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Evaluation of PNL30-35 Critical Experiments on ICSBEP

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Abstract

The International Criticality Safety Benchmark Evaluation Project (ICSBEP) is under way for the purpose of identifying, evaluating, and compiling benchmark critical experiment data into a standardized format that allows criticality analysts to easily use the data to validate calculational methods and cross sections. As part of this activity, PNL30-35 experiments, which had been adopted as benchmark problems by CSEWG in 1970s, were reevaluated, which results in some additions and modifications: changes in fuel number density, modifications to the experimental k_{eff}, *modifications to the soluble boron concentration for PNL-31, and addition of an uncertainty in the benchmark-model* k_{eff}.

Introduction

In the past, thousands of critical experiments have been performed. Many of these critical experiments can be used as benchmarks for validation of calculation techniques. However, many were performed without a high degree of quality assurance and were not well documented. The purpose of International Criticality Safety Benchmark Evaluation Project (ICSBEP) activity is to compile benchmark critical experiment data into a standardized format that allows criticality safety analysts to easily use the data to validate calculational techniques and cross sections by:

- Identifying and evaluating a comprehensive set of benchmark critical experiment data.
- Verifying the data, to the extent possible, by reviewing original and subsequently revised documentation and by talking with experimenters or individuals who were associated with the experimenters or the experimental facility.
- Compiling the data into a standardized format.
- Performing sample calculations of each experiment with standardized criticality safety neutronic codes.
- Formally documenting the work into a single source of verified benchmark critical data.

All evaluated criticality safety benchmark data are documented in the ICSBEP International Handbook of Evaluated Criticality Safety Benchmark Experiments.[1] The handbook is organized into seven different volumes according to the type of fissile material; Plutonium, Highly Enriched Uranium, Intermediate and

Mixed Enrichment Uranium, Low Enriched Uranium, Uranium-233, Mixed Plutonium-Uranium, and Special Isotope Systems. Each of these volumes are subdivided according to the physical form of the fissile material: fast, intermediate and/or thermal energy systems; Metal, Compound, Solution, and Miscellaneous Systems.

The ICSBEP was initiated in October, 1992 by the United States Department of Energy. The project became an official activity of the Organization for Economic Cooperation and Development - Nuclear Energy Agency in 1994. Seven countries, the United States, the United Kingdom, France, Japan, the Russian Federation, Hungary and Korea, are now participating to this project.

Korea has participated in ICSBEP since 1995 by evaluating the UO_2-2wt.% PuO_2 (8% ^{240}Pu) lattice experiments referred as PNL30-35 experiments[2,3,4] by Cross Section Evaluation Working Group(CSEWG) in 1970s[5]. The evaluation for PNL30-35 experiments were performed by evaluating the effect on k_{eff} of missing data, uncertainty of experiment parameters, and inconsistent published data and by discussing the experiments with one of the original experimenters. The necessity of some additions or modifications for benchmark-model were identified: changes in fuel number density, modifications to the experimental k_{eff}, modifications to the soluble boron concentration for PNL-31, and the addition of an uncertainty in the benchmark-model k_{eff}.

Description of PNL30-35 Experiments

PNL30-35 experiments are a series of six lattice experiments with UO_2-2wt.% PuO_2 (8% ^{240}Pu) which were performed in the Plutonium Recycle Critical Facility (PRCF) at Pacific Northwest Laboratory in 1975-76. Experiments with UO_2-2wt.% PuO_2(8% ^{240}Pu) fuel included rectangular, square-pitched lattices, with 0.7-inch, 0.87-inch or 0.99-inch in borated or pure water moderator. The physical layout of the tank, lattice plates and support structures, and fuel rods is shown in Figure 1. The summary of these experiments is listed in Tables 1a and 1b.

Reactor Tank and Fuel Support Plate - The aluminum reactor tank is 6 feet in diameter and 9 feet in depth, with a 0.02-inch-thick cadmium wrapper and thermal insulation on the cylindrical surface of the tank[6]. The bottom of the fuel rods were supported by two aluminum solid plates, 1/8-inch- and 1-inch-thick.

