BSC

Design Calculation or Analysis Cover Sheet

Complete only applicable items.

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3. System Waste Handling	4. Document Identifier 000-PSA-MGR0-00700-000-00A
5. Title Characteristics for the Representative Commercial Spent Fuel Assembly for Preclosure Normal Operations	
6. Group Preclosure Safety Analysis	
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8. Notes/Comments Matthew Hinds performed the WPLOAD V. 1.1 runs and provided input to Section 4.3. Helen Marr checked his work.	

Attachments	Total Number of Pages
Attachment I – Computer Files	2 + CD
Attachment II - Bounding Commercial Spent Nuclear Fuel Radionuclide Inventory	4

RECORD OF REVISIONS

9. No.	10. Reason For Revision	11. Total # of Pgs.	12. Last Pg. #	13. Originator (Print/Sign/Date)	14. Checker (Print/Sign/Date)	15. EGS (Print/Sign/Date)	16. Approved/Accepted (Print/Sign/Date)
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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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FIGURES

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ACRONYMS

BWR	boiling water reactor
DPC	dual purpose canister
GWd	gigawatt day
MWd	megawatt day
MTHM	metric ton heavy metal
MTU	metric ton uranium
PWR	pressurized water reactor
SFA	spent fuel assembly
SNF	spent nuclear fuel
TAD	Transportation, Aging, and Disposal

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1. PURPOSE

The Preclosure Safety Analysis includes evaluating the dose consequences from normal operation and potential event sequences. Dose consequences during normal operations involving commercial spent nuclear fuel (SNF) include airborne releases during handling operations and direct dose from the fuel shielded by structures or casks. The majority of commercial SNF will arrive onsite in sealed canisters. Transportation, Aging, and Disposal (TAD) canisters will be transferred from one overpack to another depending on whether the fuel will be emplaced in the repository or placed on the aging pad for aging to meet the thermal power requirements for emplacement. During this process, there are no normal airborne radioactive releases from the fuel.

Some commercial SNF will be shipped to Yucca Mountain in dual-purpose canisters (DPCs) or shipped uncanistered in transportation casks. Commercial SNF shipped in DPCs or uncanistered in transportation casks will be repackaged into TAD canisters in the Wet Handling Facility prior to being placed in waste packages for emplacement. Airborne releases of radionuclides are expected during normal repackaging operations in the Wet Handling Facility.

The purpose of this analysis is to develop characteristics and radionuclide inventories of a representative commercial SNF assembly for boiling water reactor (BWR) and pressurized water reactor (PWR) fuel for use in determining the dose consequences from normal operational airborne releases. Once the representative fuel assembly characteristics for each fuel type are determined, the radionuclide inventory and crud inventory are determined from existing inventory analyses. Fuel type in this document refers to BWR fuel and PWR fuel.

The fuel characteristics can be different for the various applications for those characteristics. For example, fuel characteristics for airborne releases during normal operations will be different than fuel characteristics for airborne releases during event sequences. Likewise, fuel characteristic for airborne releases will be different from fuel characteristics used in shielding analysis, criticality analyses, or dose rate evaluations due to the different goal of the analyses. The results of this analysis are intended solely for the use of determining the dose consequences from airborne releases from normal operations.

Attachment II provides the bounding commercial SNF radionuclide inventories for BWR and PWR fuel that can be used in Preclosure analyses to evaluate dose consequences from airborne releases as a result of potential event sequences.

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2.2.3. WPLOAD V. 1.1.2006. WINDOWS 2000. STN: 11131-1.1-00 [DIRS 178198]

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2.2.11. NRC 2000. *Standard Review Plan for Spent Fuel Dry Storage Facilities.* NUREG-1567. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 247929. [DIRS 149756]

2.2.12. BSC 2001. *Significant Radionuclides Determination.* CAL-WHS-SE-000002 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010905.0143. [DIRS 156955]

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2.3 ANALYSIS CONSTRAINTS

None

2.4 ANALYSIS OUTPUTS

This analysis will be used as input for preclosure safety analysis calculations.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

No assumption in this analysis requires verification.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1. TAD-Based Waste Stream

The TAD-based waste stream developed with a 25-kW limit on TAD canisters and a 3,600 MTHM/yr repository receipt rate during full operations provides a conservative basis for determining the characteristics of a PWR and BWR fuel assembly that reasonably represent commercial spent nuclear fuel (SNF) for use in dose consequence analysis of airborne releases during normal operations.

Rationale: The majority of the commercial SNF will arrive at the repository in Transportation, Aging, and Disposal (TAD) canisters. The TAD canisters will be transferred from one overpack to another depending on whether the fuel will be emplaced in the repository or placed on the aging pad for aging to meet the thermal power limitations for emplacement. During this process, there are no normal airborne radioactive releases from the fuel because TAD canisters are required to meet the leak-tight standards of ANSI N14.5-97 (Reference 2.2.1 [DIRS 179349], Section 3.1.6 and Reference 2.2.2 [DIRS 145735]).

The *Basis of Design for the TAD Canister-Based Repository Design Concept* (Reference 2.2.5, Section 2.2.1.3) states that 90% of the commercial SNF is expected to be shipped to the repository in TAD canisters. The remaining portion of commercial SNF will be received at the repository in DPCs or uncanistered in transportation casks. The uncanistered fuel and the fuel in the DPCs will be repackaged into TAD canisters in the Wet Handling Facility prior to being placed in waste packages for emplacement. Airborne releases of radionuclides in the Wet Handling Facility during normal operations to repackage these fuel assemblies are expected. Thus, for a TAD-based repository operation, normal operational airborne releases will occur only from DPC opening and uncanistered spent fuel handing that occurs in the Wet Handling Facility.

Utility sites are currently loading dual-purpose canisters (DPCs) for onsite dry storage of spent nuclear fuel. When TAD canisters become available, it is expected that the utilities will load their fuel for dry storage directly into TAD canisters to preclude having to repackage their fuel prior to shipping it to the repository. The fuel contained in the DPCs will have been discharged from the reactor prior to the fuel contained in the TAD canisters. This is because DPCs are in use today and have already been loaded with commercial SNF, and when TAD canisters become available, the utilities will begin loading the TAD canisters. The commercial SNF that is expected to be shipped as uncanistered assemblies in rail or truck transportation casks is also expected to be older fuel than what will be shipped in TAD canisters because these shipments are expected to be from utilities without the capability of handling the larger capacity TAD canisters.

Reference 2.2.6 provides a waste stream scenario that is based on receiving commercial SNF in 25-kW TAD canisters at an annual receipt rate of 3,600 MTHM. An annual receipt rate of 3,600 MTHM is a 20% increase above the design basis annual receipt rate of 3,000 MTHM (Section 6.1.1). This waste stream scenario is based on the concept of loading commercial SNF in TAD canisters beginning in 2011 and shipping the youngest fuel first, greater than or equal to five years old, beginning in 2017. The results used from Reference 2.2.6 (Section 7) are in the form of an Excel spreadsheet, included in Attachment I, titled "AvailShipCD-1YFF525kW3600-Norm_Rev.xls". This spreadsheet provides the identification and characteristics of each fuel assembly including, enrichment, burnup, discharge year, arrival year, MTHM, and thermal power. Reference 2.2.6 provides a conservative bases for developing characteristics for representative fuel assemblies because it is based on parameters that result in a receipt scenario that is compressed, thus the average thermal power is higher. In addition, the results of this analysis (Section 1) are conservative with respect to the projected burnup and average time out of reactor for DPCs and truck casks (Reference 2.2.6, Table 1).

Therefore, it is conservative to base the characteristics of the representative commercial SNF on an entire commercial SNF waste stream even though the fuel that will be repackaged in the Wet Handling Facility will only be a small percentage of the total inventory and is expected be older than the fuel contained in TAD canisters.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This analysis was prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Reference 2.1.1) and LS-PRO-0201, *Preclosure Safety Analyses Process* (Reference 2.1.2). Therefore, the approved version is designated as QA:QA.

4.2 USE OF SOFTWARE

This analysis used qualified (Level 1) software WPLOAD v. 1.1, STN: 11131-1.1-00, (Reference 2.2.3 [DIRS 178198]) on the Windows 2000 operating system. WPLOAD v. 1.1 is listed in the current *Qualified and Controlled Software Report,* as well as the *Repository Project Management Automation Plan* (Reference 2.1.4, Table 6-1). The application is within the range of validation for this software, as described in Reference 2.2.4 [DIRS 178197]. WPLOAD v. 1.1 was executed on a PC running Windows 2000 Professional.

The commercially available Microsoft® Office Excel 2000 spreadsheet code and Microsoft® Office Access 2000 database code, which are components of Microsoft® Office 2000 Professional, are used to perform standard mathematical and sorting functions to derive the results, which do not depend on a particular software program. These results were verified by checks using hand calculations. Microsoft® Office Excel 2000 spreadsheet code is used for graphical presentation of the results, which are verified by visual inspection. Usage of Microsoft® Office 2000 Professional in this analysis constitutes Level 2 software usage, as defined in IT-PRO-0011 (Reference 2.1.3, Attachment 12). Microsoft® Office 2000 is listed in the current *Controlled Software Report*, as well as the *Repository Project Management Automation Plan* (Reference 2.1.4, Table 6-1). Microsoft® Office Excel 2000 and Access 2000 were executed on a PC running the Microsoft® Windows 2000 Professional Service Pack 4 operating system.

4.3 REPRESENTATIVE FUEL CHARACTERISTICS METHODOLOGY

For preclosure consequence analyses, the representative spent fuel assembly will be used to evaluate normal operational releases during repository preclosure operations. The *Basis of Design for the TAD Canister-Based Repository Design Concept* (Reference 2.2.5, Section 2.2.1.3) states that the Yucca Mountain facilities shall be capable of accommodating TAD canisters. At least 90% of the commercial SNF shall be received in TAD canisters. The remaining inventory is received as bare fuel assemblies. Using a TAD-based waste stream for determining representative fuel for normal operations is conservative (Assumption 3.2.1).

A TAD-based waste stream developed with a 25-kW limit on TAD canisters (Reference 2.2.6) is used for determining the representative spent fuel assembly (SFA) characteristics. This waste stream scenario is based on the concept of loading commercial SNF in TAD canisters beginning in 2011 and shipping the youngest fuel, greater than or equal to five years old, first beginning in 2017. The results used from Reference 2.2.6, Section 7, are in the form of an Excel spreadsheet, included in Attachment I, titled "AvailShipCD-1YFF525kW3600-Norm_Rev.xls". This spreadsheet provides the identification and characteristics of each fuel assembly including, enrichment, burnup, discharge year, arrival year, MTHM, and thermal power. The "Revised Report" worksheet of the Excel spreadsheet contains 23,250 records for commercial SNF batches containing 221,714 fuel assemblies totaling 63,000 MTHM arriving at the repository.

The "AvailShipCD-1YFF525kW3600-Norm_Rev.xls" spreadsheet is used as input to the WPLOAD v. 1.1 software. WPLOAD v. 1.1 is qualified software used to develop repository loading scenarios, a preliminary step of which is the determination of thermal power at arrival of each fuel assembly, based on its initial U_{235} enrichment, burnup, and time out of reactor.

As described in Section 6.2.1 of Reference 2.2.7, WPLOAD v. 1.1 cannot fully accommodate a TAD-based scenario without certain modifications made to the raw information in the spreadsheet. This is because WPLOAD v. 1.1 does not allow for the designation of one type of vessel to remain intact (as the TAD canister), and to be aged and emplaced as-is, and another to be opened (as a DPC or transportation cask with uncanistered fuel), and its contents blended with the contents of other vessels and placed into new TAD canisters. The actual WPLOAD input file "WASTESTREAM_TAD_YFF525kW3600.TXT", included in Attachment I, was developed from the spreadsheet file, "AvailShipCD-1YFF525kW3600-Norm_Rev.xls", worksheet "Revised Report", from Reference 2.2.6, Section 7, by the process steps 2 through 5 described in Section 6.2.1 of Reference 2.2.7.

