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Evaluation of Saxton Critical Experiments

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Abstract

As a part of International Criticality Safety Benchmark Evaluation Project (ICSBEP), SAXTON critical experiments were reevaluated. The effects on k_{eff} of the uncertainties in experiment parameters, fuel rod characterization, soluble boron, critical water level, core structure, ^{241}Am and ^{241}Pu isotope number densities, random pitch error, duplicated experiment, axial fuel position, model simplification, etc., were evaluated and added in benchmark-model k_{eff}. In addition to detailed model, the simplified model for Saxton critical experiments was constructed by omitting the top, middle, and bottom grids and ignoring the fuel above water.

Introduction

Thousands of critical experiments have been performed in the past. 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)[1] 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.

As part of ICSBEP, the reevaluation for Saxton critical experiments[2] was 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.

A series of Saxton critical experiments with water moderated, single-region and multi-region UO_2-PuO_2 and/or UO_2 fueled cores was performed in the Critical Reactor Experiment (CRX) facility at the Westinghouse Reactor Evaluation Center (WREC) in 1965. The purpose of these experiments was to verify the nuclear design of the Saxton partial plutonium core. Experiments consisted of single-region experiments with natural UO_2-PuO_2 or enriched UO_2, and multi-region experiments with both natural UO_2-PuO_2 and enriched UO_2 with several different pitched lattices.

This paper documents evaluation only for six natural UO_2-6.6 wt.% PuO_2 mixed-oxide (MOX), square-pitched, partial-moderator-height lattices with five lattice pitches of 0.52 inch, 0.56 inch, 0.735 inch, 0.792 inch, and 1.04 inch in single region experiments.

Description of Saxton Critical Experiments

Core and Wave Baffle Tanks - The overall view of the CRX reactor tank is shown in Figure 1. A wave baffle tank of approximate 4-feet diameter surrounds the core grid structure and prevents water waves.

Lattice Grids - The pitch of the fuel rods was maintained by the grid structure which was composed of aluminum grid plates and grid support rods. The grid plates were positioned at three levels - top, middle, and bottom - as shown in Figure 1. The fuel rod holes in the aluminum top, middle, and bottom grid plates are 0.397 ± 0.002 inches in diameter, and the middle grid plate has additional holes of 0.193 ± 0.001 inches in diameter for water circulation. Aluminum grids of two fuel-rod-hole spacing were used to construct five values for lattice pitch. The lattice grid for 0.52-inch pitch was also used for the 0.735-inch- and 1.04-inch-pitch lattice, and the 0.56-inch-pitch lattice grid was also used for the 0.792-inch-pitch lattice. The fuel rods in the *0.735-inch-pitch and 0.792-inch-pitch lattices were diagonally located* in the 0.52-inch- and 0.56-inch-pitched grids, respectively.

Aluminum Support Plate and Slab - The grid structure was supported on a 1-inch-thick aluminum plate. The size of the plate is the same as the bottom grid plate. The 1-inch-thick aluminum slab is supported on 2-1/2-inch-thick aluminum feet which stand on a 2-inch-thick by ~6-foot-diameter aluminum slab. This 6-foot-diameter slab supports the wave baffle tank.

Fuel Rods - The natural UO_2-6.6 wt.% PuO_2 fuel was pelletized. The weights of UO_2-PuO_2, PuO_2, Pu metal, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu are 546.576, 36.074, 31.815, 28.789, 2.727, 0.283, and 0.013 g/rod, respectively. The natural UO_2-6.6 wt.% PuO_2 fuel pellet has the diameter of 0.3374 ± 0.0010 inches. The height of the pellet is 0.366 ± 0.030 inches. The pellet density is reported as 94 ± 2% of theoretical density, which is equivalent to 10.33342 g/cm^3. The fuel rod is composed of fuel pellet, top and bottom plugs, fillers, and spring. The pellets were surrounded by Zircaloy-4 clad which has 0.391 inches of outer diameter and 0.3445 inches of inner diameter. The fuel length was 36.6 ± 0.183 inches. The total fuel rod has a length of 39.051 ± 0.032 inches.[3]

Experiment Parameters - Saxton critical experiment parameters are summarized in Table 1. The experiment with 0.56-inch pitched 21x21 fuel array was performed in 337 ppm borated water moderator, and the other experiments in this evaluation were performed in pure water moderator. The moderator temperatures for the experiments ranged from 15.75°C to 25.8°C.

