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**Expected Near-Field Thermal
Environments in a Sequentially
Loaded Spent-Fuel or High-Level
Waste Repository in Salt**

L. D. Rickertsen
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EXPECTED NEAR-FIELD THERMAL ENVIRONMENTS IN A
SEQUENTIALLY LOADED SPENT-FUEL OR HIGH-LEVEL
WASTE REPOSITORY IN SALT

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ABSTRACT

This report describes the effect of realistic waste emplacement schedules on repository thermal environments. Virtually all estimates to date have been based on instantaneous loading of wastes having uniform properties throughout the repository. However, more realistic scenarios involving sequential emplacement of wastes reflect the gradual filling of the repository over its lifetime. These cases provide temperatures that can be less extreme than with the simple approximation. At isolated locations in the repository, the temperatures approach the instantaneous-loading limit. However, for most of the repository, temperature rises in the near-field are 10-40 years behind the conservative estimates depending on the waste type and the location in the repository.

Results are presented for both spent-fuel and high-level reprocessing waste repositories in salt, for a regional repository concept, and for a single national repository concept. The national repository is filled sooner and therefore more closely approximates the instantaneously loaded repository. However, temperatures in the near-field are still 20°C or more below the values in the simple model for 40 years after startup of repository emplacement operations.

The results suggest that current repository design concepts based on the instantaneous-loading predictions are very conservative. Therefore, experiments to monitor temperatures in a test and evaluation facility, for example, will need to take into account the reduced temperatures in order to provide data used in predicting repository performance.

1. INTRODUCTION

A critical factor affecting the conditions in a geologic repository for nuclear wastes is the heat generated during radioactive decay of the waste. This heat flows from the waste through the waste package, through the engineered barriers around the package, out into the host rock, into the surrounding formation, and up into the overlying strata and is eventually dissipated into the atmosphere. For spent fuel (SF) and high-level waste (HLW) resulting from reprocessing, the heat generated can be significant and can result in temperatures that could affect waste package performance, the stability of the repository mine, the integrity of the overlying rock, the local geochemistry and petrology, local fluid pressures and pore water behavior, and the regional hydrology. Therefore, considerable effort has been devoted to the development of analytic and experimental techniques to determine the expected thermal environments within the repository.

Nearly all the analyses of repository temperatures that have been made have been based on an approximation of instantaneous loading of waste into the repository. In this approach, all of this waste is assumed to have the same heat generation characteristics and, consequently, is conservative with respect to the maximum temperatures. These assumptions greatly simplify the treatment of the time dependence of the heat source in the calculations. However, in fact, the repository will be loaded not instantaneously but gradually, depending upon the rate at which waste packages arrive at the site and the emplacement logistics. As the waste packages arrive, they will be distributed throughout the repository in an orderly and deliberate sequence. Because the arrival of the wastes will take place over several years, there will be regions in the repository unfilled and therefore unaffected by temperature increases for some time after the initiation of emplacement operations. In addition to the effects of sequential loading of the waste, the heat sources will not decay uniformly throughout the repository. Waste emplaced early at one location in the repository will be likely to have decay characteristics much different from that emplaced later at another location. As a

result, both waste package thermal loadings and decay rates will vary with location in the repository. Therefore, the actual temperature distribution throughout the repository is expected to be different from that calculated using uniform decay properties and the instantaneous loading of waste.

In this report sequential-emplacement scenarios and the space and time dependence of the heat sources are explicitly taken into account to determine more realistic temperature distributions in the near-field. A realistic projection of nuclear waste production in the United States is used to determine an inventory of waste available for emplacement in a repository. Based on this inventory, the arrival rates of waste packages at the repository and the thermal characteristics of the heat sources are then determined. A repository in a salt formation is assumed, and representative designs for SF and HLW repositories are chosen for a calculational basis. Appropriate emplacement scenarios are then assumed and used to determine the time-dependent distribution of waste packages throughout the repository. The resulting heat source description is used in a full three-dimensional (3-D) calculation to predict the near-field temperatures.

Section 2 discusses the inventory of waste assumed to be generated by U.S. commercial reactors up to the year 2050 in terms of both SF for a once-through fuel cycle and canisters of HLW for a reprocessing fuel cycle. The waste is also characterized by age or the time interval since discharge from the reactor. The quantity and age of the waste are sufficient to specify its heat generation properties if the thermal power decay rate is known. The actual arrival rates and characteristics of the wastes received depend upon how much of the total waste inventory is allocated to the repository. Two concepts for this allocation are considered: (1) a national repository concept, in which the entire inventory of waste generated in the United States is assumed to be shipped to a single repository until it is filled and (2) a regional repository concept, in which the waste is distributed among several repositories located regionally within the United States. These alternative concepts provide two separate sets of cases that can be compared with the instantaneous-loading approximation.

Section 3 describes the assumed salt repositories and gives the emplacement scenarios. The designs are based on current generic salt idealizations¹ and give suitable bases to estimate the time- and space-dependent distribution of wastes throughout the repository.

The conceptual and quantitative models used in the actual calculation of temperatures in the repository are described in Sect. 4. The thermal environments calculated are representative of the average near-field temperatures in the repository host rock. Effects at distances far from the repository are not calculated because it is not expected that the peak temperatures that occur long after waste emplacement will be much affected by the details of the loading scenario. Temperatures in the immediate vicinity of the waste packages are also not calculated. It is not expected that sequential loading will have much effect on the very-near-field temperatures (waste package and immediate vicinity).

