BSC

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Complete only applicable items.

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DISCLAIMER

The calculations contained in this document were developed by Bechtel SAIC Company, LLC (BSC) and are intended solely for the use of BSC in its work for the Yucca Mountain Project.

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ACRONYMS

BWR	boiling water reactor
CRCF	Canister Receipt and Closure Facility
CSNF	commercial spent nuclear fuel
DHLW	Defense high-level waste
DOE	U.S. Department of Energy
DPC	dual-purpose canister
DTN	data tracking number
ELWS	estimated limiting waste stream
GWd/MTHM	gigawatt-days per metric ton heavy metal
IED	Interface Exchange Drawing
IHF	Initial Handling Facility
INL	Idaho National Laboratory
MCO	multi-canister overpack
MTHM	metric tons heavy metal
PWR	pressurized water reactor
SNF	spent nuclear fuel
SR	Savannah River site
TAD	Transportation, Aging and Disposal canister
TEV	Transportation and Emplacement Vehicle
UFPR	unit flux pulse temperature response
WHF	Wet Handling Facility

1. PURPOSE

The purpose of this calculation is to simulate the processing of an incoming waste stream into waste packages, simulating the required aging as applicable, and the emplacement of the waste packages into the Yucca Mountain repository.

Qualified software WPLOAD v. 2.0 will be used to determine the order and schedule of waste package emplacement based on thermal loading criteria. The results of the base calculation case will be shown to comply with thermal criteria to be referenced in the License Application. Additional calculation cases will be performed to show flexibility to varying waste stream arrival scenarios, thermal loading criteria, and thermal properties of the repository host rock layer.

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2.3 DESIGN CONSTRAINTS

None

2.4 DESIGN OUTPUTS

This calculation is performed to support information in the License Application.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

3.1.1 The commercial fuel assembly waste stream scenarios described in Section 6.1.1 are assumed as input for this calculation. The files containing the arrival order and specific characteristics of the waste form are included on CD Attachment I, as listed in Attachment III. These are non-qualified inputs for the purpose of representativeness.

Rationale: The precise shipment schedule of the commercial waste form has not yet been established, and a significant amount of the planned waste stream has not yet been produced. The intent of the Project is to analyze each drift in an as-loaded/built configuration, since the waste stream is not known and each drift will be uniquely loaded.

3.1.2 The DHLW canister arrival sequence used in this calculation is derived from Attachment I of Ref. 2.2.13, and listed in Section 6.1.3.

Rationale: The precise shipment schedule of the DHLW canisters has not yet been established. This reference is used because it is the only source of this information.

3.1.3 All DHLW canisters of each type are assumed to have the same decay heat history, as calculated and listed in Section 6.1.5. The decay heat history is derived from Ref. 2.2.11. In the reference, the decay heat of DHLW canisters from Idaho National Laboratory is listed from 2035 on, but in this calculation they are assumed to have been created in 2010, along with the other DHLW canister types.

Rationale: The single decay heat curve for DHLW canisters is derived from Ref. 2.2.11. The reference used bounding values of radionuclide inventories, and therefore provides a bounding thermal power history. Much of the DHLW has yet to be placed into canisters, so more precision is not possible at this time. It is expected that if and when the complete set of values is available, they will be below those used here. This assumption is suitable for this calculation, which determines the feasibility of thermal management and sensitivity to key parameters.

3.1.4 The rock stratigraphy throughout the repository is assumed to be the same as that identified at the G-1 Borehole.

Rationale: The G-1 Borehole is located near the center of the hottest portion of the repository (Ref. 2.2.16, Figure II-4). The G-1 Borehole is also one of the

deepest boreholes, starting at an elevation of 1,326 m (4,351 ft) (Ref. 2.2.19, file: `/Data_Grids_Faults/data/contacts00el.dat`), and extending to a depth of 1,085 m (3,558 ft). DTN: MO0012MWDGFM02.002 (Ref. 2.2.19) is cited in *IED Geotechnical and Thermal Parameters* (Ref. 2.2.23), and therefore is approved and appropriate for the intended use in this calculation.

3.1.5 All Naval canisters are assumed to have the same decay heat history.

Rationale: The single decay heat curve for Naval canisters is taken from pp. 5 through 7 of Ref. 2.2.12. Since only 400 of the 10,000-plus waste packages contain Naval canisters, the impact of this assumption is small. If a large number of Naval waste packages are to be emplaced near one location, further analysis is expected. This assumption is suitable for this calculation, which determines the feasibility of thermal management and sensitivity to key parameters.

3.1.6 It is assumed that the following DTNs, from which data was used for thermal properties of rock as described in Attachment II, will be referenced for transmittal on an IED in the future:

`MO0612MEANTHER.000`	Ref. 2.2.30	TBV-8917
`MO0702PAGLOBAL.000`	Ref. 2.2.31	TBV-8918
`SN0703PAEBSPCE.006`	Ref. 2.2.25	TBV-8901

Rationale: The data from these sources are used as input because they are the most recent values for these properties. This data is qualified, but it is not currently included on an interface exchange drawing. The future inclusion of this data on an interface exchange drawing is being tracked in the Document Input Reference System database via TBV-8917, TBV-8918, and TBV-8901.

3.1.7 It is assumed that the following DTN, from which data was used for thermal properties of rock as described in Attachment II, will be qualified and will be referenced for transmittal on an IED in the future:

`MO0709REVTHERM.000`	Ref. 2.2.29	TBV-8989

Rationale: The data from this source are used as input because they are the most recent values for these properties. This data is statused as preliminary. The future qualification of this DTN, and its inclusion on an interface exchange drawing, is being tracked in the Document Input Reference System database via TBV-8989.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 In the calculation of the unit flux pulse temperature response in Attachment II, the thermal conductivity of Alluvium is assumed to be that of Crystal-Rich Tiva/Post-Tiva. The specific heat of Alluvium and Crystal-Rich Tiva/Post-Tiva are also assumed to be the same as the specific heat of the Tpcp layer (Ref. 2.2.18 and Ref. 2.2.19).

Rationale: The thermal conductivity of Alluvium and the specific heat of Alluvium and Crystal-Rich Tiva/Post-Tiva are not currently available. Using the thermal properties of the next rock layer below is reasonable. Since the Alluvium and Crystal-Rich Tiva/Post-Tiva layers are at the top of the rock pillar, far from the region of interest, the impact of this assumption is negligible.

3.2.2 The Receipt Facility is not represented in WPLOAD v. 2.0.

Rationale: Canisters are placed into aging overpacks in the Receipt Facility. In order to simplify the process, the time required to send canisters to aging is not represented in the WPLOAD v. 2.0 simulation, as it does not affect the emplacement sequence.

3.2.3 The DOE SNF canisters are not explicitly represented in WPLOAD v. 2.0. The thermal power generated by each DOE SNF canister is not included in the calculation of total thermal power generated by the 5-DHLW waste package containing it, and the detailed DOE SNF inventory is not tracked by canister type.

Rationale: Since the DOE SNF is typically very old and/or has a low reactor burnup, its thermal power is negligible. Although they are not explicitly represented, the contractual basis for the minimum number of DOE SNF canisters accepted is maintained, through adjustment of the DHLW canister arrival quantity, as described in Section 6.1.3.

3.2.4 In creating the `.lis` files as described in Section 6.1.2, the following substitutions were made within the file listing:

- For thermal power, gamma source spectrum, neutron source spectrum, and radionuclide concentrations of the plenum and end fitting regions of longer-than-normal length fuel assemblies from the South Texas site, the information for the corresponding regions from normal-length PWR fuel assemblies was substituted.

- For thermal power, gamma source spectrum, neutron source spectrum, and radionuclide concentrations of the end fitting regions of stainless-steel clad PWR and BWR fuel assemblies, the information for the end fitting regions of non-stainless steel clad PWR and BWR fuel assemblies were substituted, respectively.

Rationale: The original source term calculations (Ref. 2.2.4 and Ref. 2.2.5) did not calculate this information for the plenum and end-fitting regions of the

South Texas fuel assemblies, or for the end-fitting regions of stainless-steel clad BWR or PWR fuel assemblies. The differences in these quantities should be negligible between a normal-length fuel assembly and a South Texas fuel assembly, or between a zirconium-clad fuel assembly and a stainless-steel clad fuel assembly, because the design and materials used in these regions is similar for both kinds of fuel assemblies in each case.

Furthermore, the neutron source intensity from these regions is negligible, and the majority of the thermal power, gamma source, and radionuclide concentrations, other than that due to Co_{60}, come from the fuel region of the fuel assembly. All fission reactions occur in the fuel region, and the neutron flux density during operation is much greater in the fuel region of the fuel assembly than in the plenum and end fitting regions.

3.2.5 DHLW canisters are processed into 5-DHLW waste packages in CRCF1 only.

Rationale: Although this does not reflect the current design philosophy, it is consistent with a previous design philosophy, changed while WPLOAD v. 2.0 was in final stages of qualification. The capability of producing 5-DHLW waste packages in all three CRCFs would allow more flexibility to arrival scenarios, hence this assumption is conservative.

3.2.6 In WPLOAD v. 2.0 the DPCs are not sent to the aging pads.

Rationale: DPCs can be placed directly into aging overpacks and aged, but for simplicity in WPLOAD they are treated as other transportation casks that must be opened, and their contents transferred to TADs for aging, as this does not affect the emplacement sequence.

3.2.7 A virtual buffer area is assumed to contain incoming batches of uncanistered CSNF assemblies when the WHF is busy, subject to its processing capacity. A virtual staging area is also assumed to contain Naval canisters and DHLW canisters, when the IHF and/or CRCF1 are busy, respectively. The capacity of these virtual areas that would be required, given the specified arrival schedule, is reported in the WPLOAD output file. However, using the methods described in Section 6.3.2 to control the emplacement of 5-DHLW waste packages invalidates these values in the output file.

Rationale: The function of the virtual staging areas may be represented during actual operations by the queueing of the arriving waste form in the rail yard.

3.2.8 Only one drift is assumed to be open for emplacement at a time.

Rationale: This assumption simplifies the logic in WPLOAD. Even if the design will allow for multiple drifts simultaneously available for emplacement, there will probably be times at which only one drift is available. Simultaneous emplacement in multiple drifts provides more options for thermal management than are included here, hence this assumption is conservative.

3.2.9 As shown in Figure 15 of Attachment II, a 2-D pillar finite element mesh is assumed to represent the repository rock stratigraphy, in the conduction-only calculation of the unit flux pulse temperature response at the mid-pillar rock location and at the drift wall. The calculation of unit flux pulse temperature response is also limited by the use of constant thermal properties in the rock. The properties used were those of rock below the boiling point.

Rationale: This is to allow for quick calculation of rock temperature at the mid-pillar location and at the drift wall thousands of times in one calculation. Since the pillar mesh is bounded by adiabatic surfaces, this approach is conservative (results in higher temperatures than expected in reality). In reality, thermal energy will be transferred away from the repository in all directions, resulting in lower mid-pillar rock temperatures near the edges of the repository than in the center.

Although using the thermal properties of rock below the boiling point results in generally lower temperatures than using the properties of dry rock, in the development of this calculation it was shown that even the case with sub-boiling rock properties results in temperatures higher than a case in which the heat of vaporization is represented. Therefore, representing the thermal properties of rock below the boiling point, and neglecting the heat of vaporization, is conservative.

3.2.10 The reactor discharge of each commercial fuel assembly, and the creation of each DHLW canister, is assumed to occur on Dec. 31 of each respective year, approximated as Jan. 1 of the following year, as listed in the waste stream input files.

Rationale: In the absence of a known date within the year, this is the bounding approach, since it results in the shortest time out of reactor, and therefore the highest thermal power due to decay heat of the fuel assembly.

3.2.11 The specific arrival dates of commercial fuel assemblies, DHLW canisters, and Naval canisters are assumed to be evenly distributed in time over each arrival year specified in the input files.

Rationale: The precise shipment schedule of the commercial waste form has not yet been established, and a significant amount of the planned waste stream has not yet been produced.

3.2.12 In this calculation the TEV is assumed to emplace a maximum of 365 waste packages per year.

Rationale: In order to simplify the process, it is assumed that the TEV will be able to emplace waste packages at a sufficient rate so as not to affect the surface facility processing or emplacement sequence. In WPLOAD v. 2.0 the time required for the TEV to return to handle the next waste package is not represented, so in effect this assumption is only included to add a one-day delay to the emplacement of each waste package.

3.2.13 Although the currently-proposed maximum receipt rate in the IHF is 24 Naval waste packages per year (according to Section 2.2.1.2 of Ref. 2.2.2), a capacity of 160 Naval waste packages per year was used in this calculation, as described in Section 6.3.1.

Rationale: As described in Section 6.3.1, this prevents delays due to the difference in processing rates in the surface facilities subject to the first-in-first-out organizational scheme, and limited by the lack of Naval canister staging.

3.2.14 According to p. 8 of Ref. 2.2.1, the processing capacity of CRCF1 is 164 waste packages per year (assuming processing of DOE waste and TADs), and the processing capacity of CRCF2 and CRCF3 is 183 waste packages per year (assuming processing of only TADs). The values used in Section 6.1.8.3 are 160 and 169, respectively. Ref. 2.2.1 is an unqualified reference, used as input in the absence of a qualified source.

Rationale: The values used in this calculation were taken from a reference that was superseded after this calculation was completed. The values are similar enough, and are conservative, and therefore do not require re-run of the calculation.

3.2.15 According to p. 11 of Ref. 2.2.26, the processing capacity of the WHF is 40 TADs per year. The value used in Section 6.1.8.1 is 27 TADs per year. Ref. 2.2.26 is an unqualified reference, used as input in the absence of a qualified source.

Rationale: The value used in this calculation was taken from a reference that was superseded after this calculation was completed. The value is similar enough to the reference, and is conservative, and therefore does not require re-run of the calculation.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation was prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Ref. 2.1.1). The waste packages are classified as Safety Category items (important to safety and important to waste isolation) in Sections 11.1.2 and 12.1.2 of Ref. 2.2.2. Therefore, the approved version of this document is designated as QA: QA.

4.2 USE OF SOFTWARE

This calculation was performed with qualified (Level 1) software WPLOAD v. 2.0 (Software Tracking Number 11131-2.0-00, Ref. 2.2.34) on the Windows 2000 operating system, on the Dell personal computers with central processing unit (CPU) numbers 150478, YMP001880, and 501927. Usage of WPLOAD v. 2.0 in this calculation constitutes Level 1 software usage, as defined in IT-PRO-0011 (Ref. 2.1.2, Attachment 12). WPLOAD v. 2.0 was used to simulate loading scenarios in the repository. This application is within the range of validation for this software, as described in Ref. 2.2.37. The input and output files of this calculation are included on CD Attachment I, as listed in Attachment III.

Microsoft Excel 97 SR-2, which is a component of Microsoft Office 97, is used for performing simple calculations and plotting results. Microsoft Excel 97 SR-2 was executed on a personal computer running the Microsoft Windows 2000 operating system. Usage of Microsoft Office in this calculation constitutes Level 2 software usage, as defined in IT-PRO-0011 (Ref. 2.1.2, Attachment 12). The simple calculations have been verified by hand, and the plots have been confirmed by visual inspection. The Microsoft Excel files are included on CD Attachment I, as listed in Attachment III.

ANSYS v. 8.0 (Ref. 2.2.38) was used to generate the unit flux pulse temperature response, as documented in Attachment II. ANSYS v. 8.0 is identified by the Software Tracking number 10364-8.0-00. Usage of ANSYS v. 8.0 in this calculation constitutes Level 1 software usage, as defined in IT-PRO-0011 (Ref. 2.1.2, Attachment 12). Calculations using the ANSYS v. 8.0 software were executed on the following Hewlett-Packard (HP) 9000 Series workstation running operating system HP-UX 11.00:

> CPU Name: Oliver, Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS M&O) Tag Number: 150688

The ANSYS v. 8.0 evaluations performed in this calculation are fully within its range of validation (Ref. 2.2.39). Therefore, ANSYS v. 8.0 is appropriate for the thermal analysis as performed in this calculation. Access to, and use of, the code for this calculation was granted by Software Configuration Management in accordance with the appropriate procedures.

WinZip version 8.1 was used on a Dell personal computer, running the Microsoft Windows 2000 operating system, to create the `.zip` files on CD Attachment I, as listed in Attachment III. Usage of WinZip version 8.1 in this calculation constitutes Level 2 software usage, as defined in IT-PRO-0011 (Ref. 2.1.2, Attachment 12). The zipped files have been verified by visual inspection.

4.3 METHOD

The emplacement of the arriving waste stream into the repository was simulated using the WPLOAD v. 2.0 software. The input permutations in each case are listed in Section 6.4. The text output files from the program were then imported and graphed using Microsoft Excel.

