235E 02
33	1.059E 03	8.352E 02	5.112E 02	4.209E 02	6.481E 02	5.245E 02	6.073E 02
34	1.028E 03	8.121E 02	4.988E 02	4.107E 02	6.311E 02	5.110E 02	5.915E 02
35	9.991E 02	7.899E 02	4.867E 02	4.008E 02	6.148E 02	4.981E 02	5.763E 02
36	9.707E 02	7.684E 02	4.749E 02	3.912E 02	5.988E 02	4.855E 02	5.614E 02
37	9.433E 02	7.476E 02	4.634E 02	3.819E 02	5.834E 02	4.733E 02	5.471E 02
38	9.169E 02	7.276E 02	4.523E 02	3.728E 02	5.684E 02	4.615E 02	5.332E 02
39	8.913E 02	7.082E 02	4.414E 02	3.639E 02	5.539E 02	4.500E 02	5.196E 02
40	8.667E 02	6.894E 02	4.309E 02	3.553E 02	5.398E 02	4.388E 02	5.065E 02
50	6.609E 02	5.326E 02	3.391E 02	2.803E 02	4.195E 02	3.434E 02	3.944E 02
60	5.134E 02	4.197E 02	2.681E 02	2.222E 02	3.294E 02	2.716E 02	3.103E 02
70	4.068E 02	3.376E 02	2.129E 02	1.769E 02	2.614E 02	2.171E 02	2.469E 02
80	3.291E 02	2.773E 02	1.697E 02	1.415E 02	2.095E 02	1.754E 02	1.983E 02
90	2.720E 02	2.328E 02	1.359E 02	1.137E 02	1.699E 02	1.435E 02	1.612E 02
100	2.297E 02	1.995E 02	1.093E 02	9.190E 01	1.394E 02	1.188E 02	1.326E 02
110	1.980E 02	1.744E 02	8.841E 01	7.473E 01	1.158E 02	9.965E 01	1.105E 02
120	1.740E 02	1.553E 02	7.196E 01	6.120E 01	9.747E 01	8.472E 01	9.326E 01
130	1.558E 02	1.406E 02	5.899E 01	5.053E 01	8.319E 01	7.305E 01	7.984E 01
140	1.417E 02	1.291E 02	4.875E 01	4.209E 01	7.199E 01	6.384E 01	6.930E 01
150	1.306E 02	1.201E 02	4.066E 01	3.542E 01	6.314E 01	5.659E 01	6.098E 01
160	1.219E 02	1.129E 02	3.425E 01	3.013E 01	5.616E 01	5.082E 01	5.440E 01
170	1.149E 02	1.070E 02	2.917E 01	2.592E 01	5.060E 01	4.619E 01	4.915E 01
180	1.092E 02	1.022E 02	2.513E 01	2.258E 01	4.615E 01	4.248E 01	4.492E 01
190	1.045E 02	9.824E 01	2.192E 01	1.991E 01	4.256E 01	3.948E 01	4.155E 01
200	1.005E 02	9.485E 01	1.935E 01	1.777E 01	3.964E 01	3.704E 01	3.878E 01
250	8.733E 01	8.323E 01	1.235E 01	1.186E 01	3.159E 01	2.970E 01	3.054E 01
300	7.913E 01	7.574E 01	9.725E 00	9.574E 00	2.708E 01	2.612E 01	2.676E 01
400	6.746E 01	6.477E 01	7.712E 00	7.678E 00	2.265E 01	2.195E 01	2.242E 01
500	5.855E 01	5.620E 01	6.603E 00	6.563E 00	1.959E 01	1.897E 01	1.933E 01
600	5.136E 01	4.919E 01	5.728E 00	5.675E 00	1.714E 01	1.655E 01	1.694E 01
700	4.548E 01	4.337E 01	4.998E 00	4.933E 00	1.512E 01	1.454E 01	1.493E 01
800	4.062E 01	3.851E 01	4.381E 00	4.307E 00	1.344E 01	1.286E 01	1.325E 01
900	3.657E 01	3.443E 01	3.857E 00	3.777E 00	1.204E 01	1.144E 01	1.184E 01
1000	3.318E 01	3.098E 01	3.412E 00	3.328E 00	1.085E 01	1.024E 01	1.065E 01
2000	1.759E 01	1.503E 01	1.349E 00	1.252E 00	5.409E 00	4.694E 00	5.174E 00
3000	1.372E 01	1.122E 01	8.906E-01	7.963E-01	4.098E 00	3.402E 00	3.869E 00
4000	1.220E 01	9.860E 00	7.581E-01	6.685E-01	3.619E 00	2.966E 00	3.403E 00
5000	1.122E 01	9.046E 00	6.945E-01	6.097E-01	3.326E 00	2.719E 00	3.124E 00
6000	1.041E 01	8.387E 00	6.479E-01	5.676E-01	3.088E 00	2.522E 00	2.902E 00
7000	9.680E 00	7.800E 00	6.075E-01	5.312E-01	2.976E 00	2.346E 00	2.702E 00
8000	9.015E 00	7.265E 00	5.708E-01	4.983E-01	2.682E 00	2.190E 00	2.520E 00