Evaluation of Saxton Critical Experiments

The effects on k_{eff} of the uncertainties in experiment parameters were calculated with deterministic codes like CASMO and ONEDANT.

Fuel Rod Data - The sum of weights of the plutonium isotopes is 31.812 g/rod, and it is slightly different from the given value of 31.815 g/rod for plutonium metal. The difference of 0.003 g/rod was taken as the uncertainty (0.00943 wt.%) for all plutonium isotope compositions. The uncertainties for uranium isotope composition are assumed to be 0.0006 wt.% for ^{234}U, 0.004 wt.% for ^{235}U, and 0.004 wt.% for ^{238}U. The uncertainties in k_{eff} due to non-uniform distribution of fuel parameters, such as pellet density, O/M ratio (the ratio of oxygen to fuel isotope number density), plutonium assay, Pu/U ratio, and impurities are calculated; according to the specification for fuel rod manufacturing[4], the ranges of fuel pellet density, O/M ratio, plutonium assay, and Pu/U ratio are ± 2% of nominal density, 1.97 - 2.02, 5.75 - 5.89%, and 0.070 - 0.072, respectively. The fuel mass was held constant in sensitivity calculations of non-uniform distribution of fuel parameters. The magnitude of uncertainties in fuel diameter and length are given as ± 0.001 inches for fuel diameter and ± 0.183 inches for fuel length. The Δk_{eff} due to the uncertainty in the clad material composition was determined by evaluating two extreme cases: minimized zirconium content and maximized zirconium content compositions. The uncertainty in clad thickness is assumed as 0.00508 centimeters (0.002 inches), which was used for the clad thickness uncertainty in PNL30-35 evaluation[5]. The fuel density was held constant in sensitivity calculations of clad thickness. The material and dimensions of plugs, fillers, and springs at the ends of the fuel rod were not given. (Al_2O_3 spacers mentioned as being at the ends of the fuel column were probably the fillers.) The sensitivity calculation was performed with the assumption that the volume of both ends of fuel rods are composed of 20% void, 40% steel, and 40% Zircaloy-4. Solid Zircaloy-4 is assumed for the ends of rods for the base case.

Soluble Boron Concentration - Borated water was used only for the Case 3 experiment which has 337 ppm boron in water. The uncertainty in soluble boron concentration was assumed as 2 ppm. The ^{10}B atom fraction of 0.199 was assumed to vary from 0.191 to 0.203.· For the Case 3 core, the effects on k_{eff} of soluble boron concentration and ^{10}B atomic fraction uncertainties are 0.012 and 0.051 %Δk_{eff}, respectively.

Fuel Support Plate - The fuel rods were supported on a 1-inch-thick aluminum slab. The uncertainty in slab thickness was assumed as ±0.3 cm. The composition for aluminum was not reported. For the uncertainty calculation of aluminum composition, two different compositions were considered: 6061 aluminum and 100 percent aluminum. The uncertainties of hole sizes (fuel rod holes and water circulation holes) were given as ±0.002 inches and ±0.001 inches, respectively.

Others - Since the space of 0.006 inches between grid and fuel rod existed, the fuel rod pitch may not be uniform over the core. So the effects on k_{eff} due to random error in fuel rod pitch are calculated. This Δk_{eff} is calculated by changing the pitch by the difference between width of the grid hole and rod diameter.

Case 2 had a duplicated experiment which was done at different temperature and had a different critical water level: 17.0°C, 80.80 cm water level for Case 2-1 and 15.75°C, 81.79 cm water level for Case 2-2 as shown in Table 1. The difference in k_{eff} between the two separate experiments is considered as experimental uncertainty for all cases. The average water level and moderator density are used for the benchmark model for case 2.

The plutonium separation date was not reported. Three years has normally been assumed as the time between plutonium separation/analysis and experiments.[6] An uncertainty of two years was assumed and the effect of ^{241}Am decayed from ^{241}Pu was calculated.

