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Validation Calculations of Simulated Shipping Container Experiments with Steel, Boral, and Cadmium Plates

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Abstract

Criticality experiments with fixed neutron poison plates for water moderated and reflected low enriched (2.35 and 4.31 wt%) UO_2 fuel rod clusters were evaluated to validate calculational techniques employed in analyzing fuel shipping and storage systems having steel, boral, or cadmium shield. Measurements were obtained for both the 2.35 wt% and the 4.31 wt% enriched rods in square pitched, water flooded lattices. The critical experiments with the 2.35 wt% enriched rods consists of three 20 x 16 or 20 x 17 fuel clusters. Three 15 x 8 fuel clusters were used in the experiments with the 4.31 wt% enriched fuel rods. In the experiments, the poison plates were placed on both sides of the centrally located fuel cluster. Critical separation between the three sub-critical fuel clusters were then measured for varying plate thicknesses and distances of the plates to the center fuel cluster. Calculations were performed for thirty eight critical configurations using KENO-V.a and MCNP. All of the results were within 1.23% in Δk when individually compared with the critical value of 1.0. Discrepancies of the code results are probably due to uncertainties in experiments and/or analytical modeling of the experiments. In general, MCNP predictions were observed to be in best agreement with the experiments.

1. Introduction

The International Criticality Safety Benchmark Evaluation Project (ICSBEP) is an ongoing criticality safety related evaluation project which is managed through the Idaho National Engineering and Environmental Laboratory (INEEL), and is contributed by many countries like Korea, the United States of America, the United Kingdom, France, Japan, the Russian Federation, and Hungary. The major purpose of the ICSBEP is to identify and evaluate set of critical benchmark data, verify the data, perform calculations of each experiments with standard criticality safety codes, and formally document the work into a single source of verified benchmark critical data. The work by the ICSBEP is a valuable tool and is intended for use by criticality safety analysts to perform necessary validations of their calculational techniques. As part of this project, validation calculations of criticality experiments[1,2] with fixed neutron poison plates for water moderated and reflected low enriched UO_2 fuel rod clusters were performed.

2. Description of Experiments

A set of criticality experiments selected consists of determining the critical separation between three sub-critical clusters of fuel rods aligned in a row with fixed poison plates parallel on either side of, and various distances from the center fuel cluster. A detailed description of each type of fuel rod can be found in References 1 and 2. The poison plates evaluated in this paper are steel, boral, and cadmium plates, and are 36.5 cm wide, and 91.5 cm long. Thickness of the neutron poison plate was varied in the experiments. Measurements were obtained for both the 2.35 wt% and the 4.31 wt% U-235 enriched UO_2 rods in square pitched, water flooded, lattices. Note that the enrichment was originally reported at 4.29 wt%, but later[3] corrected to 4.31 wt% which was used in this report. The critical experiments with the 2.35 wt% enriched fuel rods consist of three 20 x 16 or 20 x 17 fuel clusters. The radius of the 2.35 wt% enriched UO_2 rod in a unit fuel cell is 0.5588 cm, and the cladding is made of 0.0762 cm-thick 6061 aluminum. The lattice pitch of the fuel cells is 2.032 cm. The fuel length of the 2.35 wt% enriched UO_2 fuel is 91.44 cm. The UO_2 rod is clad with 6061 aluminum tubing seal welded with a lower end plug of 5052-H32 aluminum and a top plug of 1100 aluminum.

The critical experiments with the 4.31 wt% enriched fuel rods consist of three 15 x 8 fuel clusters. The radius of the UO_2 in a unit fuel cell is 0.6325 cm, and the cladding is made of 0.066 cm-thick 6061 aluminum with an inner radius of 0.6415 cm. The lattice pitch of the fuel cells is 2.54 cm. The fuel length of the 4.31 wt% UO_2 rod was originally reported to be 91.44 cm, and this value was later[4] identified as the minimum fuel length. The fuel length used in the evaluation is the average fuel length of 92.075 cm.[2] The cladding of the 4.31 wt% enriched UO_2 pellet consists of 6061 aluminum tubing supported with rubber end caps at the top and bottom of the fuel. The clusters of the 2.35 wt% and 4.31 wt% enriched UO_2 are supported on a 2.54 cm-thick acrylic plate mounted off the tank wall. A total of thirty eight critical configurations were evaluated using the experimental data taken from References 1 and 2. A short summary of information relating to selected sixteen cases of critical experiments is given in Table 1.