Finite element analysis numerical solutions were used to generate the unit flux pulse temperature response, as documented in Attachment II, using the commercially available code ANSYS v. 8.0 (Ref. 2.2.38). A 2-D representation of the rock layer stratigraphy was used to determine the rock temperature history resulting from a specified heat flux into the drift wall. The unit flux pulse temperature response was then used in WPLOAD v. 2.0 to calculate temperature history at the mid-pillar rock location and at the drift wall. This method is described in Ref. 2.2.35.

Some simple calculations were performed by hand throughout this document.

5. LIST OF ATTACHMENTS

I Compact disk

II Calculation of unit flux pulse temperature response

III List of files on CD Attachment I

6. CALCULATION

WPLOAD v. 2.0 is used to simulate the processing of an incoming waste stream into waste packages, and the emplacement of the waste packages into the repository. The order and schedule of waste package emplacement is determined based on user-specified thermal loading criteria. A detailed description of WPLOAD v. 2.0 is given in Ref. 2.2.35 and Ref. 2.2.36.

6.1 INPUTS

6.1.1 Commercial fuel assembly waste stream

The commercial fuel assembly waste stream arrival scenarios used in this calculation are the following (see Assumption 3.1.1):

- The 1999 Case B 63,000 MTHM waste stream, arriving between 2010 and 2033, was used in Cases 1 and 2 of this calculation (see Section 6.4). This waste stream sequence was truncated to 63,000 MTHM from the original 83,800 MTHM Case B waste stream described in *1999 Design Basis Waste Input Report* (Ref. 2.2.14). The waste stream arrival projection taken from this document (as with any waste stream arrival scenario at this time) is unqualified, due to its associated uncertainty. It is used here as input in the absence of a qualified source. The original Case B waste stream is characterized in Tables 9, 12, and 13, Figure 1, and Appendices B and E of Ref. 2.2.14. However, due to the truncation, the characteristics of the waste stream described in the reference do not exactly apply to the waste stream used in this calculation.

  An emplacement scenario for this waste stream compliant with the thermal criteria listed in Section 6.2 is intended to support the License Application.

- The estimated limiting waste stream (ELWS), described in Ref. 2.2.28, was used in Cases 3a, 3b, and 4 of this calculation (see Section 6.4). The waste stream arrival projection taken from this document (as with any waste stream arrival scenario at this time) is unqualified, due to its associated uncertainty. It is used here as input in the absence of a qualified source. This waste stream represents 63,000 MTHM, youngest fuel shipped first, arriving a minimum of five years out-of-reactor, with a 22-kW maximum thermal power generated within each TAD upon arrival.

Table 1 lists the quantity of waste form arriving each year in each waste stream scenario (see Assumption 3.2.11). The complete list of fuel assemblies comprising each waste stream is included in the files on CD Attachment I, as listed in Attachment III.

Table 1. Quantity of waste form (MTHM) arriving per year in each waste stream scenario

	1999 Case B 63,000 MTHM	**Estimated Limiting Waste Stream**
2010	419	0
2011	635	0
2012	1184	0
2013	1982	0
2014	≈ 3000	0
2015	≈ 3000	0
2016	≈ 3000	0
2017	≈ 3000	320
2018	≈ 3000	561
2019	≈ 3000	1056
2020	≈ 3000	1804
2021	≈ 3000	2725
2022	≈ 3000	≈ 3000
2023 through 2031	≈ 3000	≈ 3000
2032	≈ 3000	≈ 3000
2033	1786	≈ 3000
2034	0	≈ 3000
2035	0	≈ 3000
2036	0	≈ 3000
2037	0	≈ 3000
2038	0	≈ 3000
2039	0	≈ 3000
2040	0	2520

For each waste stream scenario, Table 2 lists the quantity of CSNF assemblies that arrive sealed in TADs, relative to the quantity of uncanistered fuel assemblies shipped in DPCs and/or truck transportation casks, which are placed into new TADs in the WHF.

Table 2. Relative quantities of waste form shipped in TADs and shipped uncanistered

	Number of fuel assemblies		**MTHM**	
	1999 Case B 63,000 MTHM	**ELWS YFF522kW**	**1999 Case B 63,000 MTHM**	**ELWS YFF522kW**
Uncanistered **BWR** fuel assemblies	11,298	8,158	1,983	1,299
BWR fuel assemblies arriving sealed in TADs	116,624	119,924	20,547	21,130
Uncanistered **PWR** fuel assemblies	17,607	14,547	7,448	6,136
PWR fuel assemblies arriving sealed in TADs	76,089	79,028	33,022	34,435
TOTAL	**221,618**	**221,657**	**63,000**	**63,000**

The two waste stream scenarios are characterized in Figure 1 through Figure 3. Figure 1 and Figure 2 show the burnup and time out of reactor of the fuel assemblies in each scenario. The thermal power produced by each fuel assembly at any point in time is strongly dependent on the reactor burnup of the fuel assembly and the time since its discharge from the reactor (neglecting the relatively small dependence on initial enrichment U_{235}). Figure 3 shows the total thermal power generated by the fuel assemblies in each TAD on arrival, for both waste stream cases.

In this calculation, all fuel assemblies are assumed to arrive generating a slightly higher thermal power than calculated in the waste stream references. This is because the decay heat of each fuel assembly was calculated in the references based on a specific date of discharge from the reactor, and in WPLOAD v. 2.0 it is conservatively assumed that each fuel assembly is discharged from the reactor on Dec. 31 of the known year (see Assumption 3.2.10). The greatest impact of this assumption is on the decay heat of a fuel assembly discharged in early January, and having spent the shortest possible time out of reactor (which is just over five years in the estimated limiting waste stream). In WPLOAD, this fuel assembly is assumed to have been discharged on Dec. 31, and therefore to have been just over four years out of reactor. As shown in Figure 3, although the estimated limiting waste stream scenario was created such that TADs would not arrive containing fuel assemblies generating a total thermal power in excess of 22 kW, TADs full of these worst-case fuel assemblies are assumed to arrive with up to 26 kW.

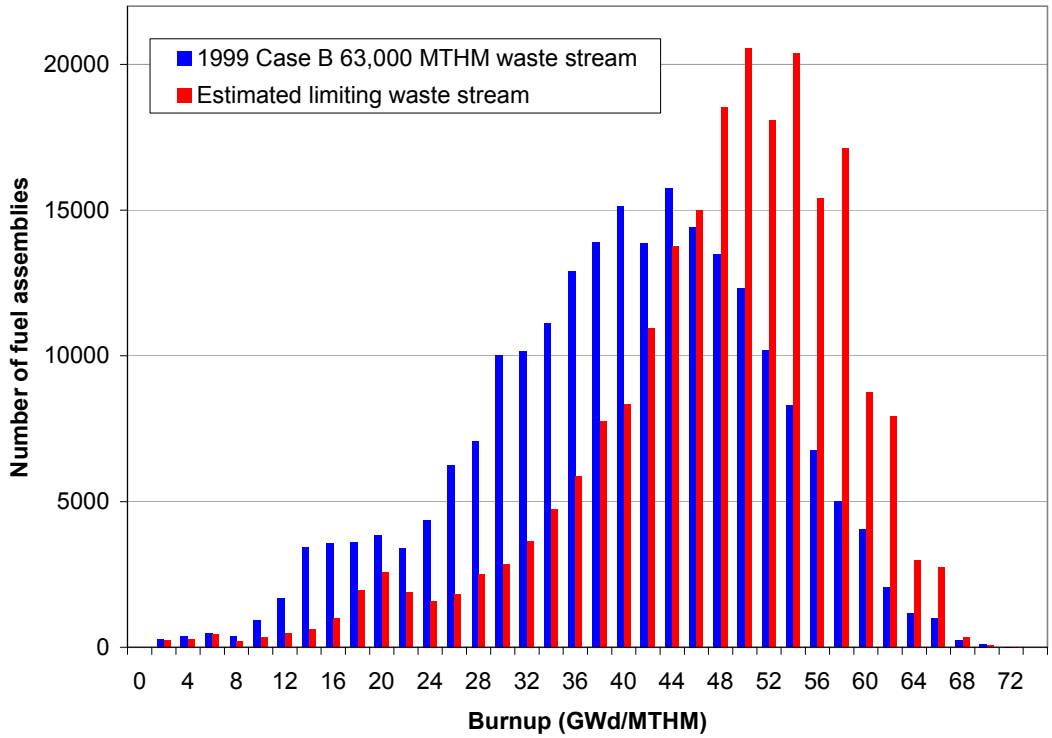

Figure 1. Reactor burnup of commercial fuel assemblies in each waste stream scenario

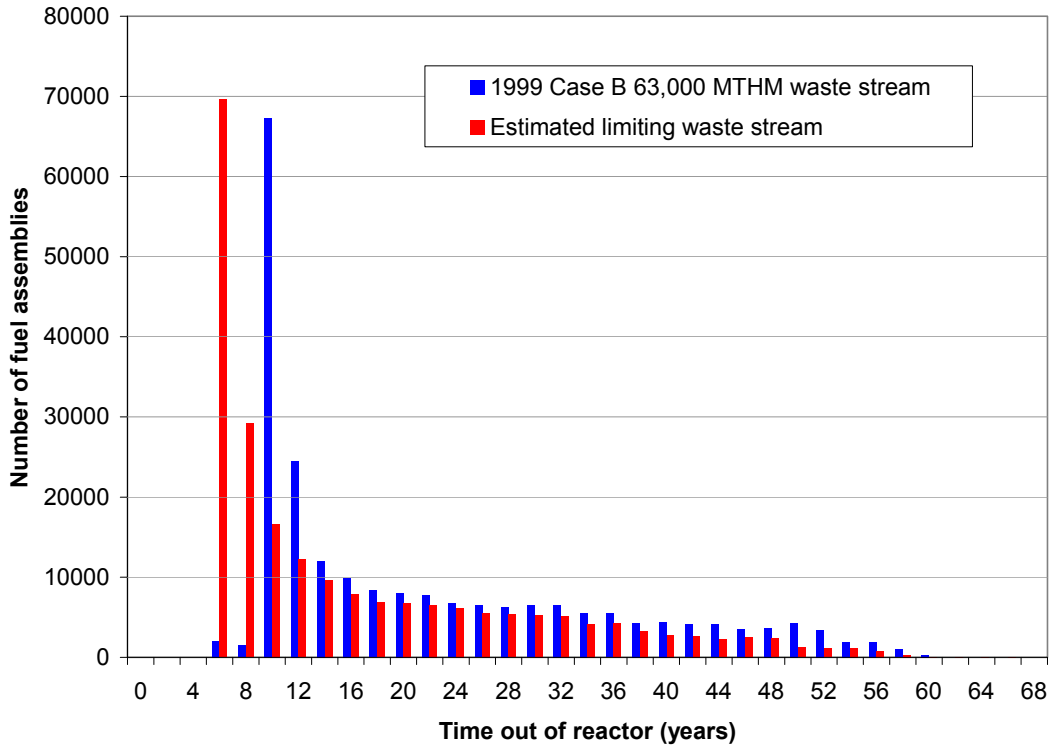

Figure 2. Time out of reactor for commercial fuel assemblies in each waste stream scenario

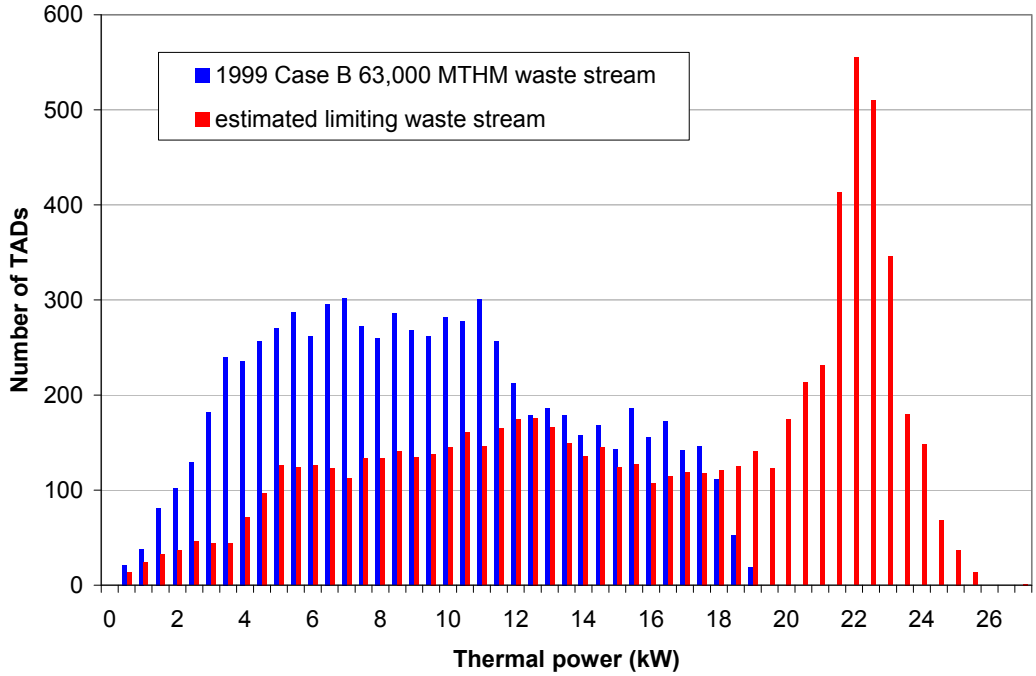

Figure 3. Thermal power generated by the fuel assemblies in each TAD upon arrival

6.1.2 Commercial fuel assembly thermal power

The thermal power produced by the radioactive decay of nuclides in each commercial fuel assembly is determined in WPLOAD v. 2.0 through interpolation on tables from files generated by the qualified ORIGEN software. These tables list the decay heat of a representative fuel assembly as a function of its burnup, initial U_{235} enrichment and time out of reactor (see Assumption 3.2.10).

The ORIGEN output containing this information is processed into `.cut.watts` files in Ref. 2.2.27. This processing results in the creation of 6,136 files, each representing an incremental change in fuel assembly burnup and initial % enrichment U_{235}, for the fuel and non-fuel regions of the following commercial fuel assembly types:

- non-stainless steel clad PWR fuel assemblies
- stainless-steel clad PWR fuel assemblies
- non-stainless steel clad BWR fuel assemblies
- stainless-steel clad BWR fuel assemblies
- Fuel assemblies from the South Texas site

These files were taken from CD Attachment II of Ref. 2.2.27 and used as input to this calculation. They are included on CD Attachment I and listed in Attachment III. The `.cut.watts` files are processed as described in Section 2.3.9 of Ref. 2.2.36, and are used to create the fuel assembly decay heat tables on which to interpolate. Although they were not used in this calculation, the `.cut.gammas`, `.cut.neutrons`, and `.cut.curies` files were also processed by WPLOAD as described in Section 2.3.9 of Ref. 2.2.36, and the resulting `.source` files are also included on CD Attachment I and listed in Attachment III.

Table 3. ORIGEN output files from Ref. 2.2.27

File extension	Content	Number of files
`.cut.curies`	Radionuclide concentration	1,534
`.cut.neutrons`	Neutron source spectrum	1,534
`.cut.gammas`	Gamma source spectrum	1,534
`.cut.watts`	Thermal power	1,534
	TOTAL	6,136

The following files are used as input by WPLOAD, and contain the listing and characteristics of the `.cut.gammas`, `.cut.neutrons`, `.cut.curies`, and `.cut.watts` files, as described in Section 2.3.9 of Ref. 2.2.36:

```
files_curies.lis
files_gammas.lis
files_neutrons.lis
files_watts.lis
```

For this calculation they were consolidated from the `.lis` files from CD Attachment II of Ref. 2.2.27. In creating these files, the following substitutions were made within the file listing (see Assumption 3.2.4):

- For thermal power, gamma source spectrum, neutron source spectrum, and radionuclide concentration of the non-fuel regions of fuel assemblies from the South Texas site, the information for the non-fuel regions of PWR fuel assemblies (not from the South Texas site) was substituted.

- For thermal power, gamma source spectrum, neutron source spectrum, and radionuclide concentration of the end fitting regions of stainless-steel clad PWR and BWR fuel assemblies, the information for the end fitting regions of non-stainless steel clad PWR and BWR fuel assemblies were substituted, respectively.

The design basis mass of heavy metal used for each of the ORIGEN calculations is listed in Table 4, which is required as input by WPLOAD, and used in the interpolation (see Section 2.3.9 of Ref. 2.2.36 for details).