After performing the necessary modification to the raw information, the WPLOAD v.1.1 waste stream input file, "WASTESTREAM_TAD_YFF525kW3600.TXT", contains 23,440 records for commercial SNF batches containing 221,901 SFAs totaling 63,000 MTHM arriving at the repository. There were 187 "XGHOST" assemblies added to the waste stream to allow the necessary blending of fuel assemblies from the DPCs or transportation casks with uncanistered fuel. The added assemblies increased the number of data records from 23,250 to 23,440.

The corresponding WPLOAD output file for the 25-kW TAD canister with a receipt rate of 3,600 MTHM/yr (Assumption 3.2.1) is "WPLOAD_OUTPUT_case1a.TXT". For the purpose of this analysis, "Section 10" of this output file, which contains the calculated thermal power upon arrival of each SFA, was extracted and imported into an Access database, "Representative SFA-3600.mdb" as the table "C1S10-Original". The WPLOAD input file was also imported into this Access database as the table "WASTESTREAM_TAD_YFF525kW3600-ORIGINAL". The input and output files for WPLOAD, as well as the Access database file and Excel spreadsheets used in this analysis, are contained in Attachment I.

Because of the addition of the 187 "XGHOST" assemblies to the WPLOAD input file, the Access tables "C1S10-Original" and "WASTESTREAM_TAD_YFF525kW3600-ORIGINAL" also contain these "XGHOST" assemblies. These Access tables were modified to delete the "XGHOST" assemblies. The modified table, "C1S10", contains 221,714 fuel assemblies and the modified table, "WASTESTREAM_TAD_YFF525kW3600", contains 23,425 data records, consistent with the number of data records and fuel assemblies from the Excel spreadsheet "AvailShipCD-1YFF525kW3600-Norm_Rev.xls".

Using an Access database, the information in "WASTESTREAM_TAD_YFF525kW3600" was cross-referenced to "C1S10" to provide annual averages for enrichment, thermal power, burnup, and decay time per SFA. BWR and PWR fuel assemblies are evaluated separately.

In order to demonstrate compliance with the annual dose limits in any year of preclosure operations, the representative spent fuel assembly is selected based on the year of operation with the highest average thermal power per assembly. Thermal power varies with fuel assembly enrichment, burnup, and time out of reactor. In general, the higher the thermal power, the higher the curie content of the fuel. Thus thermal power gives a good measure for determining the fuel characteristics that will be used for determining the radionuclide inventory. The first parameter, fuel assembly enrichment, is chosen as the average enrichment per fuel type over the entire fuel inventory. The average enrichment over the entire waste stream provides the reasonable starting basis for the representative spent fuel assembly. The remaining fuel parameter characteristics, burnup and time out of reactor, are then selected that correspond to that average thermal power for BWR and PWR assemblies from the year with the highest average thermal power. When in question as to which set of fuel characteristics to use, a curie content comparison was made and the higher was chosen (Section 6.4).

Given the enrichment, the fuel assembly thermal power in watts can be characterized by a variety of decay times and burnups to define the representative fuel. Two methods were used: 1) select the average burnup and then determine the corresponding time out of reactor that results in the peak year annual average thermal power, and 2) select the average time out of reactor and then determine the corresponding burnup that results in the peak year annual average thermal power. Curie content of the fuel with the characteristics derived from each of these two methods was determined and the method resulting in the highest curie content was selected to define the representative fuel.

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5. LIST OF ATTACHMENTS

6. ANALYSIS

6.1 INPUTS

6.1.1. Receipt Rate

The receipt rate used in this analysis is given in Table 1. The receipt rate is consistent with the annual receipt rates given in the *Basis of Design for the TAD Canister-Based Repository Design Concept* (Reference 2.2.5, Section 2.2.1.2) with the exception of year 6 and beyond. Starting in year 6, the receipt rate is increased by 20% to 3,600 MTHM/yr (Assumption 3.2.1). This increase in the receipt rate results in the commercial SNF having had less time for radioactive decay upon arrival than with a constant receipt rate of 3,000 MTHM/yr.

Table 1. Commercial Spent Nuclear Fuel Receipt Rate

Year	MTHM/yr
1	400
2	600
3	1,200
4	2,000
5	3,000
6 and beyond	3,600

6.1.2. Pressurized Water Reactor Fuel Assembly Thermal Power

The PWR fuel assembly thermal power in watts for each fuel assembly component is taken from the “PWR.thermal.source” file of Reference 2.2.7, Attachment I. Section 6.2.2 of Reference 2.2.7 describes the process for generating the “.source” files. The data tabulated in the “PWR.thermal.source” file originate from the radionuclide inventory “.cut” files of Reference 2.2.8, which are based on non-stainless steel clad PWR fuel with 0.475 MTHM per assembly. The portion of the “PWR.thermal.source” file that gives the watts for enrichment, burnup, and years out of reactor is imported into Excel files “PWR-4.2-watts.xls” and PWR-4.0-watts.xls” and summed over all fuel assembly components to provide the watts versus decay time for the various burnups. Table 2 contains the watts for the 4.2% enriched PWR fuel assembly at various burnups and decay times (See Section 6.3). Table 3 contains the watts for the 4.0% enriched PWR fuel assembly at various burnups and decay times (See Section 6.5).

Table 2. Thermal Power (Watts) per PWR Fuel Assembly with 4.2% Enrichment

Years out of reactor	Burnup (GWd/MTU)					
	30	40	48.086	50	60	70
5	765.40	1052.48	1309.82	1377.22	1742.38	2149.89
6	660.42	914.56	1147.54	1205.68	1536.41	1905.44
7	597.07	827.53	1041.38	1095.26	1399.61	1743.48
8	555.35	769.26	968.19	1017.73	1302.95	1625.78
9	524.93	727.61	914.68	961.07	1231.27	1536.10
10	502.11	694.59	872.89	917.14	1173.47	1464.42
11	483.34	668.05	838.72	880.76	1126.31	1404.51
12	467.96	645.92	810.07	850.98	1086.79	1354.46
13	454.93	626.27	784.81	824.68	1051.87	1309.92
14	442.06	608.88	763.03	801.68	1021.46	1270.01
15	431.21	593.75	742.53	780.16	992.44	1233.49
16	421.52	579.98	724.38	760.89	966.79	1199.47
17	412.09	566.35	707.49	742.99	943.52	1168.82
18	402.62	553.96	691.82	726.25	919.50	1139.53
19	394.29	541.73	676.36	709.75	898.63	1111.52
20	386.06	530.66	662.09	695.42	879.12	1085.74
21	378.94	519.72	648.97	680.26	859.75	1060.14
22	370.71	509.89	636.00	666.25	841.55	1035.78
23	363.66	500.17	622.13	652.36	823.51	1013.58
24	356.57	490.54	610.38	640.58	805.59	991.53
25	350.55	480.98	598.72	626.89	788.78	969.60
26	343.57	472.49	587.15	615.30	774.07	948.80
27	337.55	464.06	575.63	603.77	757.45	928.09
28	331.55	455.69	565.19	592.31	743.91	909.47
29	325.50	447.36	554.80	581.90	729.43	889.93
30	319.59	439.07	545.46	571.55	715.02	871.45

Source: Attachment I, Excel file “PWR-4.2-watts.xls”

Table 3. Thermal Power (Watts) per PWR Fuel Assembly with 4.0% Enrichment

Years out of reactor	Burnup (GWd/MTU)					
	30	40	48.086	50	60	70
5	770.09	1061.15	1331.84	1391.24	1763.75	2179.29
6	663.97	920.08	1158.31	1217.45	1556.43	1932.58
7	599.49	832.81	1050.00	1104.90	1415.39	1769.36
8	556.64	773.40	975.48	1026.12	1317.57	1645.32
9	527.19	731.63	920.92	969.32	1242.65	1554.50
10	503.04	697.46	878.90	924.17	1184.61	1481.68
11	484.37	670.82	844.62	887.75	1136.33	1420.64
12	468.97	648.66	814.84	857.85	1096.79	1369.35
13	455.72	628.80	789.56	830.34	1060.74	1323.69
14	442.75	611.39	767.66	806.31	1030.11	1282.65
15	431.87	595.24	746.04	784.77	1000.08	1246.13
16	422.14	581.35	727.87	764.40	974.31	1212.08
17	412.57	567.72	710.87	746.38	949.92	1179.32
18	403.17	555.27	694.18	729.61	926.89	1149.92
19	394.80	543.01	679.68	713.07	906.00	1121.89
20	386.45	531.90	665.37	697.71	884.43	1095.02
21	379.21	521.93	650.22	683.51	866.03	1068.44
22	372.05	511.08	637.21	669.47	845.80	1044.04
23	364.88	501.33	625.32	655.56	828.72	1020.81
24	357.78	491.68	613.55	642.75	810.78	997.73
25	350.74	482.10	600.87	630.05	794.94	976.78
26	344.66	473.60	589.27	617.43	778.21	954.95
27	338.72	465.16	578.75	605.89	762.58	934.23
28	332.63	456.77	568.29	594.41	747.02	914.59
29	326.66	447.43	556.89	583.99	732.53	896.03
30	320.64	440.14	546.54	572.63	718.11	876.54

Source: Attachment I, Excel file “PWR-4.0-watts.xls”.

6.1.3. Boiling Water Reactor Fuel Assembly Thermal Power

The BWR fuel assembly thermal power in watts for each fuel assembly component is taken from the "BWR.thermal.source" file of Reference 2.2.7, Attachment I. Section 6.2.2 of Reference 2.2.7 describes the process for generating the ".source" files. The data tabulated in the "BWR.thermal.source" file originate from the radionuclide inventory ".cut" files of Reference 2.2.9, which are based on non-stainless steel clad BWR fuel with 0.200 MTHM per assembly. The portion of the "BWR.thermal.source" file that gives the watts for enrichment, burnup, and years out of reactor is imported into Excel file "BWR-4.0-watts.xls" and summed over all fuel assembly components to provide the watts versus decay time for the various burnups. Table 4 contains the watts per 4.0% enriched BWR fuel assembly at various burnups and decay times (See Section 6.3).

Table 4. Thermal Power (Watts) per BWR Fuel Assembly with 4.0% Enrichment

Years out of reactor	Burnup (GWd/MTU)			
	29.50	39.34	49.17	59.00
5	273.49	371.91	483.44	611.34
6	242.01	331.77	433.03	548.66
7	222.64	305.98	399.10	507.21
8	210.38	287.21	375.24	475.94
9	200.20	273.55	357.60	452.83
10	193.00	262.99	343.09	434.86
11	186.85	254.51	330.68	419.02
12	180.87	247.01	320.36	405.28
13	175.73	239.67	311.11	392.63
14	171.73	234.29	302.93	382.06
15	167.77	227.95	295.81	371.57
16	163.75	222.65	288.85	363.14
17	160.75	218.39	281.83	353.75
18	156.77	213.16	275.95	345.42
19	153.82	208.96	269.00	337.12
20	150.89	204.69	264.18	329.87
21	147.87	200.53	258.39	322.64
22	144.96	196.30	252.63	315.45
23	141.97	193.18	247.88	309.27
24	138.99	188.97	243.15	302.12
25	137.12	185.78	238.44	296.99
26	134.16	181.60	233.84	289.87
27	132.11	178.43	229.15	284.77
28	129.26	175.27	224.47	277.67
29	126.92	172.11	219.91	272.59
30	124.68	168.96	216.35	267.52

Source: Attachment I, Excel file "BWR-4.0-watts.xls".

6.1.4. Radionuclide Inventory Files

PWR Source Term Generation and Evaluation (Reference 2.2.8) provides PWR radionuclide inventory files for various burnups and enrichments. Table VIII-1 of Reference 2.2.8 shows the enrichment and burnups that are available in the ".cut" files included Attachment X of Reference 2.2.8. The ".cut" files used in this analysis (Sections 6.3 through 6.6) are listed in Table 5.

Table 5. List of PWR ".cut" Files

File	Fuel Characteristics		
	Enrichment (%)	Burnup (GWd/MTHM)	Region
Waste.Stream.E4.R1.B10.cut	4.2	50	Fuel
Waste.Stream.E4.R2.B10.cut	4.2	50	Bottom End Fitting
Waste.Stream.E4.R3.B10.cut	4.2	50	Plenum
Waste.Stream.E4.R4.B10.cut	4.2	50	Top End Fitting
Waste.Stream.E4.R1.B11.cut	4.2	60	Fuel
Waste.Stream.E5.R1.B10.cut	4.0	50	Fuel

Source: Reference 2.2.8, Table VIII-1 and Attachment X.