9000	8.405E 00	6.775E 00	5.371E-01	4.682E-01	2.504E 00	2.045E 00	2.353E 00
10000	7.846E 00	6.325E 00	5.061E-01	4.404E-01	2.341E 00	1.912E 00	2.199E 00
11000	7.331E 00	5.911E 00	4.775E-01	4.145E-01	2.191E 00	1.789E 00	2.058E 00
12000	6.859E 00	5.531E 00	4.512E-01	3.914E-01	2.053E 00	1.674E 00	1.923E 00
13000	6.424E 00	5.181E 00	4.269E-01	3.697E-01	1.926E 00	1.573E 00	1.809E 00
14000	6.023E 00	4.858E 00	4.044E-01	3.497E-01	1.809E 00	1.477E 00	1.699E 00
15000	5.654E 00	4.561E 00	3.837E-01	3.312E-01	1.701E 00	1.389E 00	1.594E 00
16000	5.314E 00	4.287E 00	3.645E-01	3.142E-01	1.602E 00	1.307E 00	1.495E 00
17000	5.000E 00	4.034E 00	3.468E-01	2.984E-01	1.510E 00	1.232E 00	1.399E 00
18000	4.710E 00	3.801E 00	3.303E-01	2.838E-01	1.425E 00	1.163E 00	1.308E 00
19000	4.443E 00	3.585E 00	3.151E-01	2.702E-01	1.347E 00	1.099E 00	1.265E 00
20000	4.195E 00	3.385E 00	3.009E-01	2.577E-01	1.274E 00	1.040E 00	1.197E 00
21000	3.965E 00	3.200E 00	2.878E-01	2.461E-01	1.207E 00	9.846E-01	1.134E 00
22000	3.753E 00	3.029E 00	2.755E-01	2.352E-01	1.145E 00	9.336E-01	1.075E 00
23000	3.556E 00	2.870E 00	2.641E-01	2.252E-01	1.087E 00	8.864E-01	1.021E 00
24000	3.373E 00	2.722E 00	2.535E-01	2.159E-01	1.033E 00	8.423E-01	9.703E-01
25000	3.203E 00	2.585E 00	2.436E-01	2.073E-01	9.834E-01	8.016E-01	9.224E-01
26000	3.045E 00	2.457E 00	2.344E-01	1.990E-01	9.370E-01	7.635E-01	8.799E-01
27000	2.898E 00	2.339E 00	2.258E-01	1.914E-01	8.938E-01	7.283E-01	8.392E-01
28000	2.760E 00	2.228E 00	2.177E-01	1.843E-01	8.533E-01	6.952E-01	8.011E-01
29000	2.632E 00	2.125E 00	2.102E-01	1.777E-01	8.156E-01	6.645E-01	7.654E-01
30000	2.513E 00	2.028E 00	2.031E-01	1.715E-01	7.806E-01	6.356E-01	7.327E-01
40000	1.659E 00	1.339E 00	1.517E-01	1.269E-01	5.285E-01	4.299E-01	4.960E-01
50000	1.179E 00	9.525E-01	1.221E-01	1.017E-01	3.663E-01	3.144E-01	3.626E-01
60000	8.406E-01	7.138E-01	1.036E-01	8.613E-02	2.970E-01	2.630E-01	2.798E-01
70000	6.821E-01	5.553E-01	9.142E-02	7.608E-02	2.391E-01	1.959E-01	2.249E-01
80000	5.435E-01	4.452E-01	8.129E-02	6.941E-02	1.983E-01	1.634E-01	1.869E-01
90000	4.441E-01	3.666E-01	7.281E-02	6.497E-02	1.694E-01	1.404E-01	1.599E-01
100000	3.717E-01	3.097E-01	7.425E-02	6.208E-02	1.486E-01	1.240E-01	1.405E-01
150000	2.168E-01	1.902E-01	7.039E-02	5.412E-02	1.070E-01	9.199E-02	1.025E-01
200000	1.878E-01	1.706E-01	7.422E-02	6.237E-02	1.026E-01	8.943E-02	1.025E-02
250000	1.854E-01	1.717E-01	7.970E-02	6.610E-02	1.054E-01	9.250E-02	1.113E-01
300000	1.870E-01	1.756E-01	8.236E-02	6.913E-02	1.045E-01	9.575E-02	1.043E-01
400000	1.914E-01	1.817E-01	8.904E-02	7.470E-02	1.147E-01	1.019E-01	1.105E-01
500000	1.878E-01	1.830E-01	9.083E-02	7.611E-02	1.151E-01	1.028E-01	1.110E-01
1000000	1.531E-01	1.552E-01	8.202E-02	6.463E-02	9.979E-02	9.027E-02	9.665E-02
3000000	7.254E-02	7.458E-02	4.033E-02	3.176E-02	4.838E-02	4.196E-02	4.493E-02
10000000	9.374E-03	9.250E-03	4.700E-03	4.300E-03	5.468E-03	5.312E-03	5.695E-03

