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Potential Benefits of Actinide Recycle to the Yucca Mountain Repository

Brian Spencer Cowell

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I am submitting herewith a thesis written by Brian Spencer Cowell entitled "Potential Benefits of Actinide Recycle to the Yucca Mountain Repository." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.

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Potential Benefits of Actinide Recycle to the Yucca Mountain Repository

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Brian Spencer Cowell

August, 1995

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Abstract

This thesis contains an analysis of the Yucca Mountain Repository for high level nuclear wastes. A list of all the proposed waste materials was compiled. This list indicates that at the reference emplacement density of 57 kW/acre, the planned repository has insufficient capacity. Thus, incentives exist to increase the capacity by increasing the emplacement density. An alternative emplacement methodology utilizing a combination of actinide recycle, optimized geometry, and ventilated emplacement over an extended operating period promises to increase the capacity drastically.

Using previously calculated values of the decay heat in spent fuel (SF) and high level wastes (HLW) from which the actinides have been removed, one and three dimensional heat transfer calculations were performed to quantify the capacity increases for several combinations of burnup, geometry changes, and repository operating schedules. These calculations indicate that the reference emplacement density of 57 kW/acre, which corresponds to 120 fuel assemblies per acre, is overly conservative. According to these calculations, the actual limit for SF emplaced in the reference geometry is 75 kW/acre, which corresponds to 159 fuel assemblies per acre. By removing the actinides, this maximum increases to 211 assemblies per acre.

Calculations were performed for SF and HLW (SF from which the actinides have been removed via reprocessing) in optimized geometry. By spacing the radioactive material closer together, the maximum densities increase to 184 and 310 assemblies/acre for SF and HLW respectively. Similar calculations were performed for higher burnup materials, with no noticeable change in the relative results. Finally, staggered emplacement was analyzed. The maximum emplacement densities increase to 219 and 315 assemblies/acre for SF and HLW in standard geometry. In optimized geometry, the maximum densities are 222 and 590 assemblies/acre for SF and HLW.

The results reported above correspond to the reference hot repository in which the waste packages reach temperatures greater than 200°C. Licensing difficulties associated with this hot repository concept have created interest in a cold repository in which the emplacement horizon does not exceed the boiling point of water. Results for the cold repository in the standard emplacement geometry indicate the expected decrease in the allowable loadings: 68 and 91 assemblies/acre for SF and HLW respectively. For optimized geometry, the loadings increase to 93 and 133 assemblies/acre for SF and HLW. The results for staggered emplacement, however, do not show such a great decrease. In standard geometry, the loadings are 94 and 135 assemblies/acre for SF and HLW, and in optimized geometry, they are 142 and 253 assemblies/acre. This last result indicates that a cold repository, which should prove easier to license, can contain all the identified wastes if one combines actinide removal with optimized emplacement geometry and ventilated operation over an extended operating period.

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List of Acronyms

Acronym	Definition
CDB	Characteristics Data Base
DOE	United States Department of Energy
FF	far-field (Topopah Springs/Calico Hills interface 45 m below repository)
GTCC	greater than class C low level radioactive wastes
HEU	highly enriched uranium (>20 a/o fissile)
HEWEC	High Efficiency Waste Emplacement Concept
HLW	high level waste (spent fuel from which actinides have been removed)
LEU	low enriched uranium (< 20 a/o fissile)
MT	metric ton (1000 kg)
MTHM	metric tons heavy metal
MTIHM	metric tons initial heavy metal
MTU	metric tons uranium metal
MRS	Monitored Retrievable Storage
NF	near-field (one meter from waste package)
OCRWM	Office of Civilian Radioactive Waste Management
PWR	pressurized water reactor
RADDB	light water reactor Radiological Database
SCP-CDR	Site Characterization Plan - Conceptual Design Report
SF	spent fuel

1. Introduction

The recent revelations about Yucca Mountain reported in major newspapers [1] have once again focused attention on the planned geologic repository. This is just the latest controversy surrounding the project that has spent almost two billion dollars on site suitability studies over the past decade. The federal government, in the form of the Office of Civilian Radioactive Waste Management (OCRWM), plans to emplace radioactive materials such that they are isolated from human contact for many thousands of years.

Under current law [2], the Department of Energy is scheduled to take possession of spent commercial nuclear reactor fuel (SF) and high level radioactive wastes (HLW) beginning in 1998. The majority of this material has arisen from the operation of the one hundred plus commercial nuclear power stations over the last forty years. Both spent fuel and reprocessing wastes must be isolated from human contact for many thousands of years due to their high chemical and radiotoxicities. Current disposal plans call for the isolation of these wastes in a mined geologic repository, hereafter referred to only as a repository. The basic concept is to mine out emplacement tunnels, or drifts, in a stable geologic medium and to emplace the wastes in these drifts in small, individually sealed packages.

Several sites covering different geologic media including crystalline rock (granite), salt, basalt, and tuff were originally investigated for suitability [3]. However, only a single site, Yucca Mountain, Nevada, is currently under consideration. Yucca Mountain is located on federal lands about 85 miles northwest of Las Vegas, Nevada.

The mountain lies on three separate federal sites: the Nevada Test Site, the Nellis Air Force Base Bombing Range, and Bureau of Land Management lands.

Yucca Mountain is subject to a number of capacity restrictions. The most important of these is a statutory limit of 70,000 metric tons of spent fuel or its equivalent. The two other important limits are closely intertwined: the actual physically available area and the maximum allowable thermal areal loading. Numerous investigations have been conducted over the last decade both within and outside the official OCRWM program to identify techniques of increasing the capacity.

This paper analyzes one of the most promising methods of increasing the capacity that was introduced by Croff [4]. In addition to increasing the capacity by up to a factor of four or more, it also eliminates one of the other potential problems with the current repository plans - criticality. It will be extremely difficult for the OCRWM to remove all doubts about the criticality risk posed by Yucca Mountain, no matter how implausible the current theories. Removal of the fissile materials may in the end become the only option to eliminate the criticality risk completely. One of the key points of Croff's methodology is actinide removal, thus eliminating the criticality risks.

In the remainder of this paper, the Yucca Mountain repository site and concept is described. This is followed by a compilation of all the materials that have been identified as potentially reporting to the repository. Most of these materials are not recognized by the OCRWM, but are destined to be emplaced there nonetheless. A description of the current thermal analyses is followed by the results for both hot and cold repository concepts. Finally, the conclusions are summarized.

2. Yucca Mountain Repository Concept

Yucca Mountain rises some 300 meters above the surrounding valleys. The selected emplacement horizon is close to the level of the surrounding valleys. Access to the emplacement horizon therefore may be accomplished through a series of ramps into the mountain from the sides.

Yucca Mountain is perhaps more accurately described as a series of volcanic-origin ridges. The mountain runs roughly north-south, with valleys on the east and west. The upper 2000 meters at Yucca Mountain consist of a series of distinct volcanic ash flows. The rock is best described as volcanic tuff, or compacted ash. This rock has a high compressive strength, but is highly fractured in localized regions. The high compressive strength increases the mining difficulties, but contributes to drift stability once completed. The regions of fracturing are primarily associated with a number of seismic faults that run through the mountain. The fractures may result in localized drift instabilities, and additional rock stabilization will probably be required in certain regions of the repository.

The geologic strata of interest for repository development are limited to the upper 900 meters, including those above the water table and those defining the upper portion of the water table. The water table is located some 600-650 meters below the crest of the mountain, and ~300 meters below the emplacement horizon. Although groundwater flow beneath the site has not been fully characterized, it basically flows south-southeast towards Death Valley. In this study, as in most other thermal studies of Yucca Mountain, the groundwater has been assumed to be at a fixed temperature of 32° C.

Above the water table are found four stratigraphic units (from surface down): surfacial alluvial deposits, the Tiva Canyon Member, the Paintbrush Tuff unit (in which the emplacement horizon is located), and the Calico Hills unit [5]. The most important of these is the Calico Hills unit. Portions of this unit have undergone a low-temperature, low-pressure conversion into zeolitic materials. This material is expected to provide an additional barrier to radiologic release by exchanging nonradioactive atoms with any radioactive ones that escape from the engineered barriers. Protection of this natural barrier has led to the implementation of the far-field temperature limit. The zeolitic properties of the Calico Hills tuff may be either hindered or lost by exposure to excessive temperatures.

Yucca Mountain is located in an arid region that receives only 0.15 meters of precipitation (primarily as snow) per year [6]. Due to the high evapotranspirational potential at the site, most of this moisture is returned to the atmosphere. Only a small fraction, estimated to be 0.7 mm per year [7], percolates into the ground to recharge the groundwater. The water that has to be dealt with in the repository design is therefore not expected to be a significant problem. Some localized saturated zones above the water table have been found during site characterization, but these are thought to be localized regions of water perched atop impermeable rock layers. All this is not to say that the repository is completely dry. In fact, the rock in the unsaturated zone contains an appreciable quantity of water. It is 70% saturated [5], providing a potential source of water to fuel corrosion of the waste packages. This issue is discussed further in Section 6, which deals with a cold repository concept.

The reference emplacement pattern is shown in Figures 1 and 2. Figure 1, which is adapted from Reference 5, shows the entire repository with the panel access drifts and emplacement drifts shown as single lines. Figure 2 shows a portion of an emplacement drift with the individual boreholes. The repository is to be developed in seventeen individual panels, with three main drifts dividing the repository in half. As shown in Figure 1, the panels vary in both size and shape. The irregular shape is due to accommodation of the geologic characteristics of the emplacement horizon. All the facilities shown in the figure are to be developed within usable sections of the emplacement strata, the Topopah Springs Member.

Three main drifts are to be developed running south-southwest from the original development area. The waste main serves as the connection between the waste ramp and the emplacement panels through which both waste and incoming ventilation air must pass. It is a cylindrical drift, with a 24' finished diameter. The tuff main carries excavated rock or tuff and exhaust air from the active development area. The tuff main is a conventionally mined drift, with a finished width of 24' and a maximum overhead clearance of 18.5'. The service main carries fresh air into the development area, and serves as the connection for men and materials between the access shafts and the development areas. Smallest of the three mains, the conventionally mined service main has a finished width of 24' and a maximum overhead clearance of 14.5'.

Branching off from these three central drifts are two panel access drifts and a midpanel drift for each of the seventeen emplacement panels. All three of these drifts

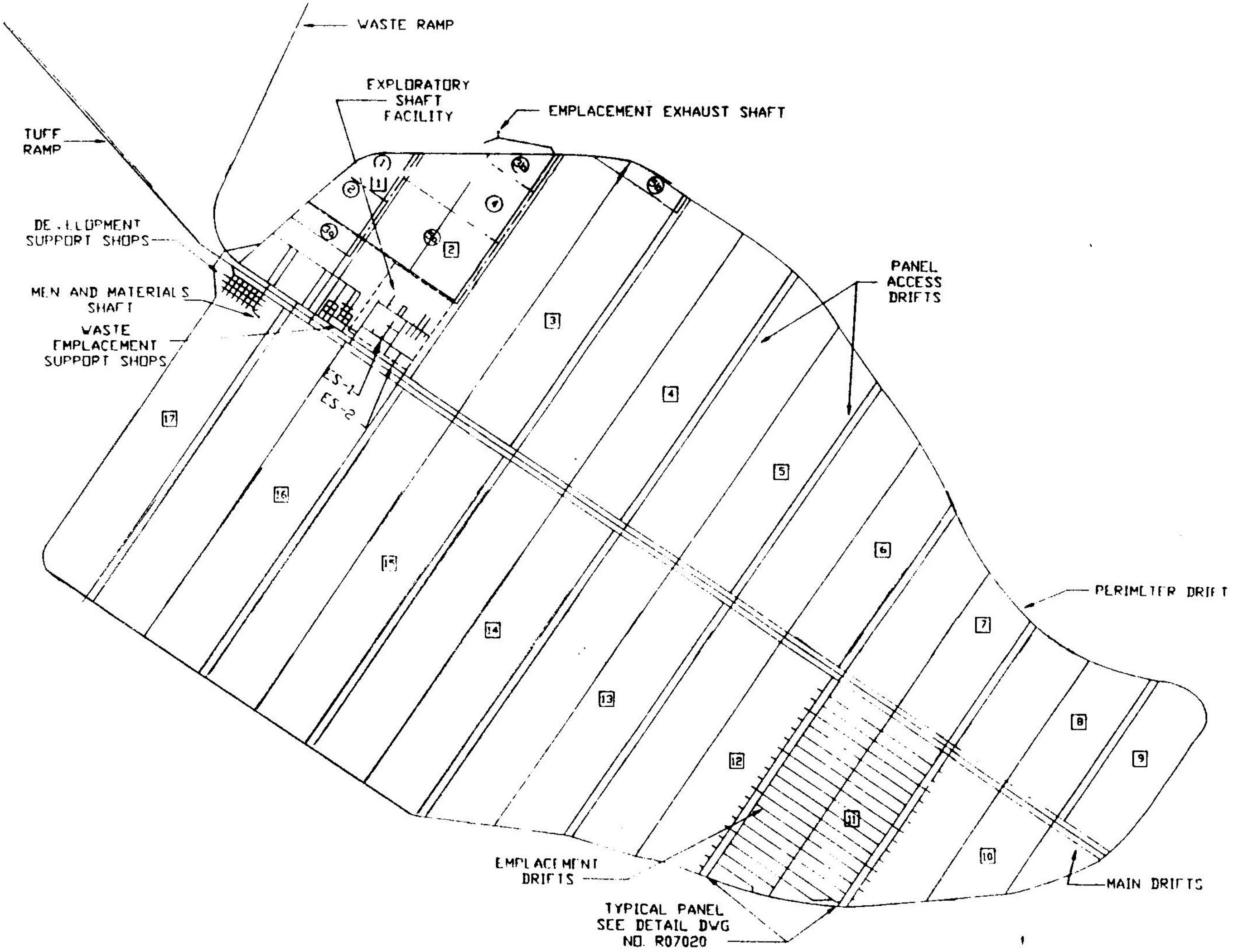

Figure 1: Layout of the Proposed Yucca Mountain Repository

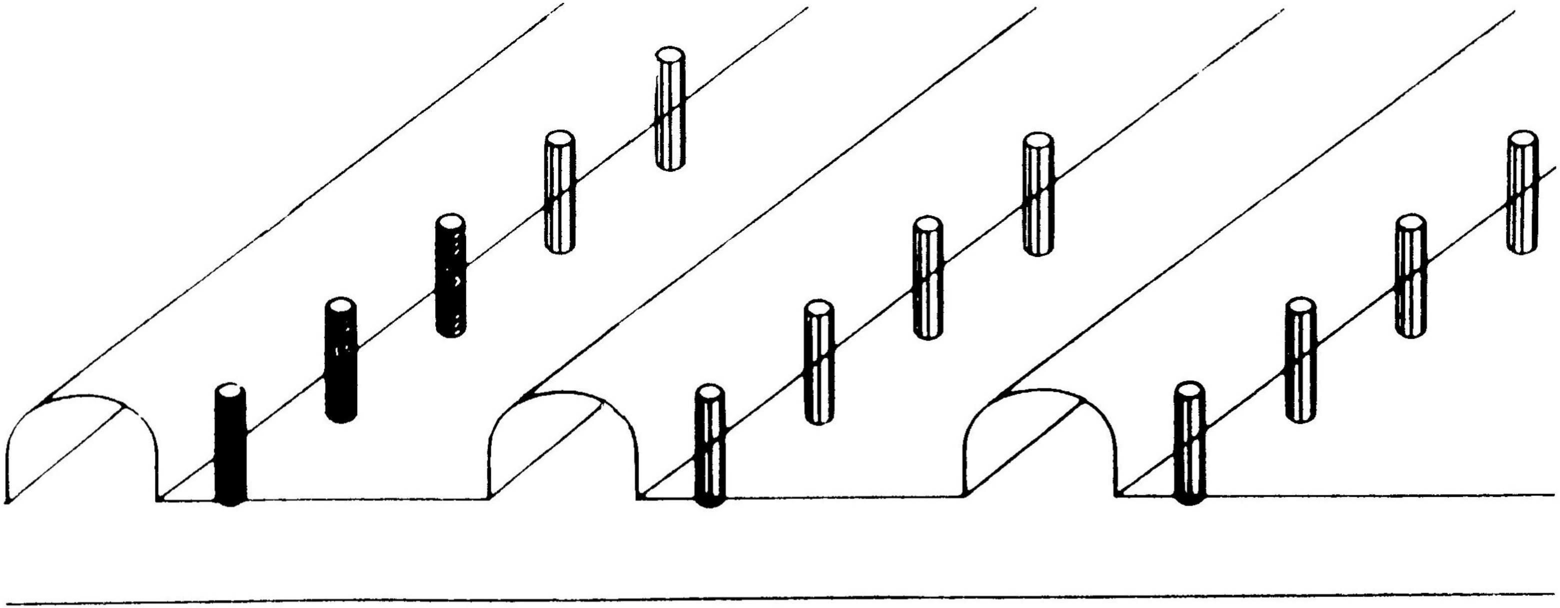

Figure 2: Closeup of an Emplacement Drift With Individual Boreholes

have a finished width of 20' and a height of 13.5'. The two panel access drifts run down the edge of the panel, forming its boundaries. The midpanel drift divides the drift into two slabs, each 700' wide. Emplacement drifts are developed perpendicular to the panel access and midpanel drifts, and parallel to the three mains. The emplacement drifts are tall and narrow, measuring 15' wide and 21.5' high. This unusual shape is required because the waste packages are to be brought in horizontally, then righted just prior to their vertical emplacement in boreholes.

The reference emplacement pattern is vertical borehole. In this pattern, cylindrical holes are drilled into the floor of the emplacement drifts, with a 15' center-to-center separation. The boreholes measure 29" in diameter. They are 25' high for spent fuel emplacement, and 20' high for the HLW packages. Adjacent drifts are developed on 126' centers.

A number of thermal limits have been developed for the repository. These are primarily meant to ensure package integrity and to prevent undesirable changes in the properties of the rock surrounding the packages. Croff assembled perhaps the best summary of these limits in Reference 4. From the package outward, these limits are described as very-near-field, near-field, and far-field. The very-near-field limits are those associated with the waste packages themselves. The near-field limits are associated with the area surrounding the packages that are perturbed as a result of the emplacement process. The far-field limits are generally for far removed sections of the mountain, several hundred feet from the emplacement zone.

Two near-field limits exist, one for each waste type. A cladding temperature limit of 350 °C exists for spent fuel, and a corresponding glass centerline limit of 500 °C exists for the high level waste (dissolved in borosilicate glass logs). Neither of the very-near-field limits is addressed in this work. The detail required to predict temperatures accurately for the very-near-field region was not modeled in this work.

The near-field temperature limits are of more interest. A maximum borehole wall temperature of 275 °C has been set. No physical meaning has been attached to this limit, and it is often used as a surrogate for the cladding temperature limit that is more difficult to check. The second near-field limit is a maximum rock temperature of 200 °C one meter from the borehole wall. This maximum temperature occurs along the centerline of a drift, between adjacent packages. This limit is set to prevent gross changes in the physical characteristics of the host rock due to thermal decomposition. The one-meter temperature limit is used throughout this report, and is hereafter referred to simply as the near-field limit as it is the only one tested in this work. Another temperature limit is sometimes associated with the near-field, and it is therefore mentioned for completeness. This is a maximum panel access drift wall temperature of 50 °C.

Two far-field temperature limits are discussed in the literature. The first is of less interest than the second, because of its conservatism. The temperature rise at the mountain's surface must be less than 6 °C. This limit, in addition to being conservative, is also hard to measure because it is well within the natural variation in the surface temperature of the mountain, and would be difficult to distinguish from background noise. The second limit is a maximum temperature of 115 °C at the interface of the Calico

Hills and the Topopah Springs strata. The Calico Hills member contains natural zeolite that could help to mitigate any leakage from the repository. The zeolitic properties of the rock would be harmed by high temperatures, and this limit is meant to prevent this damage. In the remainder of the paper, this limit at the zeolite is referred to only as the far-field limit. Some disagreement exists over exactly how far below the repository this geologic boundary exists. The values range from 45 to 60 meters. In this work, the boundary and limit were taken to be 45 meters below the emplacement horizon.

3. Materials Potentially Destined for Yucca Mountain

The OCRWM acknowledges only a limited quantity of materials potentially destined for emplacement in Yucca Mountain. This is because of a statutory limit of 70,000 metric ton (MT) set on Yucca Mountain [2]. The law, in fact, limits the emplacement to 70,000 MT prior to opening of the second repository. However, this is commonly inferred to be a de facto ultimate capacity limit because of the difficulties in siting the first repository. The OCRWM plans to emplace approximately 63,000 MT of commercial spent fuel and 7,000 MT of high level waste. The difficulty with this view is that it ignores a large quantity of material that is, in all likelihood, destined for Yucca Mountain.

The first step in this work was to identify all the materials that are being reported by their owners/caretakers as eventually reporting to the Yucca Mountain repository or its successor. It is widely acknowledged that siting a second repository may be politically impossible, and thus all this material may eventually be placed in Yucca Mountain. This assumes that the Nuclear Waste Policy Act will be revised to eliminate the capacity cap and to postpone indefinitely the siting of the second repository.