Table 4. Design basis mass of heavy metal used in ORIGEN calculations to determine decay heat of fuel assemblies

Fuel assembly type	Design basis mass of heavy metal (MTHM per assembly)	Reference
PWR fuel assemblies with non-stainless steel cladding	0.475	Section 5.2 of Ref. 2.2.4
PWR fuel assemblies with stainless steel cladding	0.475	Section 5.2 of Ref. 2.2.4
BWR fuel assemblies with non-stainless steel cladding	0.200	Section 5.3 of Ref. 2.2.5
BWR fuel assemblies with stainless steel cladding	0.200	Section 5.3 of Ref. 2.2.5
Fuel assemblies from the South Texas site	0.550	Section 5.2 of Ref. 2.2.4

6.1.3 DHLW canister arrival sequence

The DHLW canister arrival schedule used in this calculation is shown in Table 5. The arrival schedule is adapted from Attachment I of Ref. 2.2.13 (see Assumption 3.1.2), with the following modifications:

1) Yucca Mountain shall accept 7,000 MTHM of non-commercial waste form, to include two-thirds (4,667 MTHM-equivalent) DHLW canisters (approximated at 0.5 MTHM/DHLW canister [p. A-37, Ref. 2.2.15]), and one-third (2,333 MTHM-equivalent) DOE SNF (p. A-36, Ref. 2.2.15).

   The full quantity of DHLW canisters listed in Ref. 2.2.13 (about 19,000 canisters) was therefore truncated to 4,667 MTHM-equivalent (9,334 canisters), which would require **1,866** 5-DHLW waste packages to accomodate.

   The 2,500 total MTHM-equivalent of DOE SNF in Ref. 2.2.13 was also truncated to 2,333 MTHM-equivalent, by removing MCO canisters exclusively, since they are the last DOE SNF to arrive according to Ref. 2.2.13. The last 33 MCO canisters were removed, since each contains approximately 5 MTHM-equivalent (derived from Appendix A, Table A-22 of Ref. 2.2.15), for a total of 167 MTHM-equivalent DOE SNF removed. All 2,347 standard 18-inch DOE SNF canisters remain, along with 408 MCOs.

   The MCO waste form, and the 2-MCO/2-DHLW waste package containing it, are not explicitly represented in WPLOAD v. 2.0. To maintain the correct total number of waste packages, 5-DHLW waste packages are therefore used as a proxy for the 2-MCO/2-DHLW waste packages. The total number of standard 18-inch DOE SNF canisters would require 2,347 5-DHLW waste packages, and 204 more waste packages would be required to accomodate 408 MCOs. Therefore, to represent the minimum amount of DOE SNF in the contract would require 2,347 + 204 = **2,551** total 5-DHLW waste packages.

2) Since the DOE SNF waste stream requires a greater number of 5-DHLW waste packages to accomodate than the DHLW canister waste stream, 3,421 additional DHLW canisters (685 5-DHLW waste packages' worth) were added to the arrival schedule, in order to maintain the 5:1 ratio and accomodate the contractual amount of DOE SNF and DHLW canisters in the same fully loaded 5-DHLW waste packages, such that the arrival schedule will produce exactly **2,551** fully-loaded 5-DHLW waste packages. This results in a total non-commercial waste stream exceeding 7,000 MTHM. The years of added DHLW canisters are represented by the shaded rows in Table 5.

   Therefore, although the DOE SNF canisters are not explicitly represented in WPLOAD v. 2.0 (the thermal power generated by each DOE SNF canister is not included in the calculation of total thermal power generated by the 5-DHLW waste package containing it, and the detailed DOE SNF inventory is not tracked by canister type [see Assumption 3.2.3]), the number of expected DOE SNF canisters given in Ref. 2.2.13 is used to determine the total number of DHLW canisters assumed to arrive.

3) For input to WPLOAD, the arrival schedule in Table 5 was replaced with a scenario in which the same total number of DHLW canisters arrive, but all only in the first year. In the development of this calculation, this solution control method was found to better facilitate an on-demand availability of DHLW canisters in early years, as described in Section 6.3.2.1. The input schedule therefore consists of the entire DHLW canister waste stream arriving in 2010 for Cases 1 and 2, and all arriving in 2017 for Cases 3a, 3b, and 4. All DHLW canisters are therefore designated as residing in the virtual staging area until emplacement. The actual sequence in which the 5-DHLW waste packages are emplaced is given in the output file.

   Since Hanford long DHLW canisters generate a much lower thermal power per unit length than the other canister types, there are often situations in which a 5-DHLW long waste package is required in order to meet linear thermal power or peak mid-pillar temperature criteria, and a 5-DHLW short waste package will not suffice. If too many 5-DHLW long waste packages are used prematurely, it is possible to run out, at which point there could be no solution, and the WPLOAD calculation would run through many years of simulation time, before reporting an error.

   In the input file, the DHLW canisters from Idaho National Lab (INL) and the Savannah River site (SR) are listed first, before the Hanford DHLW canisters. In WPLOAD v. 2.0 this means the total quantity of INL and SR DHLW canisters will be designated as residing in the virtual staging area first. Each time the virtual staging area is checked for a group of five DHLW canisters that can be emplaced in a 5-DHLW waste package and meet the linear thermal criteria, the first DHLW canisters put onto the virtual staging area are the first to be checked. The DHLW canisters from INL and SR are therefore checked first, before those from the Hanford site. In this manner, a heirarchy is imposed on the selection of the different types of DHLW canisters, to conserve the Hanford long canisters until it is certain that no other type of DHLW canister will suffice.

See Section 6.3.2.1 for a full explanation of this method, and see Table 10 for a detailed list of case inputs.

Table 5. Nominal DHLW canister arrival schedule, derived from Ref. 2.2.13, modified to account for 2,333 MTHM-equivalent DOE SNF waste stream (does not represent the actual emplacement schedule)

arrival year	INL	HF	SR	cumulative equivalent MTHM
2010	0	88	105	96.5
2011	0	176	205	287.0
2012	0	176	205	477.5
2013	0	176	205	668.0
2014	0	176	205	858.5
2015	0	176	205	1049.0
2016	0	176	205	1239.5
2017	0	176	205	1430.0
2018	0	222	205	1643.5
2019	0	444	205	1968.0
2020	0	444	205	2292.5
2021	0	444	205	2617.0
2022	43	444	205	2963.0
2023	67	444	205	3321.0
2024	90	444	205	3690.5
2025	114	444	205	4072.0
2026	114	444	205	4453.5
2027	114	108	205	4667.0
2028	114	444	205	5048.5
2029	95	444	205	5420.5
2030	95	444	205	5792.5
2031	95	444	205	6164.5
2032	95	126	205	6379.5

6.1.4 Naval canister arrival sequence

The arrival schedule of Naval canisters used in Cases 1, 2, 3a, and 3b is taken from p. 12 of Ref. 2.2.28, and is repeated here in Table 6. The waste stream arrival projection taken from this document (as with any waste stream arrival scenario at this time) is unqualified, due to its associated uncertainty. It is used here as input in the absence of a qualified source.

As listed in Section 6.4, Case 4 is intended to bound the global effect of a disruption in the Naval waste package emplacement sequence. In Case 4, all Naval canisters are removed from the arrival sequence (except for one, since WPLOAD v. 2.0 requires a non-zero number of Naval canisters in the arrival schedule).

Table 6. Naval canister arrival schedule

Calendar year	Number of Naval canisters	Calendar year	Number of Naval canisters
2017	18	2027	24
2018	10	2028	24
2019	15	2029	24
2020	18	2030	24
2021	21	2031	24
2022	24	2032	24
2023	24	2033	24
2024	24	2034	20
2025	24	2035	10
2026	24		

6.1.5 DHLW canister thermal power history

The history of thermal power produced by each type of DHLW canister, used as input to WPLOAD v. 2.0, is listed in Table 7. The thermal power history was calculated based on the decay heat produced by the radionuclide content of the entire inventory of each type of DHLW canister (taken from CD Attachment I of Ref. 2.2.11), divided by the total expected number of each type (taken from Sections 6.3, 6.4, and 6.6 of Ref. 2.2.11). This calculation was performed in the spreadsheet file `DHLW_can_thermal_power.xls` (included on CD Attachment I as listed in Attachment III). In the reference, the decay heat history is assumed to begin in 2010 for canisters from the Savannah River Site and the Hanford site, and in 2035 for canisters from Idaho National Laboratory. In this calculation, they are all assumed to have been created in 2010 (see Assumptions 3.1.3 and 3.2.10).

Table 7. Decay heat of each type of DHLW canister (watts)

Time since creation (years)	Savannah River Site	Idaho National Laboratory	Hanford site
0	519.52	66.73	65.13
7	440.39	59.11	55.23
20	328.70	44.95	40.65
57	150.16	21.26	17.28
107	59.71	8.42	5.90
207	18.30	1.66	1.33
507	6.36	0.31	0.68
1007	3.08	0.17	0.50
2007	1.27	0.10	0.38

5007	0.72	0.07	0.32
10007	0.58	0.06	0.27
20007	0.41	0.04	0.20
50007	0.21	0.03	0.10
100007	0.12	0.02	0.04
200007	0.10	0.02	0.02
500007	0.07	0.01	0.02
1000007	0.04	0.00	0.01

6.1.6 Naval canister thermal power history

The history of thermal power produced by each Naval canister is taken from pp. 5 through 7 of Ref. 2.2.12, and is repeated here in Table 8 (see Assumption 3.1.5).

Table 8. Decay heat of each Naval canister

Time since arrival (years)	Decay heat (watts)	Time since arrival (years)	Decay heat (watts)	Time since arrival (years)	Decay heat (watts)	Time since arrival (years)	Decay heat (watts)
0	3.98e+03	20	2.25e+03	70	8.17e+02	9000	2.70e+00
1	3.75e+03	21	2.18e+03	80	6.69e+02	10000	2.70e+00
2	3.58e+03	22	2.14e+03	90	5.62e+02	20000	2.50e+00
3	3.44e+03	23	2.10e+03	100	5.01e+02	30000	2.40e+00
4	3.32e+03	24	2.07e+03	150	1.86e+02	40000	2.40e+00
5	3.22e+03	25	2.03e+03	200	8.07e+01	50000	2.50e+00
6	3.12e+03	26	1.97e+03	250	4.18e+01	60000	2.60e+00
7	3.04e+03	27	1.93e+03	300	2.55e+01	70000	2.60e+00
8	2.96e+03	28	1.89e+03	350	1.73e+01	80000	2.70e+00
9	2.89e+03	29	1.86e+03	400	1.27e+01	90000	2.80e+00
10	2.82e+03	30	1.84e+03	450	9.90e+00	100000	2.90e+00
11	2.75e+03	31	1.80e+03	500	8.00e+00	200000	3.10e+00
12	2.68e+03	32	1.75e+03	1000	3.80e+00	300000	2.80e+00
13	2.62e+03	33	1.74e+03	2000	3.10e+00	400000	2.30e+00
14	2.56e+03	34	1.71e+03	3000	3.00e+00	500000	1.90e+00
15	2.50e+03	35	1.65e+03	4000	2.90e+00	600000	1.50e+00
16	2.44e+03	40	1.49e+03	5000	2.80e+00	700000	1.30e+00
17	2.39e+03	45	1.34e+03	6000	2.80e+00	800000	1.00e+00
18	2.34e+03	50	1.27e+03	7000	2.70e+00	900000	9.00e-01
19	2.29e+03	60	1.02e+03	8000	2.70e+00	1000000	7.00e-01

6.1.7 Number and length of available emplacement drifts

The number and length of emplacement drifts used in Cases 1, 2, 3a, and 3b are taken from Section 6.6 of Ref. 2.2.17 (also see Assumption 3.2.8).

As listed in Section 6.4, Case 4 is intended to bound the global effect of a disruption in the Naval waste package emplacement sequence. Since the arrival of Naval canisters is removed from the case (see Section 6.1.4), the first four emplacement drifts are also removed from the available layout, in order to represent the missing length of the 400 Naval waste packages.

6.1.8 Surface facility processing capacity

The WPLOAD v. 2.0 surface facility process is depicted in Attachment I of Ref. 2.2.36. Each facility is represented by its processing capacity, entered as a number of units processed per year (see Assumption 3.2.2).

6.1.8.1 Wet Handling Facility

Uncanistered CSNF assemblies arriving in transportation casks (via truck, or via rail in DPCs) are canistered into TADs in the Wet Handling Facility (see Assumption 3.2.6). If the arrival frequency of these shipments exceeds the processing capacity of the WHF, the excess is accumulated in a virtual buffer area at the entrance of the WHF (see Assumption 3.2.7). The output file indicates the capacity of this buffer area that would be required in order to accomodate the waste form arrival schedule.

In the WHF, uncanistered PWR fuel assemblies are consolidated into 21-PWR TADs, and uncanistered BWR fuel assemblies are consolidated into 44-BWR TADs. The TADs produced by the WHF are then either placed into a waste package in one of the CRCFs or are sent out to aging. In this calculation the WHF processing capacity is 27 TADs filled with incoming fuel assemblies per year (see Assumption 3.2.15).

6.1.8.2 Initial Handling Facility

Arriving Naval canisters are placed into a Naval waste package in the Initial Handling Facility, which is then emplaced via the TEV. Although the currently-proposed maximum receipt rate in the IHF is 24 Naval waste packages per year (according to Section 2.2.1.2 of Ref. 2.2.2), a capacity of 160 Naval waste packages per year was used in this calculation, as described in Section 6.3.1 (see Assumption 3.2.13). As with the WHF, excess shipments of Naval canisters are accumulated in a virtual staging area, whose required capacity is listed in the output file (see Assumption 3.2.7). The TEV processing capacity in this calculation is 365 waste packages emplaced per year (see Assumption 3.2.12).

6.1.8.3 Canister Receipt and Closure Facilities

TADs arriving from the utilities or created in the WHF are processed into waste packages in either CRCF1, CRCF2, or CRCF3, or are sent out to aging, depending on (1) compliance with thermal criteria (see Section 6.2), and (2) the relative availability of each of the CRCFs. After a TAD waste package is created in the CRCF, it is emplaced in a drift via the TEV.

Arriving DHLW canisters are consolidated into either a 5-DHLW short waste package (for canisters from the Idaho National Lab, Savannah River, or West Valley facilities), or a 5-DHLW long waste package (for canisters from the Hanford site) in CRCF1 only (see Assumption 3.2.5). As with the WHF and the IHF, excess shipments of DHLW canisters are accumulated in a virtual staging area, whose required capacity is listed in the output file (see Assumption 3.2.7).

In the case of CRCF2 and CRCF3, the processing capacity is defined as a maximum number of 21-PWR TAD waste packages and/or 44-BWR TAD waste packages produced per year. In the case of CRCF1, the processing capacity is defined as a maximum number of 21-PWR TAD waste packages, 44-BWR TAD waste packages, and/or 5-DHLW waste packages produced per year.

Since CRCF1 is used to create both 5-DHLW and TAD waste packages, and CRCF2 and CRCF3 are only used to create TAD waste packages, in WPLOAD v. 2.0 TAD-processing priority is given to CRCF2 and CRCF3 (during phases in which they are operational) over CRCF1.

In this calculation the processing capacity of CRCF1 is 160 waste packages per year, and the capacity of CRCF2 and CRCF3 is 169 waste packages per year (see Assumption 3.2.14).

6.1.8.4 Three operational phases

WPLOAD v. 2.0 simulates three operational phases, defined by the availability of the surface facilities as shown below:

Operational phase	Surface facilities in operation
First phase:	IHF, WHF, CRCF1
Second phase:	IHF, WHF, CRCF1, CRCF2
Third phase*:	IHF, WHF, CRCF1, CRCF2, CRCF3

* infinite duration, beginning at the end of the second phase

In order to facilitate the virtual aging of all DHLW canisters in the first arrival year, as described in Section 6.3.2.1, the first operational phase was given a duration of only one year, during which CRCF1 was given a very low processing capacity (one waste package per year). This prevented any DHLW canisters from being emplaced in a waste package, and it forced them all to be designated as residing in a virtual staging area. A consequence of reducing the processing rate in this manner is that the arriving TADs are also sent to aging. However, in the waste

stream arrival scenarios used as input to this calculation, the amount of waste form arriving in the first year is relatively small.

The second operational phase was given a duration of four years, consistent with the start-up of CRCF3 five years after the beginning of waste receipt (Section 2.2.1.10 of Ref. 2.2.2).

6.1.9 Unit flux pulse temperature response

The unit flux pulse temperature response (UFPR) is used to determine the mid-pillar rock temperature and drift wall temperature history, as described in Section 2.3.7.1 of Ref. 2.2.36. The UFPR was generated externally in ANSYS, as documented in Attachment II.

6.1.10 Ventilation heat removal efficiency

The fraction of waste package thermal power transferred away by active ventilation during the 100-year pre-closure period is 90%, taken from file `Base Case Analysis Rev01.xls` from Ref. 2.2.24. The DTN in this reference is cited in the interface exchange drawing in Ref. 2.2.33.

6.1.11 Initial rock temperature

The initial rock temperature at the time of loading, used to determine mid-pillar and drift wall temperature history due to the emplacement of each waste package, is 23 °C. This value is estimated at a depth of 300 m from the files `Thermal gradient, SD-12.xmcd` and `Temperature1.txt` in Ref. 2.2.25.

