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Civilian Radioactive Waste Management System
Management & Operating Contractor

Range of Neutronic Parameters for Repository Criticality Analyses

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ACRONYMS AND ABBREVIATIONS

AENCF	Average Energy of a Neutron Causing Fission
at%	Atom Percent
CL	Critical Limits
CRC	Commercial Reactor Criticals
CRWMS	Civilian Radioactive Waste Management System
DOE	U.S. Department of Energy
EFPD	Effective Full Power Days
k_{eff}	k-effective
LCE	Laboratory Critical Experiments
M&O	Management and Operating Contractor
MGR	Monitored Geologic Repository
NRC	U.S. Nuclear Regulatory Commission
OCRWM	Office of Civilian Radioactive Waste Management
PWR	Pressurized Water Reactor
QA	Quality Assurance
ROA	Range of Applicability
wt%	Weight Percent

1. INTRODUCTION

The *Range of Neutronic Parameters for Repository Criticality Analyses* technical report contains a summary of the benchmark criticality analyses (including the laboratory critical experiment [LCEs] and the commercial reactor criticals [CRCs]) used to support the validation of the criticality evaluation methods. This report also documents the development of the Critical Limits (CLs) for the repository criticality analyses.

1.1 BACKGROUND

The United States Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM) is developing a methodology for criticality analysis to support disposal of commercial spent nuclear fuel in a geologic repository. A topical report (DOE OCRWM 1998a) on the disposal criticality analysis methodology was submitted to the United States Nuclear Regulatory Commission (NRC) for formal review. The following discussion provides a summary of the benchmark criticality analyses to establish a "range of applicability" (ROA) for parameters important to the criticality analyses. This discussion also documents the development of the CLs for the repository criticality analyses. This report supports the development of the disposal criticality analysis methodology.

1.2 OBJECTIVE

The objective of this report is to establish the ROA over selected parameters. The results of this will support the development and validation of the disposal criticality analysis methodology.

1.3 SCOPE

The scope of this report includes the following benchmark analyses:

- LCE Homogeneous Mixture Criticals
- LCE Lattice Criticals
- Pressurized Water Reactor (PWR) CRCs

Additional types of critical experiments may be added in revisions to this report.

1.4 QUALITY ASSURANCE

The Quality Assurance (QA) program applies to the development of this report. The data provided in this report will indirectly be used to develop the methodology for evaluating the Monitored Geologic Repository (MGR) waste package and engineered barrier segment. The QAP-2-3 (*Classification of Permanent Items*) evaluation entitled *Classification of the Preliminary MGDS Repository Design* (CRWMS M&O 1999a) has identified the waste package as a MGR item important to radiological safety and waste isolation. The Waste Package Operations manager has evaluated the technical document development activity in accordance with QAP-2-0, *Conduct of Activities*. The QAP-2-0 activity evaluation, *Neutronics Methodology - SR* (CRWMS M&O 1999b), has determined that the preparation and review of this technical document is subject to *Quality Assurance Requirements and Description* (DOE OCRWM 1998b) requirements. As specified in NLP-3-18, *Documentation of QA Controls on Drawings, Specifications, Design Analyses, and Technical Documents*, this activity is subject to QA controls.

As documented in the *Range of Neutronic Parameters Calculation File* (CRWMS M&O 1999c, pp. 20-54), the source information is taken from published reports and a handbook on benchmark experiments (Organization for Economic Cooperation and Development-Nuclear Energy Agency (OECD-NEA) 1998). Most of the LCEs are taken from OECD-NEA 1998, which is a standard handbook, generally accepted by the scientific and engineering community. OECD-NEA 1998 is used in a number of license applications and validation reports through out the nuclear industry. The data in this reference is therefore considered "Accepted Data".

As noted in Table 5-1 of CRWMS M&O 1999c, all of the CRCs and the remainder of the LCEs are taken from various industry and national laboratory reports. Information regarding the CRCs and LCEs specified in Table 5-1 of CRWMS M&O 1999c should be considered to be verified (TBV) in that the specified references are not considered accepted data sources per the retroactive procedural requirement of AP-SIII.2Q initiated by the July 27, 1999 issuance of the DOE Letter, "Accepted Data Call", from R.E. Spence to J.L. Younker (DOE 1999).

1.5 USE OF COMPUTER SOFTWARE

No scientific and engineering software or computational software was used in the development of this report.