There are numerous databases covering nuclear waste. These were used in combination with other sources to generate Table 1, a summary of the materials potentially reporting to Yucca Mountain. It must be repeated that the OCRWM does not acknowledge the existence of this material, and does not agree that it will be placed in Yucca Mountain. The primary material of interest is commercial spent fuel. This material makes up the bulk of the spent fuel - high level waste disposal problem. The

Table 1: Materials Potentially Reporting to Yucca Mountain and Their Emplacement Area Requirements

Waste Material	Estimated Quantities	Calculated Equivalent Area (10^6 m^2)*
Commercial Spent Fuel	87,700 MTIHM	6.2***
Defense HLW	~ 7,000 MTIHM equivalent	~ 0.5***
DOE HEU Spent Fuel**	≤ 370 MTIHM	2.1 - 4.2****
DOE LEU Spent Fuel	~ 2,200 MTIHM	~ 0.2***
Excess Weapons Pu	50 MTHM	0.3 - 0.6****
Greater Than Clacc C (GTCC) Wastes	2,220 - 6,500 m^3 (3250 - 9520 m^3 packaged)	TBD
Enrichment Tails (DOE)	375,000 MTU	TBD
Other Enrichment Tails	~ 100,000 MTU	TBD
Total		9.3 - 11.7
As Percent of Repository Area (5.6 x 10^6 m^2)		170% - 210%

Notes:

- OCRWM only plans to accept materials listed in the first two rows, but other entities plan to emplace the remaining materials in Yucca Mountain.
- The abbreviations used in this table are MTIHM - metric tons initial heavy metal, MTHM - metric tons heavy metal, MTU - metric tons uranium, and TBD - to be determined because the packaging requirements have not been defined.

* Area requirements do not include ramps, access tunnels, and such unusable space.

** Estimate does not include spent naval fuels.

*** Area estimate is based on SCP-CDR loading of 57 kW/acre.

**** Area estimate is based on criticality limits of < 350 - 700 g HEU or Pu per package and a minimum two meter package separation.

87,700 MT value used in the table is taken from the Integrated Data Base [8], and corresponds to the DOE/EIA "No New Orders" case. This total includes that material already removed from reactors, that currently in core, and that estimated to be burned through the end of the reactors' operating lives. This material, especially that removed from reactors in the last few years, is well characterized. It is currently stored wet in spent fuel pools at the reactor sites, or dry in sealed casks at the sites. The utilities are demanding that the DOE take possession of this material beginning in 1998 as statutorily required. The utilities hold that their contracts with the DOE call for such a transfer, while the DOE maintains this is only valid if a repository or Monitored Retrievable Storage (MRS) is operational.

Most of the spent commercial fuel is in the form of intact fuel assemblies. Some of the fuel has been disassembled to increase available storage space. All of this fuel may be disassembled at the repository and consolidated prior to emplacement. Fuel consolidation allows more fuel assemblies to be placed in a single waste canister and will allow the material to be emplaced with fewer underground operations. However, additional risk and waste generation are expected to accompany consolidation, and the fuel may therefore be emplaced intact.

The second material listed in Table 1 is defense high level waste. This material is the residue from reprocessing of production reactor fuel, research reactor fuel, and a limited amount of commercial spent fuel at West Valley. This material includes the wastes stored in the Hanford tanks, the Savannah River tanks, and the Melton Valley storage tanks among others. Most of this material has not been vitrified. The majority of it has been out of reactor for many years and is thus producing only a fraction of the decay heat that newer HLW would. For this reason, the DOE has devised a conversion factor for this material that converts it to spent fuel equivalent MTIHM. The actual number of packages has been estimated, but is highly dependent on final waste volumes to be vitrified, loadings used in the glass, etc. Due to a lack of information about this HLW, it was assumed to have the same characteristics as the spent fuel - that is, ten-year-cooled pressurized water reactor (PWR) fuel burned to 30 GW-day/MT. This is probably an overestimate of the thermal characteristics, but this is somewhat compensated by the likely underestimation of the actual quantities of waste.

The third and fourth items in the table are DOE spent fuel. This material has been binned into HEU (> 20 a/o fissile) and LEU (< 20 a/o fissile) because of the different handling requirements. These materials consist primarily of research, production, university, and experimental reactor spent fuels from both foreign and domestic sources. Prior to the policy decisions against reprocessing, most of these materials would have been reprocessed to recover their contained uranium values. However, in light of the current ban on reprocessing, this material is to be dispositioned without reprocessing. This creates a special problem for the HEU material, due to the criticality risks associated with it. No detailed criticality calculations have been performed for the emplacement of this HEU material, but conservative estimates [9] limit the per package loading to somewhere between 350 and 700 grams heavy metal per package. In addition, to limit the interaction between adjacent packages to < 5%, the package to package spacing has been set at a minimum of two meters. Very simplistic (and generous) assumptions indicate that the 370 MTIHM HEU material may require 2.1E6 m^2 (at 700 grams per package) to 4.2E6 m^2 (at 350 grams per package) for emplacement under these restrictions. This calculation highlights the great burden associated with emplacement of this material in a repository without some degree of reprocessing.

The LEU SF was treated in the same manner as the commercial and DOE HLW - i.e., assumed to be ten-year-cooled PWR fuel burned to 30 GW-day/MT. As such, the ~2200 MTIHM of LEU material requires only a minor area of 0.2E6 m^2.

The fifth material, excess weapons plutonium, has been proposed for covitrification with HLW and subsequent emplacement in Yucca Mountain. The packaging and emplacement requirements for this material are assumed to be the same as for HEU spent fuel - i.e., 350-700 grams plutonium per package and a two meter minimum package spacing. This leads to an area requirement of 0.3E6 - 0.6E6 m^2. The fate of this material is currently uncertain as ongoing DOE programs are addressing the best dispositioning technology for this material. Several of the options call for burning the plutonium as mixed oxide with the resulting spent fuel emplaced in the repository. Under such a scenario, the emplacement requirements would be reduced to those of commercial spent fuel and the required area would decrease correspondingly.

The remaining materials are relative unknowns in the repository world because they have rarely been discussed as reporting to the repository. However, as other waste management options disappear, the owners/caretakers of these materials continue to turn to Yucca Mountain as the answer to their waste management problems. Greater than Class C (GTCC) wastes [10] comprise a diverse range of materials that fall between the definitions of Class C low level waste and high level waste. Examples of materials included in this category are control rods, non-fuel assembly hardware such as grid spacers and end plates, and startup neutron sources. Much of the contamination associated with GTCC wastes is due to activation, but the half-lives of the relevant isotopes are long. The isolation needs for GTCC wastes are not as stringent as those for HLW, but no regulatory guidance on its disposal is available. Therefore, it is assumed to require the same isolation from human contact as HLW. The packaging requirements for GTCC wastes have not been determined, so no area estimates can be made. One option that may prove to be feasible is to emplace the material directly in the drifts during the final backfilling operation that closes a drift permanently.

The last two rows in the table are depleted uranium enrichment tails. They are divided between two owners: DOE and others. The 375,000 MTHM of DOE material currently exists and is the result of the last fifty years of uranium enrichment for civilian and military purposes. The 100,000 MTHM of other is an estimate of the material that will be produced by the U.S. Enrichment Corporation at the Portsmouth and Paducah Gaseous Diffusion plants and by Louisiana Enrichment Services in fulfilling commercial commitments over the next several decades. As with GTCC wastes, the packaging requirements for enrichment tails should be less stringent than those for spent fuel and HLW. No regulatory guidance is available however. This material was included because the owners/caretakers of this material have selected Yucca Mountain as the ultimate disposal location of the materials. As with GTCC wastes, the enrichment tails may be able to be emplaced directly in the drifts during backfilling operations, although some packaging would be required for transport of the material to the site and into the repository.

The net result of the research into the materials potentially reporting to Yucca Mountain is that they will not all fit if emplaced at the reference density of 57 kW/acre. The area estimates for all the material are on the order of twice the available area of 5.6E6 m^2. Due to the difficulties associated with siting a repository, incentives exist to maximize the capacity of the first repository. The remainder of this paper assesses one promising technique for accomplishing this.

Croff [4] has proposed a combination of geometric changes to the repository layout, actinide removal, and an extended operational period to increase the repository capacity. One of the keys to the success of his proposed High Efficiency Waste Emplacement Concept (HEWEC) is actinide removal. Actinides (including uranium, plutonium, and the minor actinides neptunium, americium, and curium) make up the vast majority of spent fuel mass, ~96% [11]. More importantly, they are the principal source of long term decay heat. The high level waste resulting from spent fuel reprocessing concentrates the fission products, which produce most of the short term decay heat.

For example, one year after removal from a reactor, high level waste accounts for greater than 95% of the decay heat power in the reference fuel (standard enrichment PWR fuel exposed to 30 GW-day/MT). The power fraction produced by the actinides grows slowly as the short half life fission products decay. At ten years out of reactor, the actinides account for over 17% of the decay power. At 200 years out of reactor, the actinides account for 94% of the power and at 300 years, they account for essentially all the power. The decay power curves for spent fuel and high level waste are shown in Figure 3. The dominance of the actinides at longer times is obvious from this figure. For the repository, it has been suggested, [5] and [12], that a more meaningful measure for scaling the maximum loadings is the total heat produced. The decay power curves for spent fuel and high level waste were integrated from ten years to one thousand years. The resulting integral decay heat curves are shown as a function of time on Figure 4. It is clear from this figure why the actinides dominate the long term thermal behavior of the repository. They produce four times the heat that the fission products produce over the time period of interest.

What this means to the repository is that in the near term (first hundred years), the temperature profile will be driven primarily by the fission products. However, in the longer term, the actinides will drive the temperature profile. The not so obvious effect of this is that the high level waste emplacement density is controlled only by the near-field limits, while the spent fuel density is controlled by both near-field and far-field limits. The scale of the mountain combined with the low thermal conductivity of the rock causes the temperature perturbations at the far-field to be felt only after long times (many decades).

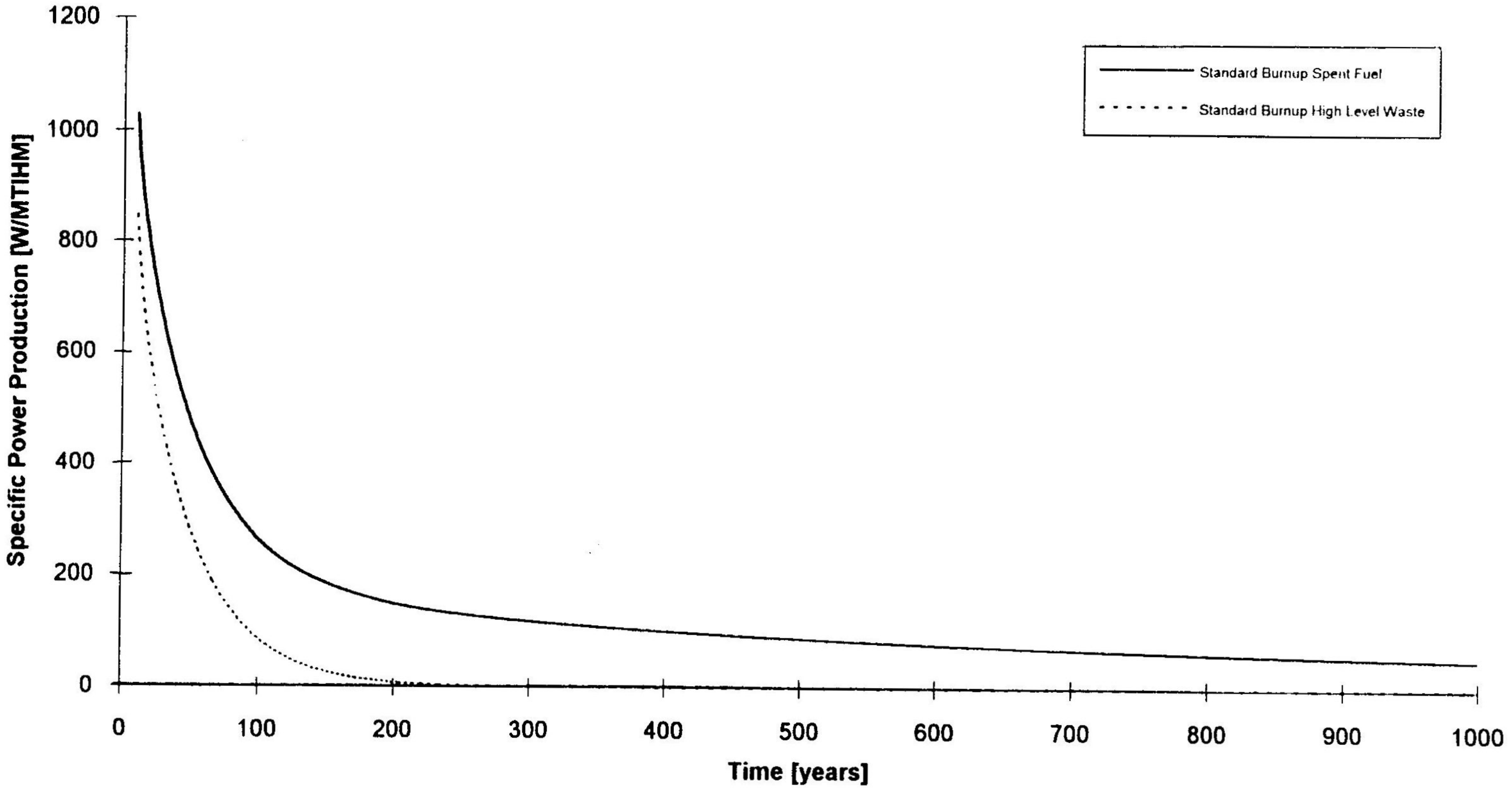

Figure 3: Decay Power as a Function of Time for SF and HLW

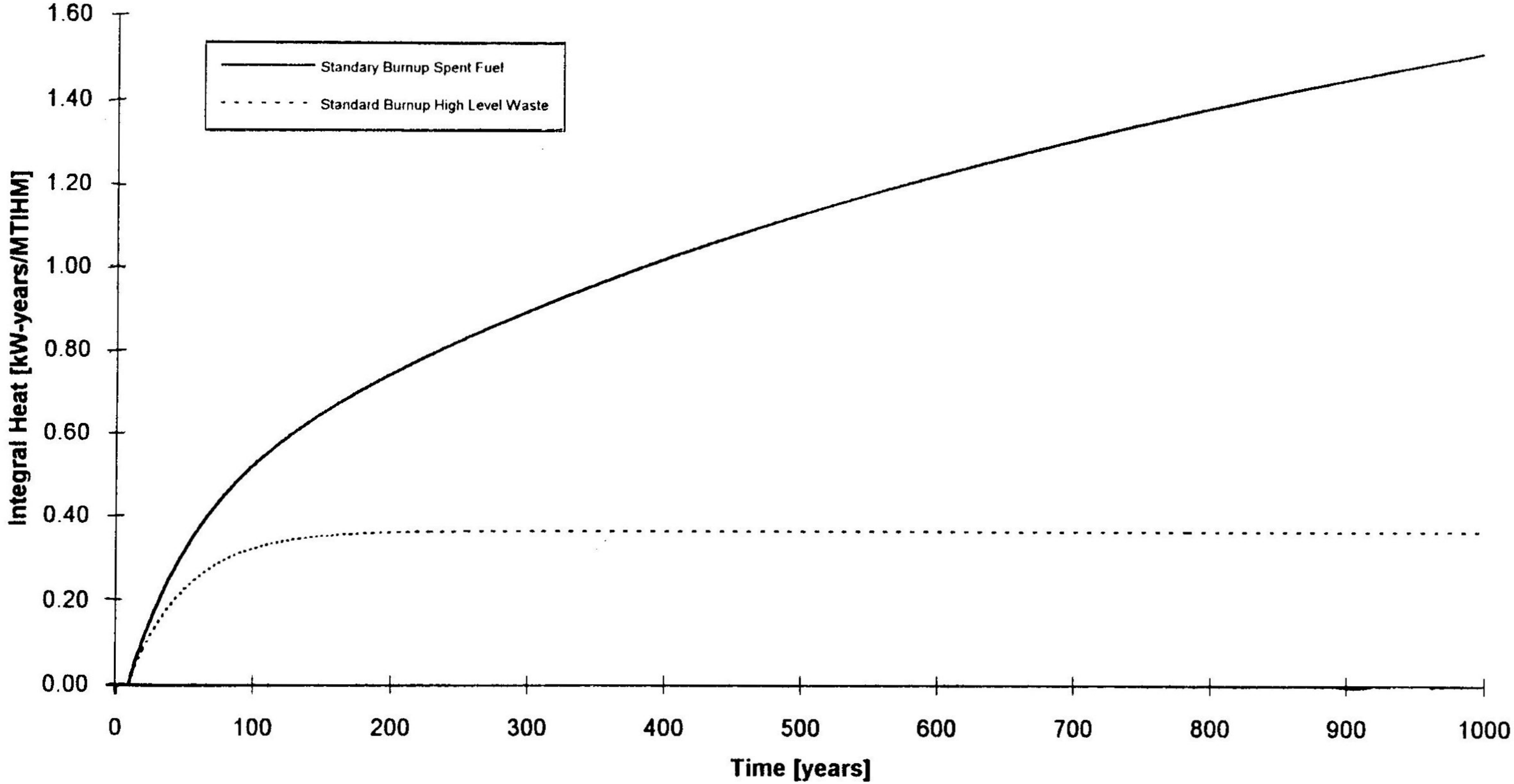

Figure 4: Integral Heat as a Function of Time for SF and HLW

4. Current Work

In order to perform heat transfer calculations for Yucca Mountain, it was necessary to generate the power production in prototypic spent fuel and high level waste. ORIGEN2 [13], developed at the Oak Ridge National Laboratory, is a code designed for this purpose. Among its other capabilities, it allows the user to obtain total mass and power by isotope for a user-specified reactor type and ultimate fuel burnup. These quantities can be obtained as a function of time.

For this exercise, the only important quantity of interest was the power production. Because the spent fuel and high level waste destined for Yucca Mountain vary greatly in initial enrichment and final burnup, a representative fuel had to be chosen. This reference is pressurized water reactor (PWR) fuel, with an initial enrichment of 3.11% and a final burnup of 30 GW-d/MT. This is consistent with the assumptions of other researchers, who have used PWR fuel with burnups ranging from 30-33 GW-d/MT.

ORIGEN2 output is widely used in the waste management field, and most of the calculations of interest for a typical fuel, such as that reference chosen for this work, have already been performed. A good summary of this type of information is available in the Characteristics Data Base [14]. The entire database has been developed under a quality assurance program. One part of the CDB is the LWR Radiological Data Base (RADDB). Along with its attached driver program, it provides information on commercial spent nuclear fuel. Available information includes the total activity in curies, the total power in watts, the total mass in grams, the total neutron production, elemental compositions, integral heat, photon spectra, activity by isotope, power by isotope, and mass by isotope.

These data are available for decay times of 1, 2, 3, 5, 10, 15, 20, 30, 50, 100, 200, 300, 500, 1000, 2000, 5000, 1E4, 2E4, 5E4, 1E5, 2E5, 5E5, and 1E6 years after reactor discharge. These times were chosen to cover the overall period sufficiently such that intermediate times could be determined through interpolation without gross error. A double interpolation routine is used by the database driver program, and it was adopted for this particular application. It should be noted that with the RADDB, and throughout this report, time is measured from reactor discharge, not from emplacement in the repository.

Table 2 gives the information taken from the RADDB and used to generate all the power inputs used in this work. Two burnups, 30 GW-d/MT and 50 GW-d/MT, are shown in the table. The first is considered an average value. The second is an upper limit on the material destined for Yucca Mountain. The higher burnup value was tested to determine the effects of burnup on repository capacity and potential capacity increase. The times in the table are those for which actual ORIGEN2 data are available in RADDB. Intermediate times are calculated internally by the heat generation code developed as part of this work, using the same double exponential interpolation procedure used by RADDB internally. This procedure is explained in Appendix A, which is adapted from Reference 14. The actual FORTRAN files used for heat generation are listed in Appendix B.

If one ignores the presence of the three main drifts, the panel access drifts, and the edge effects at the repository perimeter, one can define a unit cell that represents an average package in the middle of a panel. The smallest unit cell defined by symmetry is composed of one fourth of a waste package, along with the associated surrounding rock.

Table 2: Tabulated Power -vs- Time Data From RADDB

Time [years]	30 GW SF [W/MTIHM]	30 GW HLW [W/MTIHM]	50 GW SF [W/MTIHM]	50 GW HLW [W/MTIHM]
1	8728	8296	12350	11209
2	4536	4316	7018	6333
3	2850	2673	4746	4161
5	1615	1444	2952	2400
10	1028	846.8	1926	1395
15	878.9	690.1	1632	1120
20	788.1	594.2	1453	959.5
30	656.5	457.8	1196	736.0
50	478.5	281.7	857.1	451.7
1E2	262.4	86.8	456.9	138.8
2E2	148.6	8.4	242.3	13.4
3E2	117.9	0.8	181.7	1.3
5E2	87.75	0.04	128.8	0.1
1E3	50.95	0.03	74.69	0.05
2E3	26.92	0.03	40.85	0.04

In all these calculations for the reference SCP-CDR spacing, the unit cell is a slab of tuff, 2.0 meters by 22.9 meters by 653 meters thick [4],[15]. All of these distances are subject to some debate. Due to difficulty in locating the true *reference* values, these do not match the SCP-CDR numbers exactly. The actual reference spacing would yield a unit cell measuring 2.286 meters (7.5') by 19.202 meters (63') by approximately 600 meters.

Of all the distances describing the repository, the thickness is perhaps the one with the greatest uncertainty. It goes without saying that the mountain and its geologic strata are not uniform. Some of the members do not cover the entire mountain, and they all vary in thickness across the mountain. The overburden above the emplacement horizon also varies with location, from a maximum of around 350 meters to a minimum of 200' at the periphery. Maximum values were used for conservatism, although the additional rock is not believed to perturb the system greatly.

The lower bound for the unit cell, set 300 meters below the emplacement horizon, was taken to be the constant temperature water table. The depth of the water table is known to vary across the mountain, and thus this is at best an approximation of reality. As with the mountain surface, the maximum distance was used between the emplacement horizon and the water table for conservatism.

An additional complexity of the geologic description of Yucca Mountain that was not included in these calculations is the dip in the geologic strata. All the strata are sloped eastward approximately 5 to 8 °. The water table, the emplacement strata, and the repository drifts will all be sloped similarly. The sloping in the repository drifts will be used advantageously to encourage drainage of any infiltrated water. None of this complexity was modeled in these thermal analyses.

