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Civilian Radioactive Waste Management System
Management & Operating Contractor

Summary Report of Laboratory Critical Experiment Analyses Performed for the Disposal Criticality Analysis Methodology

Revision 01

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- Replaced all of Section 2.2
- Added Section 3.2.6
- Replaced all of Section 4
- Deleted the HXST and HXT calculations due to redundancy

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1.0 INTRODUCTION

This report, "Summary Report of Laboratory Critical Experiment Analyses Performed for the Disposal Criticality Analysis Methodology", contains a summary of the laboratory critical experiment (LCEs) analyses used to support the validation of the criticality model.

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 on the disposal criticality analysis methodology is scheduled to be submitted to the United States Nuclear Regulatory Commission (NRC) for formal review later in 1998. This technical report is one of a series of reports that provides a summary of the results of the analyses that support the development of the disposal criticality analysis methodology.

1.2 Objective

The objective of this report is to present a summary of the LCE analyses' results. These results demonstrate the ability of MCNP to accurately predict the critical multiplication factor for LWR fuel with different configurations. Results from the LCE evaluations will support the development and validation of the criticality models used in the disposal criticality analysis methodology. These models and their validation will be discussed in the Disposal Criticality Analysis Methodology Topical Report.

1.3 Scope

The scope of this Summary Report includes the LCE analytical results for the following types of critical experiments:

- Lattice Criticals, and
- Homogeneous Mixture Criticals.

Additional types of critical experiments may be added in future 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* (Reference 1, TBV-228) has identified the waste package as an MGR (formerly MGDS) item important to safety, waste isolation, and physical protection of materials. The Waste Package responsible manager has evaluated the technical document development activity in accordance with QAP-2-0, *Conduct of Activities*. The QAP-2-0 activity evaluation, *Develop Technical Documents* (Reference 2), has determined that the preparation and review of this technical document is subject to *Quality Assurance Requirements and Description* (Reference 3) 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.

1.5 Use of Computer Software

As discussed in Reference 21, the MCNP code was used to calculate k for the LCE configurations. The software specifications are as follow:

Program Name: MCNP
Version/Revision Number: Version 4B2
CSCI Number: 30033 V4BLV
Computer Type: HP 9000 Series Workstations

The input and output files for the various MCNP calculations are documented in the attachments to this calculation file as described in Sections 5 and 8, such that an independent repetition of the software use may be performed. The MCNP software used was: (a) appropriate for the application of k calculations, (b) used only within the range of validation as documented throughout References 7.3 and 7.4, (c) obtained from the Software Configuration Manager in accordance with appropriate procedures.

Title: Excel
Version/Revision Number: Microsoft® Excel 97

The Excel spreadsheet program was used for simple numeric calculations as documented in Section 6 of this calculation file. The user-defined formulas, inputs, and results were documented in sufficient detail in Section 6 to allow an independent repetition of the various computations.

2.0 ANALYSIS MODEL

This section provides a description of the models used to generate the supporting analytic results reported in this document.

2.1 Criticality Model

The criticality models used to calculate the reactivity of the various experiments are discussed in the Reference 21. The tool used to assess the reactivitity of each of the experiments is MCNP 4B (References 4 and 5), which is an implementation of the Monte Carlo method. The computer inputs for the LCE calculations are provided in Attachment 1 of Reference 21.

2.2 Cross Sections

Table 2.2-1 lists all of the MCNP cross section library identifiers (ZAIDs) used in the LCE reactivity calculations documented in Reference 21. The MCNP ZAID is used to identify a cross section library. The ZAID consists of a five-integer element and isotope identifier followed by a cross section library suffix. The first one or two integers in the ZAID refer to the atomic number of the corresponding element. The three integers preceding the decimal always refer to the isotopic mass number. The suffix identifies the library. Details are in Appendix G of Reference 5.

Table 2.2-1. MCNP Cross Section Libraries Used in the LCE Reactivity Calculations

Element/Isotope	MCNP ZAID	Element/Isotope	MCNP ZAID
H-1	1001.50c	Cr-53	24053.60c
H-3	1003.50c	Cr-54	24054.60c
He-4	2004.50c	Mn-55	25055.50c
Li-6	3006.50c	Fe-54	26054.60c
Li-7	3007.55c	Fe-56	26056.60c
Be-9	4009.50c	Fe-57	26057.60c
B-10	5010.50c	Fe-58	26058.60c
B-11	5011.56c	Co-59	27059.50c
C-natural	6000.50c	Ni-58	28058.60c
C-12	6012.50c*	Ni-60	28060.60c
N-14	7014.50c	Ni-61	28061.60c
O-16	8016.50c	Ni-62	28062.60c
F-19	9019.50c*	Ni-64	28064.60c
Na-23	11023.50c*	Cu-63	29063.60c
Mg-natural	12000.50c*	Cu-65	29065.60c
Al-27	13027.50c	Ga-natural	31000.50c*
Si-natural	14000.50c	Zr-natural	40000.60c
P-31	15031.50c	Zr-93	40093.50c
S-32	16032.50c	Nb-93	41093.50c
Cl-natural	17000.50c*	Mo-natural	42000.50c
K-natural	19000.50c*	Mo-95	42095.50c
Ca-natural	20000.50c*	Ag-107	47107.60c
Ti-natural	22000.50c	Ag-109	47109.60c
Cr-50	24050.60c	Cd-natural	48000.50c
Cr-52	24052.60c	In-natural	49000.60c

Table 2.2-1. MCNP Cross Section Libraries Used in the LCE Reactivity Calculations

Element/Isotope	MCNP ZAID	Element/Isotope	MCNP ZAID
Sn-natural	50000.35c	U-235(294)**	92235.50c*
Ba-138	56138.50c	U-235(587)**	92235.53c
Gd-152	64152.50c	U-236	92236.50c
Gd-154	64154.50c	U-237	92237.50c
Gd-155	64155.50c	U-238(294)**	92238.50c*
Gd-156	64156.50c	U-238(587)**	92238.53c
Gd-157	64157.50c	Pu-237	94237.35c
Gd-158	64158.50c	Pu-238	94238.50c
Gd-160	64160.50c	Pu-239	94239.55c
Ta-181	73181.50c	Pu-240	94240.50c
W-natural	74000.55c*	Pu-241	94241.50c
Pb-natural	82000.50c*	Pu-242	94242.50c
U-233	92233.50c	Am-241	95241.50c
U-234	92234.50c		

The set of cross section libraries in Table 2.2-1 is referred to here as the standard set. This set was taken from Reference 22, except for the ZAID entries marked with an asterisk (*). Those isotopes marked with an asterisk (*) were used in the LCEs but not in Reference 22, and are recommended in Reference 23. Reference 22 contains more isotopes than shown here. These are mainly fission products that are not present in the LCEs.