* MOX (1:1) IMPLIES A MIXED CYCLE TO FRESH FUEL RATIO OF 1 TO 1

YEARS AFTER DISCHARGE	PWR ENERGY U,PU RECYCLE (KW-YR/MT)	BWR ENERGY U,PU RECYCLE (KW-YR/MT)	PWR ENERGY FRESH U CYCLE (KW-YR/MT)	BWR ENERGY FRESH U CYCLE (KW-YR/MT)	PWR ENERGY MOX (1:1)* (KW-YR/MT)	BWR ENERGY MOX (1:1) (KW-YR/MT)	FOR AND PWR IS A 2:1 RATIO MOX (1:1) (KW-YR/MT)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.142E 01	8.304E 00	7.640E 00	5.470E 00	8.595E 00	6.125E 00	7.440E 00
3	1.815E 01	1.328E 01	1.204E 01	8.585E 00	1.357E 01	1.006E 01	1.241E 01
4	2.291E 01	1.685E 01	1.495E 01	1.121E 01	1.694E 01	1.262E 01	1.551E 01
5	2.668E 01	1.970E 01	1.730E 01	1.286E 01	1.995E 01	1.457E 01	1.734E 01
6	2.989E 01	2.214E 01	1.874E 01	1.420E 01	2.156E 01	1.614E 01	1.974E 01
7	3.276E 01	2.433E 01	2.022E 01	1.534E 01	2.315E 01	1.757E 01	2.145E 01
8	3.540E 01	2.615E 01	2.149E 01	1.635E 01	2.457E 01	1.885E 01	2.295E 01
9	3.787E 01	2.824E 01	2.264E 01	1.727E 01	2.645E 01	2.001E 01	2.432E 01
10	4.020E 01	3.003E 01	2.371E 01	1.814E 01	2.743E 01	2.111E 01	2.561E 01
11	4.242E 01	3.174E 01	2.471E 01	1.895E 01	2.914E 01	2.215E 01	2.681E 01
12	4.454E 01	3.338E 01	2.566E 01	1.972E 01	3.018E 01	2.313E 01	2.793E 01
13	4.658E 01	3.495E 01	2.657E 01	2.047E 01	3.157E 01	2.409E 01	2.910E 01
14	4.854E 01	3.647E 01	2.745E 01	2.118E 01	3.272E 01	2.500E 01	3.017E 01
15	5.043E 01	3.793E 01	2.829E 01	2.187E 01	3.382E 01	2.588E 01	3.120E 01
16	5.226E 01	3.935E 01	2.910E 01	2.253E 01	3.449E 01	2.673E 01	3.220E 01
17	5.403E 01	4.072E 01	2.989E 01	2.318E 01	3.592E 01	2.756E 01	3.317E 01
18	5.573E 01	4.204E 01	3.066E 01	2.381E 01	3.693E 01	2.837E 01	3.410E 01
19	5.738E 01	4.332E 01	3.140E 01	2.442E 01	3.789E 01	2.914E 01	3.501E 01
20	5.898E 01	4.457E 01	3.212E 01	2.501E 01	3.883E 01	2.990E 01	3.590E 01
21	6.053E 01	4.577E 01	3.283E 01	2.559E 01	3.975E 01	3.061E 01	3.675E 01
22	6.203E 01	4.694E 01	3.351E 01	2.615E 01	4.064E 01	3.135E 01	3.757E 01
23	6.349E 01	4.807E 01	3.418E 01	2.670E 01	4.151E 01	3.204E 01	3.836E 01
24	6.489E 01	4.917E 01	3.483E 01	2.723E 01	4.234E 01	3.271E 01	3.917E 01
25	6.626E 01	5.024E 01	3.546E 01	2.775E 01	4.316E 01	3.337E 01	3.992E 01
26	6.759E 01	5.128E 01	3.608E 01	2.826E 01	4.396E 01	3.401E 01	4.064E 01
27	6.887E 01	5.228E 01	3.668E 01	2.875E 01	4.473E 01	3.463E 01	4.140E 01
28	7.012E 01	5.326E 01	3.726E 01	2.923E 01	4.547E 01	3.524E 01	4.215E 01
29	7.133E 01	5.421E 01	3.784E 01	2.970E 01	4.621E 01	3.583E 01	4.279E 01
30	7.250E 01	5.513E 01	3.839E 01	3.016E 01	4.692E 01	3.640E 01	4.345E 01
31	7.364E 01	5.603E 01	3.894E 01	3.061E 01	4.761E 01	3.696E 01	4.410E 01
32	7.475E 01	5.690E 01	3.947E 01	3.105E 01	4.829E 01	3.751E 01	4.473E 01
33	7.582E 01	5.775E 01	3.999E 01	3.147E 01	4.895E 01	3.804E 01	4.535E 01
34	7.687E 01	5.857E 01	4.049E 01	3.189E 01	4.959E 01	3.856E 01	4.595E 01
35	7.788E 01	5.937E 01	4.098E 01	3.229E 01	5.020E 01	3.906E 01	4.653E 01