Croff [4] introduced the High Efficiency Waste Emplacement Concept (HEWEC), which combines actinide removal with a complex emplacement scheme and an extended repository operating life to increase the repository capacity. The concept is described more fully in Reference 4, but is summarized below for convenience.

In an given panel, the emplacement drifts are numbered. The individual boreholes are then numbered. During the first thirty years of repository operation, the odd numbered boreholes in the odd numbered drifts are filled with high level waste resulting from reprocessing of commercial spent fuel. During the second thirty year campaign, the even numbered boreholes in the even numbered drifts are filled. During the third thirty year campaign, the even numbered boreholes in the odd numbered drifts are filled. Finally, during the fourth thirty year campaign, the remaining boreholes are filled. This is shown in Figure 5. By staggering the emplacement of the waste in this manner and by providing drift ventilation throughout the extended operating period, the repository capacity can be increased.

There appear to be several keys to the success of the HEWEC. The first is removal of the long term heat source, the actinides, during reprocessing. This act cuts down the specific power by 13% over spent fuel at ten years out of the reactor. At the end of the third emplacement campaign, ninety years after opening the repository, this original material's power production is down by almost 70% over the equivalent spent fuel. It is this significant reduction in power production that results in increased capacity.

Drift Number	Borehole Number 1	2	3	4	5	6	7	8
1	①	③	①	③	①	③	①	③
2	④	②	④	②	④	②	④	②
3	①	③	①	③	①	③	①	③
4	④	②	④	②	④	②	④	②

Note: The circled numbers represent the emplacement campaign during which particular boreholes will be filled.

Figure 5: HEWEC Emplacement Pattern

Another key to the HEWEC's capacity increase is the assumption that ventilation will be continued throughout the repository's operation. The air used for ventilation will be cooled by evaporative cooling to 10°C [5]. Such a ventilation system has the capacity to remove all the heat generated by the high level waste packages. The only impediment to heat removal is the shield plug and the tuff lying between the drift and the package, five meters below the emplacement drift floor. Therefore, only a fraction of the rock's heat capacity is utilized during the active operation of the repository, and most is available after final closure. In the calculations for HEWEC emplacement, it is assumed that the ventilation system removes all the heat generated in the wastes during the first three emplacement campaigns, during which the ventilation system is operated continuously.

Finally, the HEWEC takes advantage of a more efficient emplacement pattern. The most efficient pattern would be a uniform slab of material throughout the repository horizon. Practically, one is limited by extraction ratios to removal of individual drifts. Therefore, the optimum pattern would be a uniform line source along the drift. Again, this is impossible operationally. The closest thing to such an arrangement is a series of closely spaced drifts, each of which is filled with closely spaced boreholes. The HEWEC calls for adding an additional drift between those called for in the reference design. It also calls for placing the individual boreholes closer together, again by a factor of two. This in fact increases the number of packages in a given area by a factor of four. However, this does not mean an instant increase in capacity by a factor of four, because each package under the HEWEC contains less waste.

In his paper that introduces the HEWEC [4], Croff describes some scaling calculations used to predict the temperatures at the various locations of interest based on other calculations. His assumptions were a drift center-to-center spacing of 15 meters, and a borehole center-to-center spacing of 4.0 meters. Based on results from a number of other researchers, he determined that the repository capacity could be increased by a factor of 4.7 over the reference spent fuel emplacement concept. These results are very encouraging, and justified additional effort to verify them using original heat transfer calculations. Thus, the ultimate goal of this effort was either to confirm or to disprove Croff's preliminary results for the HEWEC.

HEATING7.2b [16] was used for all the thermal calculations performed as part of this work. HEATING7 is a general purpose conduction code written at the ORNL. It is capable of solving multi-dimensional steady state and transient conduction problems with a variety of boundary conditions. All calculations were performed on a cluster of IBM RISC 6000 workstations running XLF FORTRAN.

The differential equation governing the temperature distribution within the Yucca Mountain repository and the surrounding rock as a function of time and position is given by, in the general case:

$$\Delta\big(k(\bar{r},T)\ \Delta T(\bar{r},t)\ \big) + g(\bar{r},t) = \rho(\bar{r},T)\,C_p(\bar{r},T)\,\frac{\partial T(\bar{r},T)}{\partial t}$$

where k is the thermal conductivity, $\bar{r}$ is the position vector, T is the temperature distribution, g is the heat generation, ρ is the density, C_p is the specific heat, and t is time. At the lower (z = 0) boundary that coincides with the water table, a boundary condition of the first kind was specified: T = 32°C. At the upper boundary (the surface of the mountain), a boundary condition of the third kind was specified: h = 1 W/(m^2-°C) and T_∞ = 32°C. At the other four boundaries, an insulated or mirror boundary condition was assumed such that

$$\frac{\partial T}{\partial x_+} = \frac{\partial T}{\partial x_-} = \frac{\partial T}{\partial y_+} = \frac{\partial T}{\partial y_-} = 0$$

The governing equation is nonhomogeneous and nonlinear. A number of simplifying assumptions can be made however. For example, throughout this work, the thermal conductivity, the density, and the specific heat are assumed constant with respect to both position, time, and temperature. The only remaining difficulty in the analytic solution to this problem is the heat generation term, $g(\bar{r},t)$.

For spent nuclear fuel and high level wastes, the proper form of $g(\bar{r},t)$ is a sum of exponentials. The heat generation may be derived from the equations governing the complex decay chains for all the fuel, fission products, and activation products. An analytic form for $g(\bar{r},t)$ is not available. Without an analytic expression for $g(\bar{r},t)$, the governing equation cannot be solved analytically.

At the initiation of this effort, it was anticipated that HEATING7 would be used to solve the governing heat transfer equation. It is readily able to accommodate the user-specified heat generation term. A tabular function for $g(\bar{r},t)$ was developed from ORIGEN2 results documented in the RADDB. This tabular function uses fifteen pairs of time/power data points, and a double exponential interpolation with correction for intermediate values. The actual values used are those that were given in Table 2. A total of six FORTRAN subroutines, one for each of the power input cases (SF and HLW at low burnup, staggered emplacement low burnup, and high burnup), were developed. Each program was tested by comparing some of the interpolated values against interpolated values from the RADDB.

For each case (SF or HLW and spacing), one-dimensional far-field calculations were performed for two different loadings. Peak temperatures at the far-field limit were recorded. Linear interpolation was used to determine the loading at which the far-field limit (115 °C) was reached. This was recorded as the maximum loading for a given case, and a HEATING7 run was performed to verify that the far-field temperature limit was reached but not exceeded and to obtain details about the calculation. Linear interpolation was sufficiently accurate to allow rapid convergence to the maximum loading.

After obtaining the peak loadings for each case based on the far-field limit, a detailed three dimensional calculation was performed to verify that the validity of the one-dimensional model. Because of the separation between the emplacement strata and the far-field temperature limit plane, the problem reduces to one-dimension at the far-field. The far-field temperatures predicted using the one-dimensional and three-dimensional models are plotted together in Figure 6. The two predictions are indistinguishable at the scale shown. Detailed examination of the raw data indicates that the differences are well-within one degree at all times.

The three-dimensional model was also used to verify that the far-field temperature was indeed the limiting value. The reference case, high level waste in a 2.0 by 22.9 meter

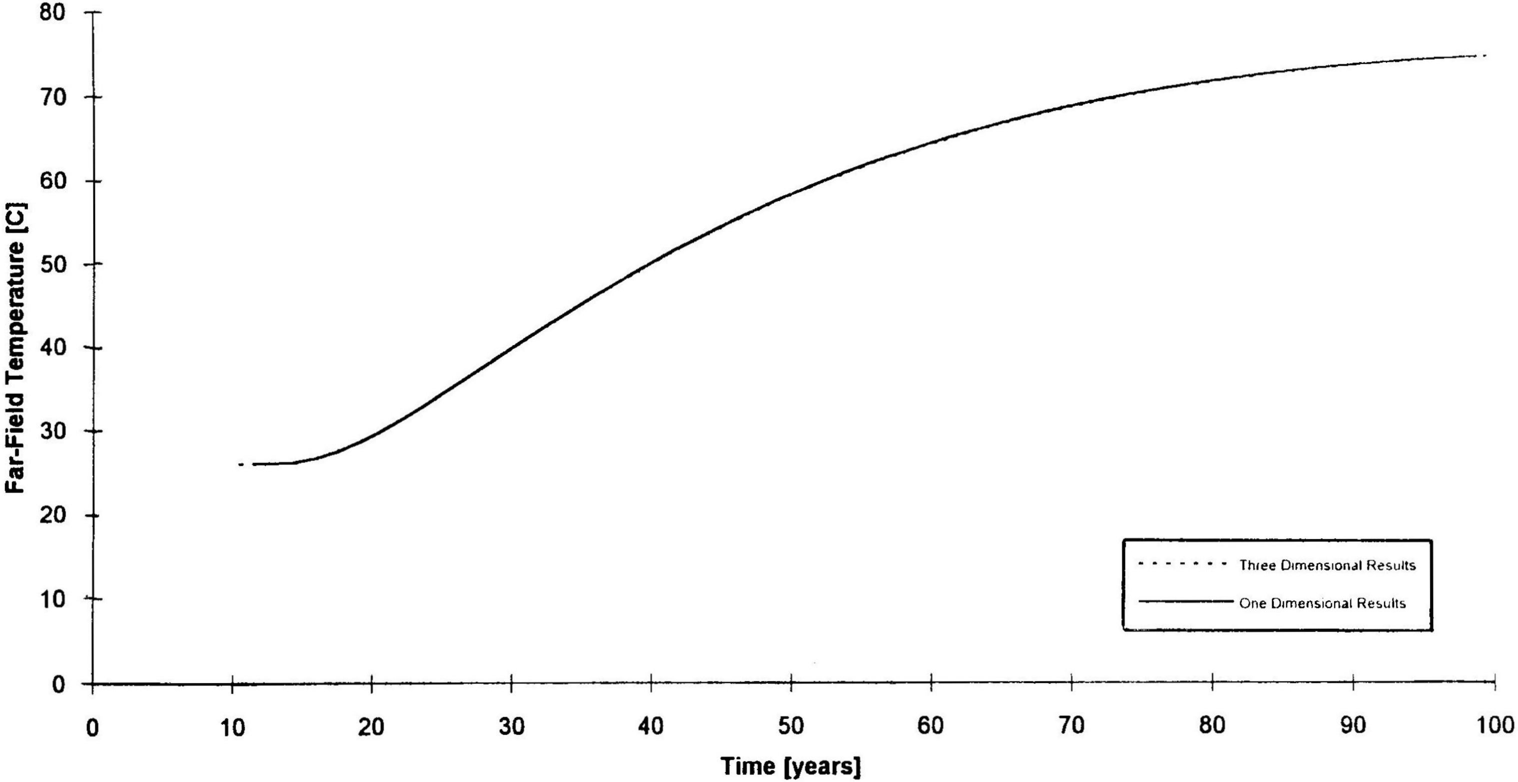

Figure 6: Comparison of One and Three Dimensional Model Results

unit cell, was checked. Surprisingly, the near-field limit was much more conservative for this particular calculation; the near-field temperature limit, rather than the far-field temperature limit, constrains the maximum loading. This indicates that the large increases claimed by some researchers [17] for the multipurpose canister, which are based only on the far-field limit, may be nonconservative. The maximum temperature at the near-field limit (one meter from the borehole wall) was much greater than the 200°C maximum allowable temperature. Therefore, it was determined that detailed three dimensional calculations would be necessary for all the cases to determine which of the two limits, near-field or far-field, would be limiting. The technique for determining the maximum loading based on the near-field limit was similar to that used for the far-field with one exception. The initial value used was the maximum loading determined from the far-field calculations. This minimized the near-field calculations because in those instances in which the far-field is in fact the conservative limit, the near-field calculations were only performed once without iteration. In these cases, the near-field temperature associated with the maximum far-field loading did not exceed the 200°C limiting value. In the other cases, two HEATING7 runs were performed for each. Interpolation was used to determine the maximum value, and a third run was used to verify this result. The input files used for the calculations are given in Appendix C. An example of one of the output files is given in Appendix D.

For most of the cases, the limit to loading results from imposition of the near-field temperature limit, not the far-field as expected. In fact, for all the high level waste cases, and some of the spent fuel cases, the near-field limit is more conservative. For these cases, the far-field calculations were rerun to obtain the far-field temperatures at the far-field point (Calico Hills interface) for the maximum loading.

What was actually determined in all these cases is the maximum density of either spent fuel or high level waste in a single package. This quantity is measured in metric tons of initial heavy metal per cubic meter (MTIHM/m^3). These numbers are not very meaningful directly, however, because they include an embedded unit cell size and power production that must be specified if the results are to be directly compared. More meaningful representations of the results are power at emplacement per unit area, equivalent fuel assemblies per unit area, equivalent PWR cores per unit area, and area required per unit PWR core. An additional problem with the use of mass per unit volume results is the assumed state of the fuel and/or high level waste in the packages. Details about the geometry of the fuel were not considered. It was assumed that for consolidated fuel, the mass loading per package could be adjusted as necessary. While this is true for high level waste, it is not exactly correct for spent fuel because consolidated spent fuel exists as discrete fuel rods. The spent fuel mass that may be loaded into a package using intact rods is therefore not a smooth function, but rather a series of step functions.

The first of these methods is the most common for reporting emplacement density, and it is perhaps the most confusing as well. Emplacement density is typically reported in units of kW/acre. The problem with this unit of measure is the number of assumptions wrapped into it. The reference emplacement density is 57 kW/acre. However, without some knowledge about the material to be emplaced, this number is meaningless. For the reference case, the 57 kW/acre is associated with standard enrichment, commercial pressurized water reactor spent fuel burned to 33 GW-d/MTIHM. Emplacement is also assumed to occur ten years after reactor discharge. Because the specific power (power/MTIHM) changes based on the presence of actinides, the final burnup, the reactor type (pressurized water, boiling water, liquid metal, etc.), and the time since reactor discharge, all these must either be specified when reporting areal densities, or their assumed values must be clear.

The alternative methods of reporting areal density are more meaningful at a glance, and the results are therefore reported using these methods in addition to the conventional power per unit area method. However, one must understand the conversions used in going from one to another. A reference fuel assembly was chosen. Because the reference fuel for this study was PWR spent fuel burned to 30 GW-d/MT, a PWR fuel assembly was used as the reference assembly. Because there is no single reference fuel assembly design, one was chosen from those available. A portion of the Characteristics Data Base, the Fuel Assembly Data Base, was used to obtain values for a reference fuel. Westinghouse 17 x 17 Standard fuel was chosen. It contains 0.4602 MTIHM/assembly. The Westinghouse four-loop PWR design chosen as the reference reactor contains 193 of these 17 x 17 assemblies in its core [18].

5. Results

For the reference emplacement concept (emplace all the waste over a thirty year operating history with each drift sealed after filling), the maximum emplacement loading was determined for the reference spacing (4.0 meter package to package and 45.8 meter drift to drift) and for the maximum density spacing (2.6 meter package to package and 22.9 meter drift to drift). These results are shown in Table 3. Several units are used to report the results. The first, kW/acre, is perhaps the most commonly used and the most commonly misunderstood. One must know the burnup and the age of the material associated with the kW/acre number for it to have meaning. In all these cases, unless otherwise stated, the fuel is ten-year-cooled, standard enrichment PWR fuel burned to 30 GW-d/MTIHM.

The second set of units in which the results are reported, assemblies per acre, attempts to remove the ambiguity associated with the kW/acre unit. Information about

Table 3: Maximum Emplacement Loadings for 30 GW-d/MTIHM SF and HLW in Reference Arrangement

Case	kW/acre	assemblies/acre	cores/acre	acres/core
Ref. HLW, 4.0 m x 45.8 m	57.0	146.3	0.76	1.32
HLW, 2.6 m x 22.9 m	121	310.6	1.61	0.62
HLW, 4.0 m x 45.8 m	82.3	211.3	1.09	0.91
Ref. SF, 4.0 m x 45.8 m	57.0	120.5	0.62	1.60
SF, 2.6 m x 22.9 m	87.0	183.9	0.95	1.05
SF, 4.0 m x 45.8 m	75.3	159.3	0.83	1.21

the age of the fuel, its type, initial enrichment, and final burnup are used to convert from kW to assemblies. As stated above, the fuel is assumed to be standard enrichment PWR fuel that has been burned to 30 GW-d/MTIHM, and has been cooled for ten years. This particular fuel produces 1028 W/MTIHM of decay power, with the actinides contributing 181.2 W/MTIHM of this and fission/activation products producing the rest [14]. Reprocessing was assumed to remove all the actinides and none of the fission products. While separation of this magnitude is impossible, the level of impurity carryover of actinides into the HLW or fission products is not important for these thermal calculations, as carryover of less than one percent is believed to be readily obtainable. Another key assumption is the assembly heavy metal content. The assembly was assumed to be a Westinghouse 17 x 17 Standard fuel assembly that contains 0.4602 MTIHM [14]. In the case of HLW, the assemblies figure is perhaps misleading because of the loss of assembly identity during reprocessing to remove the actinides. However, one may think of this number as the number of SF assemblies that are needed to generate this particular quantity of HLW.

The third set of units listed in the following tables is cores/acre. This unit puts into perspective the low power densities associated with the repository. The conversion factor used was again for a standard Westinghouse four-loop PWR, which has 193 fuel assemblies per core. The final set of units is simply the inverse of the third, acres/core. These final two sets of units were suggested [19] to help put the calculated results into a form that is easily understandable.

The near- and far-field temperatures as a function of time for the above tabulated maximum loadings are given in Figures 7 and 8. It should be repeated that these temperatures are not for equal loadings under different situations, but for the maximum loading in each situation. As one can see from Figure 7 that plots the near-field temperatures, the maximum loading in three of the four scenarios studied is determined by the near-field limit. This is obvious because three of the four reach the 200°C maximum temperature. This is substantiated by the plot of the far-field temperatures, which has only the spent fuel emplaced in a 2.6 m x 22.9 meter unit cell reaching the 115°C maximum far-field temperature. Although it is somewhat unexpected at first glance, the fact that the temperatures for SF emplacement at 2.6 m x 22.9 m are lower than those for SF at 4.0 m x 45.8 m may be easily explained. The closer spacing utilizes an additional drift, allowing a more uniform distribution of waste material. While the average density is higher for the closer spacing, each individual package actually contains less material.

Another interesting feature of the far-field temperature plot is the rapid fall-off of the far-field temperatures after only a couple of hundred years. This is another clear demonstration of the difference in long term decay heat behaviors of spent fuel and high level wastes.

It should be noted that the maximum thermal loading found for spent fuel in the SCP-CDR emplacement scenarios is higher than the reference 57 kW/acre, but this was expected. It is widely recognized that the reference value is highly conservative. The maximum allowable value was found to be 75.3 kW/acre, which is within the range of

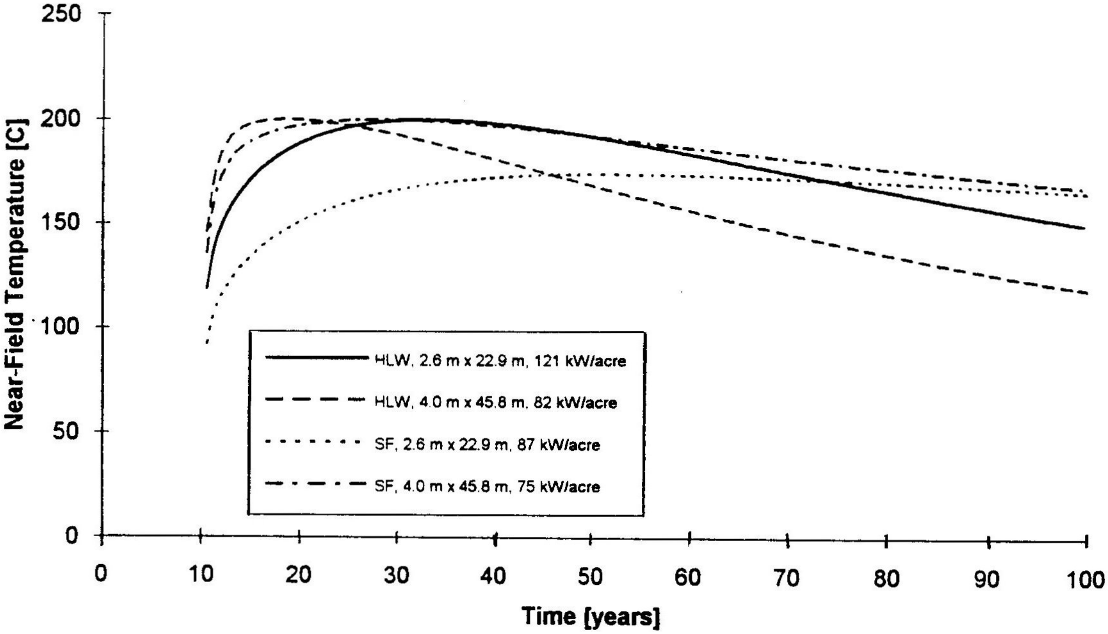

Figure 7: Near-Field Temperature for 30 GW-d/MT SF and HLW

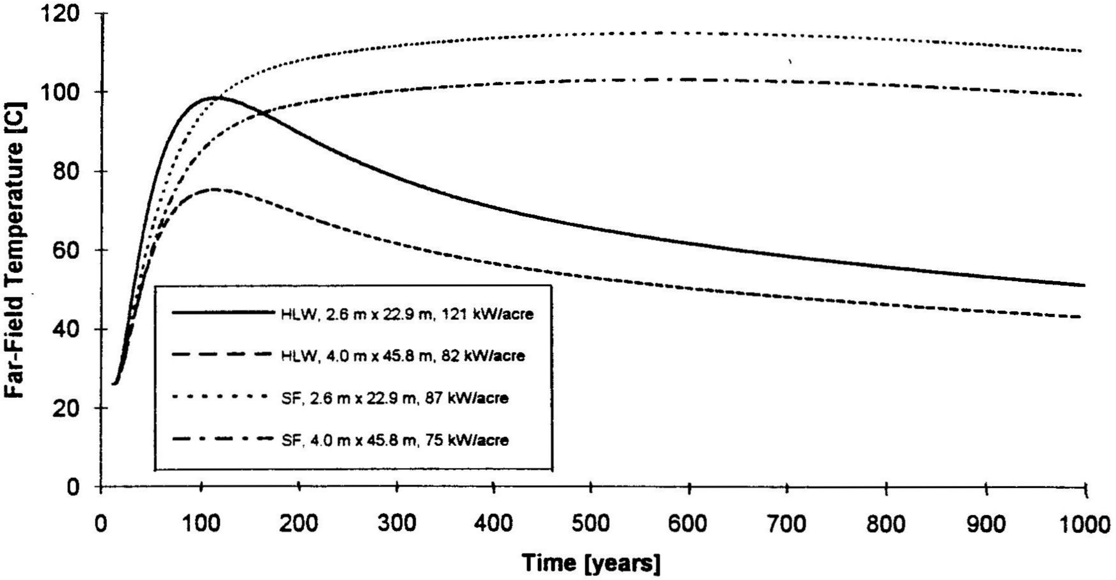

Figure 8: Far-Field Temperatures for 30 GW-d/MT SF and HLW

accepted values. It should be highlighted that this maximum is due to reaching the maximum near-field temperature, not the far-field one as many have suggested. This indicates that results based only on far-field calculations may not be conservative and should be used with caution.