Section 5 displays the results of the calculations and compares the thermal environments for the sequential-loading scenario to those for instantaneous emplacement. Section 6 gives the conclusions of this comparison.

The authors acknowledge the contribution of David Joy and Stephen McGuire of Oak Ridge National Laboratory and Michael Anthony of the Office of Nuclear Waste Isolation, who provided waste inventory and transportation data and careful answers to detailed questions regarding repository waste receipt rates.

2. EMPLACEMENT RATES

To calculate the temperature buildup in a repository, the time- and space-dependent heat generation rate must be known. Waste will begin to contribute to this temperature increase when it is emplaced in the repository, and this contribution will depend upon its age (time since discharge from the reactor) and its thermal decay, which determine its time-dependent heat generation rate in the repository. The collective effect of all the waste emplaced in the repository then gives the source term for the calculations. In this section, waste emplacement rates and age are determined for the thermal analysis to

provide the source term for the calculations. These data are based on reasonable projections regarding waste generation in the future. The actual quantities of waste to be generated are, of course, unknown. However, the assumptions regarding the projections are realistically based on a conservative growth of nuclear power. The projections determine an inventory of waste available for the repository in terms of quantity and time since discharge from the reactor. The actual receipt rates of waste depend on the locations of SF storage sites with respect to the repository (and of reprocessing plants, in the case of the reprocessing fuel cycle), the status of the SF pool capacity, and transportation requirements. Assumptions regarding these points have been made in ref. 2 and are used here to determine waste availability. In addition, the receipt rates depend on whether all the waste is shipped to a single national repository or distributed among several regional repositories. For example, a national repository may be constructed to serve the entire continental United States. This repository would receive all of the waste until its capacity was reached. In the regional repository concept, several repositories would begin operation simultaneously and receive waste from associated regions of the country. Therefore, it would be expected that the regional repositories would fill more slowly than a single national repository, thus resulting in different thermal environments. In this report both concepts are considered.

2.1 Spent-Fuel Inventory

The SF inventory will be that generated by all U.S. commercial reactors, and the quantity generated depends on the specific nuclear power growth. For this study, it is assumed that the nuclear generating capacity will grow to a maximum of 225 GW(e) by the year 2005. This growth rate is based on current trends^{1,2} and is consistent with both the Energy Information Administration medium-growth projection² and the July 1980 Department of Energy growth scenario.²

The inventory has two components: a backlog generated prior to repository startup and waste produced after the repository is opened.

The backlog must be worked off even while the newer SF is being shipped to the repository; this requirement, of course, affects the SF shipment rate. In this report, it is assumed that the repository will begin emplacement operations in the year 2000. The amount of SF generated after this time is based on projections, and the backlog takes into account already existing SF.

2.1.1 Backlog inventory

The backlog inventory consists of all the SF generated prior to the beginning of repository operations in the year 2000. To calculate this backlog, the amount of SF generated to date (end of 1980) and actually existing in SF pools is combined with projections for generation through the year 2000. Utility data were used for the backlog inventories to date.³ These data represent actual fuel assemblies discharged from U.S. light-water reactors from 1962 to 1977. For the years 1978 to 1980, utility projections indicative of operating reactors from which the actual 1977 data were extracted are used.

The resulting data are shown in Table 1 for a southern repository and in Table 2 for a national repository. The utility data are given in numbers of pressurized-water reactor (PWR) and boiling-water reactor (BWR) fuel assemblies. It has been assumed that the southern repository will receive approximately 40% of the total backlog through 1980 (based on the installed capacity in this region).

For the backlog inventory generated from 1981 through 2000, SF projections were used. Projections by state in the United States for the 225-GW(e) growth case (by 2005) were taken from ref. 2. In this case, the fraction allocated to the southern repository was based on generating capacity in the South. The backlog inventory data for 1981-2000 in ref. 2 are available only in metric tons of uranium (MTU) charged to the reactor and do not distinguish between BWR and PWR assemblies. The conversion to SF is made by assuming a 2:1 ratio of PWR to BWR SF by weight. This ratio is based on the ratio of installed capacities and does not take into account the small effect due to the difference in core sizes. The conversion is then completed by

Table 1. SF backlog inventory^a
(southern regional repository)

Year ^b	PWR	BWR	Year ^{b,c}	PWR	BWR
1962	30	75	1981	858	1179
1963	16	--	1982	976	1350
1964	15	39	1983	1303	1800
1965	15	81	1984	1421	1959
1966	15	24	1985	1690	2331
1967	16	54	1986	1863	2571
1968	15	72	1987	2017	2781
1969	31	48	1988	2158	2976
1970	22	72	1989	2332	3216
1971	46	162	1990	2349	3240
1972	113	300	1991	2601	3588
1973	66	183	1992	2670	3684
1974	200	534	1993	2516	3468
1975	374	429	1994	2779	3834
1976	445	627	1995	2529	4080
1977	538	1209	1996	2560	3531
1978	789	1257	1997	2885	3978
1979	944	1248	1998	2907	4008
1980	1170	1506	1999	2664	3672
			2000	2694	3717

^aSF assemblies.

^bYear in which the SF was discharged.

^cFrom 1981-2000 based on growth to 225 GW(e) by 2005.