2. DESCRIPTION OF CALCULATIONS

This section provides a summary of the analyzed systems used to generate the supporting analytic results reported in this document. The following subsections include summaries of the characterizations of the analyses. CRWMS M&O 1999c (pp. 20-61) documents the characterization data reported in Section 2.

CRWMS M&O 1999d provides additional information for the original set of 338 LCEs. These are the LCEs referenced in the *Disposal Criticality Analysis Methodology Topical Report* (DOE OCRWM 1998a).

2.1 DESCRIPTION OF HOMOGENEOUS LCEs

The LCEs presented in this section represent solutions and solid systems containing uranium, plutonium, or both uranium and plutonium. All of the LCEs in this section are fresh fuel experiments. CRWMS M&O 1999c (pp. 23-40) characterizes these LCE configurations.

Calling this group of experiments "homogeneous" is a misnomer. Most of the experiments are homogeneous, but the set also includes a number of arrays. Some of these arrays are multiple tanks of the same solution, and some are "piles" of uranium, polyethylene, and paraffin cubes in various configurations. The name "Homogeneous LCEs" is a carryover from the original issuance (REV 00) of CRWMS M&O 1997 and is maintained for consistency between the reports. The term "Homogeneous LCEs" is used in the rest of this document to represent the entire set listed above.

The following list is a breakdown of the "Homogeneous LCEs". Included in the list, in parentheses, is the number of experiments that fit into the given category. The terminology of "Thermal", "Intermediate", and "Fast" systems do not use the traditional definitions of these terms. These are based on the average energy of the neutrons causing fission (AENCF), and were selected for the purposes of trending (CRWMS M&O 1998a, Attachment I).

1) Homogeneous Thermal Systems (253) [AENCF = 0.0 MeV to 0.1 MeV]
   a) Mixed plutonium and natural uranium (34)
   b) Plutonium (73)
   c) High-enriched uranium, ^{235}U (105)
   d) Intermediate-enriched uranium, ^{235}U (10)
   e) Low-enriched uranium, ^{235}U (25)
   f) High-enriched uranium, ^{233}U (6)
2) Homogeneous Intermediate Systems (31) [AENCF = 0.1 MeV to 1.0 MeV]
   a) Intermediate-enriched uranium, ^{235}U (19)
   b) Low-enriched uranium, ^{235}U (12)
3) Homogeneous Fast Systems (47) [AENCF > 1.0 MeV]
   a) Plutonium (12)
   b) High-enriched uranium, ^{235}U (15)
   c) Intermediate-enriched uranium, ^{235}U (10)
   d) High-enriched uranium, ^{233}U (10)

Table 2.1-1 summarizes the characterizations presented in CRWMS M&O 1999c (pp. 23-40). The table lists the minimum and maximum values for enrichment and AENCF.

Table 2.1-1. Summary of Homogeneous LCE Characterizations

Type of System	Parameter	Minimum	Maximum
Homogeneous Thermal Systems (253)			
Mixed plutonium and natural uranium (34)	^{235}U Enrichment (wt%)	0.44%	2.29%
	^{239}Pu Enrichment (wt%)	91.10%	93.95%
	AENCF (MeV)	0.0038	0.0596
Plutonium (73)	^{239}Pu Enrichment (wt%)	95.01%	99.46%
	AENCF (MeV)	0.0025	0.0481
High-enriched uranium, ^{235}U (105)	^{235}U Enrichment (wt%)	89.04%	93.2%
	AENCF (MeV)	0.0022	0.0426
Intermediate-enriched uranium, ^{235}U (10)	^{235}U Enrichment (wt%)	29.83%	29.83%
	AENCF (MeV)	0.0455	0.0743
Low-enriched uranium, ^{235}U (25)	^{235}U Enrichment (wt%)	4.9%	10%
[TBV-1370]	AENCF (MeV)	0.0114	0.0523
High-enriched uranium, ^{233}U (6)	^{233}U Enrichment (wt%)	97.67%	99.70%
	AENCF (MeV)	0.0030	0.0374
Homogeneous Intermediate Systems (31)			
Intermediate-enriched uranium, ^{235}U (19)	^{235}U Enrichment (wt%)	29.83%	29.83%
	AENCF (MeV)	0.1041	0.2168
Low-enriched uranium, ^{235}U (12)	^{235}U Enrichment (wt%)	1.01%	1.16%
[TBV-1366]	AENCF (MeV)	0.1549	0.2541
Homogeneous Fast Systems (47)			
Plutonium (12)	^{239}Pu Enrichment (at%)	88.6%	98.2%
	AENCF (MeV)	1.4768	1.9188
High-enriched uranium, ^{235}U (15)	^{235}U Enrichment (wt%)	90%	94%
	AENCF (MeV)	1.1620	1.5979
Intermediate-enriched uranium, ^{235}U (10)	^{235}U Enrichment (wt%)	16%	55.38%
	AENCF (MeV)	1.2784	1.4403
High-enriched uranium, ^{233}U (10)	^{233}U Enrichment (wt%)	98.13%	98.20%
	AENCF (MeV)	1.5178	1.7740