Lattice Grids - The pitch of the fuel rods was maintained by two aluminum grid plates positioned near the top and bottom of active fuel. Two types of 6061-T6 aluminum "eggcrate" grids were used to construct three values for square lattice pitch; for 0.87-inch-pitched lattice and for both the 0.70- and 0.99-inch-pitched lattices.

Fuel Rods - The mixed-oxide fuel was fabricated using UO_2 and PuO_2 particles. The PuO_2 and UO_2 particles were blended and the mixture compacted within the Zircaloy-2 cladding using vibration compaction techniques, resulting in fuel densities of 9.54 g/cm^3 which are considerably lower than would be found in pellet fuel. The bottom of the fuel zone contains a layer of natural UO_2 powder which has the thickness of 0.5 cm and weight of 6 g. The cladding is made of Zircaloy-2 and welded at both ends with Zircaloy plugs.

Moderator - The borated water or unborated water was used as moderator. The moderator temperatures for six experiments ranged from 20.98 °C to 23.4 °C.

Evaluation of PNL30-35 Experiments

The reported experimental k_{eff}'s are slightly above 1.0, and the benchmark model k_{eff} is modified because of PuO_2 particle effects and different experimental temperatures. Because the benchmark model for PNL lattices includes homogeneous fuel instead of particles, the benchmark-model k_{eff} is greater than measured k_{eff} values by the magnitudes of 0.08%Δk for PNL30-31, 0.22%Δk for PNL32-33, and 0.28%Δk for PNL34-35[7]. Simplifying the model by removing the grid and replacing the natural UO_2 at the bottom of the fuel with MOX also contributed a small bias to the simplified model k_{eff}. The benchmark-model k_{eff}'s for both the detailed and simplified benchmark-models are shown in Table 2.

The effect on k_{eff} of missing data, uncertainty of experiment parameters, and inconsistent published data were evaluated, and listed in Table 3. The uncertainty in k_{eff} due to fuel rod characterization were evaluated with uncertainties in fuel isotope composition, uranium and plutonium weight fraction, fuel density, fuel rod diameter, clad thickness, and isotope composition of clad material. The effects of uncertainties in soluble boron concentration and ^{10}B atomic fraction were also evaluated. The third row of Table 3 includes the effect of existence of a lead shield and the reactor top face. Since spacing between grid and fuel rod exists, the fuel rod pitch might not be uniform over the core. So the effect on k_{eff} due to random error in fuel rod pitch is also evaluated. Half the values determined for the effects of PuO_2 particle are considered as conservative uncertainties in k_{eff} in addition to the uncertainty according to model simplifications. The resulting benchmark-model k_{eff}'s for both the detailed and simplified models, and the results of sample calculation using MCNP4 with an ENDF/B-V library for the six critical configurations are presented in Table 4.

Results and Discussions

The PNL30-35 critical arrays had been adopted as benchmark problems by CSEWG in 1970s. The additional evaluation and modifications for PNL30-35 done by ICSBEP activity are as follows;

1. Changes in fuel number density: The atomic densities of the fuel constituents were calculated based on the isotopic data, measured ~7 months after experiments, oxide density of $9.54 g/cm^3$, Avogadro's number and atomic weights. The atomic number densities for ^{241}Am and ^{241}Pu were also corrected by considering the decay time between experiment time and isotope measurement time.
2. Modifications in experimental k_{eff}: The excessive reactivities for PNL-32 and -34 are modified from 6.8 and 22.3 cents to 5.57 and 27.81 cents, respectively. PNL-32 and -34 were not fully-reflected. A 6.8 cent for PNL-32 was fully-reflected excess reactivity and a 22.3 cent for PNL-34 was fully-reflected excess reactivity with 160 rods.[8]

3. Modifications in soluble boron concentration for PNL-31: The soluble boron concentration for PNL-31 is modified from 680.9 to 687.9 ppm. All the 680.9's have been changed to 687.9's in later version of EPRI-NP-196.[8]
4. Addition of the uncertainty to benchmark-model k_{eff} : The uncertainty in k_{eff} due to uncertain fuel rod characterization, soluble boron data, reactor core structure, random pitch effect, PuO_2 particle effect, and model simplification is added in benchmark-model k_{eff}.