Table 2. SF backlog inventory^a
(national repository)

Year ^b	PWR	BWR	Year ^{b,c}	PWR	BWR
1962	74	189	1981	2153	2976
1963	40	—	1982	2631	3636
1964	36	96	1983	3412	4719
1965	38	201	1984	3580	4950
1966	36	60	1985	4285	5925
1967	40	135	1986	4800	6636
1968	36	183	1987	5100	7053
1969	76	120	1988	5380	7440
1970	54	180	1989	5880	8133
1971	114	402	1990	5926	8196
1972	282	747	1991	6097	8433
1973	165	459	1992	6558	9069
1974	499	1335	1993	6422	8883
1975	935	1071	1994	6562	9069
1976	1112	1566	1995	6968	9636
1977	1346	3024	1996	6531	9033
1978	1973	3141	1997	6855	9480
1979	2361	3117	1998	6972	9642
1980	2924	3762	1999	6625	9162
			2000	6464	8940

^aSF assemblies.

^bYear in which the SF was discharged.

^cFrom 1981-2000 based on growth to 225 GW(e) by 2005.

assuming 0.461 MTU/PWR assembly and 0.183 MTU/BWR assembly. The resulting data are shown in Table 1 for a southern repository and in Table 2 for a national repository.

2.1.2 Projected inventory

The inventory after the year 2000 is based on the forecasts of reactor usage in ref. 2. These forecasts assume that the nuclear economy will grow until 2005, at which time the last reactor(s) will go on-line. It is also assumed that the reactors will have a 40-year operational lifetime, yielding waste generation until 2045. The associated projections based on the midrange 225-GW(e) economy are given in ref. 2.

2.2 SF and HLW Emplacement Rates

The repository scenario in this study begins operations in the year 2000. Knowing the backlog and projected waste production, the SF receipt rates after 2000 can be evaluated, taking into account transportation and other logistical considerations. The resulting data are summarized in Table 3 for the southern regional repository and in Table 4 for the national repository. These data include the arrivals of projected SF as well as the rate at which the backlog is worked off. The data are given in terms of MTU (assuming 0.461 MTU/PWR assembly and 0.183 MTU/BWR assembly for the backlog). Strictly speaking, these rates are based on the receipt of canisters containing SF elements. It is assumed that the same rates apply for a reprocessing fuel cycle. The average age of the SF and HLW arriving at the repository in a given year is also given in the tables. The numerical average is used for the backlog contribution because this value for the age is only negligibly different from the decay-weighted value. For the projected inventory, the average age is taken from the data in ref. 2.

It is assumed that emplacement takes place immediately after the canisters arrive at the repository so that the emplacement rates and decay characteristics of the emplaced SF or HLW can be easily determined. Approximate emplacement rates in terms of canisters can be

Table 3. SF receipt rate and age
(southern regional repository)

Year	PWR		BWR		Total	
	MTU ^a	Age ^b	MTU	Age	MTU	Age
2000	885	22.7	485	23.6	1370	23.0
2001	1030	20.6	566	20.2	1600	20.4
2002	1050	19.4	553	19.4	1620	19.4
2003	1160	19.5	636	19.5	1690	19.5
2004	1070	19.4	587	19.4	1660	19.4
2005	1130	18.6	620	18.6	1750	18.6
2006	1150	18.4	632	18.5	1790	18.4
2007	1270	18.3	694	18.3	1960	18.3
2008	1170	17.7	642	17.8	1810	17.7
2009	1370	17.8	750	17.8	2120	17.8
2010	1400	17.9	768	17.9	2170	17.9
2011	1410	17.9	775	17.9	2190	17.9
2012	1460	17.6	800	17.6	2260	17.6
2013	1450	17.7	794	17.7	2240	17.7
2014	1510	18.0	827	18.0	2330	18.0
2015	1540	17.6	844	17.6	2380	17.6
2016	1610	17.5	884	17.5	2500	17.5
2017	1630	17.4	894	17.4	2520	17.4
2018	1630	16.8	896	17.1	2530	17.1
2019	1610	16.4	884	16.9	2500	16.9
2020	1660	15.7	910	16.4	2570	15.9
2021	1650	15.7	904	15.7	2550	15.7
2022	1690	16.1	929	16.1	2620	16.1
2023	1710	16.4	940	16.4	2650	16.4
2024	1790	16.4	984	16.4	2770	16.4
2025	1780	16.6	978	16.6	2760	16.6
2026	1790	16.5	983	16.5	2770	16.5
2027	1750	16.3	960	16.3	2710	16.3
2028	1820	16.4	998	16.4	2820	16.4
2029	1780	16.1	976	16.1	2750	16.1
2030	1730	15.6	950	15.6	2680	15.6
2031	1740	15.3	954	15.3	2690	15.3
2032	1720	15.0	943	15.0	2660	15.0
2033	1630	15.0	895	15.0	2520	15.0
2034	1620	14.6	892	14.6	2520	14.6
2035	1530	14.3	838	14.3	2364	14.3
2036	1490	14.2	816	14.2	2300	14.2
2037	1320	13.9	726	13.9	2050	13.9
2038	1260	13.6	690	13.6	1950	13.6
2039	1090	13.4	599	13.4	1690	13.4
2040	1270	15.6	698	15.6	1970	15.6

Table 3. (continued)

Year	PWR		BWR		Total	
	MTU ^a	Age ^b	MTU	Age	MTU	Age
2041	1240	16.0	682	16.0	1920	16.0
2042	1240	16.3	681	16.3	1920	16.3
2043	1250	17.3	688	17.3	1940	17.3
2044	1180	17.4	649	17.4	1830	17.4
2045	1170	17.5	644	17.5	1810	17.5
2046	1130	18.2	620	18.2	1750	18.2
2047	1210	17.3	664	17.3	1870	17.3
2048	1210	16.7	609	16.7	1820	16.7
2049	433	13.0	238	13.0	671	13.0
2050	393	12.0	216	12.0	609	12.0
2051	352	12.0	194	12.0	546	12.0
2052	241	12.0	133	12.0	374	12.0
2053	291	12.0	160	12.0	451	12.0
2054	250	11.0	138	11.0	388	11.0
2055	248	11.0	136	11.0	384	11.0
2056	149	11.0	82	11.0	231	11.0

^aAssumed 0.461 MTU/PWR assembly and 0.183 MTU/BWR assembly.