The numbers shown in parentheses and marked with a double asterisk (**) are temperatures in degrees Kelvin.

3.0 DESCRIPTION OF THE EXPERIMENT SYSTEMS

The modeled experiments are described in References 7 through 17 and References 19 and 20. The data in these references are generally accepted by the scientific and engineering community and are used in a number of license applications and validation reports through out the nuclear industry. The data in these references is therefore "Accepted Data".

3.1 Lattice Experiments

The fresh fuel LCEs presented in this section represent moderated lattice configurations containing fissile oxide fuel. Each of the LCE configurations described in this section have been analyzed with the MCNP code system using the cross section library previously described (Section 2.2). An experiment identifier for each configuration is provided for subsequent reference when the results are reported.

3.1.1 Critical Configurations of Subcritical Clusters of 2.35 wt% Enriched UO_2 Rods in Water with Fixed Neutron Absorber Plates

Experiments with subcritical clusters of low-enrichment UO_2 fuel rods were performed at the Pacific Northwest Laboratory and documented by Bierman (Reference 7). The four experiments modeled with MCNP consisted of three rectangular arrays of aluminum-clad fuel rods. The fuel rods comprising the arrays had a uniform enrichment of 2.35 wt% ^{235}U. The three arrays of fuel were arranged in a row and, in three of the experiments, sheets of neutron poison were interposed between adjacent arrays. The structure of the experimental assembly was provided by aluminum structural members on the margins of the fuel arrays. Axial support for the fuel rods was provided by an acrylic base plate. The lateral alignment of the fuel rods was provided by another acrylic plate. The experimental apparatus was closely reflected by full-density water.

The pertinent differences among these four experiments are shown in Table 3.1.1-1. These critical experiments help demonstrate the ability of MCNP to accurately predict the critical multiplication factor for configurations containing light-water reactor fuel separated by absorber plates.

Table 3.1.1-1. Differences in Absorber Plates used for Clusters of 2.35 wt% UO_2 Fuel Rods

Case	Interposed Plate
exp1	none
exp2	Boral™
exp3	Type 6061 Aluminum
exp4	Type 304 Stainless Steel

3.1.2 Critical Configurations with Subcritical Clusters of 4.31 wt% Enriched UO_2 Rods in Water with Reflecting Walls

These three experiments were also performed at the Pacific Northwest Laboratory and were documented by Bierman (References 8 and 9). In these experiments three similar fuel assemblies were laterally surrounded by reflectors of different compositions. The fuel lattices in each critical experiment contained 4.31 wt% ^{235}U enriched UO_2 fuel rods on a square pitch of 1.892 cm. The distinguishing characteristics of each experiment are given in Table 3.1.2-1. These critical experiments demonstrate the ability of MCNP to accurately predict the critical multiplication factor for configurations with different shielding materials used for reflectors.

Table 3.1.2-1. Differences in Experimental Configurations for Clusters of 2.35 wt% UO_2 Fuel Rods

Case	Reference	Reflector
exp5	8	uranium
exp6	8	lead
exp7	9	stainless steel

3.1.3 Critical Configurations with 4.31 wt% ^{235}U Enriched UO_2 Rods in Highly Borated Water Lattices

This set of four experiments was performed at the Pacific Northwest Laboratory and documented by Durst (Reference 10). These experiments used 4.31 wt% ^{235}U uniformly enriched UO_2 fuel rods arranged in square-pitch, water-moderated lattices of different size with various amounts of boric acid in the moderator. The fuel rods were clad with aluminum and were loaded into polypropylene lattice templates fastened inside a plexiglass tank. The plexiglass tank was surrounded on all four sides by an unborated water reflector and was positioned on top of a plexiglass slab. The borated water was restricted to the water volume inside the plexiglass tank.

Rectangular critical arrays were constructed by sequentially filling rows of the lattice template starting at the plexiglass tank wall. The water level in the tank was held constant by removing an appropriate volume of water as each fuel rod was loaded. These experiments were denoted as "exp8" through "exp11."

3.1.4 Critical Configurations with Neutron Flux Traps

Pacific Northwest Laboratories performed experiments studying the effect of neutron flux traps on criticality. These experiments were documented by Bierman (Reference 11) and served as the source for two configurations modeled with MCNP. These two critical experiments were each composed of four fuel rod arrays arranged in a square and separated by a neutron flux trap region. Each fuel lattice in a given configuration was nearly equal in size. Two polypropylene lattice templates were used to position the fuel rods. The fuel rods were composed of aluminum-clad 4.31 wt% ^{235}U enriched UO_2 fuel. The neutron flux traps were created by positioning two plates of Boral™ between interacting faces of each fuel lattice. The experimental configurations were moderated and closely reflected by full-density water. These experiments are denoted as "exp12" and "exp13."

3.1.5 Electric Power Research Institute 2.35 wt% Enriched Light Water Reactor Fuel Critical Configurations

Criticality experiments were sponsored by Electric Power Research Institute for light water reactor fuel configurations. These were documented by Smith (Reference 12) and subsequently described by Bowman (Reference 13). Two critical experiment configurations composed of water-moderated lattices of 2.35 wt% enriched UO_2 fuel rods were modeled with MCNP. The fuel rods were supported in a core structure composed of "eggcrate" type lattice plates with an upper lead shield. The configuration was closely reflected by full-density water laterally and below the fuel. These experiments were designated as "exp14" and "exp15."