36	7.886E 01	6.015E 01	4.146E 01	3.269E 01	5.081E 01	3.955E 01	4.710E 01
37	7.982E 01	6.091E 01	4.193E 01	3.306E 01	5.140E 01	4.004E 01	4.765E 01
38	8.075E 01	6.165E 01	4.239E 01	3.345E 01	5.198E 01	4.050E 01	4.819E 01
39	8.166E 01	6.236E 01	4.284E 01	3.382E 01	5.254E 01	4.095E 01	4.872E 01
40	8.253E 01	6.306E 01	4.327E 01	3.418E 01	5.308E 01	4.140E 01	4.923E 01
50	9.013E 01	6.914E 01	4.711E 01	3.734E 01	5.786E 01	4.529E 01	5.372E 01
60	9.597E 01	7.388E 01	5.013E 01	3.984E 01	6.159E 01	4.835E 01	5.722E 01
70	1.005E 02	7.765E 01	5.252E 01	4.183E 01	6.451E 01	5.078E 01	5.998E 01
80	1.042E 02	8.071E 01	5.443E 01	4.342E 01	6.687E 01	5.274E 01	6.221E 01
90	1.072E 02	8.326E 01	5.595E 01	4.465E 01	6.876E 01	5.433E 01	6.400E 01
100	1.097E 02	8.541E 01	5.717E 01	4.571E 01	7.030E 01	5.563E 01	6.546E 01
110	1.118E 02	8.728E 01	5.816E 01	4.654E 01	7.157E 01	5.672E 01	6.667E 01
120	1.137E 02	8.893E 01	5.895E 01	4.722E 01	7.264E 01	5.765E 01	6.769E 01
130	1.154E 02	9.041E 01	5.961E 01	4.778E 01	7.356E 01	5.844E 01	6.857E 01
140	1.168E 02	9.175E 01	6.014E 01	4.824E 01	7.430E 01	5.912E 01	6.929E 01
150	1.182E 02	9.300E 01	6.059E 01	4.863E 01	7.499E 01	5.972E 01	6.995E 01
160	1.195E 02	9.416E 01	6.096E 01	4.895E 01	7.559E 01	6.025E 01	7.053E 01
170	1.206E 02	9.526E 01	6.128E 01	4.923E 01	7.611E 01	6.074E 01	7.104E 01
180	1.218E 02	9.631E 01	6.155E 01	4.947E 01	7.661E 01	6.118E 01	7.152E 01
190	1.228E 02	9.731E 01	6.179E 01	4.965E 01	7.704E 01	6.159E 01	7.194E 01
200	1.239E 02	9.828E 01	6.199E 01	4.987E 01	7.747E 01	6.197E 01	7.235E 01
250	1.285E 02	1.027E 02	6.277E 01	5.061E 01	7.920E 01	6.363E 01	7.404E 01
300	1.327E 02	1.067E 02	6.332E 01	5.114E 01	8.066E 01	6.503E 01	7.551E 01
400	1.400E 02	1.137E 02	6.419E 01	5.200E 01	8.314E 01	6.742E 01	7.796E 01
500	1.463E 02	1.197E 02	6.490E 01	5.271E 01	8.525E 01	6.946E 01	8.004E 01
600	1.518E 02	1.250E 02	6.552E 01	5.332E 01	8.709E 01	7.124E 01	8.186E 01
700	1.566E 02	1.296E 02	6.605E 01	5.385E 01	8.869E 01	7.279E 01	8.348E 01
800	1.609E 02	1.337E 02	6.652E 01	5.431E 01	9.011E 01	7.416E 01	8.485E 01
900	1.648E 02	1.374E 02	6.693E 01	5.471E 01	9.140E 01	7.538E 01	8.611E 01
1000	1.683E 02	1.406E 02	6.730E 01	5.507E 01	9.255E 01	7.645E 01	8.724E 01
2000	1.928E 02	1.627E 02	6.952E 01	5.719E 01	1.003E 02	8.357E 01	9.481E 01
3000	2.084E 02	1.757E 02	7.062E 01	5.826E 01	1.051E 02	8.757E 01	9.929E 01
4000	2.214E 02	1.862E 02	7.145E 01	5.893E 01	1.089E 02	9.075E 01	1.029E 02
5000	2.331E 02	1.957E 02	7.217E 01	5.957E 01	1.124E 02	9.360E 01	1.062E 02
6000	2.439E 02	2.044E 02	7.284E 01	6.016E 01	1.156E 02	9.622E 01	1.092E 02
7000	2.539E 02	2.125E 02	7.347E 01	6.071E 01	1.186E 02	9.866E 01	1.120E 02
8000	2.633E 02	2.200E 02	7.406E 01	6.122E 01	1.214E 02	1.009E 02	1.146E 02
9000	2.720E 02	2.270E 02	7.461E 01	6.170E 01	1.240E 02	1.030E 02	1.170E 02