^bAverage years since discharge from reactor.

determined from the average loading per canister. For example, the conversion is often given as 1 PWR assembly (0.461 MTU)/canister or 3 BWR assemblies (0.549 MTU)/canister for the case of SF disposal.⁴ For the reprocessing fuel cycle, a conversion based on a borosilicate glass waste matrix with a fission product density corresponding to 9.77 MTU/m³ would then, for a standard HLW canister containing 178 liters of solidified HLW form, result in 1.74 MTU/canister.

3. REPOSITORY DESIGN

The canisters of SF or HLW arriving at the repository will be distributed throughout the repository in an orderly sequence based on the canisters already emplaced, loading criteria, and the repository design. A critical element in the determination of the repository

Table 4. SF receipt rate and age
(national repository)

Year	PWR		BWR		Total	
	MTU ^a	Age ^b	MTU	Age	MTU	Age
2000	3740	18.5	2050	19.0	5790	18.7
2001	4090	17.8	2250	18.3	6340	18.0
2002	4070	17.4	2240	17.6	6310	17.5
2003	4170	17.4	2290	17.6	6460	17.5
2004	4130	17.4	2270	17.6	6400	17.5
2005	3410	17.4	1870	17.5	5280	17.4
2006	2800	16.7	1540	16.9	4330	16.7
2007	2930	16.4	1610	16.8	4530	16.5
2008	2940	16.2	1610	16.5	4550	16.3
2009	3090	16.1	1690	16.4	4780	16.2
2010	3420	16.2	1880	16.4	5300	16.3
2011	3430	16.0	1880	16.0	5310	16.0
2012	3580	16.1	1970	16.1	5550	16.1
2013	3700	15.8	2030	15.8	5730	15.8
2014	3840	15.9	2110	15.9	5950	15.9
2015	3820	15.6	2100	15.6	5920	15.6
2016	3990	14.6	2190	14.6	6170	14.6
2017	4120	14.8	2260	14.8	6380	14.8
2018	4130	14.7	2270	14.7	6400	14.7
2019	4260	14.8	2340	14.8	6600	14.8
2020	4330	15.0	2380	15.0	6710	15.0
2021	4320	15.0	2370	15.0	6690	15.0
2022	4380	15.0	2400	15.0	6780	15.0
2023	4420	15.0	2420	15.0	6840	15.0
2024	4460	15.0	2450	15.0	6900	15.0
2025	4470	15.1	2460	15.1	6930	15.1

^aAssumed 0.461 MTU/PWR assembly and 0.183 MTU/per BWR assembly.

^bAverage years since discharge from reactor.

emplacement scenario is the design of the repository itself. These designs do not yet exist in detail, although generic conceptual designs based on preliminary criteria have been developed.¹ In this report, designs are described for SF and HLW repositories in salt as a basis for the determination of emplacement scenarios. Again, these bases are purely suppositional, although they are reasonable. The

designs are all based on the considerations made for salt repositories and the instantaneous-loading approximation; the designs for the southern repository, the national repository, and the instantaneously loaded repository are the same.

Once the repository layout is given, the emplacement rates can be used to determine the repository heat generation rate, which is used as the source term for calculating the temperatures in the sequentially loaded repository.

3.1 Salt SF Repository

A typical salt SF repository layout from ref. 1 is shown in Fig. 1. This design is based on the instantaneous loading of 10-year-old SF at a local loading density of 25 W/m^2 (100 kW/acre) at emplacement for both the BWR and PWR areas. Averaged over the entire repository, including passive areas of the repository, this loading corresponds to 15 W/m^2 (60 kW/acre) at emplacement, which satisfies certain thermal and mechanical criteria for a repository in salt.⁵

A modification of this design to accommodate the SF that would be sent to the southern repository is shown in Fig. 2. This repository will not accommodate all of the SF for the entire nation, but it provides a common basis for the evaluations. The total area of this repository is 860 ha (2120 acres), and the average loading at emplacement is 15 W/m^2 (60 kW/acre) for 10-year-old SF. This repository includes corridors, shaft pillars, and service areas as well as SF areas, which are all included to determine the average loading. Therefore, the maximum local areal loading in the SF area will actually be different from this value. A total of 341 ha (860 acres) is allocated to the PWR areas, and 168 ha (414 acres) is allocated to the BWR areas. The local loading density is 0.021 MTU/m^2 in the PWR areas and 0.025 MTU/m^2 in the BWR areas, which would result in a local thermal loading of 25 W/m^2 (100 kW/acre) if the SF were all instantaneously loaded at age 10 years.

The layout in Fig. 2 is divided into regions that are described in Table 5. Note that the layout is symmetric about the repository

Fig. 1. SF repository — reference design.

Fig. 2. SF repository layout.