An official evaluation results for these experiments will be published in the International Handbook of Evaluated Criticality Safety Benchmark Experiments[1] as MIX-COMP-THERM-002 upon approval by the ICSBEP Working Group.

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Table 1.a PNL Experiment Lattice Parameters.

Experiments	Loading ID	Date of Experiments	Pitch (inch)	Critical Number of Rods	Temperature(°C)
PNL-30	UL-266	27 Feb '76	0.70	469	20.98
PNL-31	UL-250	11 Feb '76	0.70	761	21.9
PNL-32	UL-189	03 Dec '75	0.87	195	22.75
PNL-33	UL-212	31 Dec '75	0.87	761	22.66
PNL-34	UL-282	05 Mar '76	0.99	161	22.15
PNL-35	UL-232	23 Jan '76	0.99	689	23.4

Table 1.b PNL Experiment Lattice Parameters.

Experiments	Boron Concentration (ppm)	Excess Reactivity (cents[a])	Boron Sensitivity (cents/ppmB)	Top Reflector Thickness inches)	Axial Buckling (m^{-2})
PNL-30	1.7 ± 0.1	+ 5.1	-	6.0	9.901
PNL-31	687.9 ± 2	+ 1.8	2.8	6.0	9.381
PNL-32	0.9 ± 0.2	+ 5.57	-	2.25	9.322
PNL-33	1090.4 ± 2	+ 6.5	2.1	6.0	9.487
PNL-34	1.6 ± 0.1	+27.81	-	0.9	9.842
PNL-35	767.2 ± 2	+ 3.8	5.1	6.0	9.480

(a) 1 cent = 3.447×10^{-5} k (Reference 2, Appendix C.)

Table 2. Experimental and Benchmark-Model k_{eff}.

Lattice Parameter	PNL-30	PNL-31	PNL-32	PNL-33	PNL-34	PNL-35
Experimental k_{eff}	1.00018	1.00006	1.00019	1.00022	1.00096	1.00013
k_{eff} of PuO_2 particle effects for homogeneous fuel	+0.0008	+0.0008	+0.0022	+0.0022	+0.0028	+0.0028
k_{eff} of temperature effects	-0.00006	-0.00016	-0.00007	+0.00011	+0.00013	-0.00029
k_{eff} of omitting grid, replacing UO_2 with MOX	+0.00074	+0.00259	+0.00002	+0.00160	+0.00049	+0.00023
Benchmark-Model k_{eff}, (Detailed)	1.0009	1.0007	1.0023	1.0025	1.0039	1.0026
Benchmark-Model k_{eff}, (Simplified)	1.0017	1.0033	1.0023	1.0041	1.0044	1.0029

Table 3. Uncertainty in Benchmark-Model k_{eff}.

Uncertainty Parameter	Δk_{eff} (%) PNL-30	Δk_{eff} (%) PNL-31	Δk_{eff} (%) PNL-32	Δk_{eff} (%) PNL-33	. Δk_{eff} (%) PNL-34	Δk_{eff} (%) PNL-35
Fuel rod Characterization	0.143	0.115	0.153	0.330	0.313	0.490
Soluble Boron	-	0.032	-	0.087	-	0.085
Reflector	0.054	0.026	0.044	0.027	0.061	0.025
Random Pitch	0.131	0.070	0.091	0.095	0.027	0.071
PuO_2 Particle Effect Bias	0.04	0.04	0.11	0.11	0.14	0.14
Model Simplification	0.117	0.121	0.113	0.119	0.112	0.107
Total Uncertainty, (Detailed Model)	0.205	0.146	0.214	0.372	0.349	0.522
Total Uncertainty, (Simplified Model)	0.236	0.190	0.242	0.391	0.367	0.533

Table 4. Benchmark-Model k_{eff} and Sample Calculation Results.