BWR Source Term Generation and Evaluation (Reference 2.2.9) provides BWR radionuclide inventory files for various burnups and enrichments. Attachment XII of Reference 2.2.9 shows the enrichment and burnups that are available in the ".cut" files included Attachment VII of Reference 2.2.9. The ".cut" files used in this analysis (Sections 6.3 through 6.6) are listed in Table 6

Table 6. List of BWR ".cut" Files

File	Fuel Characteristics		
	Enrichment (%)	Burnup* (GWd/MTHM)	Region
4.0%.50GWd.fuel.cut	4.0	49.17	Fuel
4.0%.50GWd.bottom.cut	4.0	49.17	Bottom End Fitting
4.0%.50GWd.plenum.cut	4.0	49.17	Plenum
4.0%.50GWd.top.cut	4.0	49.17	Top End Fitting
4.0%.60GWd.fuel.cut	4.0	59.00	Fuel

NOTE: *References 2.2.9, Section 6.6 and Table 48 describe the difference between the stated burnup of the ".cut" file and the actual burnup.

Source: Reference 2.2.9, Attachments VII and XII.

6.1.5. Crud Activity and Surface Area

Commercial spent nuclear fuel assembly initial crud activity is provided in Table 7. Spent Fuel Project Office Interim Staff Guidance – 5 (Reference 2.2.10 [DIRS 160582], Table 7.1) provides the initial ^{60}Co crud activity per cm^2 and *Spent Fuel Corrosion Product and Fuel Cleaning Assessment* (Reference 2.2.13 ([DIRS 146405], Tables 1 and 2) provides the initial ^{55}Fe crud activity per cm^2. The use of ^{55}Fe crud activity per cm^2 is appropriate since it is conservative and overstates the activity by as much as a factor of 10 (Reference 2.2.13 [DIRS 146405], page 7).

Table 7. Commercial Spent Nuclear Fuel Assembly Initial Crud Activities

Radionuclide	PWR (μCi/cm^2)	BWR (μCi/cm^2)
^{60}Co	140	1,254
^{55}Fe	5,902	7,415

NOTE: μCi/cm^2 = micro curies/cubic centimeters

Source: ^{60}Co crud activities are from Reference 2.2.10 ([DIRS 160582], Table 7.1)

^{55}Fe crud activities are from Reference 2.2.13 ([DIRS 146405], Tables 1 and 2)

6.1.6. Commercial Fuel Assembly Surface Area

Commercial SNF fuel assemblies have the following surface areas, A_{SFA}:

- PWR = 449,003 cm^2/assembly (Reference 2.2.8, p. 27)
- BWR = 168,148 cm^2/assembly (Reference 2.2.9, Table 45).

These surface areas are bounding estimates based on spent fuel assemblies with the highest known surface areas, which are a South Texas PWR fuel assembly (Reference 2.2.8, p. 27) and an ANF 9 × 9 JP-4 BWR fuel assembly (Reference 2.2.9, Table 45).

6.1.7. Waste Steam Input

Reference 2.2.6, Section 7, provides a waste stream scenario that is based on receiving commercial SNF in 25-kW TAD canisters at an annual receipt rate of 3,600 MTHM (Assumption 3.2.1 and Section 6.1.1), which is represented by the file "AvailShipCD-1YFF525kW3600-Norm_Rev.xls", worksheet "Revised Report". This spreadsheet provides the identification and characteristics of each fuel assembly including, enrichment, burnup, discharge year, arrival year, MTHM, and thermal power. The "Revised Report" worksheet of the Excel spreadsheet contains 23,250 records for commercial SNF batches containing 221,714 fuel assemblies totaling 63,000 MTHM arriving at the repository.

6.2 DETERMINING AVERAGES FROM THE WASTE STREAM FILES

Reference 2.2.6, Section 7, provides a waste stream scenario that is based on receiving commercial SNF in 25-kW TAD canisters at an annual receipt rate of 3,600 MTHM (Assumption 3.2.1 and Section 6.1.1), which is represented by the file "AvailShipCD-1YFF525kW3600-Norm_Rev.xls", worksheet "Revised Report". As discussed in Section 4.3, the file is modified to accommodate a TAD-based waste stream as described in Section 6.2.1 of Reference 2.2.7. The modified file, "WASTESTREAM_TAD_YFF525kW3600.TXT", is the input file for the qualified software WPLOAD V.1.1. The output file is "WPLOAD_OUTPUT_case1a.TXT". The input and output files from WPLOAD V.1.1 are contained in Attachment I.

The input file for WPLOAD V.1.1 and "Section 10" of the output file are imported into an Access database, "Representative SFA-3600.mdb". Using the sorting and query functions of Access, the annual average thermal power, decay time, and burnup for each fuel type is determined for each year of repository operation. The thermal power is given on an assembly basis, so the average is determined with the average function of Access for each year. The burnup and age are provided on a batch basis. Therefore, the average age and burnup for each year are determined in Access by queries "Weighted Average Age" and "Weighted Average Burnup".

The information is copied into the Excel file "TAD-Based Representative SFA-3600.xls" and plotted. The annual average thermal power and decay times are shown in Figure 1 for BWR fuel and in Figure 2 for PWR fuel. The year of the peak annual average thermal power is determined for each fuel type. For PWR fuel, the peak year is 2026, for BWR fuel the peak year is 2030. Both sets of data are highlighted on each figure. The annual average thermal power and burnup are shown in Figure 3 for BWR fuel and Figure 4 for PWR fuel. Again, both years of data are highlighted on each figure. Table 8 summarizes the annual averages shown in Figure 1 through Figure 4.

Table 8. Summary of Annual Average Fuel Characteristics

Fuel Type	Fuel Characteristic	Year 2026 Peak Thermal Power Year for PWR Fuel	Year 2030 Peak Thermal Power Year for BWR Fuel
PWR	Average thermal power (watts/assembly)	879.6	872.9
	Average burnup (MWd/MTU)	49,145	50,940
	Average decay (yrs)	14.9	15.7
BWR	Average thermal power (watts/assembly)	332.0	356.5
	Average burnup (MWd/MTU)	46,275	49,177
	Average decay (yrs)	14.0	13.1

Source: Attachment I, Excel file “TAD-Based Representative SFA-3600.xls”, worksheets “Average Heat” and “Ave Age_Burnup”

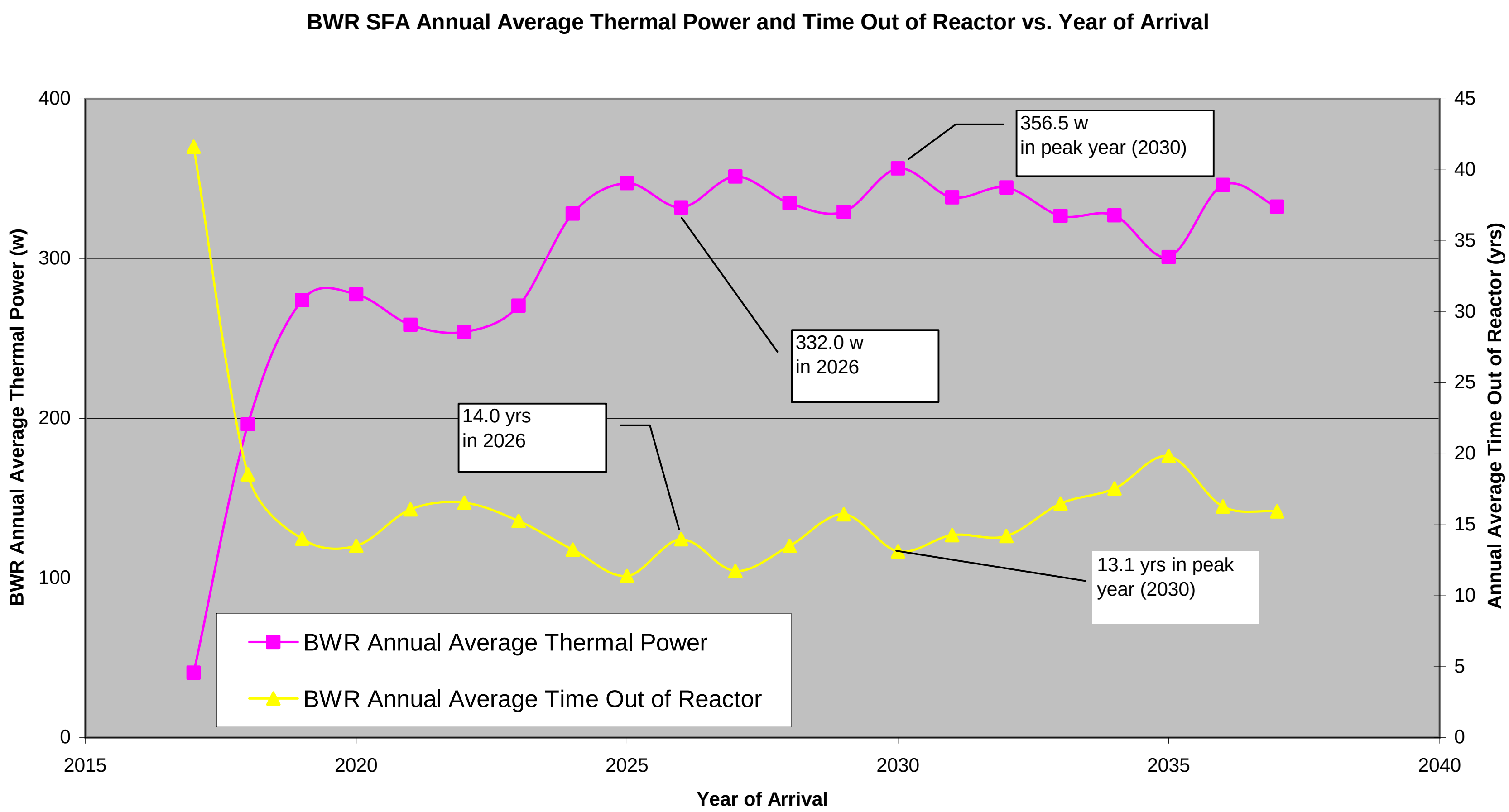

Figure 1. Boiling Water Reactor Fuel Assembly Annual Average Thermal Power and Time Out of Reactor vs. Year of Arrival