This data is qualified, but it is not currently included on an interface exchange drawing. The future inclusion of this data on an interface exchange drawing is being tracked in the Document Input Reference System database via TBV-8901 (see Assumption 3.1.6).

6.1.12 Waste package length and spacing

Table 9 lists the length of each waste package used in this calculation. The end-to-end spacing between waste packages is 10 cm (Section 8.2.1.7 of Ref. 2.2.2).

Table 9. Waste package lengths

Waste package type	Length (m)	Reference
21-PWR TAD waste package	5.850	Ref. 2.2.6
44-BWR TAD waste package	5.850	Ref. 2.2.6
5-DHLW short waste package	3.697	Ref. 2.2.7
5-DHLW long waste package	5.304	Ref. 2.2.8
Naval waste package	5.533	Average of lengths of Naval short and long WPs, from Ref. 2.2.9 and Ref. 2.2.10, respectively

6.1.13 De-rating criteria

The de-rating criteria (defined in Section 2.3.4 of Ref. 2.2.36) were set to very high values, to ensure that no new TADs filled with fuel assemblies on-site shall be de-rated (sealed with one or more fuel assembly basket cells still vacant), until there are no more fuel assemblies left to arrive.

6.2 THERMAL CRITERIA

6.2.1 Waste package thermal power at emplacement

To limit waste package internal and surface temperatures, as well as drift wall temperature, an upper limit is imposed on the total thermal power generated by the fuel assemblies within any waste package being emplaced. The upper limit on waste package thermal power at emplacement used in this calculation is 11.8 kW (consistent with License Application thermal criteria, and Section 8.2.1.5 of Ref. 2.2.2) for Cases 1 and 2, and 18.0 kW for Cases 3a, 3b, and 4 (see Table 10). Any TAD canister possessing a higher thermal power than this value will be placed into an aging overpack and put outside on the aging pads until the total thermal power generated by the fuel assemblies it contains is below this value.

6.2.2 Linear thermal power at emplacement

As an additional means of limiting drift wall temperature, an upper limit is imposed on linear thermal power at emplacement, as measured over any seven-waste package series in the repository. The upper limit on linear thermal power at emplacement used in this calculation is 1.45 kW/m (consistent with License Application thermal criteria, and Section 8.2.1.5 of Ref. 2.2.2) for Cases 1 and 2, and 2.00 kW/m for Cases 3a, 3b, and 4. Seven waste packages comprise the representative series, consistent with p. 32 of Ref. 2.2.3.

6.2.3 Peak mid-pillar temperature

The peak mid-pillar rock temperature occurring over time in the plane of each seven-waste package series is also used as a criterion to determine the loading sequence of emplacement drifts. The mid-pillar rock temperature is defined as the temperature at a point in the rock half-way between two emplacement drifts, as shown in Figure 13 in Attachment II. The temperature history at this point over hundreds of years of heat flux into the rock is determined in WPLOAD v. 2.0.

The maximum value over time of the mid-pillar rock temperature history calculated for each waste package, is defined as the peak mid-pillar temperature index corresponding to the waste package. The peak mid-pillar temperature indices of the seven waste packages in the representative series are then averaged over the series, weighted by the relative lengths of the waste packages. The resulting peak mid-pillar temperature representing the whole series is then compared to the upper limit, to serve as an emplacement criterion for each waste package (the last waste package of the seven).

The upper limit on peak mid-pillar temperature used in Cases 1, 2, 3b, and 4 is 96 °C, consistent with parameter # 05-03 of Ref. 2.2.40. The upper limit of peak mid-pillar temperature used in Case 3a is 99 °C, determined to be the lowest achievable upper limit with the estimated limiting waste stream. As discussed in Section 6.4, this case is intended to compensate for the conservatism introduced by neglecting the cooling effects of water movement and vaporization within the rock in the 2-D calculation in Attachment II. A lower limit is also imposed on peak mid-pillar temperature in order to strategically maximize the DHLW canister availability in later years, as described in Section 6.3.2.2.

6.3 SOLUTION CONTROLS

6.3.1 Control of Naval waste package queueing in the IHF

Upon arrival of a TAD, Naval canister, or group of five DHLW canisters, the decision is made either to process it into a waste package, to place it into an aging overpack and age it (in the case of TADs), or to suspend its processing and designate it as residing in a virtual zone (in the case of Naval or DHLW canisters). This decision is based in part on thermal criteria specific to the seven-waste package series that the waste package containing this canister would comprise if emplaced in the next open position in the drift, along with the six waste packages already emplaced preceding it. Therefore, although the canister has not yet entered the surface facility to be processed into a waste package, the position the waste package would occupy in the emplacement drift is already being determined.

However, by the time the processing of this canister (or group of five DHLW canisters) into a waste package is complete (dependent upon the processing rate of the surface facility), it is possible that other entities may have already entered other surface facilities, been processed into waste packages, and been emplaced in the same position intended for this first waste package. This is to be expected if the first facility processes waste packages at a significantly lower rate than the others.

The next open position in the emplacement drift must therefore be reserved for any canister (or group of five DHLW canisters) at the moment it enters the surface facility, so as not to allow any other waste package to be emplaced in that position in the drift. Subject to the limitation of sequential loading (the inability to skip over an emplaced waste package in order to load a new waste package behind it), a first-in-first-out scheme is required, as described in the following.

At any point in time, of any set of TADs, Naval canisters, and/or DHLW canisters being simultaneously processed in the IHF and/or any of the CRCFs, the first one to have entered its respective facility will be the first one of this set loaded into the TEV for emplacement, even if other waste packages from other surface facilities are ready for emplacement before the first one is ready. In this manner the position in the drift is reserved for this waste package.

As a result of the first-in-first-out scheme, if at any point in time the first entity to have entered its respective surface facility is being processed more slowly than those in other facilities, the waste package being processed more slowly could make the others wait. Even though the other waste packages are ready to be placed into the TEV, their movement would have to be

suspended. Since there are no staging areas to accomodate an accumulation of waste packages at the back end of each surface facility, the next canister scheduled to enter that facility would therefore have to be sent out to aging, until the waste package had waited its turn and had been placed into the TEV, thereby freeing up the facility. In the development of this calculation it was discovered that, due to the large disparity between the processing capacity of the IHF (24 Naval waste packages per year, or about one every 15 days) and that of the CRCFs (169 waste packages per year, or about one every two days), a significant number of TADs are sent to aging for this reason.

As an example, if a Naval canister enters the IHF on day 1, and three TADs enter the CRCFs on day 2, although the processing of all three TADs will be complete on day 3, their movement will be suspended for an additional thirteen days, since the next open position in the drift is reserved for the Naval waste package, which is still being processed by the IHF. During these thirteen days, any newly arriving TADs will have to be sent to aging. This leads to a higher required capacity of the aging pads, and fewer total TADs being processed per year than should be allowed, according to the nominal processing capacity of the CRCFs.

In this calculation the only way to compensate for this effect is to artificially increase the IHF processing capacity, to remove the disparity between the IHF capacity and that of the CRCFs. This results in the processing of all waste packages at (or much closer to) the full processing capacity of the surface facilities. No cases are presented with the nominal IHF processing capacity of 24 Naval waste packages per year, only the increased capacity of 160 per year (see Assumption 3.2.13). This invalidates the required capacity of the Naval canister virtual staging area reported in the output file.

6.3.2 Optimization of 5-DHLW waste package emplacement sequence

Since a consistently lower thermal power per unit length is generated by the contents of a 5-DHLW waste package than that of a TAD waste package, some degree of strategic positioning of 5-DHLW waste packages within the emplacement drift is important in order to meet restrictive length-based thermal criteria calculated over a series of waste packages. These criteria are linear thermal power at emplacement and peak mid-pillar temperature averaged over each seven-waste package series.

In some situations, only the emplacement of a 5-DHLW waste package will comply with one or both of these critera (for example, keeping the peak mid-pillar temperature below 96 °C). If a 5-DHLW waste package is not available it could cause delays until it arrives, per a specified schedule, or if there are no more left to arrive there could be no solution, and the WPLOAD calculation would run through many years of simulation time, before reporting an error. In other situations, a 5-DHLW waste package might be emplaced even though a commercial TAD waste package with higher thermal power might also meet the criterion. If too many 5-DHLW waste packages are used prematurely, it is possible to run out of DHLW canisters by the end, thereby causing the same problem.

In order to facilitate an optimized emplacement order of 5-DHLW waste packages, the DHLW canister shipments must be available on-demand from the DOE. A schedule of DHLW canister shipments could be strategically dictated, such that each set of five canisters would arrive as close as possible to the moment they are needed. The queueing of arriving DHLW canister shipments in the rail yard would provide a buffer against uncertainty in arrival times.

WPLOAD v. 2.0 does not allow for an adaptive, optimized DHLW canister shipment schedule. Therefore, to approximate an optimized emplacement order of DHLW canisters, the following two steps are taken in this calculation:

1) Artificial manipulation of the DHLW canister arrival schedule, intended to ensure that DHLW canisters are available as soon as possible, to be used when needed (see Section 6.3.2.1).

2) A lower limit on peak mid-pillar temperature as a loading criterion. This ensures that waste packages whose contents generate a lower thermal power per unit length (mainly 5-DHLW, especially 5-DHLW long waste packages) are not emplaced, in any situation in which a higher-thermal-power waste package (mainly TAD waste packages) would also comply. This establishes a selection heirarchy, preventing against using the 5-DHLW waste packages prematurely (see Section 6.3.2.2).

6.3.2.1 Manipulation of DHLW canister arrival schedule, to ensure availability as soon as possible

By entering the nominal DHLW canister arrival scenario listed in Table 5 in the input file `WPLOAD_HLW_ACC_FILE.TXT`, the user is subject to the limitation of DHLW canister arrivals evenly distributed in time within each year. It is therefore impossible to fully represent on-demand availability of DHLW canisters, and depending on the arrival day, some canisters will probably need to be staged in a virtual zone, if the facility is busy or if the group of five violates a thermal loading criterion. With this method, a fixed arrival schedule could be specified, then the output file would indicate precisely what capacity of DHLW canister virtual staging area would be required to accomodate the input arrival schedule. The function of this virtual staging area may be represented during actual operations by the queueing of the arriving DHLW canister shipments in the rail yard.

In the development of this calculation, it was determined that compressing the entire DHLW arrival schedule into only the first year is the most effective means of ensuring all DHLW canisters are available as soon as possible, ensuring on-demand availability. This is accomplished by forcing the CRCF1 capacity to a very low number (one waste package per year) in the first year, such that all DHLW canisters are stored in the virtual staging area in the first year. With this method, a DHLW canister arrival schedule is not specified, and the DHLW canister emplacement sequence can be inferred from the output.

Since Hanford long DHLW canisters generate a much lower thermal power per unit length than the other canister types, there are often situations in which a 5-DHLW long waste package is required in order to meet linear thermal power or peak mid-pillar temperature criteria, and a 5-DHLW short waste package will not suffice. If too many 5-DHLW long waste packages are used prematurely, it is possible to run out, at which point there could be no solution, and the WPLOAD calculation would run through many years of simulation time, before reporting an error.

In the input file, the DHLW canisters from Idaho National Lab and the Savannah River site are listed first, before the Hanford DHLW canisters. In WPLOAD v. 2.0 this means the total quantity of INL and SR DHLW canisters will be designated as residing in the virtual staging area first. Each time the virtual staging area is checked for a group of five DHLW canisters that can be emplaced in a 5-DHLW waste package and meet the linear thermal criteria, the first DHLW canisters put onto the virtual staging area are the first to be checked. The DHLW canisters from INL and SR are therefore checked first, before those from the Hanford site. In this manner the Hanford long canisters are conserved until it is certain that no other type of DHLW canister will suffice.

Using this method, the capacity of DHLW canister virtual staging area required to accomodate the input arrival schedule, as reported in the output file, is invalid. In effect, all DHLW canisters are designated as residing in the virtual staging area at one time. However, given the DHLW canister emplacement sequence in the output file, the capacity of the virtual staging area required to accomodate a given shipment schedule can be determined externally.

6.3.2.2 Lower limit on peak mid-pillar temperature, to ensure availability in later years

A lower limit is imposed on peak mid-pillar temperature as an emplacement criterion in early years, in addition to the upper limit. This ensures that waste packages whose contents generate a lower thermal power per unit length (mainly 5-DHLW, especially 5-DHLW long waste packages) are not emplaced, in any situation in which a higher-thermal-power waste package (mainly TAD waste packages) would also comply. In this manner a heirarchy is established for emplacement selection, preventing against using the 5-DHLW waste packages (especially 5-DHLW long waste packages) prematurely.

The lower limit on peak mid-pillar temperature is imposed during a specified period defined by a calendar year. After this year the lower limit is no longer used as an emplacement criterion. The value of the lower limit and the year at which to remove the lower limit may be strategically varied to get an acceptable solution. The values of the lower limit used in each calculation case are listed in Table 11.

As with the manipulation of DHLW canister arrival schedule described in Section 6.3.2.1, this method invalidates the capacity of virtual staging area required to accomodate the input arrival schedule, as reported in the output file. The required capacity of the virtual staging area, given an actual arrival schedule, would therefore need to be determined externally as described in Section 6.3.2.1.

6.4 CALCULATION CASES

Calculation Case 1 uses as input the 1999 Case B 63,000 MTHM waste stream (see Section 6.1.1), derived from the *1999 Design Basis Waste Input Report* (Ref. 2.2.14). The waste stream arrival projection taken from this document (as with any waste stream arrival scenario at this time) is unqualified, due to its associated uncertainty. It is used here as input in the absence of a qualified source. An emplacement scenario for this waste stream compliant with the thermal criteria listed in Section 6.2 is intended to support the License Application.

Calculation Case 2 is intended to show sensitivity to thermal properties of the repository host rock layer. As above, Case 2 uses as input the 1999 Case B 63,000 MTHM waste stream derived from Ref. 2.2.14. Case 2 differs from Case 1 in the repository host rock layer thermal properties, as listed in Table 10 and Attachment II.

Calculation Cases 3a and 3b are intended to show thermal flexibility by representing the estimated limiting waste stream (ELWS) described in Ref. 2.2.28. The waste stream arrival projection taken from this document (as with any waste stream arrival scenario at this time) is unqualified, due to its associated uncertainty. It is used here as input in the absence of a qualified source. The upper limit imposed on waste package thermal power at emplacement is increased to 18.0 kW, and the upper limit on linear thermal power over each seven-waste package series at emplacement is increased to 2.00 kW/m.

The estimated limiting waste stream consists of fuel assemblies generating a much higher thermal power over time than those of the 1999 Case B 63,000 MTHM waste stream (see Figure 3). In order to simulate the emplacement of this higher-thermal power waste stream in compliance with thermal loading criteria, Cases 3a and 3b provide two different ways to compensate for the conservatism of the conduction-only 2-D calculation of mid-pillar temperature history. The conduction-only 2-D calculation, as described in Attachment II, neglects the cooling effects of vaporization and water movement in the rock. According to Section 6.2 of Ref. 2.2.41, roughly 10 °C higher peak mid-pillar rock temperatures can be expected in a calculation neglecting the effect of vaporization or movement of water in the rock. To partially compensate for this conservatism, the following two calculation cases were performed:

- Case 3a simulates emplacement of the ELWS subject to a higher upper limit of peak mid-pillar temperature. This is intended to partially compensate for the margin shown in Ref. 2.2.41.

- In Case 3b, calculation of the peak mid-pillar temperature itself is performed using thermal properties in every rock layer the same as those of the repository host rock layer, consistent with Section 8.2.1.5 of Ref. 2.2.2. Since the thermal conductivity of the repository host rock layer (Tptpll) is generally higher than that of all other layers, this results in a lower peak mid-pillar temperature.

Case 4 is intended to support special emplacement considerations made for Naval waste packages. If the emplacement of Naval waste packages shall be subject to a unique set of emplacement criteria concerning thermal power and/or proximity to other waste package types, it would disrupt the emplacement order relative to the nominal scenario in Case 3b, which is shown to comply with thermal performance criteria. Since the Naval waste packages possess a relatively low thermal power at emplacement, and a relatively low peak mid-pillar temperature index, their sequence of emplacement throughout the drifts may be important in order to comply with thermal criteria, as the sequence of emplacement of 5-DHLW waste packages is shown to be in Section 6.3.2. Case 4 is intended to bound the effect of a disruption in this sequence, by removing all Naval waste packages from the emplacement sequence. The first four emplacement drifts are also removed from the repository layout, in order to represent the missing length of the 400 Naval waste packages.