3. Methodology

Calculations were performed using the Monte Carlo codes, KENO-V.a[5] and MCNP.[6] All of the calculations documented in this report were performed on an HP 9000 720 workstation with Version 9.05 operating system and Version 9.05 of the FORTRAN Compiler. KENO-V.a is part of the SCALE-4 modular code system.[7] The Hansen-Roach and the 27 group ENDF/B Version 4 cross sections were used for the evaluation. The MCNP computer code is a general purpose Monte Carlo Neutron Particle transport code that can be used to calculate eigenvalues for critical systems. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori, and uses continuous-energy cross section data. The 4A version of MCNP and the associated continuous energy ENDF/B-V cross sections were used in the evaluation.

4. Evaluation and Results

KENO-V.a and MCNP models of the 2.35 wt% enriched UO_2 fuel rod clusters contain three clusters consisting of 20 x 16 or 20 x 17 fuel rod arrays with the fixed poison plates positioned between the fuel clusters. The water reflector thickness in the X and Y direction is 30.5 cm beyond the ends of the clusters. The aluminum cladding, top and lower end plugs along with a 2.54 cm-thick acrylic plate are explicitly modeled. The axial water thicknesses modeled below the acrylic plate and above the top of fuel rods are 15.3 cm and 15.2 cm, respectively. KENO-V.a and MCNP models of the 4.31 wt% enriched UO_2 fuel rod clusters contain three clusters with the fixed poison plates. The fuel rods array modeled is 15 x 8. The UO_2 fuel, aluminum cladding, rubber end caps, and acrylic support plate are explicitly modeled. The same 30.5 cm-thick water reflector was used in X and Y directions. The axial water thicknesses modeled below the acrylic plate and above the top of fuel rods are 15.3 cm and 15.2 cm, respectively. The 2.22 cm-thick rubber end caps at the top and bottom of the fuel are explicitly modeled. Average values of the experimental data were used in the evaluation.

Using KENO-V.a and MCNP, a total of thirty eight critical configurations were evaluated. Twenty one cases involves with the 2.35 wt% enriched fuel rods and seventeen cases used the 4.31 wt% enriched fuel rods with steel, boral, and cadmium plates were evaluated. Presented in Table 2 are KENO-V.a and MCNP results ($k_{eff} \pm \sigma$) for the Table 1 cases. Generally a good agreement was observed between the calculated value and the experiment. For the total of thirty eight cases, all of the KENO-V.a and MCNP calculated values were within 1.23% (Case 16 of Table 2) in Δk when individually compared with the critical value of 1.0. MCNP predictions were observed to be in best agreement when compared to the KENO-V.a calculated values.

5. Summary and Conclusion

KENO-V.a and MCNP calculations for critical experiments with water moderated and reflected low enriched (2.35 and 4.31 wt%) UO_2 fuel rod clusters with poison plates were performed to validate calculational techniques employed in analyzing fuel shipping and storage systems with steel, boral, or cadmium shield. In the experiments, critical separation between the fuel clusters for varying distance between the poison plates and the clusters was determined. All of the results were within 1.23% in Δk when individually compared with the critical value of 1.0. Discrepancies of the code results are probably due to uncertainties in experiments and/or analytical modeling of the experiments. In general, MCNP predictions were observed to be in best agreement with the experiments. Validation calculations presented in this paper provide valuable information on applying KENO-V.a and MCNP to modeling low enriched UO_2 fuel rod clusters with the fixed poison plates, and can be used by criticality safety analysts for analyzing Light Water Reactor fuel shipping and/or storage systems which contain steel, boral, or cadmium shield. Results of this evaluation will also be included in future edition of the International Handbook of Evaluated Criticality Safety Benchmark Experiments.

6. References

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Table 1. Experimental Data on Selected Sixteen Cases of 2.35 and 4.31 wt% U-235 Enriched UO_2 Fuel Rod Clusters in Water with Poison Plates.