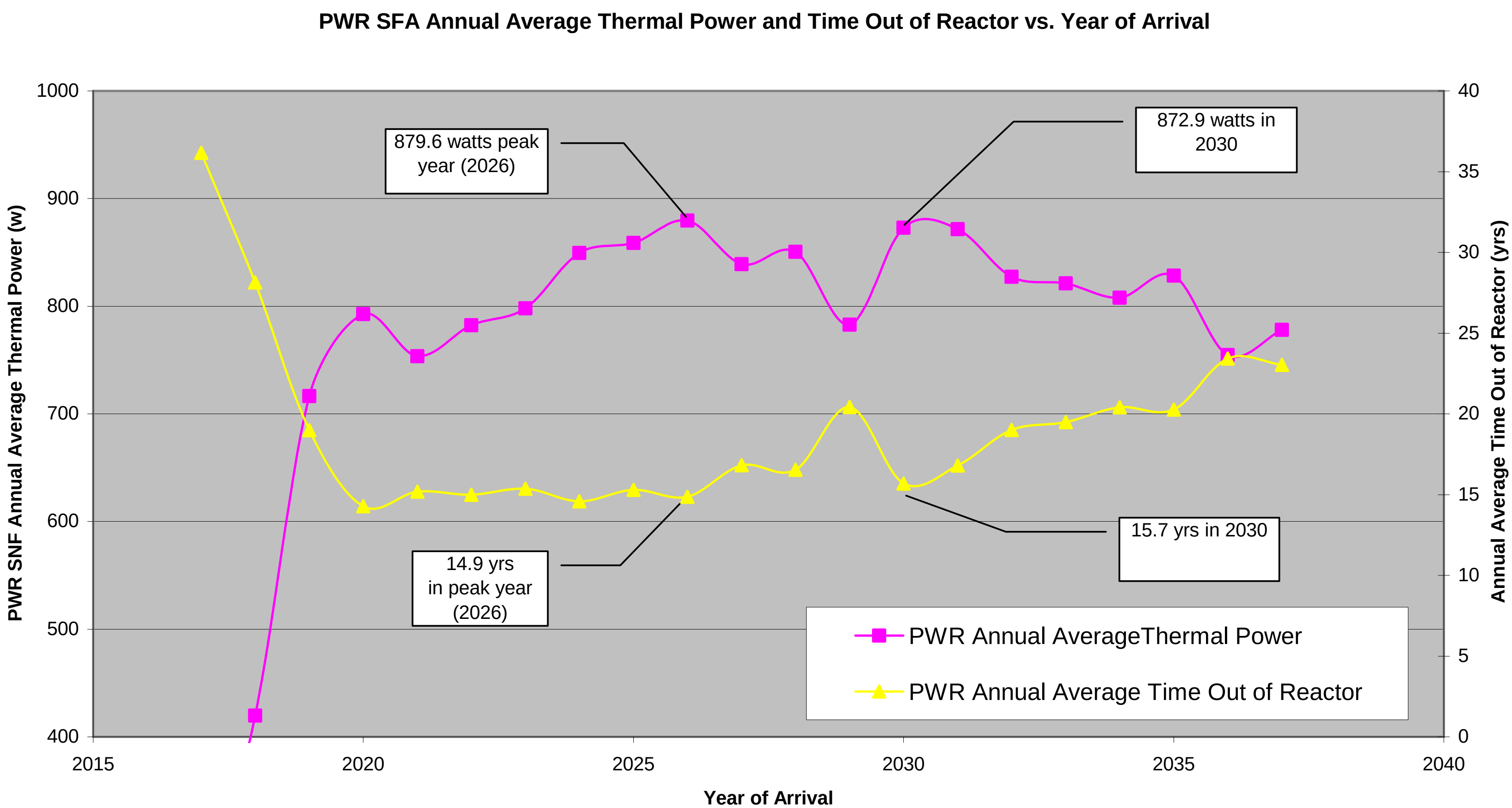

Figure 2. Pressurized Water Reactor Fuel Assembly Annual Average Thermal Power and Time Out of Reactor vs. Year of Arrival

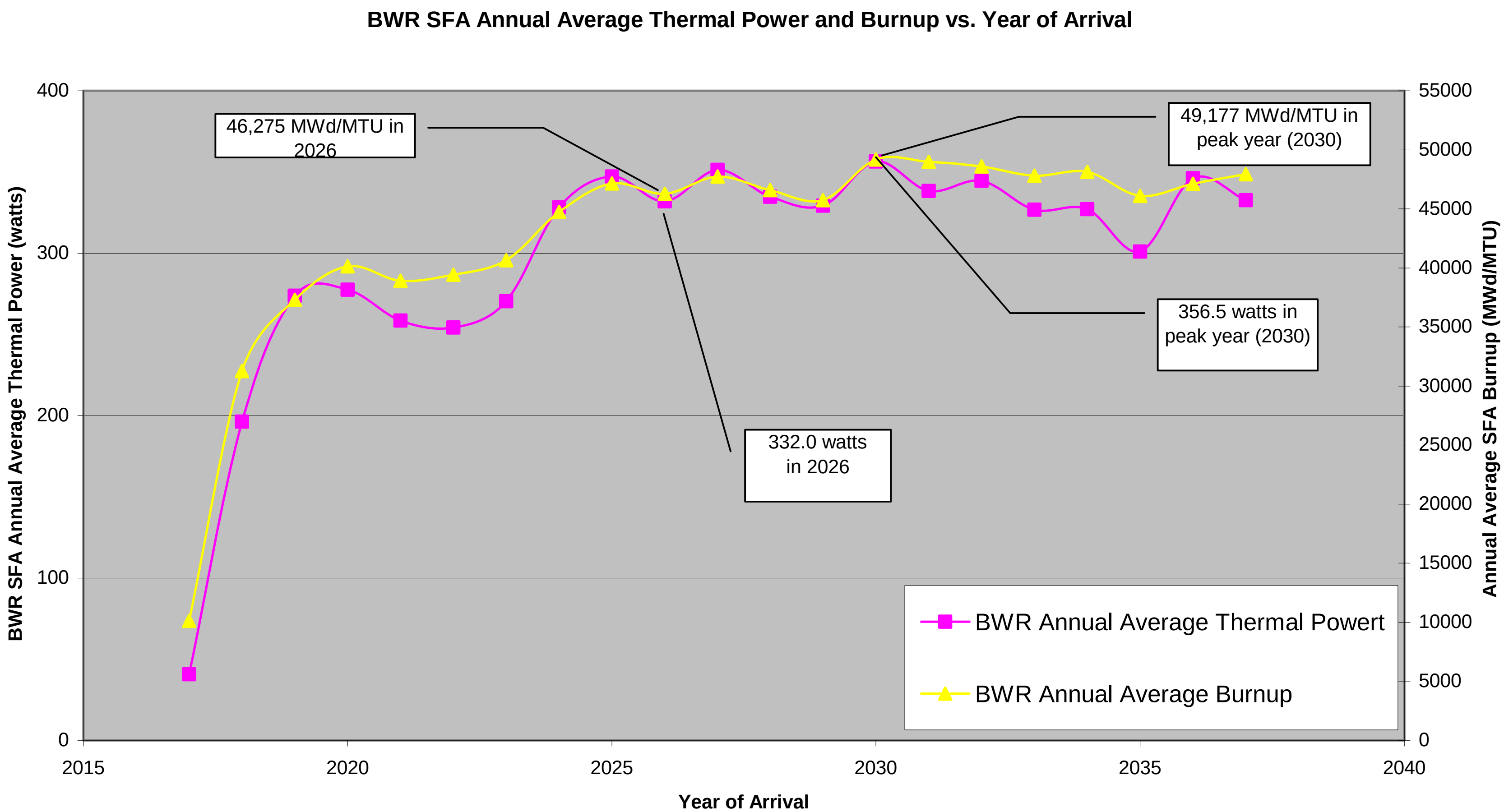

Figure 3. Boiling Water Reactor Fuel Assembly Annual Average Thermal Power and Burnup vs. Year of Arrival

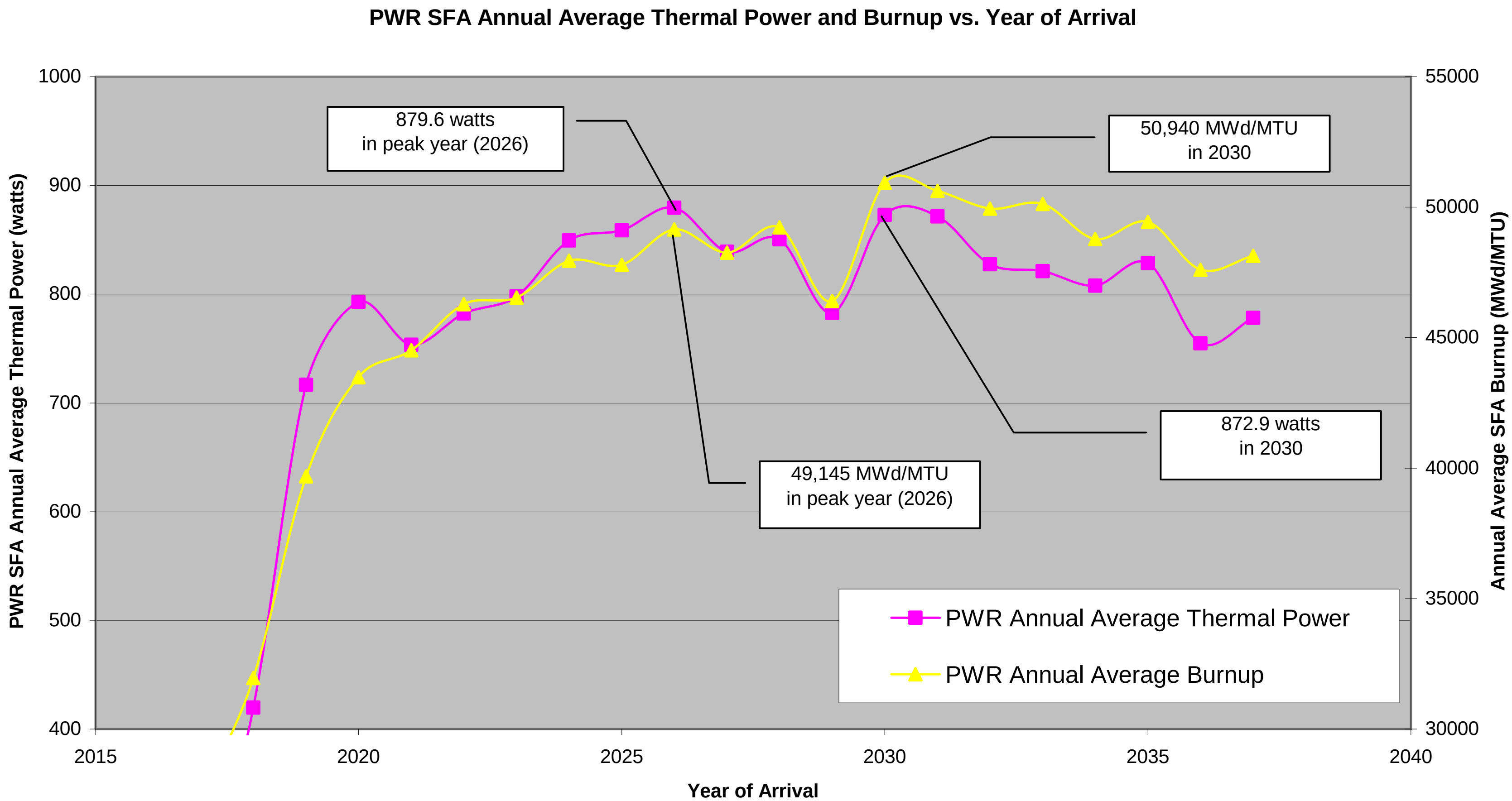

Figure 4. Pressurized Water Reactor Fuel Assembly Annual Average Thermal Power and Burnup vs. Year of Arrival

6.3 DETERMINING THE REPRESENTATIVE ENRICHMENTS

Excel is used to determine the average enrichment for each fuel type over the entire waste stream. From the Access query "Average_Burnup_per_Yr_TAD", the columns "ARRIVAL_YR", "SFA_TYPE", "SumOfNo_in_Batch", and "SumOfWtEnrich", were copied into the Excel file "Enrichment.xls", worksheet "From WPLOAD". The average enrichment for each fuel type was determined by dividing the sum of the column "SumOfWtEnrich" by the sum of the column "SumOfNo_in_Batch" for each fuel type. As a comparison, from "AvailShipCD-1YFF525kW3600-Norm_Rev.xls", the columns "Assem", "Enrich", and "Fuel Type", were copied into worksheet "From AvailShip" of the Excel file "Enrichment.xls". The data was sorted by fuel type, and the number of assemblies in the "Assem" column was multiplied by the enrichment to arrive at a weighted enrichment. The sum of the weighted enrichment was then divided by the sum of the assemblies for each fuel type to arrive at the average enrichment over the entire waste stream. The results from worksheet "From AvailShip" are the same as the results from worksheet "From WPLOAD" and the results are shown in Table 9. This comparison was done to show that adding the "XGHOST" assemblies to the WPLOAD input file and then removing them from the output files, as discussed in Section 4.3, did not change the data.

Table 9. Average Enrichment

Boiling Water Reactor	Pressurized Water Reactor
Average (%)	**Average (%)**
4.0	4.3

Source: Attachment I, Excel file "Enrichment.xls"

Based on the average enrichment as shown in Table 9, the representative BWR SNF enrichment is selected as 4.0%. As discussed in Section 6.1.4, Table VIII-1 of Reference 2.2.8 shows the enrichment and burnups that are available in the ".cut" files for PWR fuel. Both 4.2% and 4.5% enrichment fuel is available for PWR fuel. The 4.2% enrichment fuel is selected as the representative PWR SNF enrichment because it is closer to the average 4.3% and Section 6.5 shows that the curie content of the PWR fuel assembly is relatively insensitive to the enrichment of the fuel.