Table 5. Salt repository descriptions^a

Region numbers	Waste type	<u>SF repository</u>		
		m ² /region	Cans/region	MTU/region
1-9	BWR	95,400	4,280	2,350
10-15	PWR	166,000	7,490	3,450
16-20	PWR	152,000	6,880	3,170

Region numbers	<u>HLW repository</u>		
	m ² /region	Cans/region	MTU/region
1-11	235,000	2,720	4,730

^aThe repositories are symmetric about the central corridor. For SF, regions 21-40 duplicate regions 1-20; for HLW, regions 12-22 duplicate regions 1-11.

centerline. Emplacement operations are assumed to follow this symmetry; that is, storage rooms on opposite sides of the repository are assumed to be filled simultaneously. The determination of the repository heat generation rates must take this symmetry into account as well.

3.2 Salt HLW Repository

A design considered for the generic environmental impact statement for canonical HLW¹ is shown in Fig. 3. As in the SF case, the areal thermal loading within the HLW area is 25 W/m² (100 kW/acre) for 10-year-old waste. The HLW disposal requires 60% of the total repository area. The remainder is used for cladding wastes (CW), low-level

wastes (LLW), intermediate-level wastes (ILW), and the shaft pillar. The analogous layout for this study is shown in Fig. 4. Again, as in the SF case, the repository area is 860 ha (2120 acres). The HLW area is designed for 0.020 MTU/m^2 , which corresponds to the thermal limit of 25 W/m^2 (100 kW/acre) for 10-year-old waste. In this design the shaft pillar is outside the HLW area. In this case the convention is to average over only the thermally active area so that the average loading is also 25 W/m^2 . The HLW area is 515 ha, about 60% of the total. This design will accommodate about 60,000 canisters and, therefore, all of the projected waste that could be sent to either a southern regional or national HLW repository. As in the SF case, the repository design is symmetric about the centerline. The characteristics of this repository are also summarized in Table 5.

3.3 Repository Emplacement Scenarios

The SF or HLW that arrives at the repository first is assumed to be emplaced in the storage rooms farthest from the handling areas near the loading shaft. Gradually the repository is filled toward the shaft pillar, that is, from outside to inside, with canisters. Using the arrival rates in Tables 3 and 4, the emplacement scenarios can then be determined by filling the repository according to the emplacement scheme. The resulting scenarios are given in Tables 6-9. The regions specified on these tables refer to those marked in Figs. 2 and 4 and detailed in Table 5. The year given refers to the time when the last canister will be emplaced in the region. Also given is the average age of SF or HLW in the region at the time the region is filled. In these evaluations, the symmetry of the repository is taken into account. For example, the SF repository contains 40 regions. Only 20 are specified because the second 20 have characteristics duplicating those of the first 20.

It can be seen from Tables 6 and 7 that the national SF repository fills more quickly than the regional repository because of the difference in SF canister receipt rates. Furthermore, because of the difference in repository design, the HLW repository fills somewhat more rapidly than the SF repository, as can be seen by comparing Tables 6 and 8 or 7 and 9.

Fig. 4. HLW repository layout.

Table 6. Sequential-loading scenario^a — SF repository
for southern region.

BWR region ^b	Year ^c	Age ^d	PWR region ^b	Year ^c	Age ^d
1	2007.9	23.3	10	2006.5	22.4
2	2014.1	20.8	11	2011.8	20.5
3	2019.5	20.1	12	2016.4	20.0
4	2024.6	18.8	13	2020.6	18.9
5	2029.4	18.8	14	2024.7	18.1
6	2034.4	17.8	15	2028.6	18.4
7	2040.7	17.5	16	2032.2	17.6
8	2047.8	20.7	17	2036.1	16.7
9	2056.0	17.2	18	2041.1	16.8
			19	2046.3	19.6
			20	2056.0	19.2

^aEmplacement begins in the year 2000. Regions are filled successively.

^bRefer to Fig. 2.

^cYear in which the region is filled.

^dAverage age in years of all waste in region when region is filled.

Table 7. Sequential-loading scenario^a — national
SF repository

BWR region ^b	Year ^c	Age ^d	PWR region ^b	Year ^c	Age ^d
1	2002.2	19.6	10	2001.8	19.0
2	2004.3	18.6	11	2003.5	18.3
3	2006.7	18.8	12	2005.2	18.3
4	2009.6	18.0	13	2007.4	18.1
5	2012.2	17.5	14	2009.7	17.4
6	2014.5	17.0	15	2011.8	17.1
7	2016.7	16.5	16	2013.5	16.8
8	2018.8	15.8	17	2015.2	16.7
9	2020.8	15.9	18	2016.8	15.9
			19	2018.4	15.5
			20	2019.9	15.5

^aEmplacement begins in the year 2000. Regions are filled successively.

^bRefer to Fig. 2.

^cYear in which the region is filled.

^dAverage age in years of all waste in region when region is filled.

Table 8. Sequential-loading scenario^a — HLW repository in southern region

Region ^b	Year ^c	Age ^d
1	2005.8	22.8
2	2010.7	20.4
3	2014.9	19.9
4	2018.7	19.3
5	2022.4	18.0
6	2025.9	18.2
7	2029.3	18.1
8	2032.8	17.3
9	2036.7	16.6
10	2041.6	16.9
11	2046.7	19.8

^aEmplacement begins in the year 2000. Regions are filled successively.

^bRefer to Fig. 4.

^cYear in which the region is filled.

^dAverage age in years of all waste in region when region is filled.

Table 9. Sequential-loading scenario^a — national HLW repository

Region ^b	Year ^c	Age ^d
1	2001.6	19.1
2	2003.1	18.4
3	2004.5	18.2
4	2006.3	18.3
5	2008.4	17.6
6	2010.4	17.2
7	2012.1	17.0
8	2013.8	16.8
9	2015.4	16.6
10	2017.0	15.8
11	2018.5	15.4

^aEmplacement begins in the year 2000. Regions are filled successively.