Careful examination of the tabulated results reveals the relative benefits of geometry changes and actinide removal. For the reference emplacement density, actinide removal results in a loading increase equal to the fraction of power due to the actinides, ~ 21%. Comparing the reference pattern to the most efficient pattern for spent fuel indicates a 15% increase due to more efficient geometry. However, by combining the two, one can emplace over 310 equivalent assemblies HLW per acre versus 159 assemblies SF per acre, an increase of 95%.

As utilities stretch their fuel cycles to 18 or 24 months, they increase both the initial enrichment and the final burnup of the fuel. It was believed that the higher burnup fuel would affect the results obtained for standard burnup (30 GW-d/MTIHM) fuel. A set of calculations was therefore performed for high burnup spent fuel and high level waste. The specific burnup chosen is 50 GW-d/MT, which is believed to be obtainable, but near the high end of what can be expected out of current technology fuel. All other variables were maintained constant from the original calculations. The results are shown in Table 4, with the reference 30 GW-d/MTIHM SF and HLW values from the SCP-CDR included for the reader's convenience.

Table 4: Maximum Emplacement Loadings for 50 GW-d/MTIHM SF and HLW in Reference Arrangement

Case	kW/acre	assemblies/acre	cores/acre	acres/core
Ref. HLW (30 GW-d/MT) 4.0 m x 45.8 m	57.0	146.3	0.76	1.32
HLW, 2.6 m x 22.9 m	123.6	192.5	1.00	1.00
HLW, 4.0 m x 45.8 m	83.7	130.3	0.68	1.48
Ref. SF (30 GW-d/MT) 4.0 m x 45.8 m	57.0	120.5	0.62	1.60
SF, 2.6 m x 22.9 m	98.0	110.6	0.57	1.75
SF, 4.0 m x 45.8 m	76.7	86.5	0.45	2.23

One thing that is immediately obvious from these tabulated results is that one cannot emplace as many of the high burnup assemblies per acre as the low burnup assemblies. This should not be surprising because the specific power (power/unit mass fuel) increases with burnup. However, the overall qualitative results are the same. The near- and far-field temperatures are plotted in Figures 9 and 10, respectively. As with the temperature plots shown in Figures 7 and 8, the temperatures plotted are for the maximum loading in each case. The plots are not for equal loadings. The results are not substantially different from those for low burnup materials. Only the SF in the 2.6 m x 22.9 m unit cell is limited by the far-field temperature limit, as evidenced by the lower near-field temperatures plotted in Figure 9. Also, the fall off in near-field temperatures with the HLW cases is evident. These high burnup results are significant because they demonstrate the relative insensitivity of these results to burnup.

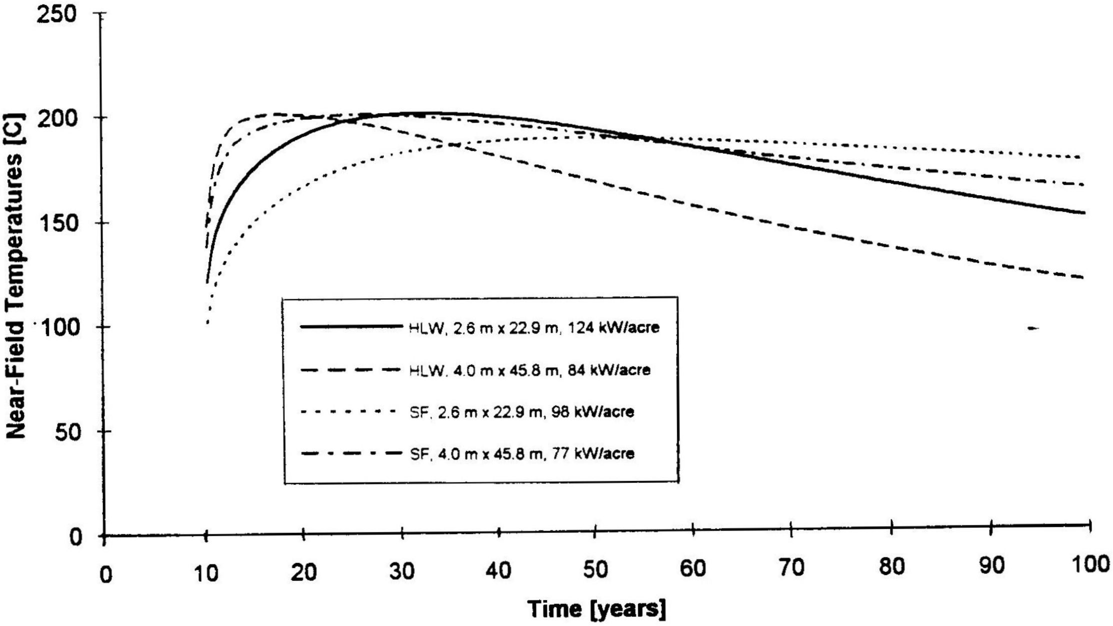

Figure 9: Near-Field Temperatures for 50 GW-d/MT SF and HLW

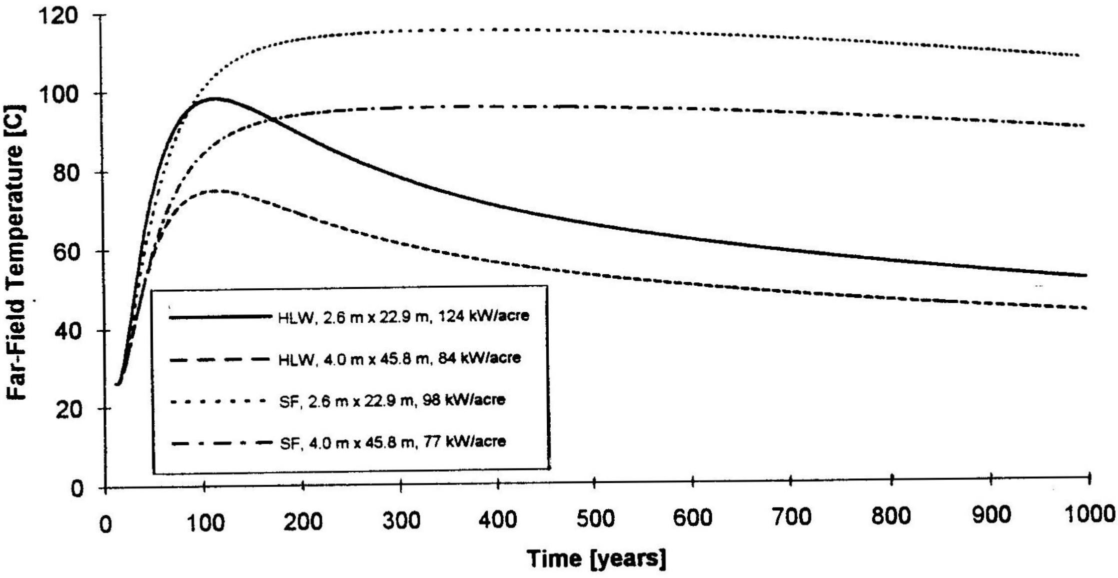

Figure 10: Far-Field Temperatures for 50 GW-d/MT SF and HLW

The most significant calculations performed combined those capacity-increasing techniques discussed above with the modified repository operating strategy proposed by Croff. These results are basically those for the HEWEC. Dramatic increases in the emplacement density are possible with this concept. The maximum loadings for SF and HLW in both the reference and maximum density geometries are listed in Table 5.

The corresponding near-field and far-field temperatures associated with the maximum loadings are plotted in Figures 11 and 12 respectively. Only SF emplacement in the maximum density geometry is restricted by the far-field temperature limit, although SF emplacement in the SCP-CDR geometry nearly reaches the 115°C maximum temperature. The difference between the performances with SF and HLW is more clearly shown in Figure 12 than in any of the previous figures because of the extended timescale.

Table 5: Maximum Emplacement Loadings for 30 GW-d/MTIHM SF and HLW in Staggered Arrangement (HEWEC)

Case	kW/acre	assemblies/acre	cores/acre	acres/core
Ref. HLW 4.0 m x 45.8 m Not HEWEC	57.0	146.3	0.76	1.32
HLW, 2.6 m x 22.9 m	230.0	590.2	3.06	0.33
HLW, 4.0 m x 45.8 m	122.7	314.9	1.63	0.61
Ref. SF 4.0 m x 45.8 m Not HEWEC	57.0	120.5	0.62	1.60
SF, 2.6 m x 22.9 m	105.0	222.0	1.15	0.87
SF, 4.0 m x 45.8 m	103.5	218.7	1.13	0.88

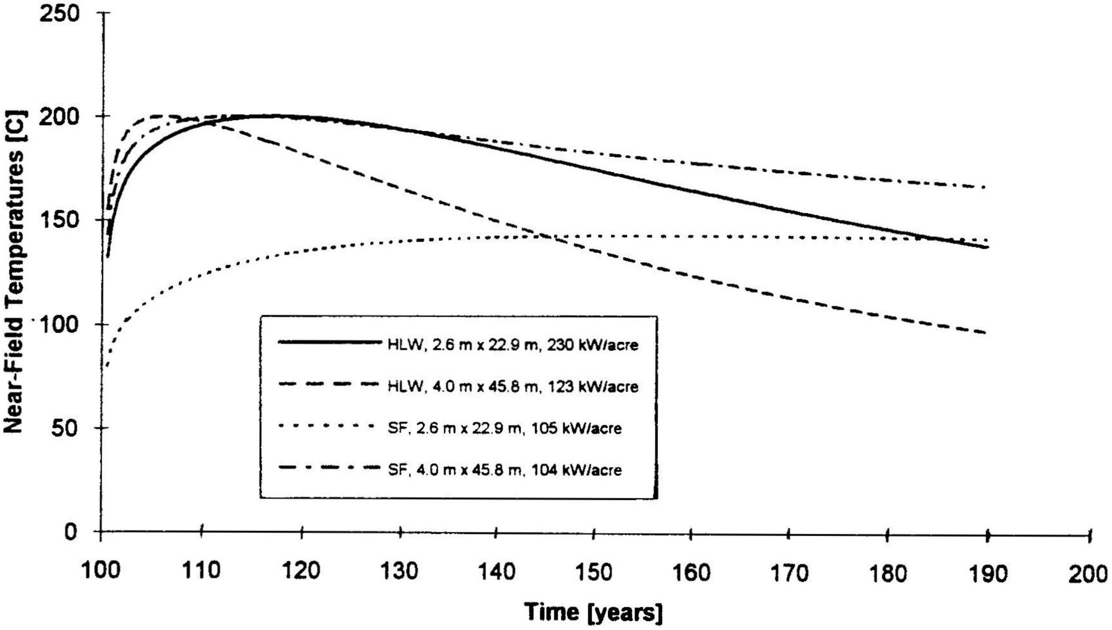

Figure 11: Near-Field Temperatures for HEWEC Emplacement

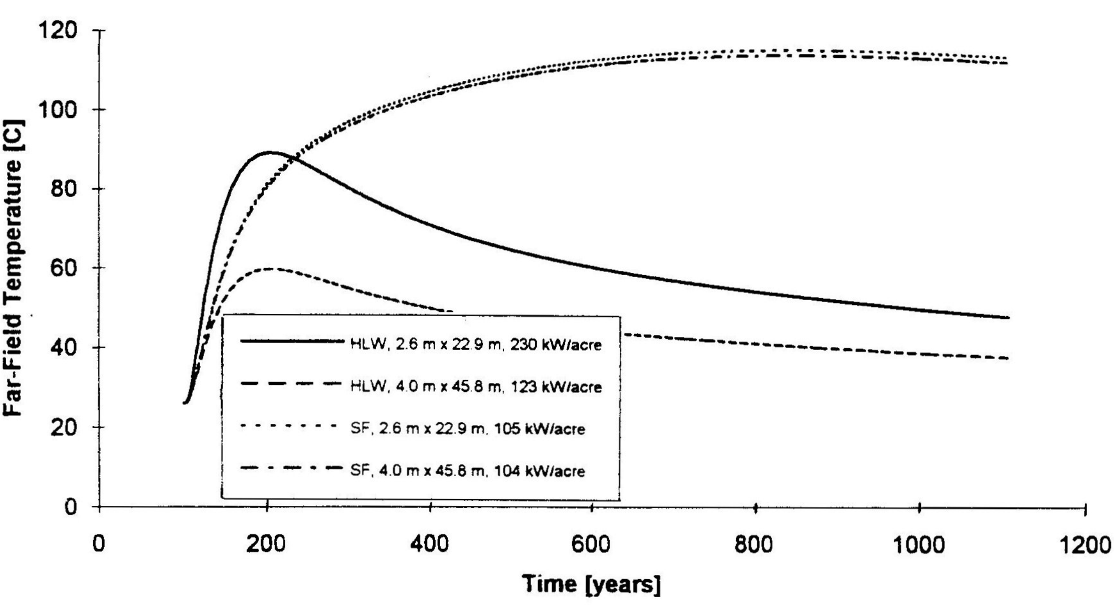

Figure 12: Far-Field Temperatures for HEWEC Emplacement

Two of the results listed in Table 5 are especially important. The first is the dramatic increase that is possible with HEWEC. The staggered emplacement of HLW in a dense emplacement geometry over an extended operating period results in a maximum emplacement density of 230 kW/acre, or the equivalent of 590 assemblies per acre. This is greater than a factor of four higher than the reference SF density of 120 assemblies per acre. This result confirms Croff's assertions that HEWEC could result in capacity increases of greater than a factor of four.

There are a number of shortcomings with the models and assumptions used in this work. One of these is the approximated geometry. The assumed distances are rough approximations to the actual (but unknown) values. They do, however, fall within the range of values used by other researchers. The effects of the use of this approximate geometry are unknown, but they are not believed to affect the results qualitatively.

Another deficiency with the models utilized is the lack of convection modeling. Some projections of the perturbed hydraulic behavior of Yucca Mountain suggest that this may be an important omission. Although the emplacement horizon and most of the thermal effects are located well above the water table in the unsaturated zone, the ambient moisture content of the tuff is high. The introduction of a large planar heat source may vaporize the ambient moisture. Due to the induced hydraulic pressure gradients, this water will rise until it reaches a sufficiently cool region that condensation may occur. The net result may be a drastic increase in the heat removal from the emplacement horizon. This phenomenon would be limited only to the initial heat up phase unless some method of water replenishment exists (such as fracture flow). These effects have not been determined because the chosen heat transfer code, HEATING7, does not include the capability of modeling convection. A more complex thermal hydraulics code would be required to quantify these effects.

A related convection effect has to do with drift ventilation, and only affects the staggered emplacement concepts. Under Croff's HEWEC methodology, the emplacement drifts are maintained open during an extended operating period. Calculations performed using the reference flow rates and air temperatures from the SCP-CDR indicate that ventilation can remove all the power generated by emplaced materials. Although some of the heat would conduct into the rock, it was assumed for the calculations reported in this paper that all the heat was removed by the ventilation system while it was in operation. The fourth emplacement campaign was assumed to occur instantaneously and to coincide with drift backfilling. The heat produced during the first ninety years of operation (the first three emplacement campaigns) was assumed to be lost to the ventilation system. This assumption greatly simplified the required models, and should not have introduced appreciable error.

One other modeling deficiency that is worth mentioning is the lack of specific modeling of the drifts. The mains, perimeter, panel access, and midpanel drifts were all ignored in the definition of the unit cell. In addition, because the reference emplacement pattern calls for backfilling of the emplacement drifts at the end of the retrievability period, they were modeled as intact tuff. Again, this is not believed to have affected the results materially. The information required to model the drift in detail is not available.

6. Cold Repository Concept

The current philosophy of the OCRWM is to design and construct a hot repository in which the heat production in the waste material is used in a supposedly helpful manner. The simplest description of this philosophy is that the heat will be used to vaporize any water surrounding the waste packages. The heat will drive the resulting vapor away from the packages, drying out the rock. The goal, which is often considered one of the thermal limits for the repository, is to maintain the repository horizon at a temperature above the boiling point of water (97°C at the emplacement horizon) for at least 300 years after emplacement. It should be noted that none of the high level waste scenarios discussed above is capable of maintaining the desired temperature. After making this discovery, it was decided to investigate an interesting possibility - a cold repository.

The advantages of a cold repository have been recognized for some time. One of the primary advantages is reduced impact on the surrounding hydrogeologic conditions in the mountain. This reduced impact in turn is believed to result in simpler characterization and licensing. For the hot repository, most of the characterization work has been conducted on the mountain as it currently exists. The hydrogeologic impact of the repository will be significant, and will change the conditions from those currently existing. No consensus about exactly what the perturbed system will look like has developed. Without a characterization of the perturbed system, it is impossible to predict the behavior of the perturbed system. This prediction is what is needed for licensing. An easy solution to this predicament is provided by the cold repository concept. Extrapolations from the unperturbed system for the limited perturbations of the cold repository are much more credible than those for the gross perturbations accompanying the hot repository.

The results for the emplacement of standard burnup (30 GW-d/MTIHM) material in a standard emplacement campaign are given in Table 6 below. The reference values for SF and HLW emplaced in the SCP-CDR arrangement (57 kW/acre) are included in the table for convenience. It should be noted that these results, even for the high density emplacement pattern (2.6 m package spacing and 22.9 m drift spacing), are not as good as the reference emplacement areal loading of 57 kW/acre. However, the high density emplacement of high level waste approaches the reference loading of 57 kW/acre, at almost 52 kW/acre. These results are consistent with the generally accepted belief that a cold repository cannot use the available area with sufficient efficiency to be a viable concept.

Table 6: Maximum Emplacement Loadings for 30 GW-d/MTIHM SF and HLW in Cold Repository Arrangement

Case	kW/acre	assemblies/acre	cores/acre	acres/core
Ref. HLW 4.0 m x 45.8 m Hot Repository	57.0	146.3	0.76	1.32
HLW, 2.6 m x 22.9 m	51.9	133.2	0.69	1.45
HLW, 4.0 m x 45.8 m	35.3	90.6	0.47	2.13
Ref. SF 4.0 m x 45.8 m Hot Repository	57.0	120.5	0.62	1.60
SF, 2.6 m x 22.9 m	43.8	92.7	0.48	2.08
SF, 4.0 m x 45.8 m	32.3	68.3	0.35	2.82

Only the near-field temperatures were monitored during these cold repository calculations because if the near-field is limited to a maximum temperature of 100°C, the far-field can never reach its maximum temperature of 115°C. The near-field temperatures are plotted as a function of time in Figure 13. The resulting curves do not differ greatly from those determined for the hot repository, with only the scales differing.

Using Croff's HEWEC methodology [4] of ventilated aging during an extended operating period, it was believed that a cold repository design could be developed that would result in more reasonable (higher) emplacement densities than those calculated for unventilated scenarios. The problem with a cold repository for emplacement of spent fuel is that the allowable emplacement density is drastically reduced, either increasing the required emplacement area or decreasing the ultimate repository capacity. By removing the long term decay heat source (the actinides) and by providing for extended cooling while the repository remains open and ventilated, it was believed that the emplacement density could be maintained at near the SCP-CDR levels without exceeding the boiling point of water. The calculational results bear this out, as shown in Table 7 and Figure 14.