6.4 DETERMINING THE REPRESENTATIVE FUEL CHARACTERISTICS

Using the thermal power in watts per assembly in Table 2 for PWR fuel and Table 4 for BWR fuel and the annual average thermal power at the peak years in Table 8, two methods are considered for determining the burnup and decay characteristics that define the representative fuel characteristics that generate the annual average thermal power at the peak year: 1) select the average burnup and then determine the corresponding decay time, and 2) select the average decay time and then determine the corresponding burnup. A simple linear interpolation method is used in the Excel file "TAD-Based Representative SFA-3600.xls" in worksheets "PWR-Interpolation" and "BWR-Interpolation" based on two-dimensional arrays of thermal power in watts per assembly versus burnup and decay from Table 2 for PWR fuel and Table 4 for BWR files of Reference 2.2.8. The decay time of 20 years was selected to give a thermal power of 879.12 watts, which is within 5% of the peak year average assembly thermal power of 879.6 watts. This same process was repeated for each recommended result.

Because the representative fuel assembly will be used in dose consequences, a comparison is made of the curie content of the recommended fuel characteristics using the two methods. The actinide and fission product nuclide inventory, from the nuclide inventory ".cut" files listed in Section 6.1.4, are summed and compared. The fuel with the highest curie content is selected as the representative fuel.

Table 11. Comparison of Curie Content for Fuel Characteristics

Fuel	Curies
PWR Fuel from Average Decay Method 60,000 MWd/MTU 20 yrs decay	2.32×10^5
PWR Fuel from Average Burnup Method 50,000 MWd/MTU 10 yrs decay	2.77×10^5
BWR Fuel from Average Decay Method 60,000 MWd/MTU* 15 yrs decay	1.01×10^5
BWR Fuel from Average Burnup Method 50,000 MWd/MTU* 10 yrs decay	1.04×10^5

NOTE: *See Table 6 for actual burnup.

Source: Attachment I, Excel file "PWR-50GWd-curies total.xls", worksheets "PWR-4.2%-50GWd-fuel" and "PWR-4.2%-60GWd-fuel"; and Excel file "BWR-4.0%-50Gwd-Curies total.xls", worksheets "BWR-4.0%-50GWd-fuel" and "BWR-4.0%-60GWd-fuel"

Based on the results of the interpolation in presented in Table 10 and the comparison of the curie content from the interpolation results presented in Table 11, the Average Burnup Method is used to define the representative fuel assembly for BWR and PWR fuel. Table 12 contains the recommended fuel characteristics.

fuel. The burnup and decay times are varied, using the two methods considered, to match the thermal power during the two years of interest: the year of peak thermal power for PWR fuel and the year of peak thermal power for BWR fuel. Table 10 shows the results of the interpolation.

Table 10. Fuel Characteristics from Interpolation

Fuel Type	Fuel Characteristic	Average Burnup Method[1]	Average Decay Method[1]
PWR	Average thermal power from peak PWR year 2026 (watts/assembly)	**879.6**	**879.6**
	Average burnup (MWd/MTU)	**49,145**	54,567
	Average decay (yrs)	10.6	**14.9**
PWR	Average thermal power from year 2030 (watts/assembly)	**872.9**	**872.9**
	Average burnup (MWd/MTU)	**50,940**	55,112
	Average decay (yrs)	12.0	**15.7**
PWR	Recommended Burnup (MWd/MTU)	50,000	60,000
	Recommended decay (yrs)	10	20
	Thermal Power (watts) (From Table 2)	917.14	879.12
BWR	Average thermal power from year 2026 (watts/assembly)	**332**	**332**
	Average burnup (MWd/MTU)	**46,275**	52,781
	Average decay (yrs)	9.1	**14.0**
BWR	Average thermal power from peak BWR year 2030 (watts/assembly)	**356.5**	**356.5**
	Average burnup (MWd/MTU)	**49,176**	54,758
	Average decay (yrs)	9.1	**13.1**
BWR	Recommended Burnup (MWd/MTU)	50,000[2]	60,000[2]
	Recommended decay (yrs)	10	15
	Thermal Power (watts) (From Table 4)	343.09	371.57

NOTE: [1]Bolded values are set and the non-bolded values are varied by interpolation.
[2]See Table 6 for actual burnup.

Source: Attachment I, Excel file "TAD-Based Representative SFA-3600.xls", worksheets "PWR-Interpolation" and "BWR-Interpolation"

Based on the results of the interpolation, a recommendation for burnup and decay time for each fuel type using each interpolation method is included in Table 10. The burnup level for each fuel type and interpolation method is selected first based on the burnups available in the ".cut" files of Reference 2.2.8 and Reference 2.2.9, and then the decay times are selected to give a thermal power within 5% of the thermal power at the peak years. For example, for PWR fuel using the Average Decay Method, the burnup ranges between 54,567 and 55,112 MWd/MTU. The burnup was increased to 60,000 MWd/MTU, because 55,000 MWD/MTU is not available in the ".cut"

Table 12. Representative Fuel Assembly Characteristics

Fuel Type	Fuel Characteristic	Representative Fuel Assembly
PWR	Enrichment (%)	4.2
	Burnup (MWd/MTU)	50,000
	Decay (yrs)	10
	Initial MTHM	0.475
	Thermal Power (watts)	917.14
BWR	Enrichment (%)	4.0
	Burnup (MWd/MTU)	50,000*
	Decay (yrs)	10
	Initial MTHM	0.200
	Thermal Power (watts)	343.09

NOTE: *See Table 6 for actual burnup.

To show how the representative fuel assemblies compares to the annual average fuel thermal power shown in Figures 1 through 4, the average thermal power is plotted with the thermal power of the representative fuel assembly. Figure 5 (Attachment I, Excel file “TAD-Based Representative SFA-3600.xls”, worksheet “PWR Average Power”) shows the comparison to representative PWR fuel and Figure 6 (Attachment I, Excel file “TAD-Based Representative SFA-3600.xls”, worksheet “BWR Average Power”) shows the comparison to representative BWR fuel.

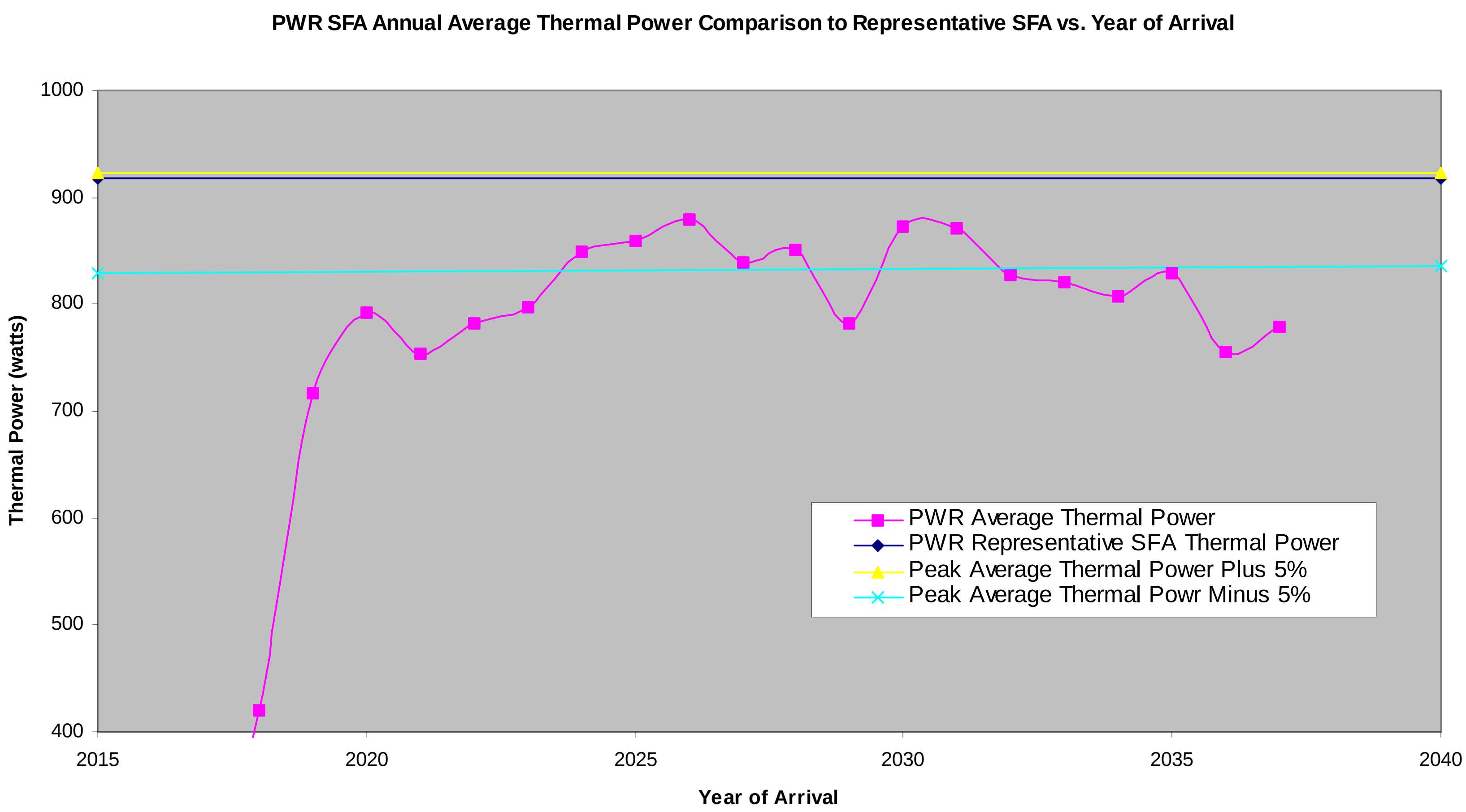

Figure 5. Thermal Power of Representative PWR Fuel Assembly Compared to Annual Average

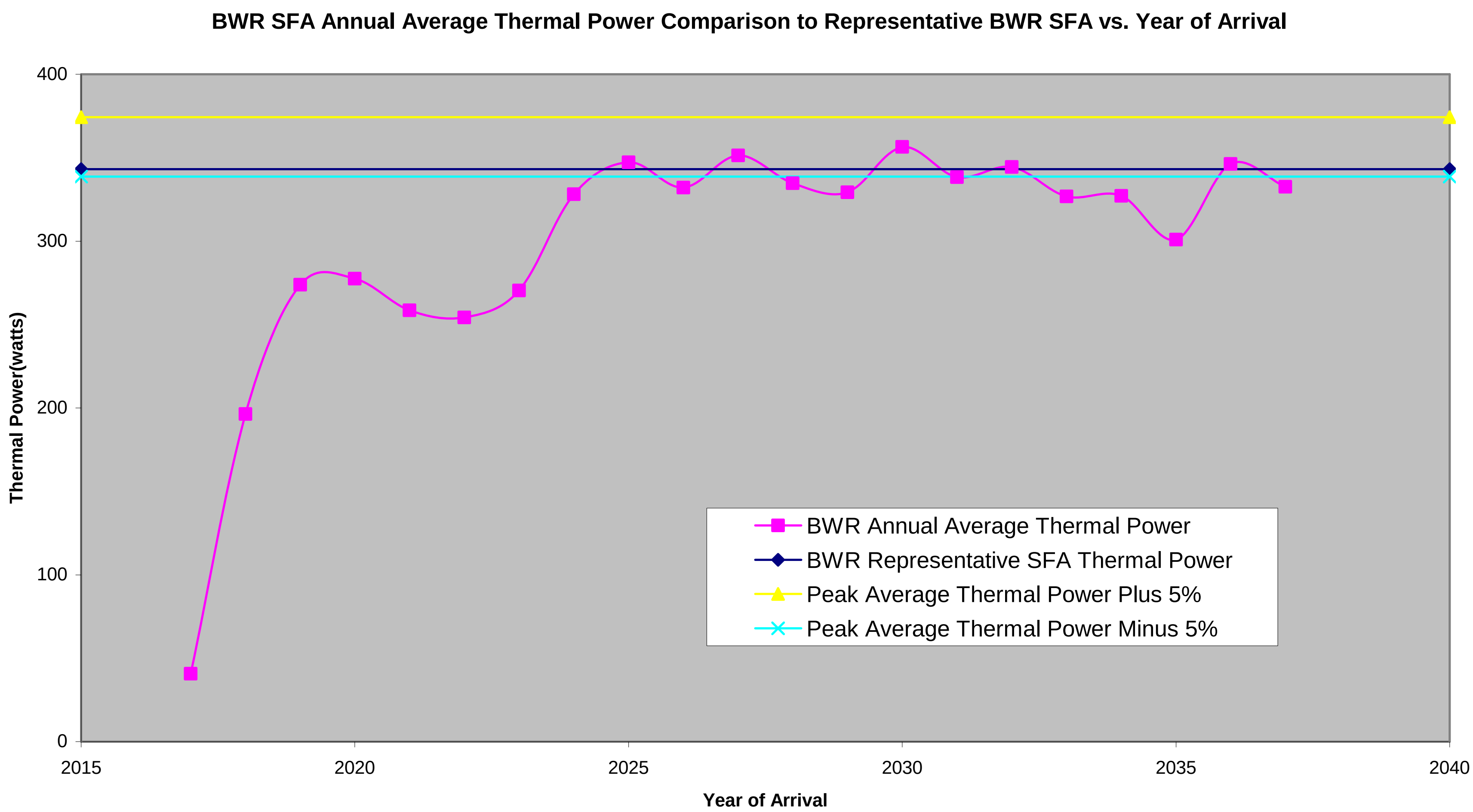

Figure 6. Thermal Power of Representative BWR Fuel Assembly Compared to Annual Average