^bRefer to Fig. 4.

^cYear in which the region is filled.

^dAverage age in years of all waste in region when region is filled.

A forecast of the effects to be expected can be seen in Figs. 5 and 6. These figures give the maximum local loading and the average loading for the repository based upon the arrival rates in Tables 3 and 4 for the southern and national repositories, respectively. It can be seen that for the southern repository (Fig. 5) the maximum local SF loading is about 21 W/m^2 whereas the average loading reaches a peak of only about 8 W/m^2 . Because the design values based on instantaneous loading are 25 W/m^2 for the local thermal loading and 15 W/m^2 for the average loading, these curves suggest that although local temperatures at an isolated location in the repository are likely to be slightly lower than the instantaneous-loading approximation, the overall effect of the realistic scenario will be very different from the simple case. Similarly, for the HLW repository the sequential loading gives a peak local loading of about 21 W/m^2 whereas the average loading is less than 10 W/m^2 . Because both the local and average design values are 25 W/m^2 in this case, an even greater difference between local and average effects is predicted. Figure 6 for the national repository suggests this difference to a lesser degree. In this case the maximum SF loadings are 21 and 14 W/m^2 for the local and average values, respectively, occurring when the repository is nearly filled. These nearly correspond to the design values. For HLW the local and average loadings are both nearly 21 W/m^2 , compared to the design value of 25 W/m^2 . Therefore, temperature environments for the national repository are expected to be somewhat closer to the instantaneous-loading approximation than are the temperature environments of the regional repository.

4. CALCULATIONAL APPROACH

The instantaneous-loading approximation considerably simplifies the calculations of the near-field thermal environment for the geologic repository. Because the SF in all packages is assumed to have the same time dependence everywhere in the repository, the repository conceptual model consists of an array of identical unit cells. The boundaries of these unit cells lie along the lines of symmetry between the packages, so the calculation reduces to the determination of temperature within a single unit cell that contains, for example, a

Fig. 5. Average and maximum local thermal loadings — southern repository.

Fig. 6. Average and maximum local thermal loadings - national repository.

single package and is subject to adiabatic or reflective boundary conditions at the boundaries. However, this simplification cannot be made for the sequentially loaded repository. Because of the nonuniform heat generation rate throughout the repository and because of the sequential loading of the packages, this symmetry does not exist for the more realistic repositories. The approach must take into account the detailed spatial variation of heat generation rates over the extent of the repository. For homogeneous media with thermal properties that do not depend upon position, a superposition technique can be used to simplify the calculation. The temperature increase due to a single package can be evaluated using semianalytic or other approaches, and the increases due to all canisters with varying arrival times and heat generation characteristics can be summed to give the overall temperature rise at a specified time and position. Unfortunately, the thermal conductivity of salt is known to depend upon temperature, so the conductivity will vary with position in the presence of any temperature gradient. Therefore, the linearity assumption needed for a superposition approach and for the application of semi-analytic methods of calculation is not applicable. A more sophisticated approach is therefore required and has been applied in this analysis. The conceptual model and the numerical approach used in this analysis are described below.

4.1 Conceptual Model

The conceptual model to be used must take into account the formation and distribution of the SF or HLW throughout the entire repository. A schematic of this model is shown in Fig. 7. The repository is shown at a horizon 600 m below the surface of the earth. The formation corresponds to a salt dome or a thick salt unit in a bedded salt formation. In the model, boundaries are assumed to extend nearly 2500 m below the repository and 3000 m horizontally beyond the repository. Such a large extent of salt does not correspond to any real formation, but this description does not significantly affect the results until long after startup of repository emplacement operations. Therefore, the results are expected to be typical of both salt domes and thick salt beds.

Fig. 7. Salt repository conceptual model.

The repository itself extends over an 860-ha area and is assumed to be 10 m thick. This thickness is somewhat larger than the actual extent of the heat generating region of the repository, which roughly corresponds to the length of the waste packages. Therefore, the calculated temperatures, which depend on the heat load per unit length of the canister, will be somewhat less than maximum local values. However, they are still expected to be a good representation of average near-field values.

The repository layout is divided into regions as in Figs. 2 or 4. Each region is sufficiently small that variations in arrival rates and heat generation characteristics within the region are not significant but large enough to facilitate the calculational technique. The regions are specified in detail in Table 5. The repository heat generation rate depends on the rate of emplacement into these regions and on the heat generation rate following emplacement. The SF or HLW emplaced into the repository is assumed to have the properties given in Table 10, which gives a generic heat generation rate/MTU as a function of the age since discharge from the reactor. These values are based on a burnup of 33,000 MWd/MTU for the PWRs and 27,500 MWd/MTU for the BWRs and ORIGEN⁶ evaluations of the radioactive decay. Tables 5 and 10 combined with the emplacement rates in Sect. 3 then define the source terms for the heat transfer calculation.

4.2 Numerical Treatment

The temperatures are obtained from the solution of the Fourier heat conduction equation for the conceptual model. The boundary conditions at the horizontal boundaries at the surface of the earth and below the repository are specified temperatures corresponding to the ambient geothermal gradient. These temperatures are 15°C at the surface of the earth and 130°C at a depth of 3000 m. The ambient temperature at the repository horizon is therefore 38°C. Adiabatic boundary conditions are used for the vertical boundaries. In any case, these boundaries are sufficiently far removed from the heat source that they have no significant effect on temperatures within the repository during the time frame of interest, approximately 1000 years or less following initial emplacement of waste in the repository.