As expected, the temperatures for the HLW cases drop much faster than those for the SF cases. The curves are different from those plotted in Figure 13 previously only in the timescale. These results for a cold repository are promising. Using Croff's methodology, a higher emplacement density than the reference 57 kW/acre can be obtained while still meeting all the thermal goals including the more stringent no-boiling criterion. While the 98.7 kW/acre areal loading may not appear to be that significant of an impact, the number of assemblies emplaced per acre is increased by more than 70%

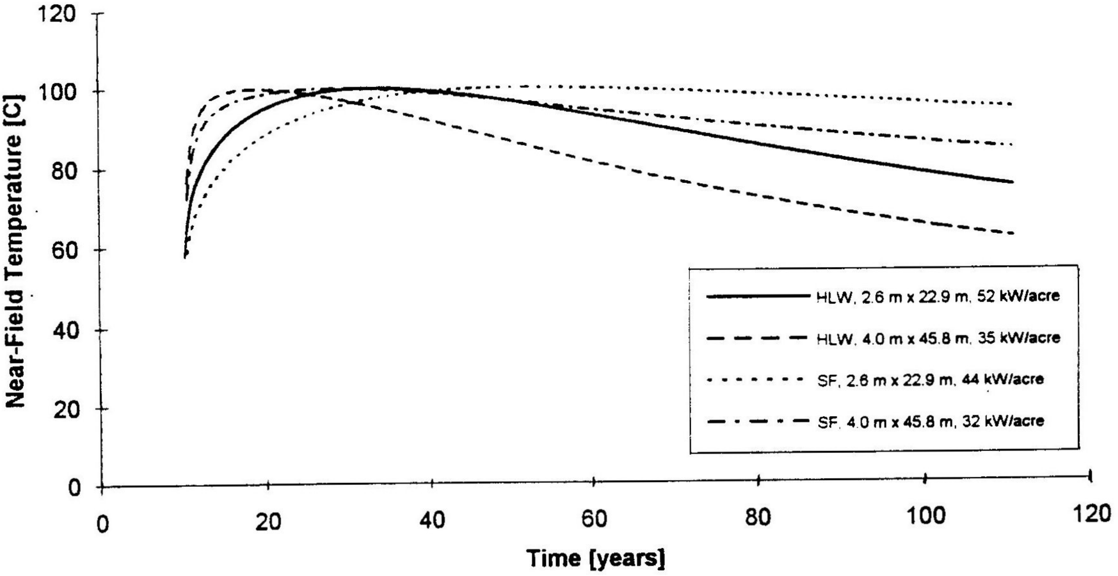

Figure 13: Near-Field Temperatures for Reference Cold Repository

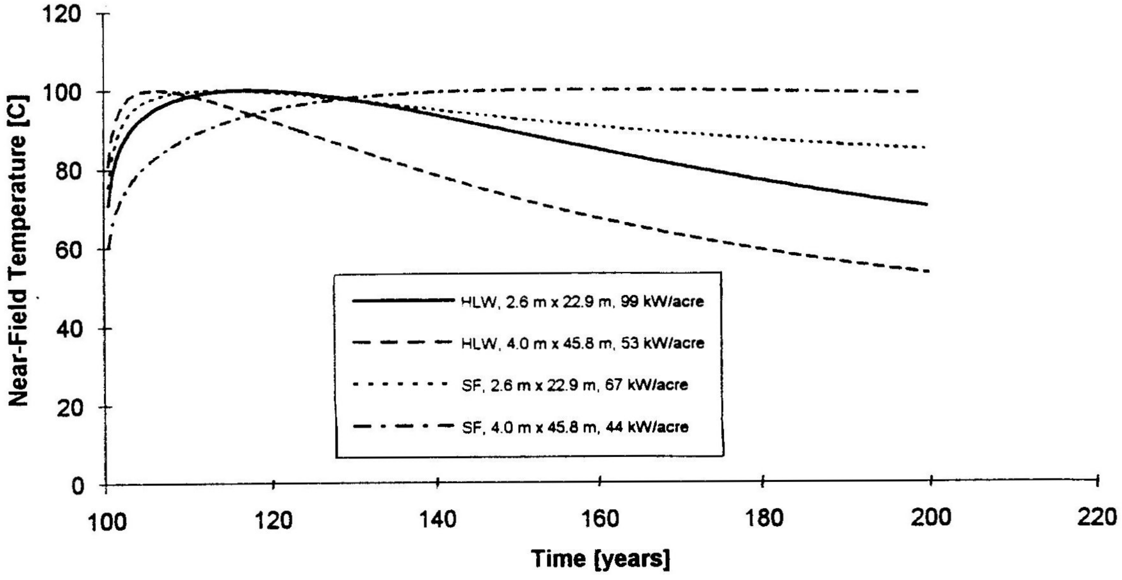

Figure 14: Near-Field Temperatures for HEWEC Cold Repository

Table 7: Maximum Emplacement Loadings for 30 GW-d/MTIHM SF and HLW in Staggered, Cold Repository Arrangement

Case	kW/acre	assemblies/acre	cores/acre	acres/core
Ref. HLW 4.0 m x 45.8 m Hot Repository Not HEWEC	57.0	146.3	0.76	1.32
HLW, 2.6 m x 22.9 m	98.7	253.3	1.31	0.76
HLW, 4.0 m x 45.8 m	52.6	135.1	0.70	1.43
Ref. SF 4.0 m x 45.8 m Hot Repository Not HEWEC	57.0	120.5	0.62	1.60
SF, 2.6 m x 22.9 m	66.9	141.5	0.73	1.36
SF, 4.0 m x 45.8 m	44.4	93.8	0.49	2.06

over the reference loading through this method. Critics will focus on the fact that all the additional effort associated with actinide removal and with extending the operating period results in a capacity increase of less than a factor of two. However, when combined with the licensing advantages, this cold design may be the best option available. Furthermore, if one is unwilling to accept actinide partitioning, one can nevertheless increase the repository capacity by using the HEWEC strategy for SF in a cold repository regime. Simply by changing the emplacement pattern and providing ventilation during an extended operating period, the allowable emplacement density may be increased from 121 intact fuel assemblies per acre to 145 intact assemblies per acre. These results definitely justify the expenditure of additional resources, not only for review of these results but also for more detailed calculations that can reduce the uncertainties.

7. Conclusions

As statutorily required, the Department of Energy in the form of the Office of Civilian Radioactive Waste Management is preparing geologic disposal capability for spent nuclear fuels and high level radioactive wastes. Yucca Mountain, Nevada, is under investigation as a host site for this repository. An upper capacity limit of 70,000 metric tons initial heavy metal, or its thermal equivalent, has been set by statute [2] for Yucca Mountain. In addition, certain physical restrictions impose another capacity limit.

While the OCRWM has ignored all materials other than civilian spent fuel and certain DOE high level wastes, many other materials have been identified by their owners/caretakers as potentially reporting to Yucca Mountain. A summary of these materials has been prepared. According to this list, the amount of material to be emplaced exceeds the actual physical area by up to a factor of two. Due to the high political, social, and financial costs of siting a repository, great incentive exists to expand the capacity of Yucca Mountain, and either postpone or eliminate the need for a second repository.

Croff, a highly respected researcher at the Oak Ridge National Laboratory, has proposed a technique for increasing the repository capacity that combines actinide removal, more efficient emplacement geometry, and active cooling throughout an extended operating period. According to his preliminary calculations, this High Efficiency Waste Emplacement Concept can increase the capacity by a factor of four over the reference scenario. The work reported in the present paper was meant to confirm Croff's preliminary results using more detailed thermal calculations.

One and three dimensional models were developed and tested to confirm that their results were consistent with accepted values. Calculations were performed for spent fuel and high level waste in two geometries: the reference geometry and the most efficient geometry. Calculations were performed for standard (30 GW-d/MT) and high (50 GW-d/MT) burnup materials. Three important results were obtained.

First, through use of the most efficient geometry and HEWEC emplacement methodology, 2.7 times as many spent fuel assemblies can be emplaced in the repository compared to the reference loading. This is without any reprocessing, and is a result of the ventilation cooling throughout an extended operating period, combined with optimized geometry. While emplacement of spent fuel containing actinides at such a high density compounds the criticality concerns, the associated capacity increase is sufficient to accommodate all the identified materials.

The second important result is a confirmation of Croff's preliminary results for the capacity increase obtainable through application of the HEWEC methodology. The detailed thermal calculations performed indicate that the capacity may be increased by greater than a factor of four. The actual value determined was slightly higher than that predicted by Croff. This indicates a potential to postpone the second repository for many years. Implementation of the HEWEC methodology also eliminates the criticality concerns for the repository because actinide removal is an integral part of the concept.

The third important result is for a cold repository. A cold repository is one in which the emplacement horizon does not exceed the boiling point of water. If boiling does not occur, the perturbance of the thermal-hydraulic conditions in Yucca Mountain will be minimal. The primary disadvantage with a cold repository is that the allowable emplacement density is very low, thus lowering the repository capacity. The calculations performed for HEWEC indicate that high level wastes can be emplaced at a higher density than the reference 57 kW/acre. In fact, 1.7 times as many fuel assemblies can be emplaced while maintaining a cold repository. With some additional cooling, it may be possible to emplace all the identified materials, after actinide removal, in Yucca Mountain while maintaining the maximum temperature below the boiling point.

Although the thermal calculations are known to have some limitations, the results are not expected to change qualitatively as a result of modeling improvements. These results are sufficiently important to justify additional investigations using more powerful models. The benefits - social, political, and financial - associated with an indefinite postponement of the second repository cannot be overstated.

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Appendices

Appendix A: Interpolation Functions

Appendix A: Interpolation Functions

This Appendix is adapted from Appendix 1C of Volume 1 of *Characteristics of Potential Repository Wastes, DOE/RW-0184-R1*. It describes the interpolation routines used by ORIGEN2 and the LWR Radiological Data Base.

A-1 Purpose

The LWR Radiological Data Base provides calculated radiological characteristics for spent fuel, including activity (curies/MTIHM), thermal output (watts/MTIHM), neutron activity (neutrons/sec/MTIHM), photon spectra (photons/sec/MTIHM in 18 energy groups), and integral heats (watt-years/MTIHM). The basic radiological data used in the Data Base were calculated by means of the ORIGEN2 code for 36 basic combinations of burnup and initial enrichment, each with 24 decay times. These 36 basic combinations and 24 decay times are listed in Table A-1. The Data Base permits the user to retrieve directly the calculated radiological characteristics for these basic combinations of burnup, initial enrichment, and decay time. In addition, interpolation routines are incorporated that permit the user to request radiological characteristics for other desired combinations of burnup, enrichment, and decay time, within the range of the basic combinations. This appendix describes the mathematical procedures used by the interpolation routines.

Table A-1: Basic Combinations of Burnup, Initial Enrichment, and Cooling Time Used in LWR Radiological Data Base

Burnup (GW-d/MTIHM)		Initial Enrichment, %		
		Low	Medium	High
BWRs	7.5	0.72	1.05	1.75
	15.0	1.09	1.79	2.49
	22.5	1.72	2.42	3.12
	30.0	2.23	2.93	3.63
	40.0	2.74	3.44	4.14
	50.0	3.04	3.74	4.44
PWRs	10	0.99	1.69	2.39
	20	1.74	2.44	3.14
	30	2.41	3.11	3.81
	40	3.02	3.72	4.42
	50	3.56	4.26	4.96
	60	4.03	4.73	5.43
Cooling Times (years)	0	15	300	20,000
	1	20	500	50,000
	2	30	1000	100,000
	3	50	2000	200,000
	5	100	5000	500,000
	10	200	10,000	1,000,000

A-2 Interpolation of Decay Time

Where interpolation is needed to estimate radiological characteristics at non-standard decay times, the method of double exponential interpolation with correction is used. This method is an extension of single exponential interpolation. Single exponential decay assumes that a radiological characteristic, i.e. decay power P, decays exponentially with a decay constant λ. If a characteristic has known values P_0 and P_1 at times t_0 and t_1 respectively, the equation for determining its value P at an intermediate time t is:

$$P = P_0 \, e^{\lambda(t-t_0)}$$

The value of λ is determined from the two known end-points of the interval, (P_0, t_0) and (P_1, t_1):

$$\lambda = \frac{-\ln(P_1/P_0)}{t_0 - t_1}$$

The method of double exponential decay assumes that the characteristic can be represented as the sum of two expressions representing a long-lived exponential decay and a short-lived exponential decay. Figure A-1 shows the procedure schematically. Four data points are needed, represented by t_1, t_2, t_3, and t_4 in ascending order of time. The desired time point, t, lies between t_2 and t_3. The long-lived decay constant is chosen so that it exactly represents the decay between t_3 and t_4. The contributions of the long-lived exponent at t_1 and t_2 are calculated and subtracted from the values of the

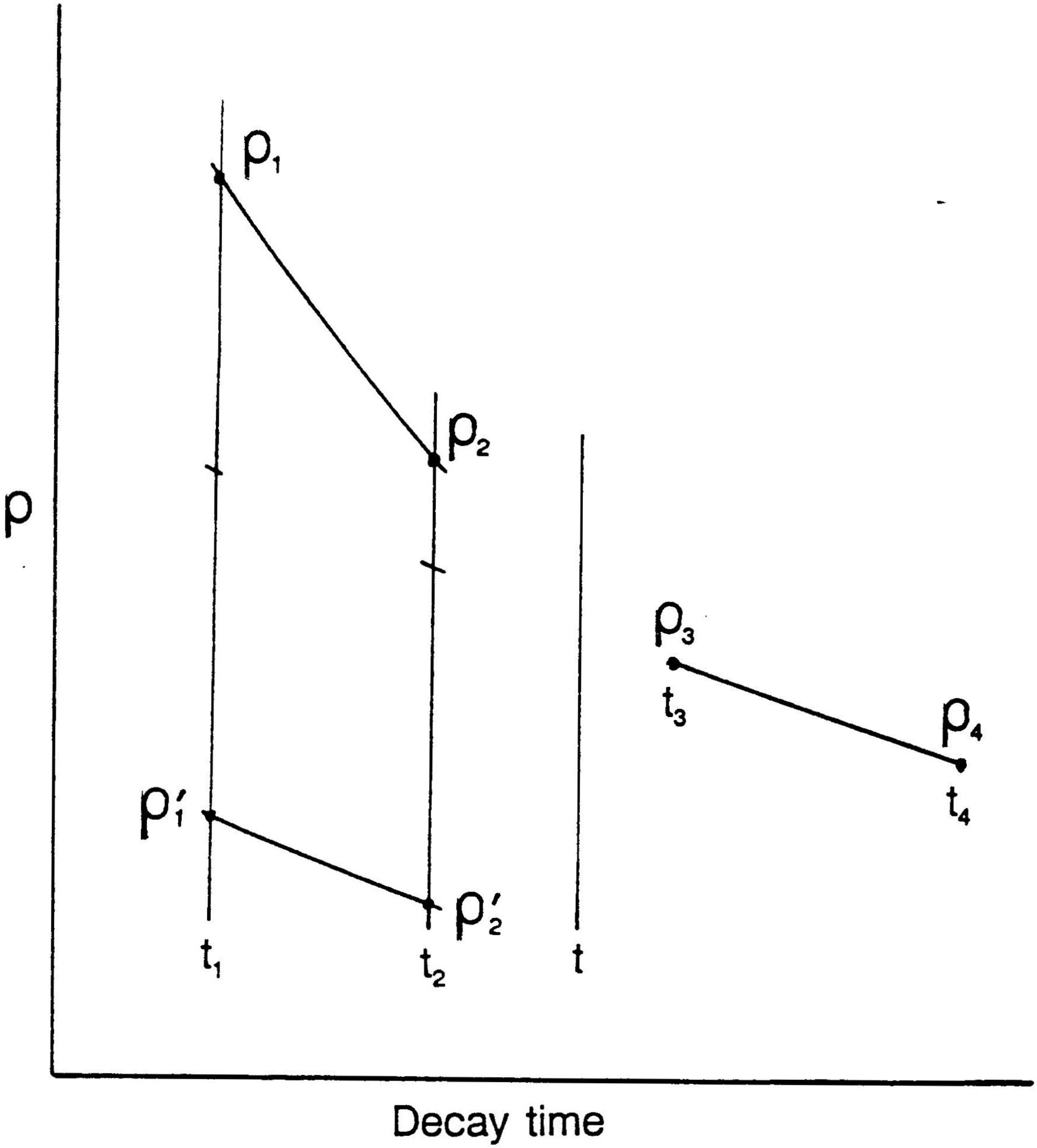

Figure A-1: Schematic of Double Exponential Decay With Correction characteristic at those points, P_1 and P_2. This gives adjusted values P_1' and P_2'. The short-lived decay constant is chosen so that it exactly represents the decay between these two adjusted points. Characteristics between t_3 and t_4 are calculated by adding the values obtained from short-lived and long-lived equations:

$$P = P_2' \, e^{S(t-t_2)} + P_3 \, e^{L(t-t_3)}$$

where:

$$S = \frac{\ln(P_1'/P_2')}{t_1 - t_2}$$

$$L = \frac{\ln(P_4/P_3)}{t_4 - t_3}$$

$$P_2' = P_2 - P_3 e^{L(t_2 - t_3)}$$

$$P_1' = P_1 - P_3 e^{L(t_1 - t_3)}$$

Because the long-lived exponential decay constant L was chosen to represent the point P_4 exactly, the above described formulation overestimates the value of P. A correction factor is subtracted to make P have the values P_2 and P_3 at times t_2 and t_3 respectively. The correction factor is given by:

$$correction = P_2' e^{S(t_3 - t_2)} \left(\frac{t - t_2}{t_3 - t_2} \right)$$

and the final expression for P is therefore:

$$P = P_2' e^{S(t - t_2)} + P_3' e^{L(t - t_3)} - P_2' e^{S(t_3 - t_2)} \left(\frac{t - t_2}{t_3 - t_2} \right)$$

Appendix B: Heat Generation FORTRAN Files

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HEAT GENERATION FOR 30 GW-d/MT SF

```
       subroutine heatgn(rvalue,r,th,z,tim,tsn,value,number,n,arg,val,
      c ntbprs,ntab,hival,loval)
       double precision rvalue,r,th,z,tim,tsn,value,l,c1,c2,s
       double precision arg(1),val(1),p(20),t(20)
       integer ntbprs(1),ntab(1)
       logical loval(1),hival(1)
       data t/1.0,2.0,3.0,5.0,10.0,15.0,20.0,30.0,50.0,100.0,200.0,
      c     300.0,500.0,1.0e3,2.0e3,5.0e3,1.0e4,2.0e4,5.0e4,1.0e5/
       data p/8728.,4536.,2850.,1615.,1028.,878.9,788.1,656.5,478.5,
      c     262.4,148.6,117.9,87.75,50.95,26.92,17.39,12.72,7.631,
      2     2.805,1.018/
       tim=tim/(365.25*24.*3600.)
       if(n.eq.0) then
         if(tim.lt.t(2))then
           rvalue=p(1)
           write(6,*)'time =  ',tim,'is too small'
           return
         else if(tim.gt.t(19))then
           rvalue=p(20)
           write(6,*)'time =  ',tim,'is too large'
           return
         else
           do I=2,19
             if(tim.ge.t(i).and.tim.lt.t(i+1))then
               l=log(p(i+2)/p(i+1))/(t(i+2)-t(i+1))
               c1=p(i-1)-p(i+1)*exp(l*(t(i-1)-t(i+1)))
               c2=p(i)-p(i+1)*exp(l*(t(i)-t(i+1)))
               s=log(c1/c2)/(t(i-1)-t(i))
               rvalue=c2*exp(s*(tim-t(i)))+p(i+1)*exp(l*
      c             (tim-t(i+1)))-c2*exp(s*(t(i+1)-t(i)))*
      2             (tim-t(i))/(t(i+1)-t(i))
               return
             end if
           end do
         end if
       end if
       write(6,*)'Problem in HEATGN.f'
       rvalue=0.0
       return
```

```
      end
```

HEAT GENERATION FOR 30 GW-d/MT HLW

```
      subroutine heatgn(rvalue,r,th,z,tim,tsn,value,number,n,arg,val,
     c ntbprs,ntab,hival,loval)
      double precision rvalue,r,th,z,tim,tsn,value,l,c1,c2,s
      double precision arg(1),val(1),p(20),t(20)
      integer ntbprs(1),ntab(1)
      logical loval(1),hival(1)
      data t/1.0,2.0,3.0,5.0,10.0,15.0,20.0,30.0,50.0,100.0,200.0,
     c      300.0,500.0,1.0e3,2.0e3,5.0e3,1.0e4,2.0e4,5.0e4,1.0e5/
      data p/8295.8,4316.3,2673.,1444.2,846.8,690.1,594.2,457.8,
     2      281.7,86.8,8.4,0.8,0.04,0.03,0.03,0.03,0.02,0.02,
     3      0.016,0.011/
      tim=tim/(365.25*24.*3600.)
      if(n.eq.0) then
         if(tim.lt.t(2))then
            rvalue=p(1)
            write(6,*)'time =  ',tim,'is too small'
            return
         else if(tim.gt.t(19))then
            rvalue=p(20)
            write(6,*)'time =  ',tim,'is too large'
            return
         else
            do i=2,19
               if(tim.ge.t(i).and.tim.lt.t(i+1))then
                  l=log(p(i+2)/p(i+1))/(t(i+2)-t(i+1))
                  c1=p(i-1)-p(i+1)*exp(l*(t(i-1)-t(i+1)))
                  c2=p(i)-p(i+1)*exp(l*(t(i)-t(i+1)))
                  s=log(c1/c2)/(t(i-1)-t(i))
                  rvalue=c2*exp(s*(tim-t(i)))+p(i+1)*exp(l*
     c                (tim-t(i+1)))-c2*exp(s*(t(i+1)-t(i)))*
     2                (tim-t(i))/(t(i+1)-t(i))
                  return
               end if
            end do
         end if
      end if
      write(6,*)'Problem in HEATGN.f'
      rvalue=0.0
      return
```

```
      end
```

HEAT GENERATION FOR 50 GW-d/MT SF

```
      subroutine heatgn(rvalue,r,th,z,tim,tsn,value,number,n,arg,val,
     c ntbprs,ntab,hival,loval)
*  This subroutine gives the power for 1 MTIHM SF with BU = 50 GW-d/MT
      double precision rvalue,r,th,z,tim,tsn,value,l,c1,c2,s
      double precision arg(1),val(1),p(20),t(20)
      integer ntbprs(1),ntab(1)
      logical loval(1),hival(1)
      data t/1.0,2.0,3.0,5.0,10.0,15.0,20.0,30.0,50.0,100.0,200.0,
     c     300.0,500.0,1.0e3,2.0e3/
      data p/12350.,7018.,4746.,2952.,1926.,1632.,1453.,1196.,
     c     857.1,456.9,242.3,181.7,128.8,74.69,40.85/
      tim=tim/(365.25*24.*3600.)
      if(n.eq.0) then
         if(tim.lt.t(2))then
            rvalue=p(1)
            write(6,*)'time =  ',tim,'is too small'
            return
         else if(tim.gt.t(19))then
            rvalue=p(20)
            write(6,*)'time =  ',tim,'is too large'
            return
         else
            do i=2,19
               if(tim.ge.t(i).and.tim.lt.t(i+1))then
                  l=log(p(i+2)/p(i+1))/(t(i+2)-t(i+1))
                  c1=p(i-1)-p(i+1)*exp(l*(t(i-1)-t(i+1)))
                  c2=p(i)-p(i+1)*exp(l*(t(i)-t(i+1)))
                  s=log(c1/c2)/(t(i-1)-t(i))
                  rvalue=c2*exp(s*(tim-t(i)))+p(i+1)*exp(l*
     c                (tim-t(i+1)))-c2*exp(s*(t(i+1)-t(i)))*
     2                (tim-t(i))/(t(i+1)-t(i))
                  return
               end if
            end do
         end if
      end if
      write(6,*)'Problem in HEAT50.f'
      rvalue=0.0
      return
```

```
      end
```