6.5 SENSITIVITY TO ENRICHMENT

The burnup and decay times are selected by linear interpolation using thermal power in watts per assembly for a given fuel enrichment. Although the fuel enrichment is chosen based on the average enrichment from the waste stream data, this section compares the results of the interpolation for the PWR fuel with an enrichment of 4.0% to the results in Table 10, which were determined with an enrichment of 4.2%. The thermal power in watts per assembly from Table 3 is used with the annual average thermal power of the peak year 2026. Only the average burnup method was performed since it has been previously demonstrated in Section 6.4 that the fuel characteristics determined by the average burnup method result in higher curie content.

Table 13. Enrichment Sensitivity

Fuel Type	Fuel Characteristic	Average Burnup Method*
PWR 4.0% Enrichment	Average thermal power from peak year 2026 (watts/assembly)	**879.6**
	Average burnup (MWd/MTU)	**49,145**
	Average decay (yrs)	10.6
Recommended	Burnup (MWd/MTU)	50,000
	Decay (yrs)	10
	Thermal Power (watts) (From Table 3)	924.17
PWR 4.2% Enrichment	Average thermal power from peak year 2026 (watts/assembly)	**879.6**
	Average burnup (MWd/MTU)	**49,145**
	Average decay (yrs)	10.6
Recommended	Burnup (MWd/MTU)	50,000
	Decay (yrs)	10
	Thermal Power (watts) (From Table 2)	917.14

NOTES: *Bolded values are set and the non-bolded values are varied by interpolation.

Source: Attachment I, Excel file “TAD-Based Representative SFA-3600.xls”, worksheet “PWR-Interpolation”

If 4.0% enrichment fuel were used as the enrichment for the representative PWR fuel assembly, the recommended resulting parameters arrived through interpolation would still be 50,000 MWd/MTU burnup with 10 yr decay time. Because the representative fuel assembly will be used in dose consequences, a comparison of the curie content of the fuel at the two enrichments is made. The results of the comparison are shown in Table 14. Only the curies for the actinides and fission products, from the nuclide inventory “.cut” files listed in Section 6.1.4, are used in this comparison.

Table 14. Comparison of Curie Content vs. Enrichment for PWR Fuel

	4.0% 50GWd/MTU at 10 yrs Decay	**4.2% 50 GWd/MTU at 10 yrs Decay**
Curies	2.75×10^5	2.77×10^5

Source: Attachment I, Excel file “PWR-50GWd-curies total.xls”, worksheets “PWR-curies-4.0-50GWd” and “PWR-4.2%-50GWd-fuel”

From this comparison, it can be seen that the curie content is relatively insensitive to enrichment and the enrichment recommended (4.2%), based on the entire waste stream as discussed in Section 6.3, is slightly more conservative than the lower enriched fuel. Therefore, the recommended fuel parameters in Table 12 are conservative for curie content.

6.6 RADIONUCLIDE INVENTORY FOR REPRESENTATIVE COMMERCIAL SPENT NUCLEAR FUEL

Radionuclides used in consequence analyses are based on the selection criteria in NUREG-1567 (Reference 2.2.11 [DIRS 149756], p. 9-11) and Spent Fuel Project Office Interim Staff Guidance-5 (Reference 2.2.10 [DIRS 160582], Attachment, Section 3). For confinement analysis, the radionuclide inventory, as a minimum, includes activity from ^{60}Co in crud, activity from iodine, other fission products that contribute greater than 0.1% of design basis fuel activity, and actinide activity that contributes greater than 0.01% of the design basis activity. These nuclides were determined for both the PWR and BWR representative fuel by dividing the activity of the nuclide, by the sum of the activity of the fission products and actinides. The screening threshold of either 0.1%, for fission products, or 0.01% for actinides, was applied. Table 15 shows the minimum set of radionuclides for consequence analysis based on the selection criteria in NUREG-1567 (Reference 2.2.11 [DIRS 149756], p. 9-11) and Spent Fuel Project Office Interim Staff Guidance-5 (Reference 2.2.10 [DIRS 160582], Attachment, Section 3).

Table 15. Minimum List of Fission Products and Actinides

PWR Radionuclides		BWR Radionuclides	
Fission Products	**Percent Contribution (%)**	**Fission Products**	**Percent Contribution (%)**
^{137m}Ba	20.563	^{137m}Ba	21.785
^{134}Cs	1.472	^{134}Cs	1.257
^{137}Cs	21.789	^{137}Cs	23.129
^{154}Eu	0.851	^{154}Eu	0.742
^{155}Eu	0.178	^{155}Eu	0.184
^{129}I	-	^{129}I	-
^{85}Kr	1.122	^{85}Kr	1.123
^{147}Pm	2.294	^{147}Pm	2.025
^{106}Rh*	0.123	-	-
^{106}Ru	0.123	-	-
^{125}Sb	0.141	^{125}Sb	0.115
^{90}Sr	14.791	^{90}Sr	15.931
^{90}Y	14.791	^{90}Y	15.931
Actinides	**Percent Contribution (%)**	**Actinides**	**Percent Contribution (%)**
^{241}Am	0.426	^{241}Am	0.358
^{244}Cm	0.934	^{244}Cm	0.866
^{238}Pu	0.999	^{238}Pu	0.979
^{239}Pu	0.065	^{239}Pu	0.052
^{240}Pu	0.115	^{240}Pu	0.122
^{241}Pu	18.759	^{241}Pu	15.067

Notes: * Can be omitted due to short half life (29.9 seconds) .

SOURCE: Attachment I, Excel file “BWR-4.0%-50Gwd-Curies total.xls”, worksheet “FP-ACT+GAS”; and Excel file “PWR-50Gwd-Curies total.xls”, worksheet “FP-ACT-GAS”

Reference 2.2.12 ([DIRS 156955]) performed a comparative analysis to identify radionuclides that are significant to offsite doses from preclosure events for SNF and high-level radioactive waste. The table on Page IV-4 of Reference 2.2.12 ([DIRS 156955]) contains the list of Department of Energy SNF radionuclides and their first generation daughter products. For consistency, the minimum list of fission products and actinides has been expanded to include the radionuclides given on page IV-4 of Reference 2.2.12 ([DIRS 156955]), if radionuclide inventory is present. The nuclide ^{106}Rh is included in the minimum list of radionuclides for PWR fuel, but is not included in the minimum list of radionuclides for BWR fuel or in the list of nuclides significant to offsite dose from page IV-4 of Reference 2.2.12 ([DIRS 156955]). The half-life for ^{106}Rh is 29.9 seconds (Reference 2.2.14 [DIRS 175238], pg. 52), thus once released; its short half-live precludes it from having any impact to dose. Therefore, ^{106}Rh is not included in the selection of radionuclides for dose consequences. The nuclides ^{14}C, ^{36}Cl, and ^{3}H are included in the selection of radionuclides because of a potential release into the atmosphere as gaseous nuclides.

Attachment II presents the radionuclide inventory for bounding fuel to be used in preclosure event sequences that result in airborne releases. The radionuclide selection process for the bounding fuel resulted the addition of three radionuclides, ^{144}Ce, ^{239}Np, and ^{144}Pr. For completeness, these three nuclides will also be included in the list of nuclides for the representative fuel to be used in dose consequences. Table 16 contains the complete list of radionuclides used for dose evaluation.

Radionuclide inventories are calculated in Reference 2.2.8 for PWR fuel and Reference 2.2.9 for BWR fuel. The ".cut" files from Reference 2.2.8 and Reference 2.2.9 contain the radionuclide inventories in curies per assembly for fission products, actinides, and light elements. The light elements consist of the activation of the fuel assembly hardware, as well as the fuel impurities. Light elements are not included in the selection criteria in NUREG-1567 (Reference 2.2.11 [DIRS 149756], p. 9-11) and Spent Fuel Project Office Interim Staff Guidance-5 (Reference 2.2.10 [DIRS 160582], Attachment, Section 3) and therefore, are not included in the radionuclides evaluated in preclosure dose analyses. However, as stated earlier, the nuclides ^{14}C, ^{36}Cl, and ^{3}H from the light element list of the ".cut" files are included in the radionuclide inventory evaluated for dose consequences because of the potential gaseous release.

For PWR fuel, the fuel assembly is divided into four regions for analysis: the top, bottom, fuel, and plenum regions (Reference 2.2.8, Table 11 and Attachment VIII). The ".cut" file for the fuel region contains the actinide and fission product radionuclides, as well as the light element radionuclides. The light elements in the active fuel region ".cut" file include the impurities in the fuel itself (Reference 2.2.8, Section 5.4.4). However, by comparing the light elements due to the fuel impurities and the light elements in the fuel region, the contribution of light elements from fuel impurities is negligible (Reference 2.2.8, Page III-7). Therefore again, only the ^{14}C, ^{36}Cl, and ^{3}H from the light elements are included in Table 16. The curies per assembly for PWR fuel are from the actinide and fission product section of "Waste.Stream.E4.R1.B10.cut" file, and the nuclides ^{14}C, ^{36}Cl, and ^{3}H from the light element section of "Waste.Stream.E4.R1.B10.cut" file, "Waste.Stream.E4.R2.B10.cut" file, "Waste.Stream.E4.R3.B10.cut" file, and "Waste.Stream.E4. R4.B10.cut" file (Reference 2.2.8, Table VIII-1 and Attachment X).

For BWR fuel, the fuel assembly is also divided into the same four regions for analysis. Thus, the radionuclide inventory for the representative BWR fuel includes the actinide and fission product section of file "4.0%.50GWd.fuel.cut" with the addition of the nuclides ^{14}C, ^{36}Cl, and ^{3}H from the light element section of the files "4.0%.50GWd.fuel.cut", "4.0%.50GWd.top.cut", "4.0%.50GWd.bottom.cut", and "4.0%.50GWd.plenum.cut" (Reference 2.2.9, Attachments VII and XII). Section 6.6 and Table 48 of References 2.2.9 describe the difference between the stated burnup of the ".cut" file and the actual burnup. For example, the file, "4.0%.50GWd.fuel.cut", actually represents BWR fuel that is 4.0% enriched with 49,170 MWd/MTU burnup.