3.1.6 Laboratory Critical Experiments from the Urania-Gadolinia: Nuclear Model Development and Critical Experiment Benchmark Report

A number of critical experiments were performed by Babcock and Wilcox for urania fuel incorporating gadolinia as an integral burnable absorber. These experiments were documented by Newman (Reference 14). The configurations modeled with MCNP included critical configurations containing arrangements of 2.46 wt% ^{235}U enriched UO_2 fuel rods, 4.02 wt% ^{235}U enriched UO_2 fuel rods, combination 4 wt% Gd_2O_3 and 96 wt% (1.944 wt% ^{235}U enriched) UO_2 fuel rods, Ag-In-Cd absorber rods, and B_4C absorber rods. The fuel rods were supported by a top and bottom aluminum "eggcrate" type grid plate. The fuel rods rested on an aluminum base plate. The central 45 x 45 array of rod lattice cells was separated into nine 15 x 15 arrays of rod lattice cells. These arrays were intended to simulate Pressurized Water Reactor fuel assembly lattices.

Descriptions of the experimental configurations are shown in Table 3.1.6-1.

Table 3.1.6-1. Urania-Gadolinia Critical Experiment Descriptions

Exp. ID	Number of 2.46 wt% U-235 Fuel Rods	Number of 4.02 wt% U-235 Fuel Rods	Number of Gd_2O_3 Fuel Rods	Number of B_4C Rods	Number of Ag-In-Cd Rods	Number of Void Rods	Number of Water Holes
ugd1	4808	0	0	0	0	0	153
ugd2	4808	0	0	0	16	0	137
ugd3	4788	0	20	0	0	0	153
ugd4	4788	0	20	0	16	0	137
ugd5	4780	0	28	0	0	0	153

Table 3.1.6-1. Urania-Gadolinia Critical Experiment Descriptions

Exp. ID	Number of 2.46 wt% U-235 Fuel Rods	Number of 4.02 wt% U-235 Fuel Rods	Number of Gd_2O_3 Fuel Rods	Number of B_4C Rods	Number of Ag-In-Cd Rods	Number of Void Rods	Number of Water Holes
ugd6	4780	0	28	0	16	0	137
ugd7	4780	0	28 (Annular)	0	0	0	153
ugd8	4772	0	36	0	0	0	153
ugd9	4772	0	36	0	16	0	137
ugd10	4772	0	36	0	0	16	137
ugd12	3920	888	0	0	0	0	153
ugd13	3920	888	0	16	0	0	137
ugd14	3920	860	28	0	0	0	153
ugd15	3920	860	28	16	0	0	137
ugd16	3920	852	36	0	0	0	153
ugd17	3920	852	36	16	0	0	137
ugd18	3676	944	0	0	0	0	180
ugd19	3676	928	16	0	0	0	180
ugd20	3676	912	32	0	0	0	180

3.1.7 Saxton UO_2 and PuO_2-UO_2 Critical Configurations

Westinghouse Electric Corporation performed small-core criticals for urania and mixed oxide fuel in the Saxton test reactor. This work was documented by Taylor (Reference 15) and subsequently described by Bowman (Reference 13). This section includes eight LCE configurations containing 5.74 wt% ^{235}U enriched UO_2 fuel rods and six LCE configurations containing 6.6 wt% PuO_2 (8 wt% ^{240}Pu)/UO_2 fuel rods. The fuel rods were loaded into a single rectangular array for each critical experiment. The fuel rods were supported by three aluminum grid plates with holes for rod emplacement. The fuel rod type, pitch, array size, moderator height, and boron concentration were adjusted in each LCE. Table 3.1.7-1 shows the various LCE fuel types.

Table 3.1.7-1. Saxton Critical Configuration Parameters

Experiment Identifier	Fuel Type
exp17	UO_2
exp18	UO_2
exp28	PuO_2-UO_2
exp29	PuO_2-UO_2
exp30	PuO_2-UO_2
exp31	PuO_2-UO_2
exp32	PuO_2-UO_2
exp33	PuO_2-UO_2

3.1.8 Critical Configurations Simulating Light Water Reactor Fuel in Close Proximity Water Storage

Babcock and Wilcox performed experiments simulating neutron multiplication in pool storage racks. These were documented by Baldwin (Reference 16). Twenty such critical configurations, each containing a 3 x 3 array of 14 x 14 fuel rod assemblies, were modeled with MCNP. Two different methods were utilized to support the fuel assemblies in the critical experiment core. The first support method used top and bottom grid plates to hold the fuel rods in place. The second support method used a bottom grid plate and vertical alignment system consisting of locating bars and fastening plates. The gaps between assemblies contained a number B_4C rods and water, stainless steel sheets and water, borated aluminum sheets and water, or only water.

The critical experiment arrays were assembled in an aluminum core tank. The fuel rods were composed of 2.46 wt% ^{235}U enriched UO_2 clad in Type 6061 aluminum. The B_4C rods were aluminum tubes filled with B_4C powder. Six sets of borated aluminum sheets were used in the critical experiments. The soluble boron concentration and moderator heights were adjusted to obtain a critical configuration.

The key parameters which distinguish the twenty critical configurations are shown in Table 3.1.8-1.

Table 3.1.8-1. Close Proximity Critical Benchmark Characterization Parameters

Critical Exp. ID	Assembly Spacing, Rod Pitch	Number of B_4C Rods	Metal Between Unit Assys
core2	0	0	n/a
core3	1	0	n/a
core4	1	84	n/a
core5	2	64	n/a
core6	2	64	n/a
core7	3	34	n/a
core8	3	34	n/a
core9	4	0	n/a
core10	3	n/a	none
core11	1	n/a	SS
core12	2	n/a	SS
core13	1	n/a	B/Al set 5
core14	1	n/a	B/Al set 4
core15	1	n/a	B/Al set 3
core16	2	n/a	B/Al set 3
core17	1	n/a	B/Al set 2
core18	2	n/a	B/Al set 2
core19	1	n/a	B/Al set 1
core20	2	n/a	B/Al set 1
core21	3	n/a	B/Al set 1

3.1.9 Electric Power Research Institute Mixed Oxide Critical Configurations

Smith (Reference 12) documented criticality tests with mixed oxide fuel performed for the Electric Power Research Institute. These same experiments were subsequently described by Bowman (Reference 13). Six critical experiment configurations composed of unborated and borated water moderated lattices of 2 wt% PuO_2 (8 wt% Pu-240)/98 wt% UO_2 (natural) fuel rods were modeled with MCNP. The fuel rods were clad with aluminum and were supported in a core structure composed of "eggcrate" type lattice plates with an upper lead shield. The configurations were closely reflected with full-density water laterally and below the core.