HEAT GENERATION FOR 50 GW-d/MT HLW

```
      subroutine heatgn(rvalue,r,th,z,tim,tsn,value,number,n,arg,val,
     c ntbprs,ntab,hival,loval)
*      This subroutine gives the power for 1 MTIHM HLW with BU = 50 GW-d/MT
      double precision rvalue,r,th,z,tim,tsn,value,l,c1,c2,s
      double precision arg(1),val(1),p(20),t(20)
      integer ntbprs(1),ntab(1)
      logical loval(1),hival(1)
      data t/1.0,2.0,3.0,5.0,10.0,15.0,20.0,30.0,50.0,100.0,200.0,
     c      300.0,500.0,1.0e3,2.0e3/
      data p/11209.,6333.,4160.8,2399.6,1394.9,1120.2,959.5,736.0,
     c      451.7,138.8,13.4,1.3,0.1,0.05,0.04/
      tim=tim/(365.25*24.*3600.)
      if(n.eq.0) then
         if(tim.lt.t(2))then
            rvalue=p(1)
            write(6,*)'time =  ',tim,'is too small'
            return
         else if(tim.gt.t(19))then
            rvalue=p(20)
            write(6,*)'time =  ',tim,'is too large'
            return
         else
            do i=2,19
               if(tim.ge.t(i).and.tim.lt.t(i+1))then
                  l=log(p(i+2)/p(i+1))/(t(i+2)-t(i+1))
                  c1=p(i-1)-p(i+1)*exp(l*(t(i-1)-t(i+1)))
                  c2=p(i)-p(i+1)*exp(l*(t(i)-t(i+1)))
                  s=log(c1/c2)/(t(i-1)-t(i))
                  rvalue=c2*exp(s*(tim-t(i)))+p(i+1)*exp(l*
     c                  (tim-t(i+1)))-c2*exp(s*(t(i+1)-t(i)))*
     2                  (tim-t(i))/(t(i+1)-t(i))
                  return
               end if
            end do
         end if
      end if
      write(6,*)'Problem in HTWO50.f'
      rvalue=0.0
      return
```

```
      end
```

HEAT GENERATION FOR HEWEC EMPLACEMENT OF SF

```
      subroutine heatgn(rvalue,r,th,z,tim,tsn,value,number,n,arg,val,
     c ntbprs,ntab,hival,loval)
      double precision rvalue,r,th,z,tim,tsn,value,l,c1,c2,s
      double precision arg(1),val(1),p(20),t(20)
      integer ntbprs(1),ntab(1)
      logical loval(1),hival(1)
      data t/1.0,2.0,3.0,5.0,10.0,15.0,20.0,30.0,50.0,100.0,200.0,
     c      300.0,500.0,1.0e3,2.0e3,5.0e3,1.0e4,2.0e4,5.0e4,1.0e5/
      data p/8728.,4536.,2850.,1615.,1028.,878.9,788.1,656.5,478.5,
     c      262.4,148.6,117.9,87.75,50.95,26.92,17.39,12.72,7.631,
     2      2.805,1.018/
      tim=tim/(365.25*24.*3600.)
      if(number.eq.1)then
         tim=tim-90.0
      else if(number.eq.2) then
         tim=tim-30.0
      else if(number.eq.4) then
         tim=tim-60.0
      else if(number.ne.3) then
         write(6,*)'Problem with Heat Generation Region Numbering'
      end if
      if(n.eq.0) then
         if(tim.lt.t(2))then
            rvalue=p(1)
            write(6,*)'time =  ',tim,'is too small'
            return
         else if(tim.gt.t(19))then
            rvalue=p(20)
            write(6,*)'time =  ',tim,'is too large'
            return
         else
            do i=2,19
               if(tim.ge.t(i).and.tim.lt.t(i+1))then
                  l=log(p(i+2)/p(i+1))/(t(i+2)-t(i+1))
                  c1=p(i-1)-p(i+1)*exp(l*(t(i-1)-t(i+1)))
                  c2=p(i)-p(i+1)*exp(l*(t(i)-t(i+1)))
                  s=log(c1/c2)/(t(i-1)-t(i))
                  rvalue=c2*exp(s*(tim-t(i)))+p(i+1)*exp(l*
     c                 (tim-t(i+1)))-c2*exp(s*(t(i+1)-t(i)))*
```

```
     2                (tim-t(i))/(t(i+1)-t(i))
                  return
               end if
            end do
         end if
      end if
      write(6,*)'Problem in HEATGN.f'
      rvalue=0.0
      return
      end
```

HEAT GENERATION FOR HEWEC EMPLACEMENT OF HLW

```
      subroutine heatgn(rvalue,r,th,z,tim,tsn,value,number,n,arg,val,
     c ntbprs,ntab,hival,loval)
      double precision rvalue,r,th,z,tim,tsn,value,l,c1,c2,s
      double precision arg(1),val(1),p(20),t(20)
      integer ntbprs(1),ntab(1)
      logical loval(1),hival(1)
      data t/1.0,2.0,3.0,5.0,10.0,15.0,20.0,30.0,50.0,100.0,200.0,
     c     300.0,500.0,1.0e3,2.0e3,5.0e3,1.0e4,2.0e4,5.0e4,1.0e5/
      data p/8295.8,4316.3,2673.,1444.2,846.8,690.1,594.2,457.8,
     2     281.7,86.8,8.4,0.8,0.04,0.03,0.03,0.03,0.02,0.02,
     3     0.016,0.011/
      tim=tim/(365.25*24.*3600.)
      if(number.eq.1)then
         tim=tim-90.0
      else if(number.eq.2) then
         tim=tim-30.0
      else if(number.eq.4) then
         tim=tim-60.0
      else if(number.ne.3) then
         write(6,*)'Problem with Heat Generation Region Numbering'
      end if
      if(n.eq.0) then
         if(tim.lt.t(2))then
            rvalue=p(1)
            write(6,*)'time = ',tim,'is too small'
            return
         else if(tim.gt.t(19))then
            rvalue=p(20)
            write(6,*)'time = ',tim,'is too large'
            return
```

```
         else
            do i=2,19
               if(tim.ge.t(i).and.tim.lt.t(i+1))then
                  l=log(p(i+2)/p(i+1))/(t(i+2)-t(i+1))
                  c1=p(i-1)-p(i+1)*exp(l*(t(i-1)-t(i+1)))
                  c2=p(i)-p(i+1)*exp(l*(t(i)-t(i+1)))
                  s=log(c1/c2)/(t(i-1)-t(i))
                  rvalue=c2*exp(s*(tim-t(i)))+p(i+1)*exp(l*
     c                  (tim-t(i+1)))-c2*exp(s*(t(i+1)-t(i)))*
     2                  (tim-t(i))/(t(i+1)-t(i))
                  return
               end if
            end do
         end if
      end if
      write(6,*)'Problem in HEATGN.f'
      rvalue=0.0
      return
      end
```

Appendix C: HEATING7 Input Files

Appendix C: HEATING7 Input Files

******* INPUT FOR NF_HLW30-2.INP *******

```
YMP Near Field, 30 GW-d/MT HLW in 2.0 x 22.9 unit cell
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used exclusively
55000  6
REGIONS
1   1    0.0  2.0    0.0  22.9    0.0  300.0
1   0     0    0      0    0      1    0
2   1    0.0  0.3   22.6  22.9    300.0  303.0
1   1     0    0      0    0      0    0
3   1    0.0  2.0    0.0  22.6    300.0  303.0
1   0     0    0      0    0      0    0
4   1    0.3  2.0    22.6  22.9    300.0  303.0
1   0     0    0      0    0      0    0
5   1    0.0  2.0    0.0  22.9    303.0  653.0
1   0     0    0      0    0      0    2
MATERIALS
1   Tuff   2.07    2340.0    840.0
HEAT GENERATIONS
*  Use a heat loading equal to 82.3 kW/acre of HLW
1   4.075   1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   2.0
   3   17
YGRID
0.0    16.0    20.0    20.9    22.6    22.9
   8      4      1      17      3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8    5    10   30   10   5    8    30
ANALYTICAL FUNCTION
```

```
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
6.3e8  9.5e8  1.3e9  1.6e9  1.9e9  3.1e9
NODES MONITORED
10000  45689  19258
TRANSIENT
1   3.15576e9
0
%
```

******* INPUT FOR NF_SF30-2.INP *******

```
YMP Near Field, 30 GW-d/MT SF in 2.0 x 22.9 unit cell
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used exclusively
250000  6
REGIONS
1   1    0.0  2.0    0.0  22.9    0.0  300.0
1   0     0    0      0    0      1     0
2   1    0.0  0.3   22.6  22.9    300.0  303.0
1   1     0    0      0    0      0     0
3   1    0.0  2.0    0.0  22.6    300.0  303.0
1   0     0    0      0    0      0     0
4   1    0.3  2.0   22.6  22.9    300.0  303.0
1   0     0    0      0    0      0     0
5   1    0.0  2.0    0.0  22.9    303.0  653.0
1   0     0    0      0    0      0     2
MATERIALS
1    Tuff    2.07    2340.0    840.0
HEAT GENERATIONS
*  Use a heat loading equal to 75.3 kW/acre of SF
1    3.072    1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1    2    32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2    1    16.5
1.0  0.0  0.0
```

```
INITIAL TEMPERATURES
1  1.0  0  0  -1
XGRID
0.0  0.3  2.0
   3   17
YGRID
0.0   16.0   20.0   20.9   22.6   22.9
   8     4     1    17     3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8   5   10   30   10   5   8   30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
6.3e8  9.5e8  1.3e9  1.6e9  1.9e9  3.1e9
NODES MONITORED
10000  45689  19258
TRANSIENT
1   3.15576e9
0
%
```

******* INPUT FOR NF_HLW30-1.INP *******

```
YMP Near Field, 30 GW-d/MT HLW in maximum loading spacing (2.6 m x 11.45 m)
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used throughout.
*  This file uses a modified unit cell with p=1.3 m  and d=11.45 m
62000  6
REGIONS
1   1   0.0  1.3    0.0  11.45    0.0  300.0
1   0    0   0      0     0       1    0
2   1   0.0  0.3   11.15  11.45    300.0  303.0
1   1    0   0      0     0       0    0
3   1   0.0  1.3    0.0  11.15    300.0  303.0
1   0    0   0      0     0       0    0
4   1   0.3  1.3    11.15  11.45    300.0  303.0
1   0    0   0      0     0       0    0
5   1   0.0  1.3    0.0  11.45    303.0  653.0
```

```
1  0   0  0    0  0    0   2
MATERIALS
1   Tuff  2.07   2340.0   840.0
HEAT GENERATIONS
*  Using the loading equal to 121.0 kW/acre HLW
1   1.947   1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   1.3
   3   10
YGRID
0.0   4.0   9.0  9.45   11.15   11.45
   2    5    1    17     3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8    5    10   30   10   5    8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
6.3e8  9.5e8  1.3e9  1.6e9  1.9e9  3.1e9
NODES MONITORED
5000  25984  10949
TRANSIENT
1   3.15576e9
0
%
```

******* INPUT FOR NF_SF30-1.INP *******

```
YMP Near Field, 30 GW-d/MT SF in maximum loading spacing (1.3 m x 11.45 m)
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
```

```
*  SI units are used throughout.
*  This file uses a modified unit cell with p=1.3 m  and d=11.45 m
52000  6
REGIONS
1   1   0.0  1.3    0.0  11.45    0.0  300.0
1   0    0   0      0    0      1    0
2   1   0.0  0.3   11.15  11.45    300.0  303.0
1   1    0   0      0    0      0    0
3   1   0.0  1.3    0.0  11.15    300.0  303.0
1   0    0   0      0    0      0    0
4   1   0.3  1.3    11.15  11.45    300.0  303.0
1   0    0   0      0    0       0    0
5   1   0.0  1.3    0.0  11.45    303.0  653.0
1   0    0   0      0    0      0    2
MATERIALS
1   Tuff   2.07    2340.0    840.0
HEAT GENERATIONS
*  Using the loading equal to 87.0 kW/acre SF
1   1.153   1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   1.3
   3   10
YGRID
0.0   4.0   9.0  9.45   11.15   11.45
   2    5    1    17     3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8    5    10   30   10   5    8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
```

```
PRINTOUT TIMES
6.3e8 9.5e8 1.3e9 1.6e9 1.9e9 3.1e9
NODES MONITORED
10000 25984 10949
TRANSIENT
1   3.15576e9
0
%
```

******* INPUT FOR NF_HLW50-2.INP *******

```
YMP Near Field, 50 GW-d/MT HLW in 2.0 x 22.9 unit cell
* Five regions are defined for unit cell in 3-D. Initial time = 10 yrs.
* SI units are used exclusively
400000 6
REGIONS
1   1   0.0 2.0   0.0 22.9    0.0 300.0
1   0    0   0    0    0     1    0
2   1   0.0 0.3  22.6 22.9   300.0 303.0
1   1    0   0    0    0     0    0
3   1   0.0 2.0   0.0 22.6   300.0 303.0
1   0    0   0    0    0     0    0
4   1   0.3 2.0   22.6 22.9   300.0 303.0
1   0    0   0    0    0      0    0
5   1   0.0 2.0   0.0 22.9   303.0 653.0
1   0    0   0    0    0     0    2
MATERIALS
1   Tuff   2.07   2340.0   840.0
HEAT GENERATIONS
* Use a heat loading equal to 83.7 kW/acre of HLW
1   2.514   1
BOUNDARY CONDITIONS
* Assume groundwater temperature constant @ 32 C
1   2   32.0

* Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0 0.0 0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   2.0
    3    17
```

```
YGRID
0.0   16.0   20.0   20.9   22.6   22.9
   8     4     1    17     3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8    5    10   30   10   5    8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
6.3e8  9.5e8  1.3e9  1.6e9  1.9e9  3.1e9
NODES MONITORED
10000  45689  19258
TRANSIENT
1   3.15576e9
0
%
```

******* INPUT FOR NF_SF50-2.INP *******

```
YMP Near Field, 50 GW-d/MT SF in 2.0 x 22.9 unit cell
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used exclusively
55000  6
REGIONS
1   1   0.0  2.0    0.0  22.9    0.0  300.0
1   0    0    0      0    0     1    0
2   1   0.0  0.3   22.6  22.9    300.0  303.0
1   1    0    0      0    0      0     0
3   1   0.0  2.0    0.0  22.6    300.0  303.0
1   0    0    0      0    0      0     0
4   1   0.3  2.0    22.6  22.9    300.0  303.0
1   0    0    0      0    0       0     0
5   1   0.0  2.0    0.0  22.9    303.0  653.0
1   0    0    0      0    0      0     2
MATERIALS
1   Tuff   2.07   2340.0   840.0
HEAT GENERATIONS
*  Use a heat loading equal to 76.7 kW/acre of SF
1   1.669   1
```

```
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   2.0
   3    17
YGRID
0.0   16.0   20.0   20.9   22.6   22.9
   8      4      1     17      3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8   5    10   30   10   5    8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
6.3e8  9.5e8  1.3e9  1.6e9  1.9e9  3.1e9
NODES MONITORED
10000  45689  19258
TRANSIENT
1   3.15576e9
0
%
```

******* INPUT FOR NF_HLW50-1.INP *******

```
YMP Near Field, 50 GW-d/MT HLW in maximum loading spacing (1.3 m x 11.45 m)
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used throughout.
*  This file uses a modified unit cell with p=1.3 m  and d=11.45 m
85000  6
REGIONS
1   1   0.0  1.3    0.0  11.45    0.0  300.0
1   0    0   0     0    0     1    0
```

```
2   1   0.0 0.3   11.15 11.45   300.0 303.0
1   1    0   0     0   0      0     0
3   1   0.0 1.3    0.0  11.15   300.0 303.0
1   0    0   0     0   0      0     0
4   1   0.3 1.3    11.15 11.45   300.0 303.0
1   0    0   0     0   0      0     0
5   1   0.0 1.3    0.0  11.45   303.0 653.0
1   0    0   0     0   0      0     2
MATERIALS
1   Tuff   2.07   2340.0   840.0
HEAT GENERATIONS
*  Using the loading equal to 123.6 kw/acre
1   1.207   1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   1.3
    3    10
YGRID
0.0   4.0   9.0   9.45   11.15   11.45
    2     5    1     17     3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8    5    10   30    10    5    8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
6.3e8  9.5e8  1.3e9  1.6e9  1.9e9  3.1e9
NODES MONITORED
10000  25984  10949
TRANSIENT
1   3.15576e9
```

```
0
%
```

******* INPUT FOR NF_SF50-1.INP *******

```
YMP Near Field, 50 GW-d/MT SF in maximum loading spacing (1.3 m x 11.45 m)
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used throughout.
*  This file uses a modified unit cell with p=1.3 m  and d=11.45 m
65000  6
REGIONS
1   1   0.0  1.3    0.0  11.45    0.0  300.0
1   0    0   0      0    0       1    0
2   1   0.0  0.3   11.15  11.45    300.0  303.0
1   1    0   0      0    0       0    0
3   1   0.0  1.3    0.0  11.15    300.0  303.0
1   0    0   0      0    0       0    0
4   1   0.3  1.3    11.15  11.45    300.0  303.0
1   0    0   0      0    0        0    0
5   1   0.0  1.3    0.0  11.45    303.0  653.0
1   0    0   0      0    0       0    2
MATERIALS
1   Tuff   2.07    2340.0    840.0
HEAT GENERATIONS
*  Using the loading equal to 98 kw/acre SF
1   .6933    1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   1.3
   3    10
YGRID
0.0    4.0    9.0   9.45    11.15    11.45
   2     5     1     17     3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
```

```
  25   8    5    10   30   10   5    8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
6.3e8  9.5e8  1.3e9  1.6e9  1.9e9  3.1e9
NODES MONITORED
10000  25984  10949
TRANSIENT
1   3.15576e9
0
%
```

******* INPUT FOR NF_HLW30-2S.INP *******

```
YMP Near Field 2.0 x 22.9 Cell, Staggered Emplacement of 30 GW HLW
*  Nine regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used throughout.
*  This file uses the SCP-CDR Unit Cell with p=2.0 m and d=22.9 m
160000  6
REGIONS
1   1    0.0  4.0    0.0  45.8     0.0  300.0
1   0     0    0     0     0    1     0
2   1    0.0  0.3    0.0   0.3   300.0  303.0
1   1     0    0     0     0    0     0
3   1    0.3  3.7    0.0   0.3   300.0  303.0
1   0     0    0     0     0    0     0
4   1    3.7  4.0    0.0   0.3   300.0  303.0
1   2     0    0     0     0    0     0
5   1    0.0  4.0    0.3   45.5  300.0  303.0
1   0     0    0     0     0    0     0
6   1    0.0  0.3   45.5   45.8  300.0  303.0
1   3     0    0     0     0    0     0
7   1    0.3  3.7   45.5   45.8  300.0  303.0
1   0     0    0     0     0    0     0
8   1    3.7  4.0   45.5   45.8  300.0  303.0
1   4     0    0     0     0    0     0
9   1    0.0  4.0    0.0   45.8  303.0  653.0
1   0     0    0     0     0    0     2
MATERIALS
```

```
1   Tuff   2.07   2340.0   840.0
HEAT GENERATIONS
*  Using the heat generation of 122.7 kW/acre HLW
1   6.074    1
2   6.074    1
3   6.074    1
4   6.074    1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0  0.3  0.5  1.3  1.6  2.0  3.0  3.3  3.7  4.0
  3    2    4    1    1    2    1    2    3
YGRID
0.0 0.3 0.5 1.5 2.0 4.0 10.0 40.0 42.0 44.0 45.0 45.5 45.8
  3   2   5   1   2   3    6    1    2    2    2    3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25    8     5    10    30    10     5     8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
4.73e9  5.99e9
NODES MONITORED
10000  41590  17161
TRANSIENT
1   6.0e9
0
%
```

******* NF_SF30-2S.INP *******

```
YMP Near Field 2.0 x 22.9 Cell, Staggered Emplacement of 30 GW SF
```

```
*  Nine regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used throughout.
*  This file uses the SCP-CDR Unit Cell with p=2.0 m and d=22.9 m
56000  6
REGIONS
1   1    0.0  4.0    0.0  45.8      0.0  300.0
1   0     0    0       0     0    1     0
2   1    0.0  0.3    0.0   0.3    300.0  303.0
1   1     0    0       0     0    0     0
3   1    0.3  3.7    0.0   0.3    300.0  303.0
1   0     0    0       0     0    0     0
4   1    3.7  4.0    0.0   0.3    300.0  303.0
1   2     0    0       0     0    0     0
5   1    0.0  4.0    0.3   45.5   300.0  303.0
1   0     0    0       0     0    0     0
6   1    0.0  0.3   45.5   45.8   300.0  303.0
1   3     0    0       0     0    0     0
7   1    0.3  3.7   45.5   45.8   300.0  303.0
1   0     0    0       0     0    0     0
8   1    3.7  4.0   45.5   45.8   300.0  303.0
1   4     0    0       0     0    0     0
9   1    0.0  4.0    0.0   45.8   303.0  653.0
1   0     0    0       0     0    0     2
MATERIALS
1   Tuff   2.07    2340.0    840.0
HEAT GENERATIONS
*  Using the heat generation equal to 103.5 kW/acre SF
1   4.219     1
2   4.219     1
3   4.219     1
4   4.219     1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0  0.3  0.5  1.3  1.6  2.0  3.0  3.3  3.7  4.0
   3   2   4   1   1   2   1   2   3
```

```
YGRID
0.0 0.3 0.5 1.5 2.0 4.0 10.0 40.0 42.0 44.0 45.0 45.5 45.8
  3  2  5  1  2  3   6   1   2   2   2   3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8    5    10    30    10    5    8    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
4.73e9  5.99e9
NODES MONITORED
10000  41590  17161
TRANSIENT
1   6.0e9
0
%
```