Table 16. Radionuclide Inventory For Representative Commercial Spent Nuclear Fuel Excluding Crud

Radionuclide	Representative PWR (Ci/fuel assembly)	Representative BWR (Ci/fuel assembly)
^{241}Am	1.18×10^{3}	3.73×10^{2}
^{242}Am	7.27	2.87
^{242m}Am	7.30	2.88
^{243}Am	2.30×10^{1}	8.63
^{137m}Ba	5.70×10^{4}	2.27×10^{4}
^{14}C	4.21×10^{-1}	2.12×10^{-1}
^{113m}Cd	1.39×10^{1}	5.24
^{144}Ce	7.26×10^{1}	1.73×10^{1}
^{36}Cl	8.49×10^{-3}	3.48×10^{-3}
^{242}Cm	6.03	2.38
^{243}Cm	1.57×10^{1}	5.55
^{244}Cm	2.59×10^{3}	9.23×10^{2}
^{245}Cm	3.37×10^{-1}	9.07×10^{-2}
^{246}Cm	1.16×10^{-1}	4.26×10^{-2}
^{134}Cs	4.08×10^{3}	1.31×10^{3}
^{135}Cs	3.74×10^{-1}	1.81×10^{-1}
^{137}Cs	6.04×10^{4}	2.41×10^{4}
^{154}Eu	2.36×10^{3}	7.73×10^{2}
^{155}Eu	4.94×10^{2}	1.92×10^{2}
^{3}H	2.44×10^{2}	1.05×10^{2}
^{129}I	2.27×10^{-2}	9.22×10^{-3}
^{85}Kr	3.11×10^{3}	1.17×10^{3}
^{93m}Nb	3.44×10^{-1}	1.58×10^{-1}
^{94}Nb	6.31×10^{-5}	2.56×10^{-5}
^{237}Np	2.53×10^{-1}	8.74×10^{-2}
^{239}Np	2.30×10^{1}	8.63
^{231}Pa	3.00×10^{-5}	1.86×10^{-5}
^{107}Pd	8.65×10^{-2}	3.45×10^{-2}
^{147}Pm	6.36×10^{3}	2.11×10^{3}
^{144}Pr	7.26×10^{1}	1.73×10^{1}
^{238}Pu	2.77×10^{3}	1.02×10^{3}
^{239}Pu	1.80×10^{2}	5.41×10^{1}
^{240}Pu	3.20×10^{2}	1.27×10^{2}
^{241}Pu	5.20×10^{4}	1.57×10^{4}
^{242}Pu	1.68	7.08×10^{-1}
^{106}Ru	3.40×10^{2}	9.05×10^{1}
^{125}Sb	3.90×10^{2}	1.20×10^{2}
^{79}Se	4.75×10^{-2}	1.97×10^{-2}
^{151}Sm	2.45×10^{2}	6.73×10^{1}
^{126}Sn	3.97×10^{-1}	1.61×10^{-1}
^{90}Sr	4.10×10^{4}	1.66×10^{4}

Table 16. Radionuclide Inventory For Representative Commercial Spent Nuclear Fuel Excluding Crud (Continued)

Radionuclide	Representative PWR (Ci/fuel assembly)	Representative BWR (Ci/fuel assembly)
^{99}Tc	9.32	3.88
^{230}Th	6.45×10^{-5}	3.06×10^{-5}
^{232}U	2.44×10^{-2}	8.74×10^{-3}
^{233}U	2.46×10^{-5}	0.00
^{234}U	6.01×10^{-1}	2.39×10^{-1}
^{235}U	7.66×10^{-3}	2.11×10^{-3}
^{236}U	1.81×10^{-1}	7.45×10^{-2}
^{238}U	1.47×10^{-1}	6.24×10^{-2}
^{90}Y	4.10×10^{4}	1.66×10^{4}
^{93}Zr	8.34×10^{-1}	3.49×10^{-1}

NOTE: Ci = curies

Source: Attachment I, Excel file “BWR-4.0%-50Gwd-Curies total.xls”, worksheet “FP-ACT+GAS”; and “PWR-50Gwd-Curies total.xls”, worksheet “FP-ACT-GAS”

The radionuclide inventory listed in Table 16 does not include the crud activities. Crud is activated corrosion products found on the exterior surface of fuel assemblies. After decaying for 5 years, the nuclide species that have significant activity in the crud are ^{55}Fe and ^{60}Co. Commercial SNF assemblies have initial crud activities at the time of discharge from the reactor as shown in Table 17.

Table 17. Commercial Spent Nuclear Fuel Assembly Initial Crud Activities

Radionuclide	PWR ($\mu Ci/cm^2$)	BWR ($\mu Ci/cm^2$)
^{60}Co	140	1,254
^{55}Fe	5,902	7,415

NOTE: $\mu Ci/cm^2$ = micro curies/cubic centimeters

Source: ^{60}Co crud activities are from Reference 2.2.10 ([DIRS 160582], Table 7.1)

^{55}Fe crud activities are from Reference 2.2.13 ([DIRS 146405], Tables 1 and 2)

The crud surface activity for a given assembly is a function of time after discharge from the reactor. The time-dependent crud surface activity is based on the following radioactive decay equation (Reference 2.2.8, p. 27):

$$N(t) = N(0)\exp\left(\frac{-t \times \ln 2}{t_{1/2}}\right) \qquad \text{(Eq. 1)}$$

where,

$N(t)$	=	crud activity at time t,
$N(0)$	=	crud activity at time 0,
$t_{1/2}$	=	radionuclide half-life in years
	=	5.271 years for ^{60}Co (Reference 2.2.14 [DIRS 175238], p. 47), and 2.73 years for ^{55}Fe (Reference 2.2.14 [DIRS 175238], p. 47)
t	=	the decay time in years.

The crud inventory, in Ci/FA on a per assembly basis, is calculated as:

$$RI_{crud} = SA_{crud} \times A_{SFA} \times conv \qquad \text{(Eq. 2)}$$

where,

RI_{crud}	=	crud radioactive inventory; Ci/FA
SA_{crud}	=	crud surface activity; μCi/cm^2
A_{SFA}	=	surface area per assembly; cm^2/FA
$conv$	=	conversion factor; 10^{-6} Ci/μCi.

Commercial SNF fuel assemblies have the following surface areas, A_{SFA}:

PWR = 449,003 cm^2/assembly (Reference 2.2.8, p. 27)

BWR = 168,148 cm^2/assembly (Reference 2.2.9, Table 45).

These surface areas are bounding estimates based on spent fuel assemblies with the highest known surface areas, which are a South Texas PWR fuel assembly (Reference 2.2.8, p. 27) and an ANF 9 × 9 JP-4 BWR fuel assembly (Reference 2.2.9, Table 45). The crud inventory for normal operations is based on a decay time of 10 years for both PWR fuel and BWR fuel, which is consistent with the decay times of the representative PWR and BWR fuel given in Table 12. Using Equations 1 and 2, the BWR and PWR crud inventory is given in Table 18.

Table 18. Crud Inventory for Representative BWR and PWR Fuel

Radionuclide In Crud	PWR Crud Inventory (Ci/FA)	BWR Crud Inventory (Ci/FA)
^{60}Co	1.69×10^{1}	5.66×10^{1}
^{55}Fe	2.09×10^{2}	9.84×10^{1}

NOTE: Ci/FA = curies per fuel assembly.

Source: Attachment I, Excel file “BWR-4.0%-50Gwd-Curies total.xls”, worksheet “CRUD”

7. RESULTS

Summaries of the results are given in Table 19 and Table 20 for the representative fuel characteristics for use in dose consequence analyses of airborne release during normal operations, and the radionuclide inventory for the representative fuels.

Table 19. Representative Fuel Assembly Characteristics

Fuel Type	Fuel Characteristic	Representative Fuel Assembly
PWR	Enrichment (%)	4.2
	Burnup (MWd/MTU)	50,000
	Decay (yrs)	10
	Initial MTHM	0.475
	Thermal Power (watts)	917.14
BWR	Enrichment (%)	4.0
	Burnup (MWd/MTU)	50,000*
	Decay (yrs)	10
	Initial MTHM	0.200
	Thermal Power (watts)	343.09

NOTE: *See Table 6 for actual burnup.

These results are conservative with respect to their intended use for dose consequences from airborne releases during normal operations. The fuel characteristics were chosen to represent the entire waste stream while airborne releases during normal operations can only occur in the Wet Handling Facility during TAD canister loading of uncanistered fuel and fuel from DPCs. At least ninety percent of the waste stream is to be received in TAD canisters (Reference 2.2.5, Section 2.2.1.3), therefore, potential airborne releases are only from the remaining portion of the waste stream. In addition, the average characteristics of fuel in DPCs is 30 GWd/MTU and 42 years out of reactor and the average characteristics of uncanistered fuel is 42 GWd/MTU and 24 years out of reactor (Reference 2.2.6, Table 1). Therefore, the characteristics of the representative fuel derived in this analysis bounds the expected characteristics of the fuel that has the potential to contribute to airborne releases during normal operations.

The characteristics of the representative fuel is one parameter used with other conservative assumptions and parameters in the dose consequence analysis to provide reasonable assurance that regulatory performance objectives are met.

Table 20. Radionuclide Inventory For Representative Commercial Spent Nuclear Fuel Including Crud

Radionuclide	Representative PWR (Ci/fuel assembly)	Representative BWR (Ci/fuel assembly)
^{241}Am	1.18×10^{3}	3.73×10^{2}
^{242}Am	7.27	2.87
^{242m}Am	7.30	2.88
^{243}Am	2.30×10^{1}	8.63
^{137m}Ba	5.70×10^{4}	2.27×10^{4}
^{14}C	4.21×10^{-1}	2.12×10^{-1}
^{113m}Cd	1.39×10^{1}	5.24
^{144}Ce	7.26×10^{1}	1.73×10^{1}
^{36}Cl	8.49×10^{-3}	3.48×10^{-3}
^{242}Cm	6.03	2.38
^{243}Cm	1.57×10^{1}	5.55
^{244}Cm	2.59×10^{3}	9.23×10^{2}
^{245}Cm	3.37×10^{-1}	9.07×10^{-2}
^{246}Cm	1.16×10^{-1}	4.26×10^{-2}
^{60}Co (crud)	1.69×10^{1}	5.66×10^{1}
^{134}Cs	4.08×10^{3}	1.31×10^{3}
^{135}Cs	3.74×10^{-1}	1.81×10^{-1}
^{137}Cs	6.04×10^{4}	2.41×10^{4}
^{154}Eu	2.36×10^{3}	7.73×10^{2}
^{155}Eu	4.94×10^{2}	1.92×10^{2}
^{55}Fe (crud)	2.09×10^{2}	9.84×10^{1}
^{3}H	2.44×10^{2}	1.05×10^{2}
^{129}I	2.27×10^{-2}	9.22×10^{-3}
^{85}Kr	3.11×10^{3}	1.17×10^{3}
^{93m}Nb	3.44×10^{-1}	1.58×10^{-1}
^{94}Nb	6.31×10^{-5}	2.56×10^{-5}
^{237}Np	2.53×10^{-1}	8.74×10^{-2}
^{239}Np	2.30×10^{1}	8.63
^{231}Pa	3.00×10^{-5}	1.86×10^{-5}
^{107}Pd	8.65×10^{-2}	3.45×10^{-2}
^{147}Pm	6.36×10^{3}	2.11×10^{3}
^{144}Pr	7.26×10^{1}	1.73×10^{1}
^{238}Pu	2.77×10^{3}	1.02×10^{3}
^{239}Pu	1.80×10^{2}	5.41×10^{1}
^{240}Pu	3.20×10^{2}	1.27×10^{2}
^{241}Pu	5.20×10^{4}	1.57×10^{4}
^{242}Pu	1.68	7.08×10^{-1}
^{106}Ru	3.40×10^{2}	9.05×10^{1}
^{125}Sb	3.90×10^{2}	1.20×10^{2}
^{79}Se	4.75×10^{-2}	1.97×10^{-2}
^{151}Sm	2.45×10^{2}	6.73×10^{1}
^{126}Sn	3.97×10^{-1}	1.61×10^{-1}

Table 20. Radionuclide Inventory For Representative Commercial Spent Nuclear Fuel Including Crud (Continued)

Radionuclide	Representative PWR (Ci/fuel assembly)	Representative BWR (Ci/fuel assembly)
^{90}Sr	4.10×10^{4}	1.66×10^{4}
^{99}Tc	9.32	3.88
^{230}Th	6.45×10^{-5}	3.06×10^{-5}
^{232}U	2.44×10^{-2}	8.74×10^{-3}
^{233}U	2.46×10^{-5}	0.00
^{234}U	6.01×10^{-1}	2.39×10^{-1}
^{235}U	7.66×10^{-3}	2.11×10^{-3}
^{236}U	1.81×10^{-1}	7.45×10^{-2}
^{238}U	1.47×10^{-1}	6.24×10^{-2}
^{90}Y	4.10×10^{4}	1.66×10^{4}
^{93}Zr	8.34×10^{-1}	3.49×10^{-1}

NOTE: Ci = curies.