10000	2.801E 02	2.336E 02	7.513E 01	6.216E 01	1.264E 02	1.050E 02	1.193E 02
11000	2.877E 02	2.397E 02	7.563E 01	6.259E 01	1.286E 02	1.069E 02	1.215E 02
12000	2.948E 02	2.454E 02	7.609E 01	6.299E 01	1.308E 02	1.086E 02	1.234E 02
13000	3.014E 02	2.508E 02	7.653E 01	6.337E 01	1.327E 02	1.102E 02	1.253E 02
14000	3.076E 02	2.559E 02	7.694E 01	6.373E 01	1.346E 02	1.117E 02	1.271E 02
15000	3.135E 02	2.605E 02	7.734E 01	6.407E 01	1.364E 02	1.132E 02	1.287E 02
16000	3.189E 02	2.649E 02	7.771E 01	6.439E 01	1.380E 02	1.145E 02	1.303E 02
17000	3.241E 02	2.691E 02	7.807E 01	6.470E 01	1.396E 02	1.158E 02	1.317E 02
18000	3.290E 02	2.730E 02	7.841E 01	6.499E 01	1.411E 02	1.170E 02	1.331E 02
19000	3.335E 02	2.767E 02	7.873E 01	6.527E 01	1.424E 02	1.181E 02	1.344E 02
20000	3.378E 02	2.802E 02	7.904E 01	6.553E 01	1.437E 02	1.192E 02	1.356E 02
21000	3.419E 02	2.835E 02	7.933E 01	6.578E 01	1.459E 02	1.202E 02	1.368E 02
22000	3.458E 02	2.866E 02	7.961E 01	6.602E 01	1.462E 02	1.212E 02	1.379E 02
23000	3.494E 02	2.895E 02	7.988E 01	6.625E 01	1.473E 02	1.221E 02	1.389E 02
24000	3.529E 02	2.923E 02	8.014E 01	6.647E 01	1.483E 02	1.229E 02	1.399E 02
25000	3.562E 02	2.950E 02	8.039E 01	6.668E 01	1.493E 02	1.238E 02	1.409E 02
26000	3.593E 02	2.975E 02	8.063E 01	6.688E 01	1.503E 02	1.245E 02	1.419E 02
27000	3.623E 02	2.999E 02	8.086E 01	6.708E 01	1.512E 02	1.253E 02	1.427E 02
28000	3.651E 02	3.022E 02	8.108E 01	6.727E 01	1.521E 02	1.260E 02	1.435E 02
29000	3.678E 02	3.043E 02	8.130E 01	6.745E 01	1.529E 02	1.267E 02	1.443E 02
30000	3.704E 02	3.064E 02	8.150E 01	6.763E 01	1.537E 02	1.273E 02	1.450E 02
40000	3.909E 02	3.230E 02	8.326E 01	6.911E 01	1.602E 02	1.326E 02	1.511E 02
50000	4.050E 02	3.344E 02	8.463E 01	7.025E 01	1.647E 02	1.363E 02	1.553E 02
60000	4.152E 02	3.426E 02	8.575E 01	7.118E 01	1.681E 02	1.390E 02	1.585E 02
70000	4.230E 02	3.490E 02	8.673E 01	7.199E 01	1.709E 02	1.412E 02	1.610E 02
80000	4.291E 02	3.539E 02	8.760E 01	7.272E 01	1.730E 02	1.430E 02	1.631E 02
90000	4.340E 02	3.580E 02	8.840E 01	7.339E 01	1.748E 02	1.445E 02	1.649E 02
100000	4.381E 02	3.614E 02	8.916E 01	7.403E 01	1.764E 02	1.459E 02	1.663E 02
150000	4.524E 02	3.736E 02	9.278E 01	7.706E 01	1.827E 02	1.512E 02	1.723E 02
200000	4.625E 02	3.826E 02	9.639E 01	8.005E 01	1.879E 02	1.557E 02	1.773E 02
250000	4.719E 02	3.912E 02	1.002E 02	8.313E 01	1.931E 02	1.601E 02	1.823E 02
300000	4.812E 02	3.999E 02	1.042E 02	8.668E 01	1.984E 02	1.650E 02	1.876E 02
400000	5.001E 02	4.178E 02	1.124E 02	9.387E 01	2.096E 02	1.749E 02	1.981E 02
500000	5.191E 02	4.361E 02	1.214E 02	1.014E 02	2.211E 02	1.851E 02	2.092E 02
1000000	6.040E 02	5.205E 02	1.650E 02	1.376E 02	2.744E 02	2.333E 02	2.611E 02
2000000	8.197E 02	7.405E 02	2.824E 02	2.359E 02	4.167E 02	3.623E 02	3.947E 02
10000000	1.036E 03	9.596E 02	3.985E 02	3.335E 02	5.574E 02	4.903E 02	5.355E 02