2.2 DESCRIPTION OF LATTICE LCEs

The LCEs presented in this section represent moderated lattice configurations. The lattice LCEs database is broken down by type of experiment. All of the LCEs in this section are fresh fuel experiments. The LCE lattice configurations are described in CRWMS M&O 1999c (pp. 38-54).

The following list is a breakdown of the "Lattice LCEs". Included in the list, in parentheses, is the number of experiments that fit into the given category.

1) Lattice Thermal Systems (78) [AENCF = 0.0 MeV to 0.1 MeV]
   a) Mixed plutonium and natural uranium fuel pins (3)
   b) High-enriched uranium, ^{235}U, fuel pins (21)
   c) High-enriched uranium, ^{235}U, fuel plates (23)
   d) High-enriched uranium, ^{235}U, cruciform fuel rods (28)
   e) Intermediate-enriched uranium, ^{235}U, fuel pins (2)
   f) Low-enriched uranium, ^{235}U, fuel pins (1)
2) Lattice Intermediate Systems (95) [AENCF = 0.1 MeV to 1.0 MeV]
   a) Mixed plutonium and natural uranium fuel pins (22)
   b) High-enriched uranium, ^{235}U, fuel pins (5)
   c) Low-enriched uranium, ^{235}U (68)

Table 2.2-1 summarizes the characterizations presented in CRWMS M&O 1999c (pp. 38-54). The table lists the minimum and maximum values for enrichment and AENCF.

Table 2.2-1. Summary of Lattice LCE Characterizations

Type of System	Parameter	Minimum	Maximum
Lattice Thermal Systems (78)			
Mixed plutonium and natural uranium fuel pins (3) *[TBV-1368, TBV-1371]*	^{235}U Enrichment (wt%)	0.71%	0.71%
	^{239}Pu Enrichment (wt%)	86.15%	90.61%
	AENCF (MeV)	0.0609	0.0819
High-enriched uranium, ^{235}U, fuel pins (21)	^{235}U Enrichment (wt%)	62.40%	62.40%
	AENCF (MeV)	0.0229	0.0799
High-enriched uranium, ^{235}U, fuel plates (23)	^{235}U Enrichment (wt%)	93.17%	93.17%
	AENCF (MeV)	0.0097	0.0147
High-enriched uranium, ^{235}U, cruciform fuel rods (28)	^{235}U Enrichment (wt%)	80%	90%
	AENCF (MeV)	0.0106	0.0919
Intermediate-enriched uranium, ^{235}U, fuel pins (2) *[TBV-1369]*	^{235}U Enrichment (wt%)	20%	20%
	AENCF (MeV)	0.0236	0.0240
Low-enriched uranium, ^{235}U, fuel pins (1)	^{235}U Enrichment (wt%)	5.74%	5.74%
	AENCF (MeV)	0.0886	0.0886
Lattice Intermediate Systems (95)			
Mixed plutonium and natural uranium fuel pins (22) *[TBV-1359, TBV-1366, TBV-1368, TBV-1371]*	^{235}U Enrichment (wt%)	0.71%	0.71%
	^{239}Pu Enrichment (wt%)	86.14%	91.84%
	AENCF (MeV)	0.1015	0.3776
High-enriched uranium, ^{235}U, fuel pins (5)	^{235}U Enrichment (wt%)	96%	96%
	AENCF (MeV)	0.2376	0.2422
Low-enriched uranium, ^{235}U, fuel pins (68)	^{235}U Enrichment (wt%)	1.15%	5.74%
[TBV-1357, TBV-1358, TBV-1359, TBV-1360, TBV-1361, TBV-1362, TBV-1363, TBV-1364, TBV-1365, TBV-1367, TBV-1368]	AENCF (MeV)	0.1025	0.4085

2.3 DESCRIPTION OF CRCs

The CRCs discussed in this section represent forty-five PWR critical state points. All of the fuel is initially low enriched uranium oxide. The state points relate to various "burnup" points for various cycles in six different reactors as shown in Table 2.3-1 and Table 2.3-2. The CRC configurations are described in CRWMS M&O 1999c (pp. 55-64) and are summarized in Table 2.3-3. All of the values presented in Section 2.3 are considered “to be verified” (TBV-1349).