Source: Attachment I, Excel file “BWR-4.0%-50Gwd-Curies total.xls”, worksheet “FP-ACT+GAS”; and “PWR-50Gwd-Curies total.xls”, worksheet “FP-ACT-GAS”

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ATTACHMENT I.

COMPUTER FILES

Attachment I consists of a compact disk that contains the following electronic files.

Table I-1. List of Computer Files

File Name	Size (kB)	Date	Time
AvailShipCD-1YFF525kW3600-Norm_Rev.xls	12,677	02/07/2007	12:43 PM
WASTESTREAM_TAD_YFF525kW3600.TXT	3,251	02/08/2007	10:28 AM
WPLOAD_OUTPUT_case1a.TXT	38,651	02/12/2007	7:33 PM
Representative SFA-3600.mdb	44,052	05/01/2007	6:00 PM
TAD-Based Representative SFA-3600.xls	829	05/03/2007	3:59 PM
Enrichment.xls	3,478	05/01/2007	5:44 PM
PWR-50Gwd-Curies total.xls	207	05/03/2007	9:23 AM
PWR-4.2-watts.xls	49	04/17/2007	11:23 AM
PWR-4.0-watts.xls	55	04/17/2007	10:56 AM
BWR-4.0%-50Gwd-Curies total.xls	148	05/03/2007	9:15 AM
BWR-4.0-watts.xls	46	04/17/2007	4:19 PM
PWR-80GWd-curies total.xls	114	05/03/2007	9:48 AM
BWR-75GWd-curies total.xls	121	05/03/2007	9:48 AM

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ATTACHMENT II.

BOUNDING COMMERCIAL SPENT NUCLEAR FUEL RADIONUCLIDE INVENTORY

The purpose of this attachment is to generate the bounding nuclide inventory to be used in preclosure event sequences that result in airborne releases. The bounding fuel characteristics listed in Table II-1 are from Reference 2.2.8, Section 5.5 for PWR fuel and Reference 2.2.9, Section 5.5.3 for BWR fuel. *PWR and BWR Source Term Sensitivity Study* (Reference 2.2.15) documents a sensitivity study comparing different versions of the codes used to determine the source terms provided in Reference 2.2.8 and Reference 2.2.9. Table 98 of Reference 2.2.15 shows that the heat, or thermal power, for the BWR bounding fuel assembly is three percent less than the comparison fuel assemblies. Reference 2.2.15, Section 6.4 concludes that there is little difference in the heat outputs between the different versions of the code used. Improvements made in the code and changes made to the nuclear cross-sections within the code are small, indicating the reliability in the methodology and relative stability in the nuclear data. Thus, the data from Reference 2.2.9 on radionuclide inventory can be used with confidence.

Table II-1. Bounding Fuel Assembly Characteristics

Fuel Type	Fuel Characteristic	Bounding Fuel Assembly
PWR	Enrichment (%)	5.0
	Burnup (MWd/MTU)	80,000
	Decay time (yrs)	5
BWR	Enrichment (%)	5.0
	Burnup (MWd/MTU)	75,000
	Decay time (yrs)	5

Source: Reference 2.2.8, Section 5.5 for PWR fuel and Reference 2.2.9, Section 5.5.3 for BWR fuel.

Section 6.6 describes the selection of the nuclides used in preclosure dose consequence analyses for normal operations. This same selection process is applied to the bounding fuel and minimum set of radionuclides for consequence analysis for event sequences based on the selection criteria in NUREG-1567 (Reference 2.2.11 [DIRS 149756], p. 9-11) and Spent Fuel Project Office Interim Staff Guidance-5 (Reference 2.2.10 [DIRS 160582], Attachment, Section 3) is listed in Table II-2. Radionuclide inventory is calculated in Reference 2.2.8 for PWR fuel and Reference 2.2.9 for BWR fuel. The ".cut" files from Reference 2.2.8 and Reference 2.2.9 contain the radionuclide inventories in curies per assembly for fission products, actinides, and light elements.

Table II-2. Minimum List of Fission Products and Actinides for Bounding Fuel

PWR Radionuclides		BWR Radionuclides	
Fission Products	**Percent Contribution (%)**	**Fission Products**	**Percent Contribution (%)**
^{137m}Ba	17.806	^{137m}Ba	19.369
^{144}Ce	1.044	^{144}Ce	0.732
^{134}Cs	7.291	^{134}Cs	6.156
^{137}Cs	18.904	^{137}Cs	20.537
^{154}Eu	1.107	^{154}Eu	0.950
^{155}Eu	0.324	^{155}Eu	0.332
^{129}I	-	^{129}I	-
^{85}Kr	1.042	^{85}Kr	1.077
^{147}Pm	4.123	^{147}Pm	3.959
^{144}Pr	1.044	^{144}Pr	0.732
^{106}Rh	2.394	^{106}Rh	1.746
^{106}Ru*	2.394	^{106}Ru*	1.746
^{125}Sb	0.337	^{125}Sb	0.271
^{90}Sr	11.738	^{90}Sr	13.373
^{90}Y	11.756	^{90}Y	13.373
Actinides	**Percent Contribution (%)**	**Actinides**	**Percent Contribution (%)**
^{241}Am	0.158	^{241}Am	0.141
^{243}Am	0.011	^{243}Am	0.010
^{244}Cm	2.521	^{244}Cm	2.039
^{239}Np	0.011	^{239}Np	0.010
^{238}Pu	1.224	^{238}Pu	1.120
^{239}Pu	0.033	^{239}Pu	0.028
^{240}Pu	0.072	^{240}Pu	0.079
^{241}Pu	14.403	^{241}Pu	11.940

Notes: * Can be omitted due to short half life (29.9 seconds).

SOURCE: Attachment I, Excel file “BWR-75Gwd-Curies total.xls”, worksheet “FP-ACT-GAS”; and Excel file “PWR-80Gwd-Curies total.xls”, worksheet “FP-ACT-GAS”

For PWR fuel, the fuel assembly is divided into four regions for analysis: the top, bottom, fuel, and plenum regions (Reference 2.2.8, Table 11 and Attachment VIII). The “.cut” file for the fuel region contains the actinide and fission product radionuclides, as well as the light element radionuclides. The curies per assembly for PWR fuel are from the actinide and fission product section of “Waste.Stream.E2.R1.B14.cut” file, and the nuclides ^{14}C, ^{36}Cl, and ^{3}H from the light element section of “Waste.Stream.E2.R1.B14.cut” file, “Waste.Stream.E2.R2.B14.cut” file, “Waste.Stream.

E2.R3.B14.cut" file, and "Waste.Stream.E2.R4.B14.cut" file (Reference 2.2.8, Table VIII-1 and Attachment X).

For BWR fuel, the fuel assembly is also divided into the same four regions for analysis. Thus, the radionuclide inventories for the representative BWR fuel are from the actinide and fission product section of file "5.0%.75GWd.fuel.cut" file with the addition of the nuclides ^{14}C, ^{36}Cl, and ^{3}H from the light element section of the files "5.0%.75GWd.fuel.cut", "5.0%.75GWd.top.cut", "5.0%.75GWd.bottom.cut", and "5.0%.75GWd.plenum.cut" (Reference 2.2.9, Attachments VII and XII). Section 6.6 and Table 48 of References 2.2.9 describe the difference between the stated burnup of the ".cut" file and the actual burnup. For example, the file, "5.0%.75GWd.fuel.cut", actually represents BWR fuel that is 5.0% enriched with 73.75 GWd/MTU burnup.

The crud inventory for event sequences are based on a decay time of 5 years for PWR and BWR fuel, which is consistent with the decay times of the bounding PWR and BWR fuel given in Table II-1. The BWR and PWR crud inventory is determined Equations 1 and 2 and are included in Table II-3.

Table II-3. Radionuclide Inventory For Bounding Fuel Including Crud

Radionuclide	Bounding PWR (Ci/fuel assembly)	Bounding BWR (Ci/fuel assembly)
^{241}Am	8.79×10^{2}	2.66×10^{2}
^{242}Am	1.01×10^{1}	3.39
^{242m}Am	1.02×10^{1}	3.40
^{243}Am	6.00×10^{1}	1.93×10^{1}
^{137m}Ba	9.89×10^{4}	3.65×10^{4}
^{14}C	5.35×10^{-1}	3.16×10^{-1}
^{113m}Cd	3.77×10^{1}	1.21×10^{1}
^{144}Ce	5.80×10^{3}	1.38×10^{3}
^{36}Cl	1.05×10^{-2}	4.99×10^{-3}
^{242}Cm	3.56×10^{1}	1.13×10^{1}
^{243}Cm	4.19×10^{1}	1.12×10^{1}
^{244}Cm	1.40×10^{4}	3.95×10^{3}
^{245}Cm	1.79	3.54×10^{-1}
^{246}Cm	1.21	2.97×10^{-1}
^{60}Co (crud)	3.26×10^{1}	1.09×10^{2}
^{134}Cs	4.05×10^{4}	1.16×10^{4}
^{135}Cs	6.34×10^{-1}	2.82×10^{-1}
^{137}Cs	1.05×10^{5}	3.87×10^{4}
^{154}Eu	6.15×10^{3}	1.79×10^{3}
^{155}Eu	1.80×10^{3}	6.25×10^{2}
^{55}Fe (crud)	7.45×10^{2}	3.50×10^{2}
^{3}H	4.95×10^{2}	1.77×10^{2}
^{129}I	3.60×10^{-2}	$1.36 \times 10\text{-}^{2}$
^{85}Kr	5.79×10^{3}	2.03×10^{3}
^{93m}Nb	3.94×10^{-1}	1.91×10^{-1}

Table II-3. Radionuclide Inventory For Bounding Fuel Including Crud (Continued)

Radionuclide	Bounding PWR (Ci/fuel assembly)	Bounding BWR (Ci/fuel assembly)
^{94}Nb	1.02×10^{-4}	3.83×10^{-5}
^{237}Np	4.01×10^{-1}	1.33×10^{-1}
^{239}Np	6.00×10^{1}	1.93×10^{1}
^{231}Pa	4.18×10^{-5}	2.94×10^{-5}
^{107}Pd	1.60×10^{-1}	5.70×10^{-2}
^{147}Pm	2.29×10^{4}	7.46×10^{3}
^{144}Pr	5.80×10^{3}	1.38×10^{3}
^{238}Pu	6.80×10^{3}	2.11×10^{3}
^{239}Pu	1.83×10^{2}	5.36×10^{1}
^{240}Pu	4.01×10^{2}	1.48×10^{2}
^{241}Pu	8.00×10^{4}	2.25×10^{4}
^{242}Pu	3.34	1.26
^{106}Ru	1.33×10^{4}	3.29×10^{3}
^{125}Sb	1.87×10^{3}	5.10×10^{2}
^{79}Se	7.35×10^{-2}	2.89×10^{-2}
^{151}Sm	3.19×10^{2}	8.22×10^{1}
^{126}Sn	6.83×10^{-1}	2.52×10^{-1}
^{90}Sr	6.52×10^{4}	2.52×10^{4}
^{99}Tc	1.34×10^{1}	5.35
^{230}Th	3.33×10^{-5}	2.05×10^{-5}
^{232}U	5.97×10^{-2}	2.00×10^{-2}
^{233}U	2.42×10^{-5}	0.00
^{234}U	5.21×10^{-1}	2.26×10^{-1}
^{235}U	3.28×10^{-3}	9.40×10^{-4}
^{236}U	2.23×10^{-1}	9.55×10^{-2}
^{238}U	1.42×10^{-1}	6.07×10^{-2}
^{90}Y	6.53×10^{4}	2.52×10^{4}
^{93}Zr	1.25	5.01×10^{-1}

NOTE: Ci = curies.

Source: Attachment I, Excel file “PWR-80GWd-curies total.xls”, worksheet “FP-ACT-GAS”, and Excel file “BWR-75GWd-curies total.xls” worksheet “FP-ACT-GAS”.