These experiments are denoted as "exp22" through "exp27."

3.1.10 Critical Triangular Lattice of MOX & UO_2 Fuel Rods

Bierman (Reference 17) documented critical experiments performed at Pacific Northwest Laboratories incorporating both urania and mixed-oxide (MOX) fuel rods in a triangular lattice. One such experiment, designated "exp34", contained a triangular lattice of uniformly distributed PuO_2-UO_2 and UO_2 fuel rods. The fuel rods were placed in a uniform distribution with a $Pu/^{235}U$ ratio approximating that of a 20,000 MWd/MTU burnup. Each PuO_2-UO_2 fuel rod was surrounded by six UO_2 fuel rods with a triangular lattice pitch. The fuel rods were supported by three polypropylene lattice plates.

3.2 Homogeneous Solution Experiments

The LCEs presented in this section represent solutions contain uranium, plutonium, or both uranium and plutonium. Each of the LCE configurations described in this section have been analyzed with the MCNP code system using the standard cross section set previously described in Section 2.2 of this document. An experiment identifier for each configuration is provided for subsequent reference in this document. With a few exceptions that are noted in the text, the vast majority of the assessed benchmarks come from the OCED compilation (Reference 19).

The following sub-sections briefly describe the LCEs according to the grouping in which the results are presented.

3.2.1 Mixed Plutonium and Natural Uranium Nitrate Solutions

The experiments involving plutonium and uranium with naturally occurring isotopic ratios are from the OECD benchmark compilation (Reference 19, Volume VI) and are summarized in Table 3.2.1-1.

Table 3.2.1-1. Benchmark Problem Summary for Configurations Incorporating Mixed Plutonium and Natural Uranium Nitrate Solutions

Class	Case Name
MIX-SOL-THERM-001	PNL3187
	PNL3391
	PNL3492
	PNL3593
	PNL3694
	PNL3795
	PNL3896
	PNL3897
	PNL3898
	PNL3808
	PNL3999
	PNL5300
MIX-SOL-THERM-002	PNL1158
	PNL1159
	PNL1161
MIX-SOL-THERM-003	awre1
	awre2
	awre3
	awre4
	awre5
	awre6
	awre7
	awre8
	awre9
	awre10
MIX-SOL-THERM-004	PNL1577

Table 3.2.1-1. Benchmark Problem Summary for Configurations Incorporating Mixed Plutonium and Natural Uranium Nitrate Solutions

Class	Case Name
	PNL1678
	PNL1783
	PNL1868
	PNL1969
	PNL2070
	PNL2565
	PNL2666
	PNL2767

3.2.2 Plutonium Nitrate Solutions

The experiments involving plutonium are from the OECD benchmark compilation (Reference 19, Volume I) and are summarized in Table 3.2.2-1.

Table 3.2.2-1. Benchmark Problem Summary for Configurations Incorporating Plutonium Nitrate Solutions

Class	Case Name
PU-SOL-THERM-001	PUST1T1
	PUST1T2
	PUST1T3
	PUST1T4
	PUST1T5
	PUST1T6
PU-SOL-THERM-003	PU003-1
	PU003-2
	PU003-3

Table 3.2.2-1. Benchmark Problem Summary for Configurations Incorporating Plutonium Nitrate Solutions

Class	Case Name
	PU003-4
	PU003-5
	PU003-6
	PU003-7
	PU003-8
PU-SOL-THERM-004	PU004-1
	PU004-2
	PU004-3
	PU004-4
	PU004-5
	PU004-6
	PU004-7
	PU004-8
	PU004-9
	PU04-10
	PU04-11
	PU04-12
	PU04-13
PU-SOL-THERM-005	PU005-1
	PU005-2
	PU005-3
	PU005-4
	PU005-5
	PU005-6
	PU005-7
	PU005-8
	PU005-9

Table 3.2.2-1. Benchmark Problem Summary for Configurations Incorporating Plutonium Nitrate Solutions

Class	Case Name
PU-SOL-THERM-007	PU007-2
	PU007-3
	PU007-5
	PU007-6
	PU007-7
	PU007-8
	PU007-9
	PU07-10
PU-SOL-THERM-009	PUST9-1
	PUST9-2
	PUST9-3
PU-SOL-THERM-0010	PU10091
	PU10092
	PU10093
	PU10111
	PU10112
	PU10113
	PU10114
	PU10115
	PU10116
	PU10117
	PU10121
	PU10122
	PU10123
	PU10124
PU-SOL-THERM-0011	PU11161
	PU11162

Table 3.2.2-1. Benchmark Problem Summary for Configurations Incorporating Plutonium Nitrate Solutions

Class	Case Name
	PU11163
	PU11164
	PU11165
	PU11181
	PU11182
	PU11183
	PU11184
	PU11185
	PU11186
	PU11187

3.2.3 Highly Enriched Uranium Nitrate Solutions

The experiments involving highly enriched uranium are from the OECD benchmark compilation (Reference 19, Volume II) and are summarized in Table 3.2.3-1.