Reference 2 gives two inconsistent axial positions of the bottom of the fuel, 0.5 inches and 0.75 inches for the distance between the top of the bottom grid and bottom of the fuel. The effect on k_{eff} due to the difference of 0.25 inches in fuel position was calculated.

Some model simplifications (100% Al composition, no reflection beyond 30 cm of water below and side) were judged to have negligible effects on k_{eff}. However, the model may be simplified by omitting the top, middle, and bottom grids and ignoring the fuel above water. The additional uncertainty was calculated with MCNP and was included in the benchmark model k_{eff}.

The uncertainties in k_{eff} due to the uncertainties in experiment parameters are summarized in Table 2.

Evaluation Results and Discussions

As a part of ICSBEP activity, Saxton critical experiments were reevaluated. The effects on k_{eff} of the uncertainties in experiment parameters, fuel rod characterization, soluble boron, critical water level, core structure, ^{241}Am and ^{241}Pu isotope number densities, random pitch error, duplicated experiment, axial fuel position, model simplification, etc., were evaluated and added in benchmark-model k_{eff}.

The simplified models for Saxton critical experiments were constructed by omitting the top, middle, and bottom grids and ignoring the fuel above water. The benchmark model k_{eff}'s for detailed and simplified models and the results of sample calculations using MCNP with the ENDF/B-V library for the six critical configurations are presented in Table 3.

REFERENCES

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3. E.A. Bassler, D.C. Fischer, N.J. Georges, E.A. McCabe, SAXTON Plutonium Program: Mechanical, Thermal and Hydraulic Design of Saxton Partial Plutonium Core, WCAP-3385-52 (EURAEC-1491), December 1965.
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5. Hyung-kook Joo, Rectangular Arrays of Water Moderated UO_2-2.0wt.% PuO_2 Fuel Rods, MIX-COMP-THERM-002, ICSBEP Handbook, 1997.
6. Personal communication, Bill Carlson, March 1997.

Table 1. Saxton Critical Experiment Lattice Parameters.

Experiment No.	Date (1965)	Lattice	Pitch (in.)	Soluble Boron (ppm)	Water Temperature (°C)	Critical Water Height (cm)[(a)]	Axial Buckling $\times 10^3$ (cm^{-2})
Case 1	6/8	22×23	0.52	0	25.8	82.90	1.07
Case 2-1[(b)]	4/15	19×19	0.56	0	17.0	80.80	1.14
Case 2-2[(b)]	6/3	19×19	0.56	0	15.75	81.79	1.11
Case 3	5/11	21×21	0.56	337	18.0	88.06	0.964
Case 4	6/9	13×13	0.73539	0	24.1	68.41	1.61
Case 5	4/20	12×12	0.79196	0	16.1	76.76	1.34
Case 6	6/16	11×11	1.04	0	19.9	79.50	1.25

(a) Water heights are referenced to the bottom of the fuel.

(b) Two separate experiments were performed.

Table 2. Uncertainty in Benchmark-Model k_{eff}.

Parameter	Δk_{eff} (%) for Case 1	Δk_{eff} (%) for Case 2	Δk_{eff} (%) for Case 3	Δk_{eff} (%) for Case 4	Δk_{eff} (%) for Case 5	Δk_{eff} (%) for Case 6
Fuel Rod Characterization	0.690	0.548	0.497	0.240	0.190	0.120
Soluble Boron	-	-	0.052	-	-	-
Critical Water Level	0.049	0.050	0.040	0.074	0.053	0.060
Core Structure	0.017	0.024	0.004	0.029	0.032	0.046
Experimental, Am, Uncertainty, etc.	0.169	0.158	0.147	0.127	0.123	0.137
Δk_{eff} for Omitted Grids and Dry Lattice[(a)]	0.126	0.129	0.129	0.128	0.127	0.117
Total Uncertainty,[(b)] Detailed Model	0.712	0.573	0.522	0.283	0.235	0.197
Total Uncertainty,[(c)] Simplified Model	0.723	0.587	0.538	0.311	0.267	0.229

(a) The uncertainty of the difference between MCNP results for simplified and detailed models; applicable to simplified model only.

(b) Square root of sum of squares of individual Δk_{eff} values.