Table 10. Generic heat generation rates

Age of waste ^a	Rate (kW/MTU)		
	SF-PWR	SF-BWR	HLW
10	1.19	0.996	1.24
15	1.00	0.836	1.01
20	0.890	0.746	0.857
25	0.808	0.678	0.745
30	0.739	0.620	0.658
40	0.624	0.525	0.497
50	0.534	0.450	0.385
100	0.289	0.249	0.161
200	0.163	0.143	0.037
400	0.110	0.098	0.021
1000	0.055	0.050	0.010

^aYears since reactor discharge.

The thermal conductivity of the salt host rock is taken from ref. 7 and is given in Table 11. The volumetric heat capacity is assumed to be essentially constant and equal to $1.83 \times 10^{-6} \text{ J/m}^3 \cdot \text{K}$.

A 3-D finite-difference approach is used for the numerical determinations. The HEATING5 heat conduction code⁸ was used. This code allows the treatment of the nonlinear thermal properties of the salt host rock and has been successfully applied in the past to the calculation of near-field thermal environments for salt repositories.⁹ A Crank-Nicolson scheme is used to set up the finite-difference equations, which are solved with a successive overrelaxation iteration approach. Care has been given to mesh spacing, time steps, and convergence criteria to ensure a numerical uncertainty in the calculated temperature rises of less than 5%.

Table 11. Assumed thermal conductivity of salt.

Temperature (°C)	Conductivity (W/m·K)
0	6.11
50	5.02
100	4.20
150	3.60
200	3.11
250	2.77
300	2.49
350	2.30

5. RESULTS

5.1 Salt SF Repository

The calculated maximum temperature histories for a sequentially loaded southern SF repository are shown in Fig. 8. In this figure the maximum temperature in the sequentially loaded repository is compared with that in the instantaneously loaded repository. It can be seen that actual repository temperatures will lag behind the instantaneous-loading approximation results by 20 to 40 years and that peak values of the maximum temperature will fall about 20°C below the value in the more simplistic instantaneous-loading model. Eventually, at times which are long compared to the emplacement period, the predictions converge and the instantaneous-loading case provides a fairly accurate representation of the near-field temperatures.

Depending on the emplacement scenario and the heat generation characteristics of the SF, the location where the maximum temperature occurs moves as the SF is emplaced in the repository. Also seen in Fig. 8 is a comparison of the maximum temperature history with the temperature history at a reference point. The time axis in this figure refers to the time after emplacement. The reference point

Fig. 8. Southern salt SF repository temperature histories.

corresponds to the location of maximum temperature occurrence in the instantaneous loading case. As can be seen, the maximum temperature location moves toward the reference point, crosses it, and moves on. The comparison between the reference temperature and the temperature at the same point in the instantaneously loaded repository shows an even larger difference than before. In this case the temperature remains at ambient values for many years until the SF is emplaced near this location. Eventually the effects of the details of the emplacement scenario are lost and the temperatures fall off together.

The results for a national SF repository in salt are shown in Fig. 9. In this case it can be seen that the sequentially loaded repository temperatures approach the instantaneously loaded repository values more quickly because more SF is available and the repository is loaded more quickly. The peak temperatures in the two cases differ by less than 5°C. At long times, as in the case of the regional repository, the temperatures tend to converge. However, the maximum temperatures for the sequentially loaded repository actually exceed the values for the idealized repository. This difference is due to the heat generation characteristics for the realistic case. The instantaneously loaded SF is all assumed to be 10 years old in the year 2000 and is therefore 30 years old 20 years after repository startup. The SF going into the sequentially loaded national repository 20 years after startup is approximately 15 years old, nearly 15 years younger, with a correspondingly higher heat generation rate. The maximum temperatures depend on all the SF in the repository; nevertheless, this difference persists long after the emplacement period and is reflected in the crossover shown in Fig. 9.

The results just discussed refer to isolated points within the repository. For much of the repository, however, the difference between the actual temperatures and the conservative estimates will last even longer. A feeling for the distribution of temperatures in the repositories can be obtained in Figs. 10-12. In these figures the temperatures at the repository horizon are shown for the southern and national sequentially loaded repositories and for the instantaneously loaded repository at 10, 30, and 60 years after repository startup.

Fig. 9. National salt SF repository temperature histories.

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Fig. 10. Temperatures of SF repositories 10 years after emplacement.

Fig. 11. Temperatures of SF repositories 30 years after emplacement.

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Fig. 12. Temperatures of SF repositories 60 years after emplacement.

Because of the symmetry in the repository layout and the emplacement of SF about the repository centerline, the temperature distributions are also symmetric. To clarify the display, only half the distribution is shown. The location of the shaft area in these figures can be identified with the areas in Fig. 2 to orient the display.

The distributions for the SF repositories show large regions within the repository that will remain at ambient temperatures for many years in contrast to the instantaneous-loading representation. In the first 10 years, temperature increases occur only in the end wings of the repository, producing the "psychiatrist's couch" shape of the distribution. Eventually, much later, the central PWR area temperatures will increase. A temperature profile across the repository dramatically illustrates the effect. Figure 13 gives these profiles across the section labeled A-A in Fig. 2. The maximum temperatures in the repository occur across this section. It can be seen that at selected points in this model, substantial temperature rises on the order of 85°C occur. However, for most of the profile, there is a wide variation between the realistic repository results and the conservative limit.