******* INPUT FOR NF_HLW30-1S.INP *******

```
YMP Near Field 1.3 x 11.45 Unit Cell, Staggered Emplacement of 30 GW HLW
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used throughout.
*  This file uses a modified unit cell with p=1.3 m  and d=11.45 m
54000  6
REGIONS
1   1   0.0  2.6    0.0  22.9     0.0  300.0
1   0    0    0     0    0    1    0
2   1   0.0  0.3    0.0   0.3   300.0  303.0
1   1    0    0     0    0    0    0
3   1   0.3  2.3    0.0   0.3   300.0  303.0
1   0    0    0     0    0    0    0
4   1   2.3  2.6    0.0   0.3   300.0  303.0
1   2    0    0     0    0    0    0
5   1   0.0  2.6    0.3   22.6   300.0  303.0
1   0    0    0     0    0    0    0
6   1   0.0  0.3   22.6   22.9   300.0  303.0
1   3    0    0     0    0    0    0
7   1   0.3  2.3   22.6   22.9   300.0  303.0
1   0    0    0     0    0    0    0
```

```
8   1   2.3  2.6   22.6   22.9   300.0  303.0
1   4    0   0      0    0   0     0
9   1   0.0  2.6    0.0   22.9   303.0  653.0
1   0    0   0      0    0   0     2
MATERIALS
1   Tuff   2.07    2340.0    840.0
HEAT GENERATIONS
*  Using the heat generation equal to 230.0 kW/acre HLW
1   3.700     1
2   3.700     1
3   3.700     1
4   3.700     1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0  0.0  0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.5   2.1   2.6
   5    8    5
YGRID
0.0   0.5   1.5   2.5   4.5   18.5   20.5   21.0   21.4   22.4   22.9
   5    5    2    2    7     2      1      1      5      5
ZGRID
0.0  250.0  295.0  300.0  303.0  308.0  353.0  653.0
  25     45     10     30     10      9     30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
4.73e9  5.99e9
NODES MONITORED
10000  64990  20521
TRANSIENT
1   6.0e9
0
```

%

```
***** INPUT FOR NF_SF30-1S.INP *****
YMP Near Field 1.3 x 11.45 Cell, Staggered Emplacement of 30 GW SF
*  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
*  SI units are used throughout.
*  This file uses a modified unit cell with p=1.3 m  and d=11.45 m
350000  6
REGIONS
1   1    0.0  2.6    0.0  22.9      0.0  300.0
1   0     0    0      0    0    1     0
2   1    0.0  0.3    0.0   0.3    300.0  303.0
1   1     0    0      0    0    0     0
3   1    0.3  2.3    0.0   0.3    300.0  303.0
1   0     0    0      0    0    0     0
4   1    2.3  2.6    0.0   0.3    300.0  303.0
1   2     0    0      0    0    0     0
5   1    0.0  2.6    0.3   22.6   300.0  303.0
1   0     0    0      0    0    0     0
6   1    0.0  0.3   22.6   22.9   300.0  303.0
1   3     0    0      0    0    0     0
7   1    0.3  2.3   22.6   22.9   300.0  303.0
1   0     0    0      0    0    0     0
8   1    2.3  2.6   22.6   22.9   300.0  303.0
1   4     0    0      0    0    0     0
9   1    0.0  2.6    0.0   22.9   303.0  653.0
1   0     0    0      0    0    0     2
MATERIALS
1   Tuff   2.07    2340.0    840.0
HEAT GENERATIONS
*  Using the heat generation equal to 105.0 kW/acre SF
1    1.392     1
2    1.392     1
3    1.392     1
4    1.392     1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1    16.5
1.0  0.0  0.0
```

```
INITIAL TEMPERATURES
1  1.0  0  0  -1
XGRID
0.0  0.5  2.1  2.6
  5   8   5
YGRID
0.0  0.5  1.5  2.5  4.5  18.5  20.5  21.0  21.4  22.4  22.9
  5   5   2   2   7    2     1     1     5     5
ZGRID
0.0 250.0 295.0 300.0 303.0 308.0 353.0 653.0
  25   45    10    30    10    9    30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0, 653.0  16.5
PRINTOUT TIMES
4.73e9  5.99e9
NODES MONITORED
10000  64990  20521
TRANSIENT
1   6.0e9
0
%
```

******* INPUT FOR FF_HLW30-2.INP *******

```
YMP Far Field, 30 GW-d/MT HLW in 2.0x22.9 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
190000  9  3.15576e8
REGIONS
1    1     0.0    300.0
1    0     1      0
2    1    300.0   303.0
1    1     0      0
3    1    303.0   653.0
1    0     0      2
MATERIALS
1    Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 82.3 kW/acre HLW
```

```
1   8.007e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2     32.0

2    1     16.5
1.0  0.0    0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0   300.0   303.0  653.0
  300     30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0,  655.0  16.5
PRINTOUT TIMES
1.0e10  2.0e10  3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.16e10
0
%
```

******* INPUT FOR FF_SF30-2.INP *******

```
YMP Far Field, 30 GW-d/MT SF in 2.0x22.9 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
190000  9  3.15576e8
REGIONS
1    1     0.0    300.0
1    0     1       0
2    1    300.0   303.0
1    1     0       0
3    1    303.0   653.0
1    0     0       2
```

```
MATERIALS
1   Tuff  2.07   2340.0    840.0
HEAT GENERATIONS
*  Set the loading equal to 75.3 kW/acre SF
1   6.307e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0

2    1    16.5
1.0  0.0   0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0,  655.0  16.5
PRINTOUT TIMES
1.0e10  2.0e10  3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.16e10
0
%
```

******* INPUT FOR FF_HLW30-1.INP *******

```
YMP Far Field, 30 GW-d/MT HLW in 1.3x11.45 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
400000  9  3.15576e8
REGIONS
1    1    0.0    300.0
1    0    1      0
```

```
2   1    300.0  303.0
1   1     0      0
3   1    303.0  653.0
1   0    0     2
MATERIALS
1    Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 121.0 kW/acre HLW
1    11.772e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2     32.0

2    1     16.5
1.0  0.0    0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0   300.0  303.0  653.0
  300     30      350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0,  655.0  16.5
PRINTOUT TIMES
1.0e10  2.0e10  3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000    256
TRANSIENT
1   3.16e10
0
%
```

***** INPUT FOR FF_SF30-1.INP *****

```
YMP Far Field, 30 GW-d/MT SF in 1.3x11.45 Unit Cell
*     Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*     Standard SI units are used throughout
```

```
190000 9 3.15576e8
REGIONS
1   1     0.0   300.0
1   0     1      0
2   1    300.0  303.0
1   1     0      0
3   1    303.0  653.0
1   0     0      2
MATERIALS
1    Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 87.0 kW/acre SF
1   6.969e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0

2    1    16.5
1.0  0.0   0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0,  655.0 16.5
PRINTOUT TIMES
1.0e10  2.0e10  3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000    256
TRANSIENT
1  3.16e10
0
%
```

***** INPUT FOR FF_HLW50-2.INP *****

```
YMP Far Field, 50 GW-d/MT HLW in 2.0x22.9 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
400000  9  3.15576e8
REGIONS
1    1     0.0    300.0
1    0     1      0
2    1    300.0  303.0
1    1     0      0
3    1    303.0  653.0
1    0     0      2
MATERIALS
1    Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 83.7 kW/acre HLW
1    4.940e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0

2    1    16.5
1.0  0.0   0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0,  655.0  16.5
PRINTOUT TIMES
1.0e10  2.0e10  3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000    256
TRANSIENT
1   3.16e10
```

```
0
%
```

******* INPUT FOR FF_SF50-2.INP *******

```
YMP Far Field, 50 GW-d/MT SF in 2.0x22.9 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
400000  9  3.15576e8
REGIONS
1    1     0.0    300.0
1    0     1      0
2    1    300.0   303.0
1    1     0      0
3    1    303.0   653.0
1    0     0      2
MATERIALS
1    Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 76.7 kW/acre SF
1   3.280e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0

2    1    16.5
1.0  0.0   0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0,  655.0 16.5
PRINTOUT TIMES
1.0e10  2.0e10  3.0e10
NODES MONITORED
```

```
* monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.16e10
0
%
```

******* INPUT FOR FF_HLW50-1.INP *******

```
YMP Far Field, 50 GW-d/MT HLW in 1.3x11.45 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
400000  9  3.15576e8
REGIONS
1    1     0.0    300.0
1    0     1      0
2    1    300.0   303.0
1    1     0      0
3    1    303.0   653.0
1    0     0      2
MATERIALS
1    Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 123.6 kW/acre HLW
1    7.298e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0

2    1    16.5
1.0  0.0   0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0  32.0,  655.0  16.5
```

```
PRINTOUT TIMES
1.0e10  2.0e10  3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000    256
TRANSIENT
1  3.16e10
0
%
```

******* INPUT FOR FF_SF50-1.INP *******

```
YMP Far Field, 50 GW-d/MT SF in 1.3x11.45 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
400000  9  3.15576e8
REGIONS
1    1      0.0    300.0
1    0      1       0
2    1    300.0   303.0
1    1      0       0
3    1    303.0   653.0
1    0      0       2
MATERIALS
1     Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 98.0 kW/acre SF
1   4.192e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1     2     32.0

2     1     16.5
1.0   0.0    0.0
INITIAL TEMPERATURES
1    1.0    -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0   300.0   303.0   653.0
  300     30      350
ANALYTICAL FUNCTION
1
```

```
TABULAR FUNCTION
1
0.0 32.0, 655.0 16.5
PRINTOUT TIMES
1.0e10 2.0e10 3.0e10
NODES MONITORED
* monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.16e10
0
%
```

******* INPUT FOR FF_HLW30-2S.INP *******

```
YMP Far Field, 30 GW-d/MT HLW Staggered in 2.0x22.9 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
190000 9 3.15576e9
REGIONS
1   1    0.0   300.0
1   0    1     0
2   1   300.0  303.0
1   1    0     0
3   1   303.0  653.0
1   0    0     2
MATERIALS
1   Tuff  2.07   2340.0   840.0
HEAT GENERATIONS
* Set the loading equal to 122.7 kW/acre HLW
1   11.936e-3  1
BOUNDARY CONDITIONS
* Assume constant ground water temperature = 32 C
* Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1   2   32.0

2   1   16.5
1.0  0.0   0.0
INITIAL TEMPERATURES
1  1.0  -1
XGRID
* Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30    350
```

```
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0, 655.0 16.5
PRINTOUT TIMES
1.0e10 2.0e10 3.0e10
NODES MONITORED
* monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.5e10
0
%
```

******* INPUT FOR FF_SF30-2S.INP *******

```
YMP Far Field, 30 GW-d/MT SF Staggered in 2.0x22.9 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
190000  9  3.15576e9
REGIONS
1    1     0.0    300.0
1    0     1      0
2    1    300.0   303.0
1    1     0      0
3    1    303.0   653.0
1    0     0      2
MATERIALS
1    Tuff  2.07    2340.0    840.0
HEAT GENERATIONS
* Set the loading equal to 103.5 kW/acre SF
1   8.291e-3  1
BOUNDARY CONDITIONS
* Assume constant ground water temperature = 32 C
* Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0

2    1    16.5
1.0   0.0    0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
```

```
* Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30    350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0, 655.0 16.5
PRINTOUT TIMES
1.0e10 2.0e10 3.0e10
NODES MONITORED
* monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.5e10
0
%
```

******* INPUT FOR FF_HLW30-1S.INP *******

```
YMP Far Field, 30 GW-d/MT HLW Staggered in 1.3x11.45 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
190000 9 3.15576e9
REGIONS
1    1     0.0    300.0
1    0     1      0
2    1    300.0  303.0
1    1     0      0
3    1    303.0  653.0
1    0     0      2
MATERIALS
1    Tuff  2.07    2340.0    840.0
HEAT GENERATIONS
* Set the loading equal to 230.0 kW/acre HLW
1   22.372e-3  1
BOUNDARY CONDITIONS
* Assume constant ground water temperature = 32 C
* Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0

2    1    16.5
1.0  0.0    0.0
```

```
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0, 655.0 16.5
PRINTOUT TIMES
1.0e10 2.0e10 3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.5e10
0
%
```

******* INPUT FOR FF_SF30-1S.INP *******

```
YMP Far Field, 30 GW-d/MT SF Staggered in 1.3x11.45 Unit Cell
*    Three regions defined with emplacement in region 2.  Initial time = 10 yrs
*    Standard SI units are used throughout
190000 9 3.15576e9
REGIONS
1   1      0.0    300.0
1   0      1      0
2   1    300.0   303.0
1   1      0      0
3   1    303.0   653.0
1   0      0      2
MATERIALS
1    Tuff  2.07    2340.0     840.0
HEAT GENERATIONS
*  Set the loading equal to 105.0 kW/acre SF
1   8.416e-3  1
BOUNDARY CONDITIONS
*  Assume constant ground water temperature = 32 C
*  Assume constant ambient temp = 16.5 C and h = 1.0 W/(m2 C)
1    2    32.0
```

```
2    1    16.5
1.0  0.0   0.0
INITIAL TEMPERATURES
1   1.0   -1
XGRID
*  Use 1 meter nodes except within heat generation zone, where 0.1 m
0.0  300.0  303.0  653.0
  300    30     350
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0, 655.0 16.5
PRINTOUT TIMES
1.0e10 2.0e10 3.0e10
NODES MONITORED
*  monitor the plane 255 m above the groundwater, or 45 m below emplacement
10000   256
TRANSIENT
1  3.5e10
0
%
```