Table 10. Inputs used in calculation cases

	Case 1	Case 2	Case 3a	Case 3b	Case 4
	1999 Waste Stream	**1999 Waste Stream, with sensitivity to repository host rock layer thermal properties**	**Estimated Limiting Waste Stream, with elevated peak mid-pillar temperature criterion**	**Estimated Limiting Waste Stream, using same properties for all rock layers as those of the repository host rock layer**	**Bounding Case Showing Effect of Special Consideration for Naval Waste Packages**
Commercial fuel assembly waste stream	1999 Case B 63,000 MTHM	1999 Case B 63,000 MTHM	ELWS YFF5 22 kW	ELWS YFF5 22 kW	ELWS YFF5 22 kW
DHLW canister arrival schedule[1]	available in 2010 by demand[1]	available in 2010 by demand[1]	available in 2017 by demand[1]	available in 2017 by demand[1]	available in 2017 by demand[1]
Naval canister arrival schedule	nominal, arrival begins in 2010	nominal, arrival begins in 2010	nominal, arrival begins in 2017	nominal, arrival begins in 2017	nominal, arrival begins in 2017
Repository host rock (Tptpll) layer thermal properties used to determine mid-pillar rock temperature	property values from qualified DTN transmitted on an IED[2]	more recent property values, global-mean value of thermal conductivity[3]	more recent property values, global-mean value of thermal conductivity[3]	more recent property values, global-mean value of thermal conductivity[3], all rock layers assumed to have the same properties as the repository host layer	more recent property values, global-mean value of thermal conductivity[3], all rock layers assumed to have the same properties as the repository host layer
Repository host rock (Tptpll) layer thermal properties used to determine drift wall temperature	property values from qualified DTN transmitted on an IED[2]	more recent property values, global-mean value of thermal conductivity[3]	more recent property values, 10th-percentile value of thermal conductivity[4]	more recent property values, 10th-percentile value of thermal conductivity[4]	more recent property values, 10th-percentile value of thermal conductivity[4]
Upper limit on waste package thermal power at emplacement	11.8 kW	11.8 kW	18.0 kW	18.0 kW	18.0 kW
Upper limit on linear thermal power at emplacement	1.45 kW/m	1.45 kW/m	2.00 kW/m	2.00 kW/m	2.00 kW/m
Number of waste packages in representative series	seven waste packages	seven waste packages	seven waste packages	seven waste packages	seven waste packages
Ventilation heat removal efficiency during pre-closure	0.90	0.90	0.90	0.90	0.90
Upper limit on peak mid-pillar temperature	96 °C	96 °C	99 °C	96 °C	96 °C
Repository closure year	2110	2110	2117	2117	2117

(1) subject to manipulation of arrival schedule, as descr bed in Section 6.1.3

(2) property values from a DTN transmitted on an IED (no further verification required, see Table 16)

(3) more recent property values from a DTN not yet transmitted on an IED (carries TBV status), with thermal conductivity taken from the case with global mean value of percolation flux (see Table 16)

(4) more recent property values from a DTN not yet transmitted on an IED (carries TBV status), with thermal conductivity taken from the case with 10th-percentile value of percolation flux (see Table 16)

7. RESULTS AND CONCLUSIONS

The outputs of this calculation are reasonable compared to the inputs, and the results are suitable for the intended use. This calculation provides appropriate bounding thermal results for design guidance at this time, and demonstrates that a wide range of receipt scenarios will meet thermal criteria.

7.1 RESULTS

Table 11 lists the results of this calculation. The output files of the WPLOAD executions are included on CD Attachment I, as listed in Attachment III.

Table 11. Results

	Case 1	Case 2	Case 3a	Case 3b	Case 4
	1999 Waste Stream	**1999 Waste Stream, with sensitivity to repository host rock layer thermal properties**	**Estimated Limiting Waste Stream, with elevated peak mid-pillar temperature criterion**	**Estimated Limiting Waste Stream, using same properties for all rock layers as those of the repository host rock layer**	**Bounding Case Showing Effect of Special Consideration for Naval Waste Packages**
INPUTS					
Commercial fuel assembly waste stream	1999 Case B 63,000 MTHM	1999 Case B 63,000 MTHM	ELWS YFF5 22 kW	ELWS YFF5 22 kW	ELWS YFF5 22 kW
Repository host rock (Tptpll) layer thermal properties used to determine mid-pillar rock temperature	property values from qualified DTN transmitted on an IED[1]	more recent property values, global-mean value of thermal conductivity[2]	more recent property values, global-mean value of thermal conductivity[2]	more recent property values, global-mean value of thermal conductivity[2], all rock layers assumed to have the same properties as the repository host layer	more recent property values, global-mean value of thermal conductivity[2], all rock layers assumed to have the same properties as the repository host layer
Repository host rock (Tptpll) layer thermal properties used to determine drift wall temperature	property values from qualified DTN transmitted on an IED[1]	more recent property values, global-mean value of thermal conductivity[2]	more recent property values, 10th-percentile value of thermal conductivity[3]	more recent property values, 10th-percentile value of thermal conductivity[3]	more recent property values, 10th-percentile value of thermal conductivity[3]
Upper limit on waste package thermal power at emplacement	11.8 kW	11.8 kW	18.0 kW	18.0 kW	18.0 kW
Upper limit on linear thermal power at emplacement	1.45 kW/m	1.45 kW/m	2.00 kW/m	2.00 kW/m	2.00 kW/m
Upper limit on peak mid-pillar temperature	96 °C	96 °C	99 °C	96 °C	96 °C
Lower limit on peak mid-pillar temperature	90.5 °C	83 °C	90 °C	90 °C	90 °C
Year to begin accepting waste	2010	2010	2017	2017	2017
Year of repository closure	2110	2110	2117	2117	2117
RESULTS					
Number of emplacement drifts used	**91**	**91**	**91**	**91**	**91**
Year to finish emplacement	**2066**	**2066**	**2052**	**2057**	**2055**
Required aging pad capacity	**2,247 TADs**	**1,891 TADs**	**1,134 TADs**	**1,673 TADs**	**1,514 TADs**

(1) property values from a DTN transmitted on an IED (no further verification required, see Table 16)

(2) more recent property values from a DTN not yet transmitted on an IED (carries TBV status), with thermal conductivity taken from the case with global mean value of percolation flux (see Table 16)

(3) more recent property values from a DTN not yet transmitted on an IED (carries TBV status), with thermal conductivity taken from the case with 10th-percentile value of percolation flux (see Table 16)

Table 12 lists the number of waste packages of each type, produced in each of the calculation cases.

Table 12. Number of waste packages of each type

	1999 Case B 63,000 MTHM waste stream (Cases 1 and 2)	**Estimated limiting waste stream (Cases 3a and 3b)**
shipped 21-PWR TAD	3,627	3,766
created on-site 21-PWR TAD	838	692
shipped 44-BWR TAD	2,657	2,729
created on-site 44-BWR TAD	256	185
5-DHLW short	1,131	1,131
5-DHLW long	1,421	1,421
Naval	400	400
TOTAL	**10,330**	**10,324**

Figure 4 through Figure 8 show the peak mid-pillar temperature corresponding to each seven-waste package series in each case. These figures illustrate the upper limit imposed on peak mid-pillar temperature throughout emplacement, as well as the lower limit imposed on peak mid-pillar temperature in early years. As described in Section 6.3.2.2, the lower limit is imposed in order to delay emplacement of the 5-DHLW long waste packages until they are necessary. The results for Case 3a (Figure 6) show compliance with a higher peak mid-pillar temperature criterion, as explained in Section 6.4.

The points dipping below the lower limit in Figure 4 through Figure 8 represent seven-waste package series affected by the artificial lower limit imposed on the individual waste package peak mid-pillar temperature index, as described in Section 2.3.7.5 of Ref. 2.2.36. As described in the reference, the artificial lower limit on individual waste package peak mid-pillar temperature index is intended to prevent long (possibly infinite) delays in emplacement due to the combination of waste packages with very low and very high peak mid-pillar temperature indices emplaced in the same seven-waste package series. As stated in the reference, the artificial lower limit on the index allows emplacement to proceed without delay, at the expense of a temporary, very slightly conservative modification in the peak mid-pillar temperature criterion. Figure 4 illustrates this effect, as many seven-waste package series are observed to be emplaced at slightly lower than the upper limit and (more noticeably in the figures) slightly lower than the lower limit.

Figure 9 and Figure 10 show the thermal power generated by the fuel assemblies in each TAD that is sent to the aging pad, upon its arrival and upon its emplacement in a waste package, for Case 1 (to show emplacement of the 1999 Case B waste stream) and Case 3a (to show emplacement of the estimated limiting waste stream). Each waste package is represented by one red point and one corresponding blue point, illustrating the effect of aging. The 11-year period of no emplacement in Figure 9 is due to a situation in which there is no potential waste package that possesses a peak mid-pillar temperature index between the imposed upper and lower limits. The upper limit represents a design criterion, and the lower limit is applied for reasons explained in Section 6.3.2.2. As a result this situation may arise, delaying emplacement until the lower limit is removed (in this case 2064). In this case, the 11-year period of no emplacement does not prolong the overall time required for waste emplacement, since there are TADs that require aging until 2064 to decay to 11.8 kW.

Figure 11 and Figure 12 show the actual emplacement sequence of the three types of DHLW canisters for Case 1 and Case 3a. As described in Section 6.3.2.2, due to the lower limit imposed on peak mid-pillar temperature, the emplacement of the majority of 5-DHLW long waste packages was delayed until later years. As described in Section 6.3.2.1, due to the specified arrival of all the DHLW short canisters before the DHLW long canisters, and the subsequent placement in the virtual staging area in that order, the emplacement of all 5-DHLW short waste packages occurs before the emplacement of 5-DHLW long waste packages.

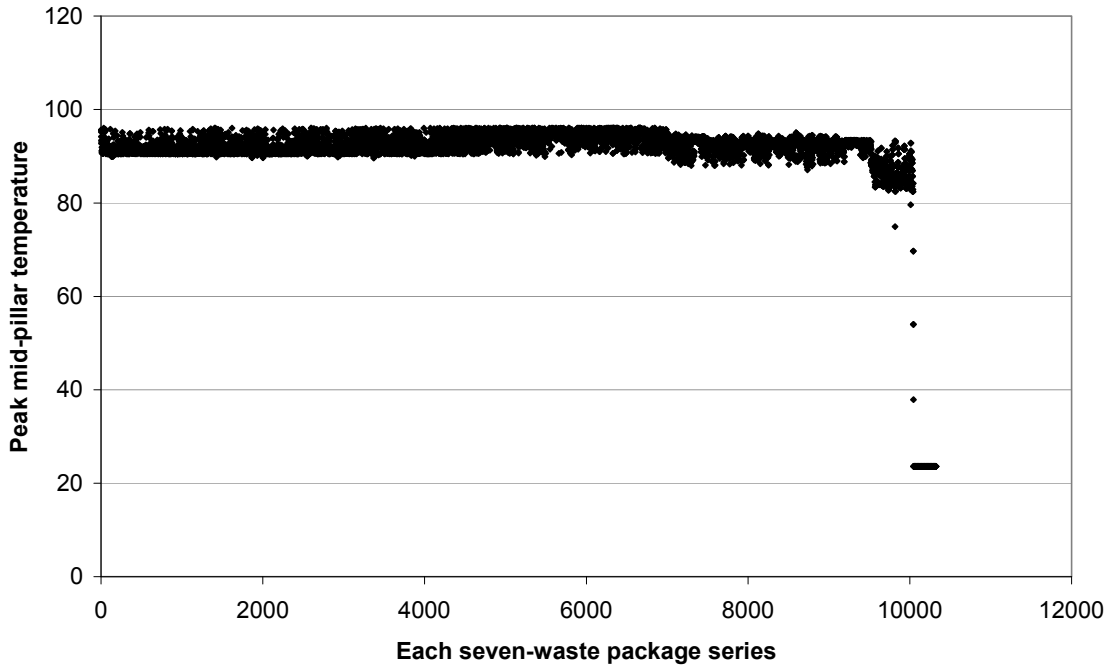

Figure 4. Case 1: Peak mid-pillar temperature (°C) over each seven-waste package series

Case 2a

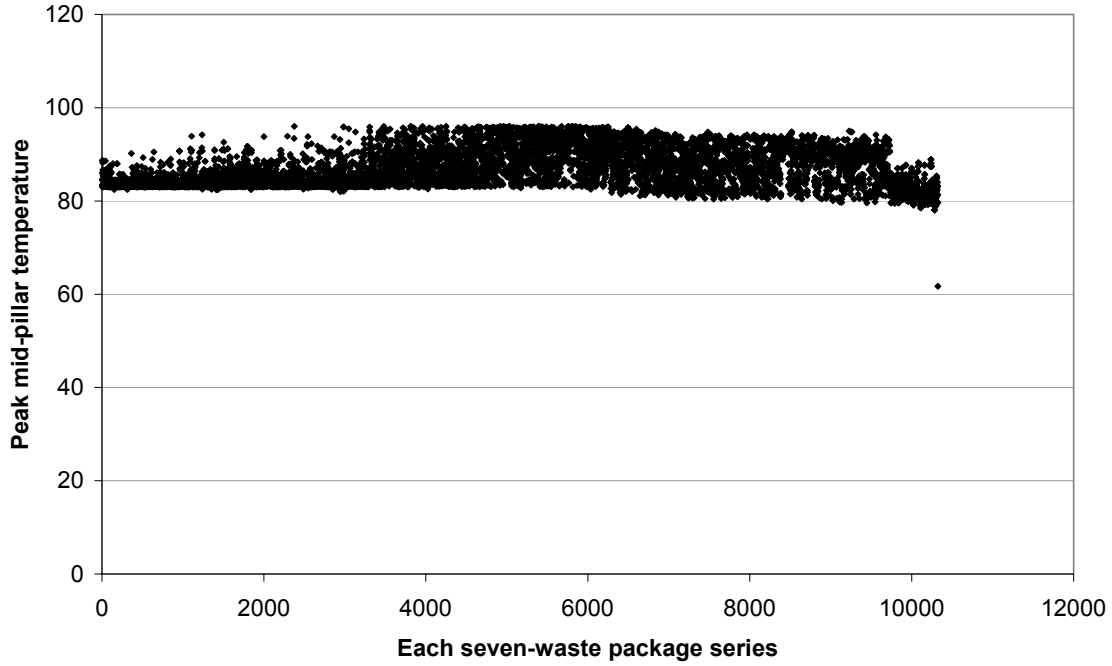

Figure 5. Case 2: Peak mid-pillar temperature (°C) over each seven-waste package series

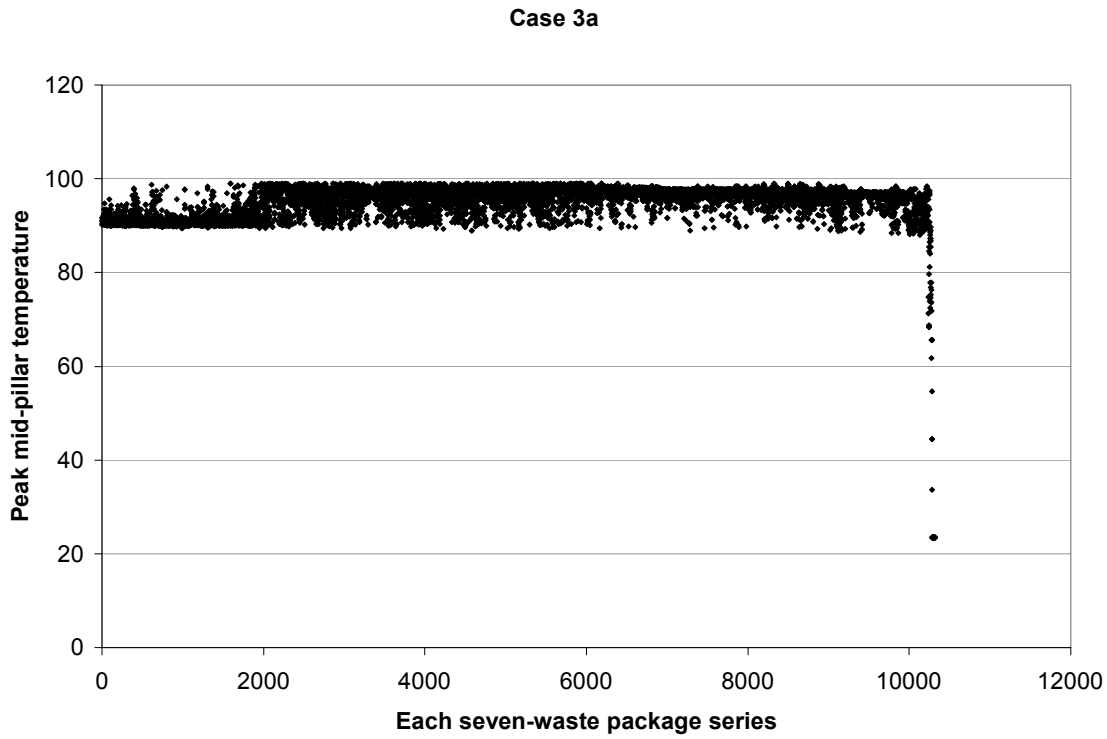

Figure 6. Case 3a: Peak mid-pillar temperature (°C) over each seven-waste package series