5.2 Salt HLW Repository

In Figs. 14-19 analogous comparisons are made for the salt HLW repository. Figure 14 gives the comparison of temperature histories for the southern HLW repository. The characteristic delay between the reference point temperature and the instantaneous-loading approximation is about 30 years, 20 years of which is due to the delay in loading the waste near the reference location. The peak temperature rise differs by only about 25% in the two cases. Figure 15 shows the results for a national HLW repository in salt. In this case, although the delay is less, the peak temperatures for the realistic repository still remain well below those for the simple model. The comparison of temperature distributions is shown in Figs. 16, 17, and 18 at 10, 25, and 50 years after repository startup, respectively. It can be seen that the HLW repository fills more rapidly than an equivalent SF repository; therefore, actual temperatures will be closer to the approximation than in the SF case.

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AT 10 YEARS

AT 30 YEARS

AT 60 YEARS

Fig. 13. Temperature profiles for SF repositories.

Fig. 14. Southern salt HLW repository temperature histories.

Fig. 15. National salt HLW repository temperature histories.

Fig. 16. Temperatures of HLW repositories 10 years after emplacement.

Fig. 17. Temperatures of HLW repositories 25 years after emplacement.

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Fig. 18. Temperatures of HLW repositories 50 years after emplacement.

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AT 10 YEARS

AT 25 YEARS

AT 50 YEARS

Fig. 19. Temperature profiles for HLW repositories.

Even so, the differences are large. Less than half the southern repository HLW area has any significant temperature increase in the first 25 years; by this time the instantaneously loaded repository has nearly reached its peak temperature throughout. The national repository is loaded more quickly, so temperature increases in the regions close to the shaft, which are loaded last, occur earlier. Nevertheless, the repository is less than half-full 10 years after the start of emplacement (due to the availability of waste), and the 50°C temperature rise at this time obtained with the instantaneous-loading approximation is a poor representation of the actual environment.

These points are illustrated quantitatively in the temperature profiles in Fig. 19. These profiles are evaluated at section B-B in Fig. 4, corresponding to the section of maximum temperature rise in the repository. At the HLW area midpoint 25 years after startup, the temperature rise is less than 5°C for the southern repository and less than 40°C for the national repository whereas the instantaneous-loading temperature rise is 60°C. At no point did the temperature rise in the sequentially loaded model exceed 75% of the rise in the instantaneously loaded model.

6. CONCLUSIONS

The temperature distributions and histories that will actually occur in a repository will vary markedly from the instantaneous-loading idealizations calculated heretofore. At a specific location in the repository, both the time before any significant rise in temperature occurs and the peak temperature itself could be quite different from the results for the more simplistic model. In spite of this characteristic, peak temperatures predicted in the instantaneous-loading approximation are not significantly different from the peak overall repository temperatures in the more realistic model, particularly in the case of the national repository concept. The approximate values are normally somewhat larger and therefore provide conservative estimates of the thermal environments in the first 100 years following repository startup. At later times the instantaneously loaded repository may actually predict temperatures that are slightly low because of the variation in heat generation properties in actual repositories.

Even so, the differences in these values from the actual temperatures are expected to be small, and the simple model is probably useful in estimating worst-case conditions, even at long times.

However, the instantaneous-loading approximation does not provide an accurate picture of temperatures at specific locations in the repository. For example, the use of this approximation to extrapolate early measured temperatures to eventual repository thermal environments will provide special difficulties. The results imply substantial differences between the actual temperatures calculated in both the instantaneous- and sequential-loading models and the shapes of the temperature history curves for early times. Therefore, simple scaling rules or effective conductivities will not be useful, and the more realistic models will be necessary to predict the spatially dependent temperatures. Likewise the use of temperatures in the early stages of a repository or test facility will require some care to predict long-term performance. In the sequential-loading calculations, large regions loaded quickly give, in the first 10 years, a thermal response that is quite small. Therefore, to provide meaningful measurements, special experiments will have to be designed to exaggerate these responses. Analyses of these measurements will clearly need to take into account the detailed distribution of heat sources in order to give useful interpretation to the results. The extension to the environments associated with the eventual distributions within a repository will also need care and will require detailed modeling to provide useful predictions.

Finally, based on thermal environments alone, it is clear that repository designs are very conservative. In some cases, these designs are based on temperature rises calculated in the simple models that will be considerably reduced in actuality. For example, the shaft pillars will be designed to take into account temperature gradients and to ensure their mechanical stability in the presence of these gradients. Yet it is clear, at least for the first 60 years of repository life, that the actual temperature gradients in the shaft pillar will be much less than those calculated in the instantaneous-loading approximation. Therefore, the repository designs themselves may be influenced by the results from the sequential-loading models.

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688. R. F. Turner, General Atomic Company, Box 81608, San Diego, CA 92138
689. U.S. Department of Energy, Library Room 1223, 20 Massachusetts Avenue NW, Washington, DC 20001
690. U.S. Department of Energy, Region IX Office, ATTN: Public Reading Room, 111 Pine Street, San Francisco, CA 94111
691. Maurice A. Van Nostrand, Chairman, Iowa State Commerce Commission, Statehouse, Des Moines, IA 50319
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- 709. Woodward-Clyde Consultants, Library, Western Region 3 Embarcadero Center, Suite 700, San Francisco, CA 94111
- 710. Kenneth S. Wurm, Battelle's Columbus Laboratories, Room 11-3082, X-4322, Columbus, OH 43201
- 711. P. A. Ybarra, Rockwell Hanford Operations, Energy Systems Group, P.O. Box 800, Richland, WA 99352
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- 713. Michael Zolensky, Pennsylvania State University, 236 Deike Building, University Park, PA 16802