Appendix D: Sample HEATING7 Output

Appendix D: Sample HEATING7 Output

```
Current Time: Tue Jun 21 16:04:01 1994        Computer: IBM/AIX


H   H EEEEE   AAA   TTTTT III  N   N   GGG
H   H E      A   A    T    I   N   N  G   G
H   H E      A   A    T    I   NN  N  G
HHHHH EEE    AAAAA    T    I   N N N  G
H   H E      A   A    T    I   N  NN  G  GG
H   H E      A   A    T    I   N   N  G   G
H   H EEEEE  A   A    T   III  N   N   GGG


Version       : HEATING 7.2b
Release date : Feb. 9, 1993


Contacts     : Kenneth W. Childs   or   Gary E. Giles
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Address      : Heat Transfer and Fluid Flow Group
               Computing Applications Division
               Oak Ridge National Laboratory
               Post Office Box 2003
               Oak Ridge, Tennessee 37831-7039


    ******************************      ECHO      OF      INPUT      DATA
******************************


Record
   1 YMP Near Field, 30 GW-d/MT HLW in 2.0 x 22.9 unit cell
   2 *  Five regions are defined for unit cell in 3-D.  Initial time = 10 yrs.
   3 *  SI units are used exclusively
   4 55000  6
   5 REGIONS
   6 1    1    0.0  2.0    0.0  22.9    0.0  300.0
   7 1    0    0    0      0    0       1    0
   8 2    1    0.0  0.3    22.6 22.9    300.0 303.0
   9 1    1    0    0      0    0       0    0
  10 3    1    0.0  2.0    0.0  22.6    300.0 303.0
```

```
1  0   0  0   0  0    0    0
4   1   0.3  2.0   22.6  22.9   300.0  303.0
1  0   0  0   0  0    0    0
5   1   0.0  2.0   0.0  22.9   303.0  653.0
1  0   0  0   0  0    0    2
MATERIALS
1   Tuff  2.07   2340.0   840.0
HEAT GENERATIONS
*  Use a heat loading equal to 82.3 kW/acre of HLW
1   4.075   1
BOUNDARY CONDITIONS
*  Assume groundwater temperature constant @ 32 C
1   2   32.0

*  Assume constant ambient temperature = 16.5 C and h = 1.0 W/(m2 C)
2   1   16.5
1.0 0.0 0.0
INITIAL TEMPERATURES
1   1.0   0   0   -1
XGRID
0.0   0.3   2.0
   3   17
YGRID
0.0   16.0   20.0   20.9   22.6   22.9
   8     4     1     17     3
ZGRID
0.0 250.0 290.0 295.0 300.0 303.0 308.0 313.0 353.0 653.0
  25   8   5   10   30   10   5   8   30
ANALYTICAL FUNCTION
1

TABULAR FUNCTION
1
0.0 32.0, 653.0 16.5
PRINTOUT TIMES
6.3e8 9.5e8 1.3e9 1.6e9 1.9e9 3.1e9
NODES MONITORED
10000 45689 19258
TRANSIENT
1   3.15576e9
0
%
```

```
     *****************************     CASE     DESCRIPTION
*****************************

YMP Near Field, 30 GW-d/MT HLW in 2.0 x 22.9 unit cell


  *********************  SUMMARY  OF  PARAMETER  CARD  DATA
**********************

Maximum cpu time    - 55000.00 seconds
Geometry type number -    6 (or xyz )
Initial time        -  0.0000000D+00
Temperature units   -  Fahrenheit (Significant only if radiation involved)

This is a restart of previous case          - Yes
Read node-to-node connector data file          - No
Redirect or suppress convergence information   - Yes (Suppress)

Output selected information during calculations - No


   **************************     SUMMARY     OF     REGION     DATA
**************************

Region  Material  Initial   Heat Gen.
Number   Number  Temp. No.  Number
   1       1        1        0
   2       1        1        1
   3       1        1        0
   4       1        1        0
   5       1        1        0


      ------------------ Dimensions / Boundary Numbers ------------------
 Region     First Axis           Second Axis           Third Axis
 Number  Smaller    Larger    Smaller    Larger     Smaller    Larger
   1  0.0000E+00  2.0000E+00  0.0000E+00  2.2900E+01  0.0000E+00  3.0000E+02
      0      0      0      0      1      0
   2  0.0000E+00  3.0000E-01  2.2600E+01  2.2900E+01  3.0000E+02  3.0300E+02
      0      0      0      0      0      0
   3  0.0000E+00  2.0000E+00  0.0000E+00  2.2600E+01  3.0000E+02  3.0300E+02
      0      0      0      0      0      0
```

```
   4 3.0000E-01  2.0000E+00  2.2600E+01  2.2900E+01  3.0000E+02  3.0300E+02
     0       0       0       0       0       0
   5 0.0000E+00  2.0000E+00  0.0000E+00  2.2900E+01  3.0300E+02  6.5300E+02
     0       0       0       0       0       2


   **************************    SUMMARY    OF    MATERIAL    DATA
*************************


Material  Material    ----------- Thermal Parameters -----------  Phase
 Number     Name    -- Temperature-Dependent Function Numbers --  Change
              Conductivity     Density   Specific Heat
   1     tuff      2.070000D+00   2.340000D+03   8.400000D+02    No
                        0              0              0


  *********************  SUMMARY  OF  INITIAL  TEMPERATURE  DATA
*******************


Number    Initial      Position-Dependent Function Numbers
       Temperature       x or r    y or th    z or p
  1    1.00000D+00          0         0         -1


  ********************  SUMMARY  OF  HEAT  GENERATION  RATE  DATA
*******************


Number   Power   Time-, Temperature-, and Position-Dependent Function Numbers
      Density       Time   Temperature  X or R   Y or Theta   Z or Phi
  1  4.07500D+00      1        0          0         0           0


  *********************  SUMMARY  OF  BOUNDARY  CONDITION  DATA
********************


Number:    1               Type:  Specified Surface Temperature
  Temperature and Any Functions Used to Define Dependence:
         Temperature       :  3.200000E+01

Number:    2               Type:  Surface-to-Environment
  Temperature and Any Functions Used to Define Dependence:
         Temperature       :  1.650000E+01
  Heat Transfer Coefficients and Any Functions Used to Define Dependence:
```

```
        Forced Convection  :  1.000000E+00


    ************************** SUMMARY   OF   GRID   STRUCTURE
**************************

X (or R) Gross Grid Lines and Number of Divisions
  0.000000E+00  3.000000E-01  2.000000E+00
        3          17

X (or R) Fine Grid Lines Generated by HEATING
   1 0.00000E+00    2 1.00000E-01    3 2.00000E-01    4 3.00000E-01
   5 4.00000E-01    6 5.00000E-01    7 6.00000E-01    8 7.00000E-01
   9 8.00000E-01   10 9.00000E-01   11 1.00000E+00   12 1.10000E+00
  13 1.20000E+00   14 1.30000E+00   15 1.40000E+00   16 1.50000E+00
  17 1.60000E+00   18 1.70000E+00   19 1.80000E+00   20 1.90000E+00
  21 2.00000E+00

Y (or Theta) Gross Grid Lines and Number of Divisions
  0.000000E+00  1.600000E+01  2.000000E+01  2.090000E+01  2.260000E+01
  2.290000E+01
        8         4          1          17          3

Y (or Theta) Fine Grid Lines Generated by HEATING
   1 0.00000E+00    2 2.00000E+00    3 4.00000E+00    4 6.00000E+00
   5 8.00000E+00    6 1.00000E+01    7 1.20000E+01    8 1.40000E+01
   9 1.60000E+01   10 1.70000E+01   11 1.80000E+01   12 1.90000E+01
  13 2.00000E+01   14 2.09000E+01   15 2.10000E+01   16 2.11000E+01
  17 2.12000E+01   18 2.13000E+01   19 2.14000E+01   20 2.15000E+01
  21 2.16000E+01   22 2.17000E+01   23 2.18000E+01   24 2.19000E+01
  25 2.20000E+01   26 2.21000E+01   27 2.22000E+01   28 2.23000E+01
  29 2.24000E+01   30 2.25000E+01   31 2.26000E+01   32 2.27000E+01
  33 2.28000E+01   34 2.29000E+01

Z (or Phi) Gross Grid Lines and Number of Divisions
  0.000000E+00  2.500000E+02  2.900000E+02  2.950000E+02  3.000000E+02
  3.030000E+02  3.080000E+02  3.130000E+02  3.530000E+02  6.530000E+02
       25          8          5          10          30
       10          5          8          30

Z (or Phi) Fine Grid Lines Generated by HEATING
   1 0.00000E+00    2 1.00000E+01    3 2.00000E+01    4 3.00000E+01
   5 4.00000E+01    6 5.00000E+01    7 6.00000E+01    8 7.00000E+01
```

```
  9 8.00000E+01   10 9.00000E+01   11 1.00000E+02   12 1.10000E+02
 13 1.20000E+02   14 1.30000E+02   15 1.40000E+02   16 1.50000E+02
 17 1.60000E+02   18 1.70000E+02   19 1.80000E+02   20 1.90000E+02
 21 2.00000E+02   22 2.10000E+02   23 2.20000E+02   24 2.30000E+02
 25 2.40000E+02   26 2.50000E+02   27 2.55000E+02   28 2.60000E+02
 29 2.65000E+02   30 2.70000E+02   31 2.75000E+02   32 2.80000E+02
 33 2.85000E+02   34 2.90000E+02   35 2.91000E+02   36 2.92000E+02
 37 2.93000E+02   38 2.94000E+02   39 2.95000E+02   40 2.95500E+02
 41 2.96000E+02   42 2.96500E+02   43 2.97000E+02   44 2.97500E+02
 45 2.98000E+02   46 2.98500E+02   47 2.99000E+02   48 2.99500E+02
 49 3.00000E+02   50 3.00100E+02   51 3.00200E+02   52 3.00300E+02
 53 3.00400E+02   54 3.00500E+02   55 3.00600E+02   56 3.00700E+02
 57 3.00800E+02   58 3.00900E+02   59 3.01000E+02   60 3.01100E+02
 61 3.01200E+02   62 3.01300E+02   63 3.01400E+02   64 3.01500E+02
 65 3.01600E+02   66 3.01700E+02   67 3.01800E+02   68 3.01900E+02
 69 3.02000E+02   70 3.02100E+02   71 3.02200E+02   72 3.02300E+02
 73 3.02400E+02   74 3.02500E+02   75 3.02600E+02   76 3.02700E+02
 77 3.02800E+02   78 3.02900E+02   79 3.03000E+02   80 3.03500E+02
 81 3.04000E+02   82 3.04500E+02   83 3.05000E+02   84 3.05500E+02
 85 3.06000E+02   86 3.06500E+02   87 3.07000E+02   88 3.07500E+02
 89 3.08000E+02   90 3.09000E+02   91 3.10000E+02   92 3.11000E+02
 93 3.12000E+02   94 3.13000E+02   95 3.18000E+02   96 3.23000E+02
 97 3.28000E+02   98 3.33000E+02   99 3.38000E+02  100 3.43000E+02
101 3.48000E+02  102 3.53000E+02  103 3.63000E+02  104 3.73000E+02
105 3.83000E+02  106 3.93000E+02  107 4.03000E+02  108 4.13000E+02
109 4.23000E+02  110 4.33000E+02  111 4.43000E+02  112 4.53000E+02
113 4.63000E+02  114 4.73000E+02  115 4.83000E+02  116 4.93000E+02
117 5.03000E+02  118 5.13000E+02  119 5.23000E+02  120 5.33000E+02
121 5.43000E+02  122 5.53000E+02  123 5.63000E+02  124 5.73000E+02
125 5.83000E+02  126 5.93000E+02  127 6.03000E+02  128 6.13000E+02
129 6.23000E+02  130 6.33000E+02  131 6.43000E+02  132 6.53000E+02


   ************************   LISTING   OF   ANALYTICAL   FUNCTIONS
************************


f(v)= a(1) + a(2)*v + a(3)*v**2 + a(4)*cos(a(5)*v) + a(6)*exp(a(7)*v)
        + a(8)*sin(a(9)*v) + a(10)*log(a(11)*v)

Analytical Function Number:   1
          USER-SUPPLIED SUBROUTINE
```

```
   ************************   LISTING   OF   TABULAR   FUNCTIONS
***********************

   Table number -      1          Number of pairs -      2

      Argument        Value       (Min) <- Relative Value -> (Max)
   0.00000000D+00   3.20000000D+01     **************************
   6.53000000D+02   1.65000000D+01     *


   *********************   TABLE   OF   SPECIFIED   OUTPUT   TIMES
***********************

   1  6.30000E+08    2  9.50000E+08    3  1.30000E+09    4  1.60000E+09
   5  1.90000E+09    6  3.10000E+09


 ***************** MONITORING OF SELECTED NODAL TEMPERATURES
*****************

  Temperatures of the following nodes will be monitored every10000
  iterations or time steps.

 Node        Grid Location                 Coordinate Values
 Number     i     j     k      x (or r)     y (or theta)    z (or phi)
 45689     14    34    64     1.300000D+00   2.290000D+01   3.015000D+02
 19258      1    34    27     0.000000D+00   2.290000D+01   2.550000D+02


  ******************   SOURCES   OF   NON-LINEARITY   IN   THE   MODEL
*******************

  The model is linear.


 ************* NUMBER OF PARAMETERS SPECIFIED BY THE INPUT DATA
*************

  Regions                          5
  Materials                        1
  Phase changes                      0
  Initial temperatures                1
  Heat generations                    1
```

```
  Boundary conditions                          2
  Gross grid lines along x or r axis             3
  Fine  grid lines along x or r axis           21
  Gross grid lines along y or theta axis          6
  Fine  grid lines along y or theta axis         34
  Gross grid lines along z or phi axis           10
  Fine  grid lines along z or phi axis          132
  Analytic functions                         1
  Tabular functions                          1
  Node-to-node connectors                        0
  Transient printout times                   6
  Nodes for monitoring of temperatures              2
  Number of nodes                        94248
  Number of specified-temperature nodes          714
  Position-dependent boundary temperature nodes     1


 ************ MEMORY REQUIREMENTS FOR VARIABLY DIMENSIONED
ARRAYS ************

  Phase 1     5K
  Phase 2 14457K
  Phase 3 24307K
  Phase 4 27315K


     ******************************        INITIAL        CONDITIONS
******************************

 Number of time steps completed  =           0
 Current time step             =  0.00000000D+00
 Current problem time           =  2.98153890D+09
 Elapsed cpu time (hr:min:sec)  =     00:02:29.58

 Minimum Temperature = 1.65481E+01   at node 93535
 Maximum Temperature = 1.40554E+02   at node 45676

 HEAT GENERATION
  Number            Current Rate (energy/time)
                  (Modeled)    (Neglected)
    1             1.08683E+02  0.00000E+00

 BOUNDARY HEAT FLOW
```

```
  Number  Environment  Current Rate (energy/time)
       Temperature    (Modeled)    (Neglected)
     1    3.20000E+01   2.20218E+00   0.00000E+00
     2    1.65000E+01  -2.20334E+00   0.00000E+00
    ---               ------------  ------------
    Sum                -1.16235E-03   0.00000E+00




***********************************************************************
*********

          BEGIN TRANSIENT CALCULATION - EXPLICIT TECHNIQUE


***********************************************************************
*********



 Maximum of the stability criterion -  4.7355138D+03
 Median of the stability criterion  -  2.3737944D+03
 Minimum of the stability criterion -  1.5826087D+03 for point 55629

 The input time step size is  0.0000000D+00.
 the time step size will be set to the stability criterion of  1.5826087D+03.


    **************************      TRANSIENT      SOLUTION      OUTPUT
*************************

 Number of time steps completed =          74852
 Current time step              =  1.58260870D+03
 Current problem time           =  3.10000033D+09
 Elapsed cpu time (hr:min:sec)  =     04:03:38.10

 Minimum Temperature = 1.65482E+01   at node 93535
 Maximum Temperature = 1.36148E+02   at node 45676

 HEAT GENERATION
  Number            Current Rate (energy/time)
                 (Modeled)    (Neglected)
     1           9.95361E+01   0.00000E+00
```

```
BOUNDARY HEAT FLOW
 Number  Environment  Current Rate (energy/time)
     Temperature    (Modeled)   (Neglected)
   1   3.20000E+01  2.18347E+00  0.00000E+00
   2   1.65000E+01 -2.20576E+00  0.00000E+00
  ---              ------------ ------------
  Sum               -2.22915E-02  0.00000E+00


    ***************************     TRANSIENT     SOLUTION     OUTPUT
*************************

Number of time steps completed  =         110085
Current time step               = 1.58260870D+03
Current problem time            = 3.15576038D+09
Elapsed cpu time (hr:min:sec)   =    05:57:02.16

Minimum Temperature = 1.65482E+01   at node 93535
Maximum Temperature = 1.34165E+02   at node 45676

HEAT GENERATION
 Number             Current Rate (energy/time)
                  (Modeled)   (Neglected)
   1              9.55018E+01  0.00000E+00

BOUNDARY HEAT FLOW
 Number  Environment  Current Rate (energy/time)
     Temperature    (Modeled)   (Neglected)
   1   3.20000E+01  2.17301E+00  0.00000E+00
   2   1.65000E+01 -2.20705E+00  0.00000E+00
  ---              ------------ ------------
  Sum               -3.40430E-02  0.00000E+00


The transient calculations have been completed.
Final time is    3.15576D+09
Number of time steps completed =110085


    ***************************     END     OF     HEATING     EXECUTION
*************************

YMP Near Field, 30 GW-d/MT HLW in 2.0 x 22.9 unit cell
```

```
***** Number of warnings --   0
***** Number of errors    --   0


TITLE="YMP Near Field, 30 GW-d/MT HLW in 2.0 x 22.9 unit cell              "
VARIABLES=
 NOIT   Time       "45689"    "19258"
ZONE T="Transient "
  10000 3.3140E+08 1.4569E+02 2.5947E+01
  20000 3.4723E+08 1.6686E+02 2.5947E+01
  30000 3.6305E+08 1.7770E+02 2.5948E+01
  40000 3.7888E+08 1.8438E+02 2.5951E+01
  50000 3.9471E+08 1.8885E+02 2.5961E+01
  60000 4.1053E+08 1.9197E+02 2.5985E+01
  70000 4.2636E+08 1.9422E+02 2.6028E+01
  80000 4.4218E+08 1.9586E+02 2.6097E+01
  90000 4.5801E+08 1.9707E+02 2.6194E+01
 100000 4.7384E+08 1.9795E+02 2.6322E+01
 110000 4.8966E+08 1.9862E+02 2.6483E+01
 120000 5.0549E+08 1.9914E+02 2.6677E+01
 130000 5.2132E+08 1.9952E+02 2.6904E+01
 140000 5.3714E+08 1.9980E+02 2.7162E+01
 150000 5.5297E+08 1.9998E+02 2.7450E+01
 160000 5.6879E+08 2.0009E+02 2.7767E+01
 170000 5.8462E+08 2.0013E+02 2.8111E+01
 180000 6.0045E+08 2.0011E+02 2.8480E+01
 190000 6.1627E+08 2.0004E+02 2.8872E+01
 200000 6.3210E+08 1.9992E+02 2.9285E+01
 210000 6.4792E+08 1.9976E+02 2.9718E+01
 220000 6.6375E+08 1.9958E+02 3.0168E+01
 230000 6.7958E+08 1.9936E+02 3.0634E+01
 240000 6.9540E+08 1.9912E+02 3.1113E+01
 250000 7.1123E+08 1.9885E+02 3.1606E+01
 260000 7.2705E+08 1.9856E+02 3.2109E+01
 270000 7.4288E+08 1.9824E+02 3.2622E+01
 280000 7.5871E+08 1.9790E+02 3.3143E+01
 290000 7.7453E+08 1.9755E+02 3.3671E+01
 300000 7.9036E+08 1.9717E+02 3.4206E+01
 310000 8.0618E+08 1.9678E+02 3.4745E+01
 320000 8.2201E+08 1.9637E+02 3.5288E+01
 330000 8.3784E+08 1.9594E+02 3.5835E+01
 340000 8.5366E+08 1.9550E+02 3.6384E+01
 350000 8.6949E+08 1.9504E+02 3.6934E+01
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360000	8.8532E+08	1.9457E+02	3.7485E+01
370000	9.0114E+08	1.9409E+02	3.8037E+01
380000	9.1697E+08	1.9360E+02	3.8588E+01
390000	9.3279E+08	1.9309E+02	3.9139E+01
400000	9.4862E+08	1.9257E+02	3.9688E+01
410000	9.6445E+08	1.9205E+02	4.0236E+01
420000	9.8027E+08	1.9151E+02	4.0782E+01
430000	9.9610E+08	1.9097E+02	4.1325E+01
440000	1.0119E+09	1.9042E+02	4.1865E+01
450000	1.0277E+09	1.8986E+02	4.2402E+01
460000	1.0436E+09	1.8930E+02	4.2936E+01
470000	1.0594E+09	1.8873E+02	4.3466E+01
480000	1.0752E+09	1.8816E+02	4.3993E+01
490000	1.0911E+09	1.8758E+02	4.4515E+01
500000	1.1069E+09	1.8699E+02	4.5033E+01
510000	1.1227E+09	1.8640E+02	4.5547E+01
520000	1.1385E+09	1.8581E+02	4.6055E+01
530000	1.1544E+09	1.8522E+02	4.6560E+01
540000	1.1702E+09	1.8462E+02	4.7059E+01
550000	1.1860E+09	1.8401E+02	4.7554E+01
560000	1.2018E+09	1.8341E+02	4.8043E+01
570000	1.2177E+09	1.8280E+02	4.8527E+01
580000	1.2335E+09	1.8219E+02	4.9006E+01
590000	1.2493E+09	1.8157E+02	4.9480E+01
600000	1.2651E+09	1.8096E+02	4.9949E+01
610000	1.2810E+09	1.8034E+02	5.0412E+01
620000	1.2968E+09	1.7972E+02	5.0869E+01
630000	1.3126E+09	1.7910E+02	5.1322E+01
640000	1.3284E+09	1.7848E+02	5.1768E+01
650000	1.3443E+09	1.7786E+02	5.2210E+01
660000	1.3601E+09	1.7724E+02	5.2645E+01
670000	1.3759E+09	1.7661E+02	5.3076E+01
680000	1.3917E+09	1.7599E+02	5.3500E+01

10000	1.4183E+09	1.7494E+02	5.4200E+01
20000	1.4341E+09	1.7432E+02	5.4610E+01
30000	1.4499E+09	1.7369E+02	5.5015E+01
40000	1.4658E+09	1.7307E+02	5.5414E+01
50000	1.4816E+09	1.7244E+02	5.5807E+01
60000	1.4974E+09	1.7182E+02	5.6195E+01
70000	1.5132E+09	1.7120E+02	5.6578E+01
80000	1.5291E+09	1.7057E+02	5.6955E+01
90000	1.5449E+09	1.6995E+02	5.7327E+01

100000	1.5607E+09	1.6933E+02	5.7694E+01
110000	1.5765E+09	1.6871E+02	5.8055E+01
120000	1.5924E+09	1.6809E+02	5.8411E+01
130000	1.6082E+09	1.6747E+02	5.8762E+01
140000	1.6240E+09	1.6686E+02	5.9107E+01
150000	1.6399E+09	1.6624E+02	5.9448E+01
160000	1.6557E+09	1.6563E+02	5.9783E+01

10000	1.6739E+09	1.6492E+02	6.0164E+01
20000	1.6898E+09	1.6431E+02	6.0488E+01
30000	1.7056E+09	1.6370E+02	6.0807E+01
40000	1.7214E+09	1.6310E+02	6.1122E+01
50000	1.7373E+09	1.6249E+02	6.1431E+01
60000	1.7531E+09	1.6189E+02	6.1736E+01
70000	1.7689E+09	1.6129E+02	6.2036E+01
80000	1.7847E+09	1.6069E+02	6.2331E+01
90000	1.8006E+09	1.6009E+02	6.2621E+01
100000	1.8164E+09	1.5950E+02	6.2907E+01
110000	1.8322E+09	1.5890E+02	6.3188E+01
120000	1.8480E+09	1.5831E+02	6.3464E+01
130000	1.8639E+09	1.5773E+02	6.3736E+01
140000	1.8797E+09	1.5714E+02	6.4003E+01
150000	1.8955E+09	1.5656E+02	6.4266E+01
160000	1.9113E+09	1.5597E+02	6.4525E+01
170000	1.9272E+09	1.5540E+02	6.4779E+01
180000	1.9430E+09	1.5482E+02	6.5029E+01
190000	1.9588E+09	1.5425E+02	6.5274E+01
200000	1.9746E+09	1.5367E+02	6.5516E+01
210000	1.9905E+09	1.5311E+02	6.5753E+01
220000	2.0063E+09	1.5254E+02	6.5986E+01
230000	2.0221E+09	1.5198E+02	6.6215E+01
240000	2.0379E+09	1.5141E+02	6.6440E+01
250000	2.0538E+09	1.5086E+02	6.6661E+01
260000	2.0696E+09	1.5030E+02	6.6878E+01

10000	2.0996E+09	1.4925E+02	6.7278E+01
20000	2.1154E+09	1.4870E+02	6.7484E+01
30000	2.1313E+09	1.4816E+02	6.7686E+01
40000	2.1471E+09	1.4762E+02	6.7885E+01
50000	2.1629E+09	1.4708E+02	6.8080E+01
60000	2.1787E+09	1.4654E+02	6.8271E+01
70000	2.1946E+09	1.4600E+02	6.8458E+01
80000	2.2104E+09	1.4547E+02	6.8642E+01

90000	2.2262E+09	1.4494E+02	6.8823E+01
100000	2.2420E+09	1.4442E+02	6.9000E+01
110000	2.2579E+09	1.4389E+02	6.9174E+01
120000	2.2737E+09	1.4337E+02	6.9344E+01
130000	2.2895E+09	1.4285E+02	6.9511E+01
140000	2.3053E+09	1.4234E+02	6.9675E+01
150000	2.3212E+09	1.4182E+02	6.9835E+01
160000	2.3370E+09	1.4131E+02	6.9992E+01
170000	2.3528E+09	1.4081E+02	7.0146E+01
180000	2.3686E+09	1.4030E+02	7.0297E+01
190000	2.3845E+09	1.3980E+02	7.0445E+01
200000	2.4003E+09	1.3930E+02	7.0590E+01
210000	2.4161E+09	1.3881E+02	7.0732E+01
220000	2.4320E+09	1.3831E+02	7.0871E+01
230000	2.4478E+09	1.3782E+02	7.1007E+01
240000	2.4636E+09	1.3733E+02	7.1140E+01
250000	2.4794E+09	1.3685E+02	7.1271E+01
260000	2.4953E+09	1.3637E+02	7.1398E+01
270000	2.5111E+09	1.3589E+02	7.1523E+01

10000	2.5413E+09	1.3498E+02	7.1753E+01
20000	2.5571E+09	1.3451E+02	7.1870E+01
30000	2.5729E+09	1.3404E+02	7.1985E+01
40000	2.5888E+09	1.3357E+02	7.2096E+01
50000	2.6046E+09	1.3311E+02	7.2206E+01
60000	2.6204E+09	1.3265E+02	7.2312E+01
70000	2.6362E+09	1.3219E+02	7.2416E+01
80000	2.6521E+09	1.3174E+02	7.2518E+01
90000	2.6679E+09	1.3128E+02	7.2617E+01
100000	2.6837E+09	1.3084E+02	7.2714E+01
110000	2.6996E+09	1.3039E+02	7.2809E+01
120000	2.7154E+09	1.2994E+02	7.2901E+01
130000	2.7312E+09	1.2950E+02	7.2991E+01
140000	2.7470E+09	1.2906E+02	7.3079E+01
150000	2.7629E+09	1.2863E+02	7.3164E+01
160000	2.7787E+09	1.2819E+02	7.3247E+01
170000	2.7945E+09	1.2776E+02	7.3328E+01
180000	2.8103E+09	1.2733E+02	7.3407E+01
190000	2.8262E+09	1.2691E+02	7.3484E+01
200000	2.8420E+09	1.2649E+02	7.3559E+01
210000	2.8578E+09	1.2607E+02	7.3632E+01
220000	2.8736E+09	1.2565E+02	7.3703E+01
230000	2.8895E+09	1.2523E+02	7.3771E+01

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240000  2.9053E+09  1.2482E+02  7.3838E+01
250000  2.9211E+09  1.2441E+02  7.3903E+01
260000  2.9369E+09  1.2400E+02  7.3966E+01
270000  2.9528E+09  1.2360E+02  7.4027E+01
280000  2.9686E+09  1.2319E+02  7.4086E+01

 10000  2.9974E+09  1.2247E+02  7.4189E+01
 20000  3.0132E+09  1.2207E+02  7.4243E+01
 30000  3.0290E+09  1.2168E+02  7.4296E+01
 40000  3.0448E+09  1.2129E+02  7.4346E+01
 50000  3.0607E+09  1.2090E+02  7.4395E+01
 60000  3.0765E+09  1.2052E+02  7.4443E+01
 70000  3.0923E+09  1.2013E+02  7.4488E+01
 80000  3.1081E+09  1.1975E+02  7.4532E+01
 90000  3.1240E+09  1.1938E+02  7.4575E+01
100000  3.1398E+09  1.1900E+02  7.4616E+01
110000  3.1556E+09  1.1863E+02  7.4655E+01
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Vita

Brian Spencer Cowell was born May 2, 1969. He was raised in Nashville, Tennessee, where he attended McGavock High School. After graduating as valedictorian in 1987, he entered the University of Tennessee, Knoxville majoring in nuclear engineering. In May, 1991 received a Bachelor of Science degree, graduating at the top of his class. He began working full-time for the Oak Ridge National Laboratory and entered graduate school part-time in June 1991.