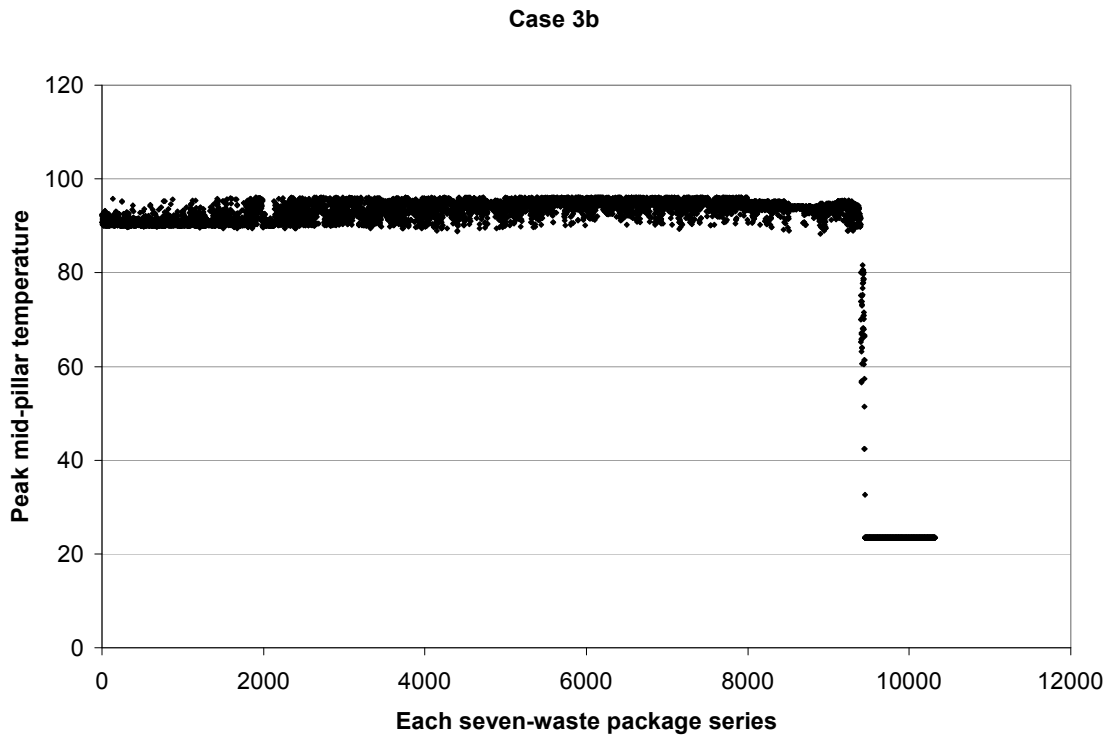

Figure 7. Case 3b: Peak mid-pillar temperature (°C) over each seven-waste package series

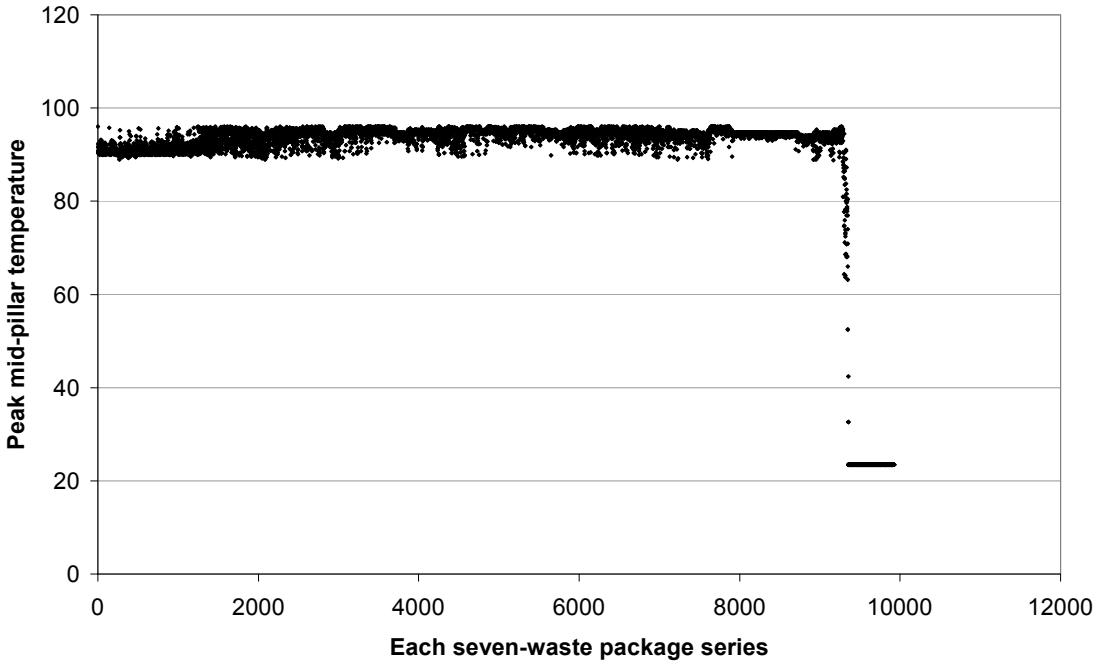

Figure 8. Case 4: Peak mid-pillar temperature (°C) over each seven-waste package series

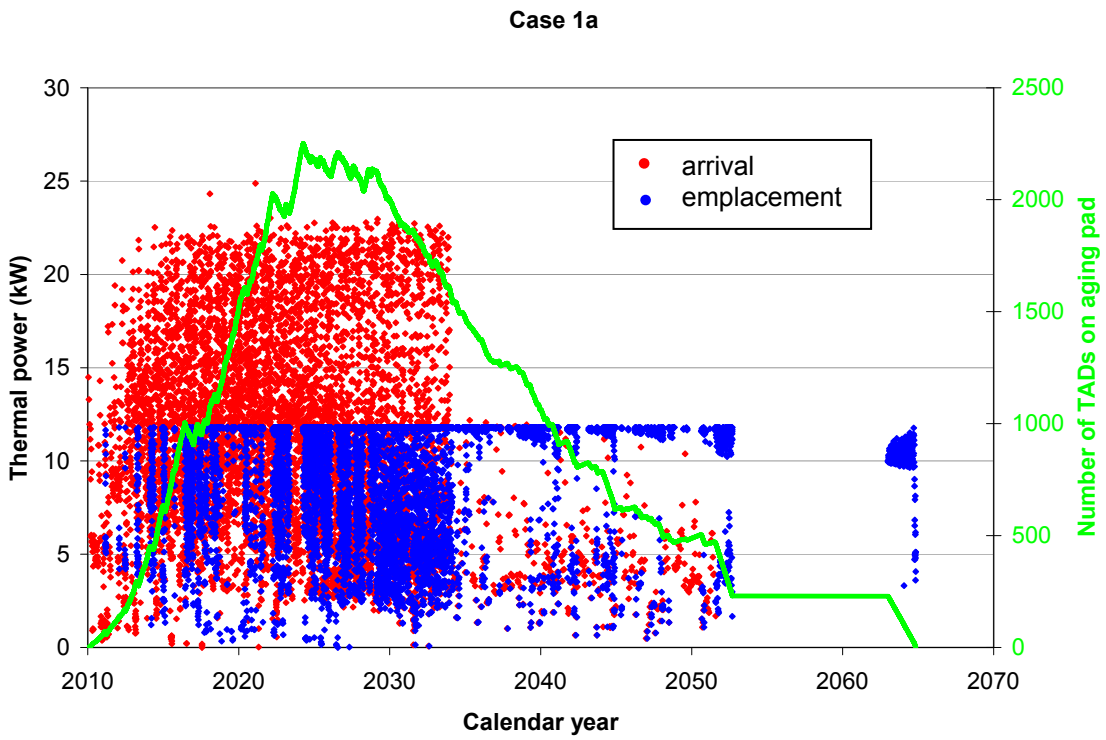

Figure 9. Case 1: Thermal power in each TAD that is sent to the aging pad, upon its arrival and upon its emplacement, plotted with the number of TADs on the aging pads over time

Figure 10. Case 3a: Thermal power in each TAD that is sent to the aging pad, upon its arrival and upon its emplacement, plotted with the number of TADs on the aging pads over time

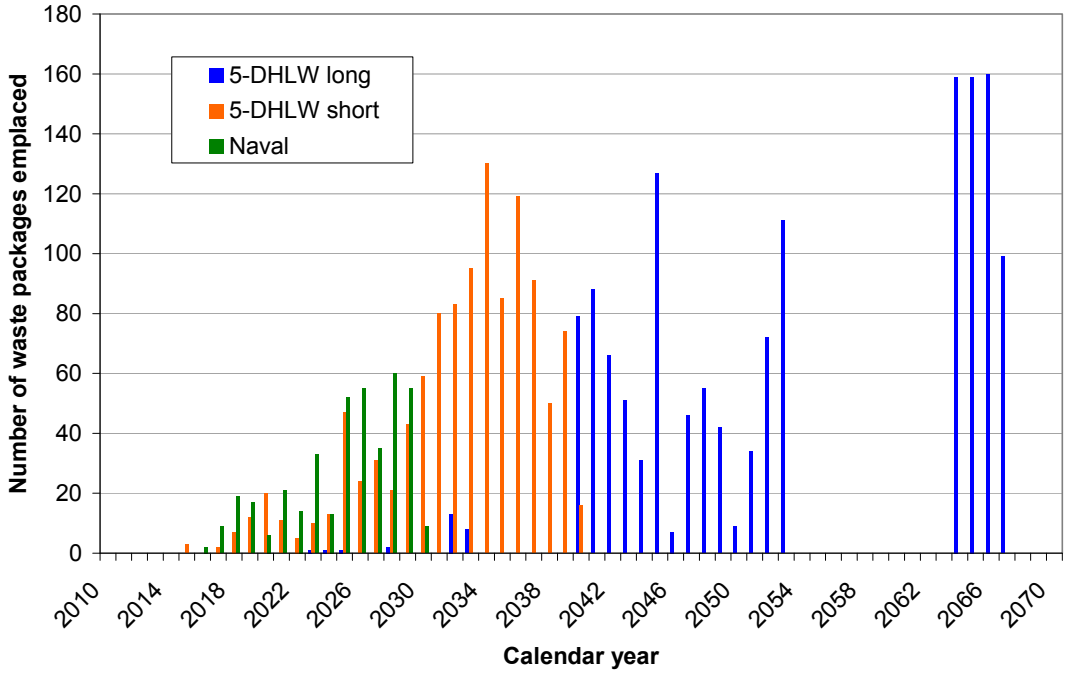

Figure 11. Case 1: Year of emplacement of non-commercial waste

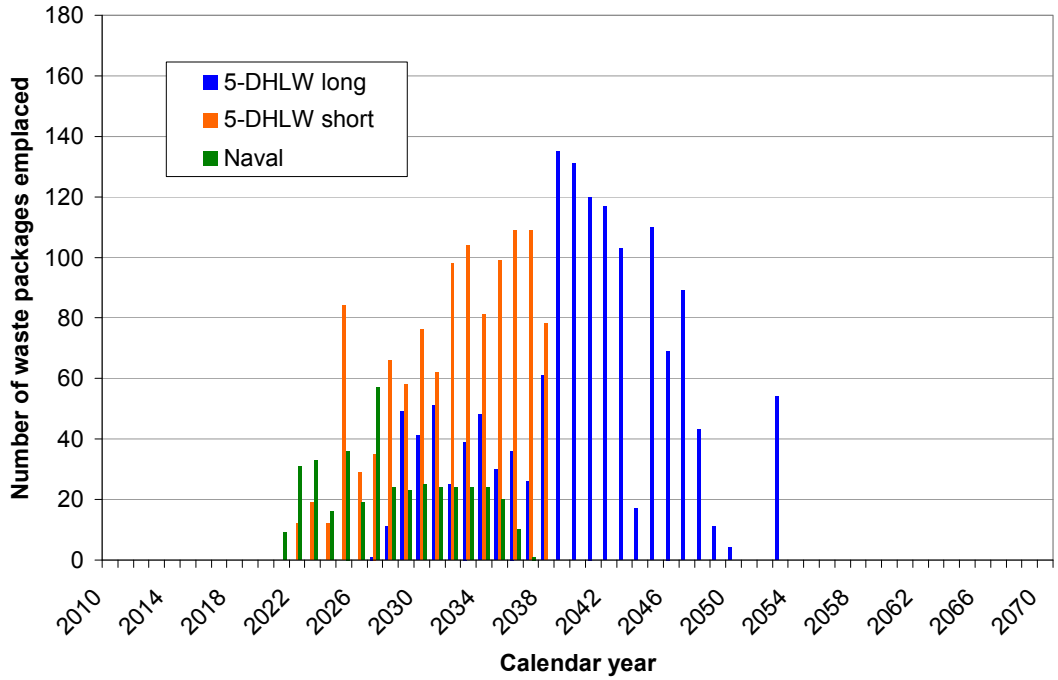

Figure 12. Case 3a: Year of emplacement of non-commercial waste

7.1.1 Three- and seven-waste-package average of peak drift wall temperature index

The peak drift wall temperature index corresponding to each waste package is calculated in the same manner as the peak mid-pillar temperature index, as described in Attachment II. Since the drift wall temperature index is calculated from a 2-D finite element representation, in effect it is the maximum value of drift wall temperature that would occur in an entire repository loaded with waste packages identical to the waste package in question. The host rock thermal conductivity value taken from the tenth-percentile percolation flux case from Ref. 2.2.31 was used to generate the UFPR to calculate the drift wall temperature history in Case 3b, as listed in Table 17.

As stated in Attachment II, due to the higher-order effect of radiative heat transfer between neighboring waste packages on drift wall temperature immediately above a given waste package, as well as the absence of the latent heat of vaporization within the rock, significant conservative error may be introduced by calculating the drift wall temperature using the same 2-D approximation used to calculate mid-pillar temperature (Section 2.3.7.6 of Ref. 2.2.36).

However, the peak drift wall temperature index of each waste package is used here to show relative variation in local drift wall temperature. Among many sets of seven consecutive waste packages in the Case 3b loading scenario, all of which possess a peak mid-pillar temperature below the upper limit of 96 °C, the seven-waste package series with the highest average of three consecutive drift wall temperature indices, and the series with the highest average of seven consecutive drift wall temperature indices were selected. These two sets of waste packages bound the possibilities of highest average drift wall temperature along the seven-waste package series, and highest variation within the seven-waste package series, leading to local regions of high drift wall temperature. The two representative series are listed in Table 13 and Table 14.

Each set of seven waste packages could later represent a reasonably limiting case for an explicit 3-D calculation to determine the actual maximum drift wall temperature along the series. A 3-D ANSYS finite element calculation would show the higher-order effect of radiative heat transfer between neighboring waste packages, causing local drift wall temperature variations. The 3-D calculation could also represent the effect of the latent heat of vaporization within the rock.

Table 13. Seven-waste package series containing the highest three-point running average of individual waste package drift wall temperature index in the repository (227.4 °C)

	Waste package length (m)	Drift number	Position number	Individual waste package drift wall temperature index (°C)
5-DHLW long waste package	5.304	80	6	24.2
5-DHLW long waste package	5.304	80	7	24.2
21-PWR TAD waste package	5.850	80	8	238.0
21-PWR TAD waste package	5.850	80	9	253.9
44-BWR TAD waste package	5.850	80	10	190.2
21-PWR TAD waste package	5.850	80	11	158.5
21-PWR TAD waste package	5.850	80	12	114.8

Table 14. Seven-waste package series containing the highest seven-point running average of individual waste package drift wall temperature index in the repository (152.5 °C)

	Waste package length (m)	Drift number	Position number	Individual waste package drift wall temperature index (°C)
21-PWR TAD waste package	5.850	63	63	222.7
44-BWR TAD waste package	5.850	63	64	63.2
44-BWR TAD waste package	5.850	63	65	136.5
21-PWR TAD waste package	5.850	63	66	235.6
44-BWR TAD waste package	5.850	63	67	62.7
44-BWR TAD waste package	5.850	63	68	179.7
44-BWR TAD waste package	5.850	63	69	167.1

7.2 CONCLUSION

This calculation has simulated the processing of two largely different waste stream scenarios into waste packages, the required aging, and the emplacement of the waste packages into the Yucca Mountain repository. The order and schedule of waste package emplacement was determined, based on thermal loading criteria and arrival scenario. This calculation shows that the 1999 Case B 63,000 MTHM waste stream, as well as the estimated limiting waste stream, can be emplaced in the repository and meet thermal limits, stay within facility capacities, and complete emplacement and ventilation on schedule. Two cases are presented to compensate for some of the conservative margin introduced by neglecting the effect of water movement and vaporization in the rock.