(Note: EFPD = Effective Full Power Days)

Table 2.3-1. Commercial Reactor Criticals State Points

State Point	Reactor	Cycle	Time of Measurement EFPD
1	Crystal River, Unit #3	1a	0.0
2	Crystal River, Unit #3	1b	268.8
3	Crystal River, Unit #3	1b	411.0
4	Crystal River, Unit #3	2	0.0
5	Crystal River, Unit #3	3	0.0
6	Crystal River, Unit #3	3	168.5
7	Crystal River, Unit #3	3	250.0
8	Crystal River, Unit #3	4	0.0
9	Crystal River, Unit #3	4	228.1
10	Crystal River, Unit #3	4	253.0
11	Crystal River, Unit #3	5	0.0
12	Crystal River, Unit #3	5	388.5
13	Crystal River, Unit #3	6	0.0
14	Crystal River, Unit #3	6	96.0
15	Crystal River, Unit #3	6	400.0
16	Crystal River, Unit #3	7	0.0
17	Crystal River, Unit #3	7	260.3
18	Crystal River, Unit #3	7	291.0
19	Crystal River, Unit #3	7	319.0
20	Crystal River, Unit #3	7	462.3
21	Crystal River, Unit #3	7	479.0
22	Crystal River, Unit #3	8	0.0
23	Crystal River, Unit #3	8	97.6
24	Crystal River, Unit #3	8	139.8
25	Crystal River, Unit #3	8	404.0

Table 2.3-1. Commercial Reactor Criticals State Points

State Point	Reactor	Cycle	Time of Measurement EFPD
26	Crystal River, Unit #3	8	409.6
27	Crystal River, Unit #3	8	515.5
28	Crystal River, Unit #3	9	0.0
29	Crystal River, Unit #3	9	158.8
30	Crystal River, Unit #3	9	219.0
31	Crystal River, Unit #3	9	363.1
32	Crystal River, Unit #3	10	0.0
33	Crystal River, Unit #3	10	573.7
36	Sequoyah, Unit #2	1	0.0
37	Sequoyah, Unit #2	3	0.0
38	Sequoyah, Unit #2	3	210.9
46	McGuire, Unit #1	1	0.0
47	McGuire, Unit #1	6	0.0
48	McGuire, Unit #1	6	62.4
49	McGuire, Unit #1	7	0.0
50	McGuire, Unit #1	7	129.0
51	McGuire, Unit #1	7	282.3
59	Three Mile Island, Unit #1	1	0.0
60	Three Mile Island, Unit #1	5	0.0
61	Three Mile Island, Unit #1	5	114.4

Table 2.3-2. Commercial Reactor Criticals Fuel Characterizations

State Point	Initial Enrichment (wt% ^{235}U)	Burnup (GWd/MTU)		
		Minimum	Maximum	Core Average
1	2.445	0	0	0
2	2.446	4	11	8
3	2.446	7	16	12
4	2.670	0	17	9
5	2.693	0	20	8
6	2.693	3	25	13
7	2.693	4	28	15
8	2.648	0	18	7
9	2.648	6	25	14
10	2.648	7	26	15
11	2.915	0	17	7
12	2.915	9	28	19
13	3.210	0	22	12
14	3.210	3	25	15
15	3.210	13	35	24
16	3.554	0	25	10
17	3.554	6	33	18
18	3.554	7	34	19
19	3.554	8	35	20
20	3.554	11	39	24
21	3.554	12	40	25
22	3.755	0	31	12
23	3.755	3	32	15
24	3.755	4	33	17
25	3.755	11	36	25
26	3.755	11	36	25
27	3.755	14	39	28

Table 2.3-2. Commercial Reactor Criticals Fuel Characterizations

State Point	Initial Enrichment (wt% ^{235}U)	Burnup (GWd/MTU)		
		Minimum	Maximum	Core Average
28	3.892	0	35	14
29	3.892	5	37	19
30	3.892	7	37	21
31	3.892	11	40	25
32	4.015	0	35	15
33	4.015	18	49	33
36	2.535	0	0	0
37	3.427	0	27	11
38	3.427	7	34	19
46	2.602	0	0	0
47	3.472	0	28	12
48	3.472	2	31	14
49	3.618	0	27	11
50	3.618	4	32	16
51	3.618	9	38	23
59	2.633	0	0	0
60	2.820	0	25	10
61	2.820	2	28	14