Case No.	Fuel Clusters	Fuel Rod Enrichment (wt%)	Plate/Poison Material	Poison Content (wt%)	Poison Plate Thickness (mm)	Distance to Fuel Cluster[a] (mm)	Critical Separation between Fuel Clusters[b] (mm)
1	3 - 20 x 16	2.35	Steel/Boron	0	4.85 ± 0.15	6.45 ± 0.06	68.8 ± 0.2
2	3 - 20 x 16	2.35	Steel/Boron	0	3.02 ± 0.13	40.42 ± 0.70	77.6 ± 0.3
3	3 - 20 x 17	2.35	Steel/Boron	1.05	2.98 ± 0.06	6.45 ± 0.06	75.6 ± 0.2
4	3 - 20 x 17	2.35	Steel/Boron	1.62	2.98 ± 0.06	40.42 ± 0.70	95.2 ± 0.3
5	3 - 15 x 8	4.31	Steel/Boron	0	3.02 ± 0.13	4.28 ± 0.32	92.2 ± 0.1
6	3 - 15 x 8	4.31	Steel/Boron	1.05	2.98 ± 0.06	32.77 ± 0.32	80.8 ± 0.2
7	3 - 15 x 8	4.31	Steel/Boron	1.62	2.98 ± 0.06	32.77 ± 0.32	79.0 ± 0.3
8	3 - 20 x 17	2.35	Boral	-	7.13 ± 0.11	44.42 ± 0.60	90.3 ± 0.5
9	3 - 15 x 8	4.31	Boral	-	7.13 ± 0.11	32.77 ± 0.32	67.2 ± 0.1
10	3 - 20 x 17	2.35	Cadmium	-	0.610 ± 0.025	14.82 ± 0.70	76.0 ± 0.2
11	3 - 20 x 17	2.35	Cadmium	-	0.291 ± 0.010	14.82 ± 0.70	77.8 ± 1.0
12	3 - 20 x 17	2.35	Cadmium	-	0.901 ± 0.027	14.82 ± 0.70	75.4 ± 0.3
13	3 - 15 x 8	4.31	Cadmium	-	0.291 ± 0.010	7.009 ± 0.29	59.3 ± 0.4
14	3 - 15 x 8	4.31	Cadmium	-	0.610 ± 0.025	32.77 ± 0.32	74.2 ± 0.2
15	3 - 15 x 8	4.31	Cadmium	-	0.901 ± 0.027	32.77 ± 0.32	73.8 ± 0.2
16	3 - 15 x 8	4.31	Cadmium	-	2.006 ± 0.051	5.29 ± 0.29	56.8 ± 0.1

(a) Perpendicular distance between the cell boundary of the center fuel cluster and the surface of the poison plate

(b) Perpendicular distance between the cell boundaries of the fuel clusters

Table 2. KENO-V.a and MCNP Results ($k_{eff} \pm \sigma$) for Sixteen Cases in Table 1.

Case No.	Fuel Clusters	Fuel Rod Enrichment (wt%)	Plate/Poison Material	Critical Separation (mm)	KENO-V.a		MCNP
					Hansen-Roach	27 Group	
1	3 - 20 x 16	2.35	Steel/Boron	68.8	0.9912 ± 0.0016	0.9904 ± 0.0017	0.9965 ± 0.0015
2	3 - 20 x 16	2.35	Steel/Boron	77.6	0.9921 ± 0.0018	0.9950 ± 0.0018	0.9974 ± 0.0016
3	3 - 20 x 17	2.35	Steel/Boron	75.6	0.9948 ± 0.0015	0.9918 ± 0.0015	0.9929 ± 0.0017
4	3 - 20 x 17	2.35	Steel/Boron	95.2	0.9940 ± 0.0018	0.9915 ± 0.0017	0.9965 ± 0.0016
5	3 - 15 x 8	4.31	Steel/Boron	92.2	0.9959 ± 0.0018	0.9951 ± 0.0019	0.9924 ± 0.0019
6	3 - 15 x 8	4.31	Steel/Boron	80.8	0.9997 ± 0.0017	0.9954 ± 0.0017	0.9985 ± 0.0019
7	3 - 15 x 8	4.31	Steel/Boron	79.0	0.9961 ± 0.0020	0.9931 ± 0.0021	0.9990 ± 0.0017
8	3 - 20 x 17	2.35	Boral	90.3	0.9906 ± 0.0019	0.9935 ± 0.0018	0.9958 ± 0.0016
9	3 - 15 x 8	4.31	Boral	67.2	1.0017 ± 0.0018	0.9947 ± 0.0019	0.9983 ± 0.0018
10	3 - 20 x 17	2.35	Cadmium	76.0	0.9947 ± 0.0017	0.9917 ± 0.0018	0.9978 ± 0.0015
11	3 - 20 x 17	2.35	Cadmium	77.8	0.9891 ± 0.0018	0.9916 ± 0.0017	0.9957 ± 0.0016
12	3 - 20 x 17	2.35	Cadmium	75.4	0.9943 ± 0.0017	0.9918 ± 0.0017	0.9991 ± 0.0015
13	3 - 15 x 8	4.31	Cadmium	59.3	0.9976 ± 0.0017	0.9962 ± 0.0019	0.9988 ± 0.0018
14	3 - 15 x 8	4.31	Cadmium	74.2	0.9985 ± 0.0018	0.9928 ± 0.0017	1.0010 ± 0.0019
15	3 - 15 x 8	4.31	Cadmium	73.8	0.9983 ± 0.0019	0.9974 ± 0.0018	0.9997 ± 0.0019
16	3 - 15 x 8	4.31	Cadmium	56.8	0.9979 ± 0.0018	0.9877 ± 0.0018	0.9964 ± 0.0021