Table 3. Benchmark-Model k_{eff} and Sample Calculation Results.

Parameter \ Experiments		Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
Benchmark-Model k_{eff}	Detailed Model	1.0000 (± 0.0071)	1.0000 (± 0.0057)	1.0000 (± 0.0052)	1.0000 (± 0.0028)	1.0000 (± 0.0024)	1.0000 (± 0.0020)
	Simplified Model	1.0028 (± 0.0072)	1.0019 (± 0.0059)	1.0000[a)] (± 0.0054)	1.0027 (± 0.0031)	1.0049 (± 0.0027)	1.0000[a)] (± 0.0023)
Calculation Results	Detailed Model	0.9955 (± 0.0009)	0.9989 (± 0.0009)	0.9988 (± 0.0009)	1.0015 (± 0.0008)	1.0013 (± 0.0009)	1.0061 (± 0.0009)
	Simplified Model	0.9983 (± 0.0009)	1.0008 (± 0.0009)	0.9993 (± 0.0009)	1.0042 (± 0.0010)	1.0062 (± 0.0009)	1.0065 (± 0.0008)

(a) Δk_{eff} between detailed and simplified models was less than 1σ of the difference calculation.

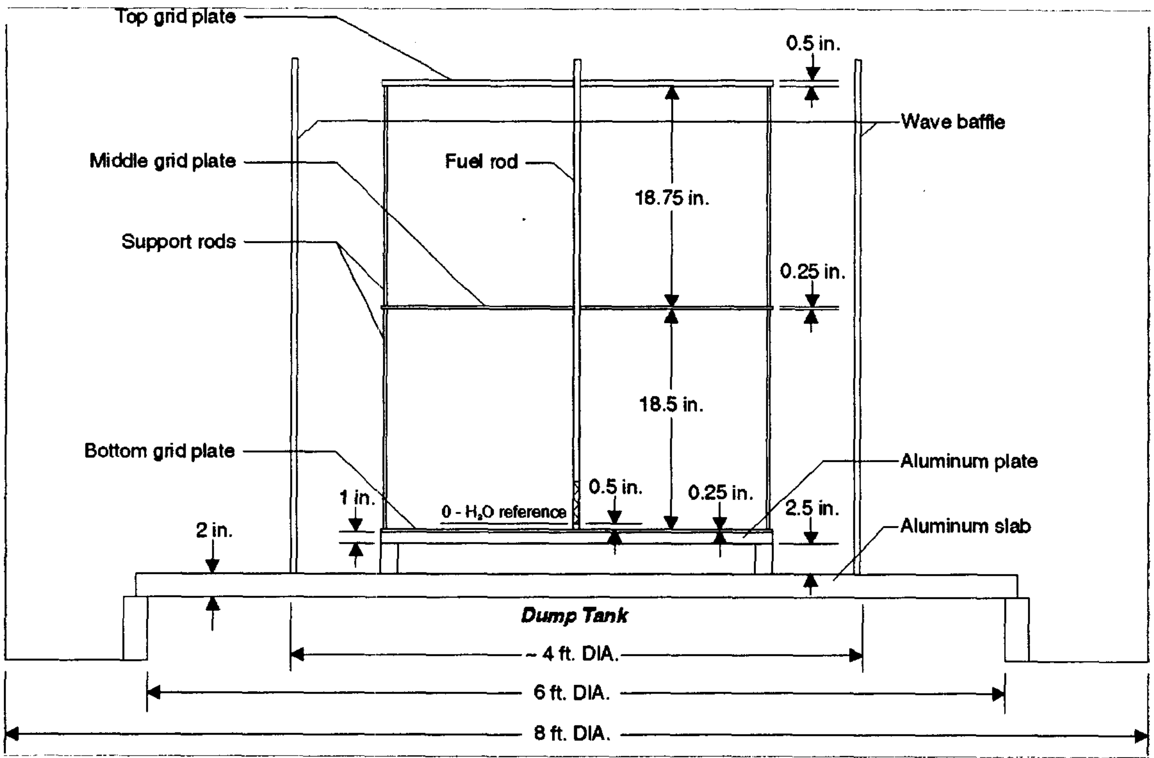

Figure 1. CRX Core Tank - Side Elevation.