* MOX (1:3) IMPLIES A MIXED OXIDE TO FRESH FUEL RATIO OF 1 TO 3

POWER AND ENERGY AS A FUNCTION OF TIME

PWR AND BWR (WATTS/MTHM) *

SPENT FUEL

TIME AFTER DISCHARGE (YEARS)	PWR POWER (WATTS)	BWR POWER (WATTS)	PWR AND BWR IN A 2 TO 1 RATIO	ENERGY (KW-YR/MTHM)
1	10402.54	7682.16	9495.75	0.0
2	5625.49	4226.43	5159.13	7.11
3	3587.00	2738.24	3304.08	11.27
4	2559.55	1985.55	2368.29	14.08
5	2004.11	1577.18	1861.80	16.19
6	1682.07	1339.64	1567.93	17.90
7	1481.93	1191.45	1385.10	19.37
8	1349.10	1092.64	1263.61	20.70
9	1255.57	1022.66	1177.93	21.92
10	1186.23	970.42	1114.29	23.06
11	1132.49	929.62	1064.87	24.15
12	1089.20	896.49	1024.96	25.20
13	1053.13	868.66	991.64	26.20
14	1022.20	844.61	963.00	27.18
15	995.00	823.30	937.77	28.13
16	970.57	804.05	915.06	29.06
17	948.23	786.36	894.28	29.96
18	927.53	769.88	874.98	30.85
19	908.13	754.36	856.85	31.71
20	889.72	739.63	839.69	32.56
21	872.19	725.56	823.31	33.39
22	855.40	712.04	807.61	34.21
23	839.23	699.01	792.49	35.01
24	823.62	686.41	777.88	35.79
25	808.51	674.20	763.74	36.56
26	793.86	662.34	750.02	37.32
27	779.63	650.82	736.69	38.06
28	765.79	639.61	723.73	38.79
29	752.33	628.69	711.11	39.51
30	739.21	618.04	698.82	40.22
31	726.43	607.67	686.84	40.91
32	713.97	597.55	675.16	41.59
33	701.82	587.67	663.77	42.26
34	689.95	578.03	652.65	42.92
35	678.40	568.62	641.80	43.56
36	667.10	559.44	631.21	44.20
37	656.08	550.46	620.87	44.83
38	645.32	541.69	610.78	45.44
39	634.81	533.13	600.92	46.05
40	624.54	524.76	591.28	46.65
50	533.95	450.78	506.23	52.12
60	461.69	391.59	438.32	56.84
70	403.72	343.97	383.80	60.94
80	357.01	305.52	339.85	64.55
90	319.24	274.35	304.27	67.77
100	288.56	248.98	275.37	70.67
110	263.54	228.23	251.77	73.30
120	243.01	211.18	232.40	75.72
130	226.08	197.07	216.41	77.96
140	212.01	185.32	203.11	80.06
150	200.23	175.46	191.97	82.04
160	190.29	167.11	182.56	83.91
170	181.82	159.97	174.53	85.69
180	174.53	153.91	167.63	87.40
190	168.21	148.45	161.62	89.05
200	162.67	143.73	156.35	90.64
250	142.47	126.41	137.12	97.97
300	128.96	114.68	124.20	104.49
400	109.87	97.99	105.91	115.97
500	95.78	85.63	92.39	125.87
600	84.55	75.76	81.62	134.56