Table 3.2.3-1. Benchmark Problem Summary for Configurations Incorporating Highly Enriched Uranium Nitrate Solutions

Class	Case Name
HEU-SOL-THERM-001	HEST1-1
	HEST1-2
	HEST1-3
	HEST1-4
	HEST1-5
	HEST1-6
	HEST1-7
	HEST1-8
	HEST1-9

Table 3.2.3-1. Benchmark Problem Summary for Configurations Incorporating Highly Enriched Uranium Nitrate Solutions

Class	Case Name
	HEST110
HEU-SOL-THERM-002	HEST2-1
	HEST2-2
	HEST2-3
	HEST2-4
	HEST2-5
	HEST2-6
	HEST2-7
	HEST2-8
	HEST2-9
	HEST2-10
	HEST2-11
	HEST2-12
	HEST2-13
	HEST2-14
HEU-SOL-THERM-003	HEUST31
	HEUST32
	HEUST33
	HEUST34
	HEUST35
	HEUST36
	HEUST37
	HEUST38
	HEUST39
	HEST310
	HEST311
	HEST312

Table 3.2.3-1. Benchmark Problem Summary for Configurations Incorporating Highly Enriched Uranium Nitrate Solutions

Class	Case Name
	HEST313
	HEST314
	HEST315
	HEST316
	HEST317
	HEST318
	HEST319
HEU-SOL-THERM-007	HEUST71
	HEUST72
	HEUST73
	HEUST74
	HEUST75
	HEUST76
	HEUST77
	HEUST78
	HEUST79
	HEST710
	HEST711
	HEST712
	HEST713
	HEST714
	HEST715
	HEST716
	HEST717
HEU-SOL-THERM-008	HEUST81
	HEUST83
	HEUST86

Table 3.2.3-1. Benchmark Problem Summary for Configurations Incorporating Highly Enriched Uranium Nitrate Solutions

Class	Case Name
	HEUST89
	HEST813
HEU-SOL-THERM-013	HEST131
	HEST132
	HEST133
	HEST134
HEU-SOL-THERM-0014	HEST141
	HEST142
	HEST143
HEU-SOL-THERM-0015	HEST151
	HEST152
	HEST153
	HEST154
	HEST155
HEU-SOL-THERM-0016	HEST161
	HEST162
	HEST163
HEU-SOL-THERM-0017	HEST171
	HEST172
	HEST173
	HEST174
	HEST175
	HEST176
	HEST177
	HEST178
HEU-SOL-THERM-0018	HEST181
	HEST182

Table 3.2.3-1. Benchmark Problem Summary for Configurations Incorporating Highly Enriched Uranium Nitrate Solutions

Class	Case Name
	HEST183
	HEST184
	HEST185
	HEST186
	HEST187
	HEST188
	HEST189
	HST1810
	HST1811
	HST1812
HEU-SOL-THERM-0019	HEST191
	HEST192
	HEST193

3.2.4 Intermediate-Enrichment Uranium Solutions

The experiments involving intermediate-enrichment uranium are from the OECD benchmark compilation (Reference 19, Volume III). All involve arrays of polyethylene-moderated U(30)F_4-Polytetraflouroethlyene one-inch cubes. These experiments are denoted as IECT101 through IECT129.

3.2.5 Low-Enrichment Uranium Solutions

The first set of experiments involving low-enrichment uranium are from the OECD benchmark compilation (Reference 19, Volume IV), while the second set (case prefix "LEUJ") are from work at the Japan Atomic Energy Research Institute (Reference 20). These problems are summarized in Table 3.2.5-1.

Table 3.2.5-1. Benchmark Problem Summary for Configurations Incorporating Low-Enrichment Uranium Solutions

Class	Case Name
LEU-SOL-THERM-002	LEUST21
	LEUST22
	LEUST23
JAERI	LEUJA01
	LEUJA29
	LEUJA33
	LEUJA34
	LEUJA46
	LEUJA51
	LEUJA54
	LEUJA14
	LEUJA30
	LEUJA32
	LEUJA36
	LEUJA49

3.2.6 ^{233}U Fuel Homogeneous Criticals

The experiments involving ^{233}U Fuel are from the OECD benchmark compilation (Reference 24). All involve spheres of enriched ^{233}U Fuel. The first ten are fast-metal systems. These experiments are denoted as u2331a through u2336a. The other six are thermal solutions systems. These experiments are denoted as u233s1 through u233s6.

4.0 LCE ANALYSES RESULTS

4.1 Lattice Criticals

This section tabulates the MCNP k_{eff} results for the LCEs (from Reference 21) according to experimental similarities. Tables 4.1-1 and 4.1-2 present the results for the LCEs according to the following distinct experimental classifications:

Table 4.1-1	Moderated Lattices Containing UO_2 Fuel
Table 4.1-2	Moderated Lattices Containing Mixed Oxide Fuel

Future revisions of this report may include additional LCEs, including some that incorporated metallic uranium and plutonium.

The tables include the calculated values for k_{eff}, standard deviation (sigma) and the average energy of a neutron causing fission (AENCF). The values are all taken from the MCNP output files.

Table 4.1-1. Moderated Lattices Containing UO_2 Fuel

Experiment	k_{eff}	sigma	AENCF
core2	1.00058	0.00159	0.199882
core3	1.00019	0.00148	0.180775
core4	0.99480	0.00150	0.179075
core5	0.99445	0.00153	0.169188
core6	0.99556	0.00152	0.172157
core7	0.99463	0.00151	0.159626
core8	0.98895	0.00149	0.164962
core9	0.99298	0.00144	0.155275
core10	0.99511	0.00148	0.160364
core11	0.99699	0.00148	0.178931
core12	0.99549	0.00151	0.166711
core13	0.99933	0.00151	0.180752
core15	0.99107	0.00157	0.183477
core16	0.99041	0.00150	0.169517
core17	0.99365	0.00151	0.18187
core18	0.99470	0.00150	0.16855

Table 4.1-1. Moderated Lattices Containing UO_2 Fuel

Experiment	k_{eff}	sigma	AENCF
core19	0.99383	0.00153	0.183538
core20	0.99392	0.00151	0.169332
core21	0.99160	0.00140	0.162252
exp1	1.00084	0.00088	0.120951
exp2	0.99842	0.00088	0.124688
exp3	0.99898	0.00089	0.121718
exp4	1.00104	0.00087	0.120029
exp5	1.00037	0.00107	0.279679
exp6	0.99675	0.00103	0.176621
exp7	0.99724	0.00111	0.178401
exp8	1.00719	0.00110	0.177353
exp9	1.00827	0.00099	0.221705
exp10	1.0066	0.00174	0.223902
exp11	1.00358	0.00157	0.266427
exp12	1.00546	0.00108	0.194612
exp13	1.00371	0.00113	0.194207
exp14	0.99593	0.00099	0.209445
exp15	1.00074	0.00087	0.109843
exp17	1.00218	0.00186	0.156366
exp18	1.00503	0.00167	0.088632
ugd1	1.00033	0.00143	0.201321
ugd2	0.99945	0.00145	0.198281
ugd3	1.00054	0.00147	0.199481
ugd4	1.00193	0.00150	0.199852
ugd5	0.99955	0.00154	0.197517
ugd6	0.99996	0.00152	0.197747
ugd7	1.00410	0.00148	0.196752
ugd8	0.99929	0.00154	0.197561