Parameter \ Experiments		PNL-30	PNL-31	PNL-32	PNL-33	PNL-34	PNL-35
Benchmark-Model k_{eff}	Detailed Model	1.0009 (± 0.0021)	1.0007 (± 0.0015)	1.0023 (± 0.0021)	1.0025 (± 0.0037)	1.0039 (± 0.0035)	1.0026 (± 0.0052)
	Simplified Model	1.0017 (± 0.0024)	1.0033 (± 0.0019)	1.0023 (± 0.0024)	1.0041 (± 0.0039)	1.0044 (± 0.0037)	1.0029 (± 0.0053)
Calculation Results	Detailed Model	0.9952 (± 0.0008)	0.9982 (± 0.0008)	1.0014 (± 0.0008)	1.0065 (± 0.0008)	1.0050 (± 0.0008)	1.0079 (± 0.0008)
	Simplified Model	0.9959 (± 0.0008)	1.0007 (± 0.0008)	1.0014 (± 0.0008)	1.0081 (± 0.0008)	1.0055 (± 0.0008)	1.0081 (± 0.0008)

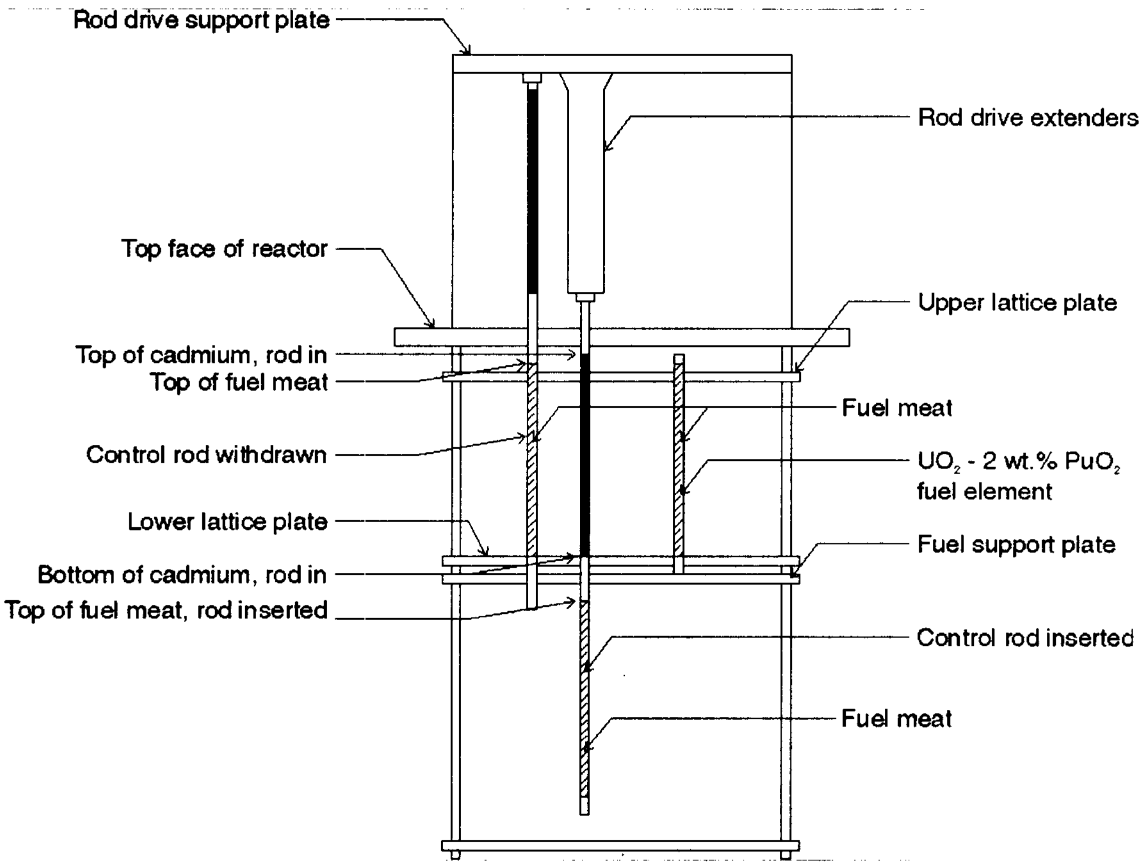

Figure 1. PRCF Lattice Support Structure.