*PWR Burnup 33,000 MW/MT; BWR Burnup 27,500 MW/MT

POWER AND ENERGY AS A FUNCTION OF TIME (CONTINUED)

TIME AFTER DISCHARGE (YEARS)	PWR POWER (WATTS)	BWR POWER (WATTS)	PWR AND BWR IN A 2 TO 1 RATIO	ENERGY (KW-YR/MTHM)
700	75.31	67.64	72.76	142.27
800	67.58	60.84	65.33	149.17
900	61.03	55.08	59.05	155.39
1000	55.47	50.18	53.71	161.02
2000	29.18	26.99	28.45	200.77
3000	22.69	21.20	22.20	225.96
4000	20.30	19.00	19.87	246.97
5000	18.82	17.61	18.42	266.10
6000	17.51	16.47	17.23	283.92
7000	16.53	15.44	16.17	300.62
8000	15.54	14.51	15.20	316.29
9000	14.63	13.65	14.31	331.04
10000	13.80	12.86	13.49	344.93
11000	13.03	12.14	12.73	358.04
12000	12.32	11.47	12.04	370.42
13000	11.57	10.85	11.40	382.14
14000	11.06	10.28	10.80	393.23
15000	10.50	9.75	10.25	403.76
16000	9.99	9.26	9.74	413.75
17000	9.50	8.81	9.27	423.26
18000	9.05	8.39	8.83	432.31
19000	8.64	8.00	8.42	440.94
20000	8.25	7.63	8.05	449.17
21000	7.89	7.29	7.69	457.04
22000	7.55	6.98	7.36	464.56
23000	7.24	6.68	7.05	471.76
24000	6.94	6.40	6.76	478.67
25000	6.66	6.14	6.49	485.30
26000	6.40	5.90	6.24	491.66
27000	6.16	5.67	6.00	497.77
28000	5.93	5.45	5.77	503.66
29000	5.71	5.25	5.56	509.32
30000	5.51	5.06	5.36	514.78
40000	3.96	3.62	3.85	560.38
50000	2.98	2.72	2.89	593.86
60000	2.32	2.10	2.25	619.44
70000	1.85	1.67	1.79	639.54
80000	1.51	1.35	1.45	655.70
90000	1.25	1.12	1.21	668.99
100000	1.07	0.95	1.03	680.15
150000	0.67	0.57	0.64	720.98
200000	0.58	0.50	0.56	750.71
250000	0.57	0.48	0.54	778.10
300000	0.56	0.48	0.53	804.95
400000	0.55	0.47	0.52	857.66
500000	0.52	0.45	0.49	906.38
1000000	0.39	0.35	0.38	1124.77
3000000	0.23	0.21	0.22	1707.84
10000000	0.12	0.11	0.12	2842.13

Source: OWI Waste Projection Data - Memo 9, D. W. Turner to W. A. Burnett, Aug. 17, 1977.