Table 4.1-1. Moderated Lattices Containing UO_2 Fuel

Experiment	k_{eff}	sigma	AENCF
ugd9	1.00135	0.00156	0.198726
ugd10	0.99790	0.00144	0.201104
ugd12	0.99940	0.00161	0.209648
ugd13	1.00049	0.00155	0.208409
ugd14	1.00066	0.00156	0.204162
ugd15	1.00158	0.00151	0.205600
ugd16	1.00335	0.00151	0.206480
ugd17	0.99912	0.00151	0.203413
ugd18	0.99876	0.00150	0.208511
ugd19	1.00133	0.00153	0.210113
ugd20	1.00322	0.00153	0.206980

Table 4.1-2. Moderated Lattices Containing Mixed Oxide Fuel

Experiment	k_{eff}	sigma	AENCF
exp22	0.99624	0.00174	0.255567
exp23	1.00050	0.00169	0.273969
exp24	1.00302	0.00171	0.161276
exp25	1.00835	0.00161	0.189442
exp26	1.00709	0.00160	0.131923
exp27	1.00752	0.00155	0.153718
exp28	1.00021	0.00170	0.229279
exp29	1.00506	0.00166	0.191841
exp30	1.00003	0.00187	0.200936
exp31	1.00682	0.00181	0.120431
exp32	1.00626	0.00182	0.107321
exp33	1.00739	0.00171	0.079640
exp34	0.98750	0.00168	0.377618

4.2 Homogeneous Criticals

This section tabulates the MCNP k_{eff} results for the LCEs (from Reference 18) according to experimental similarities. Tables 4.2-1 through 4.2-6 present the results for the LCEs according to the following distinct experimental classifications:

Table 4.2-1	Homogeneous Critical Experiments Using Mixed Nitrate Solutions
Table 4.2-2	Homogeneous Critical Experiments Using Pu Nitrate Solutions
Table 4.2-3	Homogeneous Critical Experiments Using HEU Nitrate Solutions
Table 4.2-4	Homogeneous Critical Experiments Using IEU Nitrate Solutions
Table 4.2-5	Homogeneous Critical Experiments Using LEU Nitrate Solutions
Table 4.2-6	Homogeneous Critical Experiments Using ^{233}U Fuel

Here "Highly Enriched Uranium" means in excess of 89 weight percent ^{235}U, "Low-enrichment Uranium" mean less than 10 weight percent ^{235}U, and "Intermediate-enrichment Uranium" has an enrichment of about 30 weight percent.

The column identified as AENCF contains the average energy of the neutron causing fission. It is a measure of the energy spectrum of the neutrons and has units of MeV.

Table 4.2-1. Homogeneous Critical Experiments Using Mixed Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
PNL3187	0.99821	0.00116	0.041582
PNL3391	0.99318	0.00112	0.040747
PNL3492	0.99619	0.00113	0.043860
PNL3593	0.99694	0.00121	0.046137
PNL3694	1.00275	0.00113	0.044829
PNL3795	1.00302	0.00117	0.039649
PNL3808	1.00178	0.00095	0.020591
PNL3896	1.00263	0.00110	0.023571
PNL3897	1.00323	0.00125	0.014467
PNL3898	1.00297	0.00118	0.029730
PNL3999	1.00707	0.00108	0.029328
PNL5300	1.00670	0.00105	0.029174
PNL1158	1.00686	0.00067	0.003929
PNL1159	1.00558	0.00064	0.003800

Table 4.2-1. Homogeneous Critical Experiments Using Mixed Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
PNL1161	1.00751	0.00066	0.005965
awre1	1.01511	0.00120	0.031334
awre2	1.01167	0.00117	0.032057
awre3	1.01028	0.00114	0.031828
awre4	1.00486	0.00111	0.032283
awre5	1.00875	0.00101	0.010617
awre6	1.01337	0.00108	0.010534
awre7	1.00640	0.00102	0.010888
awre8	1.01255	0.00091	0.006840
awre9	1.00977	0.00088	0.006836
awre10	1.00839	0.00081	0.006482
PNL1577	0.99645	0.00128	0.059559
PNL1678	0.99976	0.00115	0.050685
PNL1783	0.99976	0.00115	0.053863
PNL1868	1.00247	0.00119	0.034163
PNL1969	0.99967	0.00111	0.033596
PNL2070	0.99925	0.00115	0.037432
PNL2565	1.00363	0.00112	0.012952
PNL2666	1.00337	0.00105	0.011603
PNL2767	1.00629	0.00113	0.011971

Table 4.2-2. Homogeneous Critical Experiments Using Pu Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
PUST1T1	1.00995	0.00102	0.012518
PUST1T2	1.01109	0.00100	0.017021
PUST1T3	1.01396	0.00094	0.021585
PUST1T4	1.00643	0.00104	0.023968
PUST1T5	1.01014	0.00101	0.024792
PUST1T6	1.00831	0.00104	0.048089
PU003-1	1.00962	0.00091	0.006226
PU003-2	1.00885	0.00091	0.006513
PU003-3	1.01228	0.00092	0.006925
PU003-4	1.00965	0.00094	0.007195
PU003-5	1.01393	0.00092	0.007852
PU003-6	1.01214	0.00091	0.008450
PU003-7	1.01369	0.00093	0.006783
PU003-8	1.01175	0.00095	0.007028
PU004-1	1.01134	0.00088	0.005243
PU004-2	1.00448	0.00082	0.005405
PU004-3	1.00916	0.00087	0.005380
PU004-4	1.00712	0.00086	0.005613
PU004-5	1.00753	0.00091	0.005428
PU004-6	1.00862	0.00087	0.005640
PU004-7	1.01248	0.00090	0.005604
PU004-8	1.00778	0.00086	0.006204
PU004-9	1.00965	0.00089	0.006190
PU005-1	1.00860	0.00088	0.005705
PU005-2	1.00908	0.00088	0.005888
PU005-3	1.01116	0.00091	0.006202
PU005-4	1.01197	0.00093	0.006641
PU005-5	1.01367	0.00090	0.007233