Table 2.3-3. Summary of CRC Characterizations

Parameter	Minimum	Maximum
Initial Enrichment (wt% ^{235}U)	2.445%	4.015%
Burnup – Minimum (GWd/MTU)	0	18
Burnup – Maximum (GWd/MTU)	0	49
Burnup – Core Averaged (GWd/MTU)	0	33
AENCF (MeV)	0.2344	0.2660

2.4 SUMMARY OF THE BENCHMARK AND REPOSITORY CALCULATIONS

A complete list of expected repository values is not available at this time. No comparison can be made between the expected repository values and the benchmarked values. This comparison needs to be considered in future, waste form specific, validation reports.

3. PARAMETERS OF SIGNIFICANCE

This section investigates the range of applicability for select parameters. These parameters are chosen because of their effect on reactivity. Table 3-1 lists the benchmarked range of parameters. This is a summary of the information listed in the tables presented previously. These values are considered "to be verified". Any use of these values must carry the assigned "TBV" tracking number as identified in the previous sections.

Table 3-1. Benchmarked Range of Parameters For Repository Calculations

Parameter	Minimum	Maximum
Uranium Enrichment for Homogeneous Calculations (wt% ^{235}U)	0.44%	94%
Plutonium Enrichment for Homogeneous Calculations (wt% ^{239}Pu)	88.6%	99.46%
Uranium Enrichment for Lattices (wt% ^{235}U)	0.71%	96%
Plutonium Enrichment for Lattices (wt% ^{239}Pu)	86.14%	91.84%
Initial Enrichment for CRC (wt% ^{235}U)	2.445%	4.015%
Core Average Burnup (GWd/MTU)	0.0	33.06
Assembly Burnup (GWd/MTU)	0.0	49.2
AENCF (MeV)	0.0022	1.9188

To establish CLs, and ultimately the Ranges of Applicability (ROA), for the repository calculations, the multiplication factor k_{eff} can be trended on several neutronic parameters to obtain a bias trend related to one of the candidate parameters. CRWMS M&O 1998a offers examples of CL development. However, these are only for the purposes of example. The real CLs for each waste form will be based on benchmark results that are directly applicable to the waste form. These will likely be covered in the waste form specific validation reports.

The ROA is a combination of the benchmarked range and the trended range. In many cases the ROA, the benchmarked range, and the trended range will be identical. However, a trend may not be applicable over the entire benchmarked range, possibly due to the scarcity of benchmarks at one end of the benchmarked range. In such an instance, the ROA will be smaller than the benchmarked range, and will be more similar to the trended range.

4. CONCLUSIONS

This document presents an approach to developing a Range of Applicability for the MGR criticality analyses. It is not a validation of the codes or methods for any specific waste form or waste package. The specific waste forms/packages will be addressed in future validation reports, which will be submitted as part of the License Application for the MGR.

Although this document establishes specific benchmarked ranges for the parameters, this does not limit the repository to only materials that fall in these ranges. Calculations for criticality analyses may include values outside of these ranges, but the reports evaluating these future repository calculations must include a justification for why the calculations are validated. If a repository waste is outside of the defined range of applicability, additional margin or uncertainty may be needed to ensure subcriticality. The alternative is to add benchmark critical data that covers the extended range and calculate a revised critical limit.

Extension of the range of applicability should be based on trends in the bias as a function of system parameters and, if the extension is large, should be confirmed by alternate means. There is no available guidance on what constitutes a large extension, nor any guidance on how to extend trends in the bias. In all cases, extension of the bias and uncertainty requires the determination and understanding of the trends in the bias and uncertainty. If this extension is made, a detailed justification of the need for an extension, along with a thorough description of the method and procedure used to estimate the bias and uncertainty in this extended range shall be documented and approved.

The data reported herein that are not identified with TBV are acceptable for quality affecting activities. TBV data specified in Section 2 will require the release of the assigned TBV prior to its use in quality affecting activities or in analyses affecting procurement, construction, or fabrication. These TBVs include TBV-1349 and TBV-1357 through TBV-1370

This report is a revision of a first of a kind report. The only differences between this revision and the initial issuance are the inclusion of additional benchmark calculations and updated report formatting. There are no other similar documents existing for the MGR project.

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