5.2 Appendix B. Maximum HLW Centerline Temperature

The centerline and canister wall temperatures will reach near maximum in a relatively short time; steady-state can therefore be assumed. For an infinite cylinder with a uniform heat generation (Q), the temperature drop from the centerline to the surface of a cylinder of radius r is

$$T_c - T(r) = \frac{Qr^2}{4k} . \tag{B.1}$$

The maximum possible temperature will occur at the centerline when the canister surface is at its permissible maximum, 375°C (707°F). For 2.1 kW in a canister that is 1 ft in diam, and 8 ft high,

$$Q = \frac{3413 \times 2.1}{6.28} = 1141 \text{ Btu/hr}\cdot\text{ft}^3. \tag{B.2}$$

Using the flat-plate equation as an approximation, the temperature drop across the canister wall is (k steel = 25 Btu/hr•ft•°F)

$$\Delta T = \frac{q\Delta X}{Ak} = \frac{3413 \times 2.1 \times 0.375}{\pi \times 1 \times 8 \times 25 \times 12} = 0.36°\text{F}. \tag{B.3}$$

For calcine (k = 0.25 Btu/hr•ft•°F),

$$T_c = 707 + \frac{1141 \times (0.5)^2}{4 \times 0.25} + 0.4 = 993°\text{F } (534°\text{C}). \tag{B.4}$$

For glass (k = 0.66 Btu/hr•ft•°F).

$$T_c = 707 + \frac{1141 \times (0.5)^2}{4 \times 0.66} + 0.4 = 815°\text{F } (435°\text{C}). \tag{B.5}$$

INTERNAL DISTRIBUTION

1. G. D. Brunton
2. H. C. Claiborne
3. L. R. Dole
4. D. E. Ferguson
5. G. H. Jenks
6. R. K. Kibbe
7. R. A. Kisner
8. G. H. Llewellyn
9. T. F. Lomenick
10. A. L. Lotts
11-20. W. C. McClain
21-22. ORNL Laboratory Records
23. ORNL Central Research Library
24. ORNL Technical Library
25. Y-12 Records - RC
26-27. Y-12 Records

EXTERNAL DISTRIBUTION

Battelle Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352
28. A. M. Platt

Bechtel Corporation, 50 Beale Street, P.O. Box 3965, San Francisco, CA 94119
29. N. A. Norman

DELFT University of Technology, 20 Mijnbouwstraat, P.O. Box 5028, 2600 GA Delft, Netherlands
30. Ir Wim M.G.T. van den Broek

Institut für Tieflagerung, Wissenschaftliche Abteilung, 3392 Clausthal-Zellerfeld, Federal Republic of Germany
31. K. Kühn
32. G. Staupendahl

Kaiser Engineers, Kaiser Center, 300 Lakeside Drive, Oakland, CA 94604
33. J. S. Ritchie

Lawrence Livermore Laboratory, University of California. P.O. Box 808, Livermore, CA 94550
34. H. C. Heard

Louisiana State University, Institute for Environmental Studies, P.O. Drawer JD, Baton Rouge, LA 70803
35. R. L. Thoms

Netherlands Energy Research Foundation, Technical Service Department, Westernduinweg 3, Petten (N.H.), Netherlands
36. J. Hamstra

Office of Nuclear Waste Isolation, Battelle Memorial Institute, 505 King Avenue, Columbus, OH 43201
37. W. A. Carbiener
38-42. N. E. Carter
43. R. B. Laughon
44. M. M. Lemcoe
45. S. C. Matthews
46. G. E. Raines

RE/SPEC Inc., P.O. Box 725, Rapid City, SD 57709
47. P. F. Gnirk

Sandia Laboratories, P.O. Box 5800, Albuquerque, NM 87185
48. L. R. Hill
49. D. E. Munson
50. P. D. O'Brien
51. J. R. Tillerson
52. A. R. Sattler
53. L. W. Scully
54. W. Wawersik
55. W. D. Weart

Science Applications, Inc., P.O. Box 843, Oak Ridge, TN 37830
56. R. E. Wilhems

Science Applications, Inc., 8201 Capwell Drive, Oakland, CA 94621
57. R. Hofmann

Texas A&M University, Department of Petroleum Engineering, College Station, TX 77843
58-67. J. E. Russell

University of Minnesota, Department of Civil and Mineral Engineering, Minneapolis, MN 55455
68. S. L. Crouch
69. C. M. St. John

U.S. Geological Survey, 12201 Sunrise Valley Drive, Reston, VA 22092
70. P. R. Stevens

Vanderbilt University, P.O. Box 1596, Station B, Nashville, TN 37325
71. F. L. Parker

Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN 37830
72-73. D. E. Large

Department of Energy, Richland Operations Office-Columbus, 505 King Avenue, Columbus, OH 43201
74. J. O. Neff

Department of Energy, Office of Nuclear Waste Management, Mail Stop B107, Washington, DC 20545
75. C. R. Cooley
76. W. Eister
77. C. A. Heath