Table 4.2-2. Homogeneous Critical Experiments Using Pu Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
PU005-6	1.01020	0.00095	0.007658
PU005-7	1.01073	0.00094	0.008384
PU005-8	1.00799	0.00091	0.005933
PU005-9	1.01023	0.00089	0.006305
PU007-2	1.01024	0.00102	0.040210
PU007-3	1.00591	0.00111	0.039276
PU007-5	1.01502	0.00106	0.017640
PU007-6	1.00873	0.00101	0.017989
PU007-7	1.01053	0.00103	0.017830
PU007-8	1.00254	0.00103	0.018102
PU007-9	1.00327	0.00106	0.018152
PU04-10	1.00987	0.00092	0.007148
PU04-11	1.00950	0.00092	0.008047
PU04-12	1.01108	0.00087	0.005935
PU04-13	1.00856	0.00091	0.005785
PU07-10	1.00706	0.00104	0.016530
PU10091	1.02337	0.00101	0.016753
PU10092	1.02091	0.00097	0.012989
PU10093	1.01316	0.00097	0.009941
PU10111	1.01879	0.00099	0.010009
PU10112	1.01543	0.00098	0.008734
PU10113	1.01615	0.00092	0.008516
PU10114	1.00903	0.00091	0.007897
PU10115	1.01069	0.00093	0.007546
PU10116	1.01992	0.00101	0.011144
PU10117	1.01146	0.00092	0.008794
PU10121	1.01560	0.00097	0.008959
PU10122	1.01616	0.00095	0.007758

Table 4.2-2. Homogeneous Critical Experiments Using Pu Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
PU10123	1.02352	0.00094	0.006905
PU10124	1.01642	0.00087	0.006102
PU11161	1.01661	0.00103	0.007377
PU11162	1.02377	0.00101	0.007772
PU11163	1.02224	0.00101	0.008269
PU11164	1.01688	0.00105	0.008450
PU11165	1.01338	0.00104	0.009729
PU11181	1.00169	0.00089	0.005050
PU11182	1.00680	0.00088	0.005489
PU11183	1.00336	0.00097	0.005140
PU11184	1.00285	0.00088	0.005468
PU11185	1.01131	0.00093	0.005932
PU11186	1.00796	0.00097	0.006329
PU11187	1.00792	0.00088	0.005482
PUST9-1	1.01886	0.00088	0.002566
PUST9-2	1.02390	0.00089	0.002664
PUST9-3	1.02176	0.00089	0.002464

Table 4.2-3. Homogeneous Critical Experiments Using HEU Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
HEST1-1	1.00187	0.00144	0.015759
HEST110	0.99468	0.00178	0.007573
HEST1-2	0.99948	0.00208	0.038569
HEST1-3	1.00453	0.00199	0.015461
HEST131	1.00138	0.00053	0.002654
HEST132	1.00020	0.00057	0.003069
HEST133	0.99521	0.00060	0.003605
HEST134	0.99824	0.00066	0.003785
HEST1-4	1.00130	0.00203	0.040502
HEST141	0.99801	0.00121	0.007269
HEST142	1.01252	0.00121	0.007369
HEST143	1.02159	0.00102	0.007908
HEST1-5	1.00361	0.00166	0.006505
HEST151	1.00390	0.00136	0.010470
HEST152	0.99502	0.00126	0.010092
HEST153	1.00999	0.00127	0.011274
HEST154	1.01658	0.00121	0.010771
HEST155	1.01218	0.00104	0.011098
HEST1-6	1.01038	0.00187	0.006781
HEST161	0.99346	0.00131	0.015165
HEST162	1.01032	0.00125	0.015001
HEST163	1.02295	0.00114	0.015973
HEST1-7	1.00230	0.00201	0.015014
HEST171	0.99660	0.00132	0.018899
HEST172	0.98362	0.00126	0.020954
HEST173	0.98345	0.00139	0.020040
HEST174	1.00204	0.00132	0.019386
HEST175	1.01159	0.00124	0.019935

Table 4.2-3. Homogeneous Critical Experiments Using HEU Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
HEST176	1.00677	0.00127	0.022091
HEST177	1.01209	0.00105	0.020445
HEST178	1.00635	0.00123	0.022161
HEST1-8	1.00505	0.00213	0.016100
HEST181	0.99334	0.00136	0.028440
HEST182	0.99132	0.00135	0.031524
HEST183	0.99434	0.00143	0.029903
HEST184	1.00191	0.00118	0.028945
HEST185	0.99568	0.00142	0.032662
HEST186	0.99667	0.00136	0.030660
HEST187	1.01176	0.00134	0.029683
HEST188	1.01178	0.00128	0.033348
HEST189	1.00973	0.00118	0.030876
HEST1-9	0.99973	0.00212	0.040991
HEST191	1.00280	0.00121	0.042621
HEST192	1.00401	0.00127	0.039202
HEST193	0.99925	0.00111	0.041469
HEST2-1	1.00513	0.00146	0.015512
HEST210	1.00549	0.00185	0.006603
HEST211	1.00568	0.00224	0.015510
HEST212	1.00870	0.00235	0.014357
HEST213	1.00564	0.00234	0.037033
HEST214	1.00965	0.00238	0.033554
HEST2-2	1.01236	0.00218	0.015066
HEST2-3	1.00368	0.00239	0.035869
HEST2-4	1.01063	0.00219	0.034601
HEST2-5	1.00601	0.00213	0.015802
HEST2-6	1.01719	0.00228	0.014689