An additional case is presented to support special emplacement considerations made for Naval waste packages. Emplacement of the entire waste stream without the relatively low-power Naval waste packages has been demonstrated. Since waste package emplacement can be accomplished without including Naval packages in the queue, and considering their lower power output compared to the remainder of the queue, special emplacement considerations can be accommodated for Naval waste packages.

ATTACHMENT II – Calculation of Unit Flux Pulse Temperature Response

The input files containing the unit flux pulse temperature response (UFPR) were created as described in the following. See Section 2.3.7.1 of Ref. 2.2.36 for details.

The unit flux pulse response is defined as the mid-pillar temperature history from zero to 3,000 years resulting from a single year-long application of thermal flux, representing a linear thermal power of 1 kW/m, into the rock through the drift wall, in the 2-D pillar representation shown in Figure 13.

Approximating heat transfer within the rock as conduction-only, the mid-pillar temperature is derived from superposition of the temperature responses of a large number of finite pulses of heat flux into the rock, each with a unit value.

The unit flux pulse temperature response is used to calculate the temperature at any point in the rock. This methodology is described in the following.

The unit flux pulse temperature response can be used with the superposition method to calculate the temperature at any point in the rock. Consider an arbitrary thermal flux applied to a solid. Due to the superposition principle of heat conduction, the temperature response at any point within the solid can be calculated by summing the temperature responses at that point from individual constant fluxes applied over short time intervals in such a manner that the summation of the constant fluxes approximates the arbitrary flux history.

Suppose that the unit flux pulse temperature response (S), defined as the transient rock temperature increase above the initial temperature, is tabulated at every $n \cdot \Delta t$ for n = 1, 2, 3, ... (refer to Figure 14).

Now suppose an arbitrary flux (Q) is available in functional or tabulated form (refer to Figure 14). In order to calculate the temperature T due to the arbitrary flux at $t = 7 \cdot \Delta t$ (the "7" is arbitrary, for illustration only), the temperature contribution from each of the applied single pulses within each Δt is scaled by the flux at the time the flux was applied, and the temperature contributions summed. In order to illustrate this, consider the temperature S contribution due to the pulse applied in the first Δt between t_0 and t_1, the temperature response will age, or decay, to the value indicated at S_7. But the S-versus-t plot is based on a unit flux, therefore S_7 must be scaled by the value of the arbitrary flux applied in the first Δt, so the contribution to the temperature T at t_7 due to this flux is $S_7 \cdot Q_1$.

Likewise consider the contribution to the temperature T due to the flux applied between t_6 and t_7. This temperature response is S_1 because it is (only) one Δt from its origin in time. This value of S_1 is scaled by the flux used between the times indicated. Thus the contribution to the temperature T at t_7 due to this flux is $S_1 \cdot Q_7$, and this is added to the sum of contributions, and also illustrated in the plot of T versus t (Figure 14).

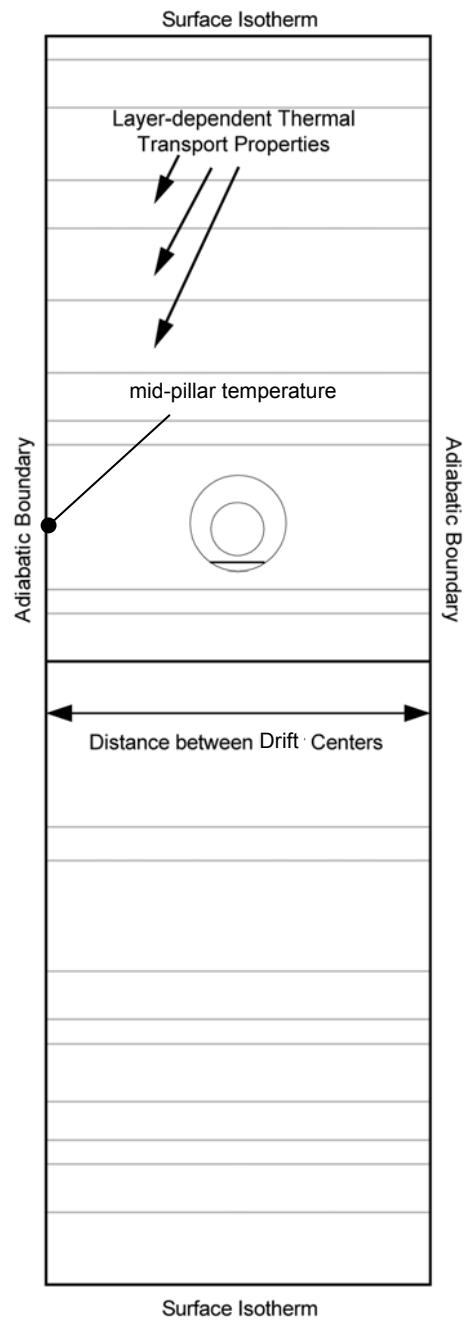

Figure 13. Pillar representation used to determine mid-pillar rock temperature

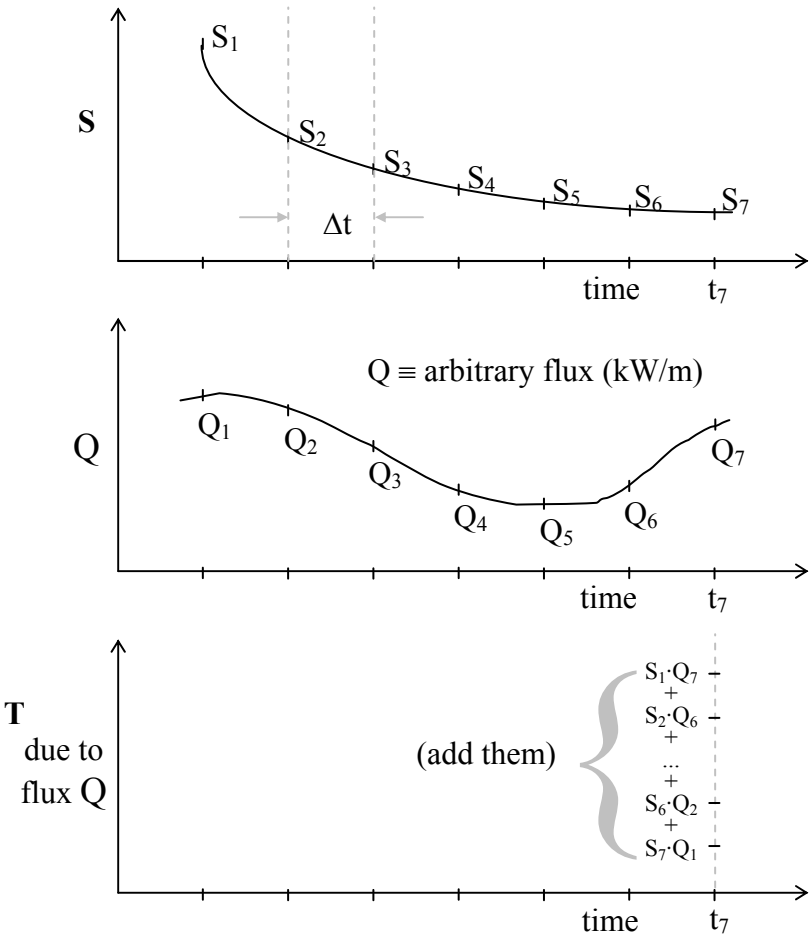

Figure 14. Arbitrary example of superposition method

In general, suppose the time index of interest is N, and the time is $t = N \cdot \Delta t$. The mid-pillar rock temperature at time N is calculated from the following:

$$T_N \quad T_i + \sum_{n \quad 1}^{N} S_n Q_{N-n+1}$$

In WPLOAD v. 2.0, the function (Q) is the long-term history of linear thermal power flux into the rock (kW/m) from a single waste package, and the function (S) is taken from the UFPR input file. The user has the option to specify the initial uniform rock temperature T_i. The long-term mid-pillar rock temperature history (T) is then calculated based on the single waste package, and therefore it is effectively the mid-pillar rock temperature history that would result in an entire repository loaded with waste packages identical to the waste package in question.

The finite element mesh shown in Figure 15, which represents the repository as a 2-D pillar of layered rock strata, was used in ANSYS to calculate the mid-pillar rock temperature history and the drift wall temperature history due to a unit heat flux into the wall of the emplacement drift

(see Assumption 3.2.9). The input and output files to ANSYS v. 8.0 are included on CD Attachment I, as listed in Attachment III.

Four calculation cases were performed, to generate four sets of unit flux pulse temperature responses.

A) Case A was performed using the data from Ref. 2.2.20, Ref. 2.2.21, and Ref. 2.2.22 as the thermal properties of all rock layers.

B) Case B was performed using the same properties of non-repository rock layers as in Case A. The density and specific heat of the repository host rock layer (Tptpll) were taken from Ref. 2.2.29. The value of Tptpll thermal conductivity from the global mean percolation flux case of Ref. 2.2.30 was used. This case is intended to show sensitivity of the mid-pillar rock temperature to variance in repository host rock layer thermal properties.

C) Case C was performed using the same properties of non-repository rock layers as in Case A. The density and specific heat of the repository host rock layer (Tptpll) were taken from Ref. 2.2.29. The value of Tptpll thermal conductivity from the tenth-percentile percolation flux case of Ref. 2.2.31 was used. This case is only used to generate drift wall temperature values, for use in Section 7.1. The mid-pillar temperature response of Case C was not used in this calculation.

The data used from Ref. 2.2.29 is preliminary. The future qualification of this data, and its inclusion on an interface exchange drawing, is being tracked in the Document Input Reference System database via TBV-8989 (see Assumption 3.1.7).

The data used from Ref. 2.2.30 and Ref. 2.2.31 is qualified, but it is not currently included on an interface exchange drawing. The future inclusion of this data on an interface exchange drawing is being tracked in the Document Input Reference System database via TBV-8917 and TBV-8918, respectively (see Assumption 3.1.6).

Due to the higher-order effect of radiative heat transfer between neighboring waste packages on drift wall temperature immediately above a given waste package, as well as the inability to represent phase change of water within the rock, significant error may be introduced by calculating the drift wall temperature using the same 2-D approximation used to calculate mid-pillar rock temperature (Section 2.3.7.6 of Ref. 2.2.36).

D) Case D was performed using thermal properties in every rock layer the same as those of the repository host rock layer. Since the thermal conductivity of the repository host rock layer (Tptpll) is generally higher than that of all other layers, this results in a lower peak mid-pillar temperature.

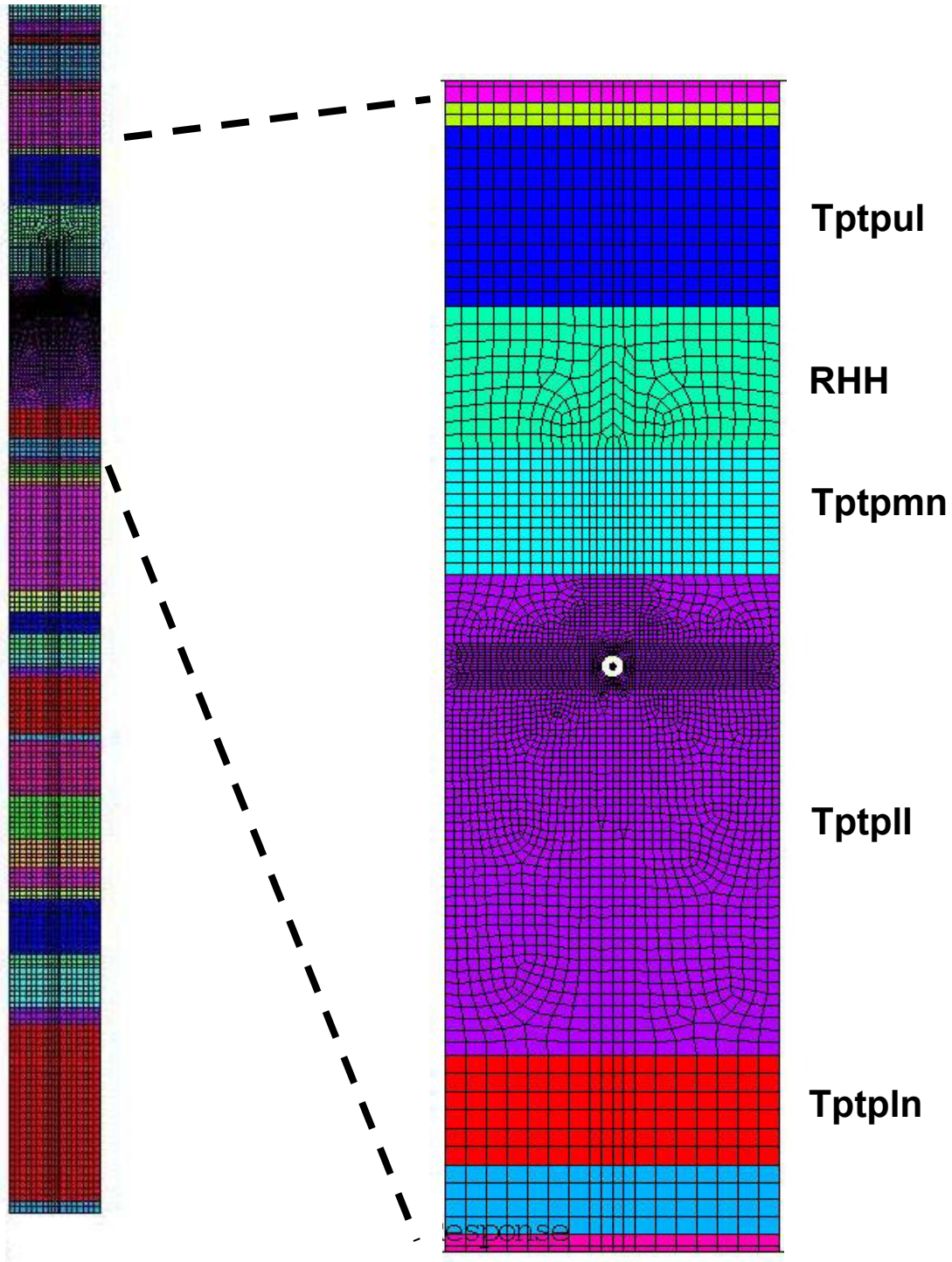

Figure 15. Finite element mesh representation used to calculate mid-pillar rock temperature history

The thermal properties of each non-repository rock layer represented in ANSYS Cases A, B, and C are listed in Table 15. These properties were taken from their respective references as the values for rock below the boiling point. Case D represented the properties of all rock layers the same as those of the repository host rock layer.

Table 15. Thermal properties of non-repository rock layers

Abbreviation	Geologic Framework Model Unit [h]	Thickness (ft) [a]	Thickness (m)	Dry Bulk Density (kg/m^3)	Wet Matrix Thermal Conductivity (T < 95 °C) (W/m·K)	Specific Heat (J/kg·K)
QaBase [f]	Alluvium	60	18.3	2190 [c]	1.81 [c]	913 [b]
Qa [f]		0	0.0	2190 [c]	1.81 [c]	913 [b]
Tmr [f]	Crystal-Rich Tiva/Post-Tiva	0	0.0	2190 [c]	1.81 [c]	913 [b]
Tpk [f]		0	0.0	2190 [c]	1.81 [c]	913 [b]
Tpc_un	Tpcp [e]	0	0.0	2190 [c]	1.81 [c]	913 [b]
Tpcpv3	Tpcpv3	0	0.0	2310 [c]	0.80 [c]	1245 [b]
Tpcpv2	Tpcpv2	0	0.0	1460 [c]	1.06 [c]	1245 [b]
Tpcpv1	Tpcpv1	0	0.0	1460 [c]	1.06 [c]	1291 [b]
Tpbt4	Tpbt4	0	0.0	1460 [c]	1.06 [c]	1291 [b]
Tpy	Yucca	42	12.8	1460 [c]	1.06 [c]	1291 [b]
Tpbt3	Tpbt3_dc	33	10.1	1460 [c]	1.06 [c]	1291 [b]
Tpp	Pah	100	30.5	1460 [c]	1.06 [c]	1291 [b]
Tpbt2	Tpbt2	30	9.1	1460 [c]	1.06 [c]	1291 [b]
Tptrv3	Tptrv3	0	0.0	1460 [c]	1.06 [c]	1291 [b]
Tptrv2	Tptrv2	5	1.5	1460 [c]	1.06 [c]	1291 [b]
Tptrv1	Tptrv1	10	3.0	2310 [c]	0.80 [c]	894 [b]
Tptrn	Tptrn	158	48.2	2190 [c]	1.81 [c]	891 [b]
Tptrl	Tptrl	19	5.8	2190 [c]	1.81 [c]	891 [b]
Tptf	Tptf	0	0.0	2190 [c]	1.81 [c]	891 [b]
Tptpul	Tptpul	144	43.9	1834 [d]	1.77 [d]	938 [b]
RHH	RHHtop	113	34.4	1834 [d]	1.77 [d]	938 [b]
Tptpmn	Tptpmn	101	30.8	2148 [d]	2.07 [d]	908 [b]
Tptpll	**Tptpll**	**384**	**117.0**	**see Table 16 and Table 17**	**see Table 16 and Table 17**	**see Table 16 and Table 17**
Tptpln	Tptpln	88	26.8	2211 [d]	2.13 [d]	896 [b]
Tptpv3	Tptpv3	55	16.8	2310 [c]	0.80 [c]	907 [b]
Tptpv2	Tptpv2	18	5.5	1460 [c]	1.06 [c]	1095 [b]
Tptpv1	Tptpv1	43	13.1	1460 [c]	1.06 [c]	1245 [b]
Tpbt1	Tpbt1	22	6.7	1460 [c]	1.06 [c]	1245 [b]
Tac [g]	Calico	311	94.8	1670 [c]	1.26 [c]	1403 [b]
Tacbt	Calicobt	63	19.2	1670 [c]	1.26 [c]	1247 [b]
Tcpuv	Prowuv	64	19.5	1790 [c]	1.13 [c]	1367 [b]

Tcpuc	Prowuc	58	17.7	1790 [c]	1.13 [c]	1043 [b]
Tcpm	Prowmd	40	12.2	2070 [c]	1.63 [c]	1043 [b]
Tcplc	Prowlc	26	7.9	1790 [c]	1.13 [c]	1043 [b]
Tcplv	Prowlv	169	51.5	1790 [c]	1.13 [c]	1293 [b]
Tcpbt	Prowbt	18	5.5	1790 [c]	1.13 [c]	1293 [b]
Tcbuv	Bullfroguv	164	50.0	1880 [c]	1.19 [c]	1293 [b]
Tcbuc	Bullfroguc	124	37.8	1880 [c]	1.19 [c]	946 [b]
Tcbm	Bullfrogmd	86	26.2	2260 [c]	1.81 [c]	946 [b]
Tcblc	Bullfroglc	0	0.0	1880 [c]	1.19 [c]	946 [b]
Tcblv	Bullfroglv	55	16.8	1880 [c]	1.19 [c]	1234 [b]
Tcbbt	Bullfrogbt	38	11.6	1880 [c]	1.19 [c]	1234 [b]
Tctuv	Tramuv	161	49.1	1760 [c]	1.10 [c]	1234 [b]
Tctuc	Tramuc	40	12.2	1760 [c]	1.10 [c]	1328 [b]
Tctm	Trammd	116	35.4	2140 [c]	1.63 [c]	1328 [b]
Tctlc	Tramlc	49	14.9	1760 [c]	1.10 [c]	1328 [b]
Tctlv	Tramlv	517	157.6	1760 [c]	1.10 [c]	1190 [b]
Tctbt	Trambt	36	11.0	1760 [c]	1.10 [c]	1190 [b]

(a) DTN: MO0012MWDGFM02.002 (Ref. 2.2.19)
file: `/Data_Grids_Faults/data/contacts00el.dat`
cited in Interface Exchange Drawing 800-IED-MGR0-00401-000-00G (Ref. 2.2.23)

Based on G-1 Borehole data (see Assumption 3.1.4). Comparing Figures II-4 and III-1 of Ref. 2.2.16, it can be seen that the G-1 Borehole is located closest to drift 3-15W. Page III-5 of Ref. 2.2.16 gives the elevation of drift 3-15W as 1055.22 m (3462 ft).

(b) DTN: SN0307T0510902.003 (Ref. 2.2.21)
file: `/Rock_GrainMass_heat_capacity_edited.zip/rock_mass_heat_capacity (edited) .xls`
cited in Interface Exchange Drawing 800-IED-MGR0-00402-000-00A (Ref. 2.2.32)

(c) DTN: SN0303T0503102.008 (Ref. 2.2.20)
file: `NonrepositoryThermalConductivityModel_031403.xls`
cited in Interface Exchange Drawing 800-IED-MGR0-00402-000-00A (Ref. 2.2.32)

(d) DTN: SN0404T0503102.011 (Ref. 2.2.22)
file: `SN0404T0503102.011ReadMe.doc`, p.1
cited in Interface Exchange Drawing 800-IED-MGR0-00402-000-00A (Ref. 2.2.32)

(e) Ref. 2.2.19 indicates that the Tpc_un layer lies above the Tpcpv3 layer, either within the Tpcp layer or the Crystal-Rich Tiva/Post-Tiva layer, which have the same thermal properties (See Assumption 3.2.1)

(f) See Assumption 3.2.1

(g) Values are average of Tac1, Tac2, Tac3, and Tac4.

(h) The correlation between the abbreviations and geologic framework model unit names is given in Table 6-2 of Ref. 2.2.18.

Table 16 lists the host rock layer thermal properties used in each case to calculate the unit flux pulse temperature reponse. The unit flux pulse temperature responses from Cases A, B, C, and D were used in the respective numbered cases in this calculation as listed in Table 17.

Table 16. Host rock layer (Tptpll) thermal properties used in four ANSYS cases to calculate the unit flux pulse temperature response

ANSYS pulse response case used:	density (kg/m^3)	thermal conductivity (W/m·K)	specific heat (J/kg·K)
Case A	1979 [d]	1.89 [d]	926 [b]
Case B	2112.9 [I]	1.87 [J]	1107.8 [I]
Case C	2112.9 [I]	1.69 [k]	1107.8 [I]
Case D	2112.9 [I] same for all rock layers	1.87 [J] same for all rock layers	1107.8 [I] same for all rock layers

Table 17. Host rock layer (Tptpll) thermal properties

WPLOAD case used in:	Property used for calculating:	ANSYS pulse response case used:	density (kg/m^3)	thermal conductivity (W/m·K)	specific heat (J/kg·K)
Case 1	mid-pillar rock temperature	Case A	1979 [d]	1.89 [d]	926 [b]
Case 1	drift wall temperature	Case A	1979 [d]	1.89 [d]	926 [b]
Case 2	mid-pillar rock temperature	Case B	2112.9 [I]	1.87 [J]	1107.8 [I]
Case 2	drift wall temperature	Case B	2112.9 [I]	1.87 [J]	1107.8 [I]
Case 3a	mid-pillar rock temperature	Case B	2112.9 [I]	1.87 [J]	1107.8 [I]
Case 3a	drift wall temperature	Case C	2112.9 [I]	1.69 [k]	1107.8 [I]
Case 3b	mid-pillar rock temperature	Case D	2112.9 [I] same for all rock layers	1.87 [J] same for all rock layers	1107.8 [I] same for all rock layers
Case 3b	drift wall temperature	Case C	2112.9 [I]	1.69 [k]	1107.8 [I]
Case 4	mid-pillar rock temperature	Case D	2112.9 [I] same for all rock layers	1.87 [J] same for all rock layers	1107.8 [I] same for all rock layers
Case 4	drift wall temperature	Case C	2112.9 [I]	1.69 [k]	1107.8 [I]

(I) DTN: MO0709REVTHERM.000 (Ref. 2.2.29)
file: `Summary of Thermal Properties.xls`

(J) DTN: MO0612MEANTHER.000 (Ref. 2.2.30)
file: `Repository Unit Mean Kthermal.xls`

(k) DTN: MO0702PAGLOBAL.000 (Ref. 2.2.31)
file: `Repository Unit 10P_90P Wet Kthermal.xls`

The full temperature history at the mid-pillar rock location and at the drift wall was extracted from the ANSYS output files, imported into Excel spreadsheets, and manipulated to produce the UFPR in tabular form. The UFPR was then converted to the WPLOAD text input file for each case. The ANSYS output files, the Excel spreadsheet files, and the corresponding WPLOAD input files are included on CD Attachment I and listed in Attachment III.

ATTACHMENT III – List of files on CD Attachment I

Table 18. List of files on CD Attachment I

File name	Description	File size (kB)
WASTESTREAM_1999B.TXT	WPLOAD input file: 1999 Case B 63,000 MTHM waste stream input file	3,201
WASTESTREAM_ELWS.TXT	WPLOAD input file: ELWS YFF5 22kW waste stream input file	3,005
WPLOAD_HLW_ACC_FILE.TXT	WPLOAD input file: DHLW canister arrival schedule input file	1
WPLOAD_HLW_HEAT_FILE.TXT	WPLOAD input file: DHLW canister thermal power history input file	1
WPLOAD_NAVY_ACC_FILE.TXT	WPLOAD input file: Naval canister arrival schedule input file for Cases 1, 2, 3a, and 3b	1
WPLOAD_NAVY_ACC_FILE_Case4.TXT	WPLOAD input file: Naval cannister arrival schedule input file for Case 4	1
WPLOAD_NAVY_HEAT_FILE.TXT	WPLOAD input file: Naval canister thermal power history input file	1
WPLOAD_INPUT_DRIFTS.TXT	WPLOAD input file: Number and length of available emplacement drifts, used in Cases 1, 2, 3a, and 3b	7
WPLOAD_INPUT_DRIFTS_Case4.TXT	WPLOAD input file: Number and length of available emplacement drifts, used in Case 4.	7
WPLOAD_UFPR_TIMNRL_TIMRL.TXT	WPLOAD input file: Unit flux pulse temperature responses from Case A (see Attachment II)	94
WPLOAD_UFPR_MEAN_K.TXT	WPLOAD input file: Unit flux pulse temperature responses from Case B (see Attachment II)	103
WPLOAD_UFPR_10THPCT_K.TXT	WPLOAD input file: Unit flux pulse temperature responses from Case C (see Attachment II)	106
WPLOAD_UFPR_ALL_LYRS_SM_PRP.TXT	WPLOAD input file: Unit flux pulse temperature responses from Case D (see Attachment II)	97
WPLOAD_HGEN_ARRAY_Case3b.TXT	Intermediate file from Case 3b – thermal power generated by each fuel assembly in each arriving batch	8,120
WPLOAD_OUTPUT_CASE1.TXT	WPLOAD output file for Case 1	41,792
WPLOAD_OUTPUT_CASE2.TXT	WPLOAD output file for Case 2	41,769
WPLOAD_OUTPUT_CASE3a.TXT	WPLOAD output file for Case 3a	41,767
WPLOAD_OUTPUT_CASE3b.TXT	WPLOAD output file for Case 3b	41,778
WPLOAD_OUTPUT_CASE4.TXT	WPLOAD output file for Case 4	41,262
UFPR_process_10_14_07.xls	Spreadsheet file for processing of unit flux pulse temperature responses (see Attachment II)	1,486
DHLW_can_arr_sched.xls	Spreadsheet file containing the manipulation of the DHLW canister arrival schedule, as described in Section 6.3.2.1	30
DHLW_can_thermal_power.xls	Spreadsheet file containing the calculation of DHLW canister thermal power history, as described in Section 6.1.5	236
source_thermal.zip	Intermediate files containing thermal power generated from fuel assemblies (see Section 6.1.2)	1,664

source_nuclide.zip	Intermediate files containing radionuclide concentrations in fuel assemblies (see Section 6.1.2)	9,195
source_cobalt.zip	Intermediate files containing cobalt concentrations in fuel assemblies (see Section 6.1.2)	752
source_gamma.zip	Intermediate files containing gamma source spectrums from fuel assemblies (see Section 6.1.2)	22,885
source_neutron.zip	Intermediate files containing neutron source spectrums from fuel assemblies (see Section 6.1.2)	10,682
files_curies.lis	list of commercial fuel assembly radionuclide content files read by WPLOAD v. 2.0	122
files_gammas.lis	list of commercial fuel assembly gamma source spectrum files read by WPLOAD v. 2.0	122
files_neutrons.lis	list of commercial fuel assembly neutron source spectrum files read by WPLOAD v. 2.0	126
files_watts.lis	list of commercial fuel assembly thermal power files read by WPLOAD v. 2.0	120
BWR_WS_curies.zip	.cut.curies files containing radionuclide concentrations from non-stainless steel clad BWR fuel assemblies (see Section 6.1.2)	14,217
BWR_SS_curies.zip	.cut.curies files containing radionuclide concentrations from stainless-steel clad BWR fuel assemblies (see Section 6.1.2)	595
PWR_WS_curies.zip	.cut.curies files containing radionuclide concentrations from non-stainless steel clad PWR fuel assemblies (see Section 6.1.2)	20,938
PWR_SS_curies.zip	.cut.curies files containing radionuclide concentrations from stainless-steel clad PWR fuel assemblies (see Section 6.1.2)	3,305
South_Texas_curies.zip	.cut.curies files containing radionuclide concentrations from South Texas fuel assemblies (see Section 6.1.2)	4,894
BWR_WS_gammas.zip	.cut.gammas files containing gamma source spectrums from non-stainless steel clad BWR fuel assemblies (see Section 6.1.2)	15,864
BWR_SS_gammas.zip	.cut.gammas files containing gamma source spectrums from stainless-steel clad BWR fuel assemblies (see Section 6.1.2)	605
PWR_WS_gammas.zip	.cut.gammas files containing gamma source spectrums from non-stainless steel clad PWR fuel assemblies (see Section 6.1.2)	18,337
PWR_SS_gammas.zip	.cut.gammas files containing gamma source spectrums from stainless-steel clad PWR fuel assemblies (see Section 6.1.2)	3,043
South_Texas_gammas.zip	.cut.gammas files containing gamma source spectrums from South Texas fuel assemblies (see Section 6.1.2)	4,721
BWR_WS_neutrons.zip	.cut.neutrons files containing neutron source spectrums from non-stainless steel clad BWR fuel assemblies (see Section 6.1.2)	2,853
BWR_SS_neutrons.zip	.cut.neutrons files containing neutron source spectrums from stainless-steel clad BWR fuel assemblies (see Section 6.1.2)	119

PWR_WS_neutrons.zip	.cut.neutrons files containing neutron source spectrums from non-stainless steel clad PWR fuel assemblies (see Section 6.1.2)	4,025
PWR_SS_neutrons.zip	.cut.neutrons files containing neutron source spectrums from stainless-steel clad PWR fuel assemblies (see Section 6.1.2)	659
South_Texas_neutrons.zip	.cut.neutrons files containing neutron source spectrums from South Texas fuel assemblies (see Section 6.1.2)	851
BWR_WS_watts.zip	.cut.watts files containing thermal power from non-stainless steel clad BWR fuel assemblies (see Section 6.1.2)	10,718
BWR_SS_watts.zip	.cut.watts files containing thermal power from stainless-steel clad BWR fuel assemblies (see Section 6.1.2)	449
PWR_WS_watts.zip	.cut.watts files containing thermal power from non-stainless steel clad PWR fuel assemblies (see Section 6.1.2)	16,592
PWR_SS_watts.zip	.cut.watts files containing thermal power from stainless-steel clad PWR fuel assemblies (see Section 6.1.2)	2,602
South_Texas_watts.zip	.cut.watts files containing thermal power from South Texas fuel assemblies (see Section 6.1.2)	3,771
GeoStratData_06_05_07_wet.inp	Case A: ANSYS input file, contains thermal properties of rock	6
TP_09_18_07_Tim.inp	Case A: ANSYS main input file	29
TP_09_18_07_Tim.out	Case A: ANSYS output file	9,788
TP_09_18_07_Tim.parm	Case A: ANSYS parameter file, contains temperature history at mid-pillar rock location and at drift wall	560
GeoStratData_09_05_07_mean_k.inp	Case B: ANSYS input file, contains thermal properties of rock	6
TP_09_05_07_mean_k.inp	Case B: ANSYS main input file	29
TP_09_05_07_mean_k.out	Case B: ANSYS output file	9,788
TP_09_05_07_mean_k.parm	Case B: ANSYS parameter file, contains temperature history at mid-pillar rock location and at drift wall	560
GeoStratData_09_05_07_10thpct_k.inp	Case C: ANSYS input file, contains thermal properties of rock	6
TP_09_05_07_10thpct_k.inp	Case C: ANSYS main input file	29
TP_09_05_07_10thpct_k.out	Case C: ANSYS output file	9,788
TP_09_05_07_10thpct_k.parm	Case C: ANSYS parameter file, contains temperature history at mid-pillar rock location and at drift wall	560
GSD_Ernie_onelayer.inp	Case D: ANSYS input file, contains thermal properties of rock	6
TP_Ernie_onelayer_3000.inp	Case D: ANSYS main input file	31
TP_Ernie_onelayer_3000.out	Case D: ANSYS output file	9,792
TP_Ernie_onelayer_3000.parm	Case D: ANSYS parameter file, contains temperature history at mid-pillar rock location and at drift wall	560