Table 4.2-3. Homogeneous Critical Experiments Using HEU Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
HEST2-7	1.00383	0.00217	0.036593
HEST2-8	1.00883	0.00244	0.034229
HEST2-9	1.00270	0.00204	0.007065
HEST310	1.00102	0.00243	0.038165
HEST311	1.00606	0.00232	0.035663
HEST312	1.00740	0.00204	0.006511
HEST313	1.00045	0.00185	0.006536
HEST314	1.00822	0.00205	0.007036
HEST315	0.99620	0.00186	0.007179
HEST316	1.00356	0.00241	0.015926
HEST317	1.00604	0.00213	0.014981
HEST318	1.00007	0.00225	0.038422
HEST319	1.01306	0.00225	0.034143
HEST710	1.01186	0.00111	0.008599
HEST711	1.00896	0.00124	0.035134
HEST712	1.00746	0.00106	0.008552
HEST713	1.00897	0.00120	0.035199
HEST714	1.00811	0.00126	0.036173
HEST715	1.00388	0.00134	0.035741
HEST716	1.00658	0.00122	0.036319
HEST717	1.00756	0.00124	0.035831
HEST813	1.00616	0.00190	0.035577
HEUST31	1.00665	0.00211	0.006568
HEUST32	1.00723	0.00206	0.006768
HEUST33	1.00774	0.00240	0.016279
HEUST34	1.00491	0.00208	0.015393
HEUST35	0.99683	0.00230	0.038043
HEUST36	1.00523	0.00210	0.035380

Table 4.2-3. Homogeneous Critical Experiments Using HEU Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
HEUST37	1.00585	0.00173	0.006852
HEUST38	1.01086	0.00202	0.016389
HEUST39	1.01063	0.00204	0.015120
HEUST71	1.01399	0.00115	0.007028
HEUST72	1.01391	0.00133	0.036071
HEUST73	1.00773	0.00101	0.007132
HEUST74	1.01250	0.00123	0.035101
HEUST75	1.00867	0.00101	0.008402
HEUST76	1.00684	0.00136	0.037673
HEUST77	1.00792	0.00110	0.008429
HEUST78	1.00333	0.00128	0.038245
HEUST79	1.00834	0.00114	0.008985
HEUST81	1.00193	0.00138	0.006661
HEUST83	0.99730	0.00190	0.006444
HEUST86	1.00890	0.00221	0.037853
HEUST89	1.00274	0.00129	0.006428
HST1810	1.02605	0.00121	0.034433
HST1811	1.02880	0.00115	0.031820
HST1812	1.01997	0.00093	0.032765

Table 4.2-4. Homogeneous Critical Experiments Using IEU Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
IECT101	0.99580	0.00100	0.218800
IECT102	0.99960	0.00090	0.157600
IECT103	0.99390	0.00100	0.105000
IECT104	0.99750	0.00100	0.074400
IECT105	1.00780	0.00080	0.045500
IECT106	1.00070	0.00110	0.107700
IECT107	0.99780	0.00100	0.110600
IECT108	0.99680	0.00100	0.119200
IECT109	1.00170	0.00090	0.168100
IECT110	0.99490	0.00100	0.157100
IECT111	0.99440	0.00100	0.157700
IECT112	0.99600	0.00110	0.156500
IECT113	0.99960	0.00110	0.073900
IECT114	0.99900	0.00100	0.074300
IECT115	0.99990	0.00100	0.073200
IECT116	1.00210	0.00100	0.055000
IECT117	0.99580	0.00100	0.207200
IECT118	0.99700	0.00110	0.132800
IECT119	1.00290	0.00090	0.065500
IECT120	1.00270	0.00100	0.155400
IECT121	0.99680	0.00100	0.212500
IECT122	0.99540	0.00100	0.197200
IECT123	0.99300	0.00140	0.127700
IECT124	1.00036	0.00105	0.133048
IECT125	1.00160	0.00100	0.060100
IECT126	1.00610	0.00090	0.056200
IECT127	1.00340	0.00090	0.055900
IECT128	1.00340	0.00090	0.159000

Table 4.2-4. Homogeneous Critical Experiments Using IEU Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
IECT129	1.00180	0.00100	0.151600

Table 4.2-5. Homogeneous Critical Experiments Using LEU Nitrate Solutions

Experiment	k_{eff}	sigma	AENCF
LEUST21	0.99892	0.00053	0.024872
LEUST22	0.99469	0.00061	0.028323
LEUST23	1.00078	0.00057	0.026654
LEUJA01	1.00425	0.00085	0.018964
LEUJA14	0.99755	0.00094	0.020010
LEUJA29	1.00377	0.00082	0.018058
LEUJA30	0.99885	0.00086	0.018812
LEUJA32	1.00143	0.00086	0.017567
LEUJA33	0.99961	0.00090	0.016621
LEUJA34	1.00290	0.00079	0.015895
LEUJA36	1.00185	0.00084	0.016651
LEUJA46	1.00311	0.00080	0.015353
LEUJA49	0.99875	0.00078	0.015933
LEUJA51	1.00279	0.00070	0.014792
LEUJA54	1.00246	0.00072	0.014396

Table 4.2-6. Homogeneous Critical Experiments Using ^{233}U Fuel

Experiment	k_{eff}	sigma	AENCF
u2331a	0.99297	0.00038	1.773851
u2332a	0.99547	0.00038	1.737015
u2332b	0.99807	0.00039	1.707885
u2333a	0.99583	0.00041	1.748316
u2333b	0.99771	0.00041	1.762311
u2334a1	1.00380	0.00041	1.611865
u2334b1	1.00705	0.00042	1.517767
u2335a	0.99351	0.00043	1.619497
u2335b	0.99681	0.00045	1.518707
u2336a	1.00057	0.00045	1.774030
u233s1	1.00153	0.00037	0.03738
u233s2	1.00029	0.00038	0.003903
u233s3	1.00045	0.00040	0.004022
u233s4	0.99951	0.00040	0.004325
u233s5	0.99856	0.00039	0.004352
u233s6	0.99826	0.00027	0.003012

5.0 CONCLUSIONS

The data reported herein is acceptable for quality affecting activities and for use in analyses affecting procurement, construction, or fabrication. The classification analysis for the repository (which includes the waste package) carries TBV-228 because of the preliminary status of the basis for the MGR design. This report conservatively assumes that the resolution of TBV-228 will find the waste package to be quality affecting; consequently, use of any of the data reported herein does not need to carry TBV-228.

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