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CRITICALITY CONTROL IN SHIPMENTS OF FISSILE MATERIALS

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ABSTRACT

This paper describes a procedure for finite-array criticality analysis to ensure criticality safety of shipments of fissile materials in U.S. DOE-certified packages. After the procedure has been performed, one can obtain the minimum transport index and determine the maximum number of fissile packages allowable in a shipment that meets the 10 CFR 71 criticality safety requirements.

I. INTRODUCTION

In fulfilling its diverse civilian and defense missions, the U.S. Department of Energy must transport various types of nuclear materials in certified packages within the country. A record of safe transportation of nuclear radioactive materials has been maintained in the U.S. for more than 50 years. Before a package can be certified for transportation, it must meet three basic packaging safety design requirements, i.e., subcriticality, radiation shielding, and containment of radioactive materials, and must be in compliance with government safety regulations promulgated in the Code of Federal Regulations, 10 CFR Part 71.[1] The package certification process begins when an applicant submits a Safety Analysis Report for Packaging (SARP) and requests that DOE headquarters approve the package.[2] The DOE-HQ approval is based on rigorous and independent technical review of the SARP, conducted according to the DOE Packaging Review Guide.[3] The technical review is usually an iterative process of questions and responses between the SARP review and package design teams that continues until all issues are resolved. The reviewers also verify, through independent confirmatory evaluation, that the SARP has indeed demonstrated compliance with all applicable safety regulations and standards. The outcome of the SARP review is documented in a Safety Evaluation Report (SER), which provides the technical basis for issuing a Certificate of Compliance (CoC) for the package. The SER is part of the approval record of the package and is accessible to the public.

Criticality safety in shipments of nuclear fissile materials is ensured by compliance with the requirements in 10 CFR 71. This compliance can be achieved by following the guidance for the design and review of transportation packaging for fissile and other radioactive materials.[3,4] Design and review of criticality safety of a fissile-material package generally requires complicated computational analyses, and the results must be clearly communicated in terms that can be understood by all involved parties, including shippers, couriers, and receivers. One such term is the transport index (TI), which for purposes of criticality control, is used to limit the maximum number of packages in a shipment; it is defined as

$$TI = \frac{50}{N} \qquad (1)$$

where N is a number derived from the maximum allowable number of packages in a shipment that is criticality-safe under various conditions specified in 10 CFR 71.59. Any package that contains nuclear fissile materials must have a TI value specified in CoC. This paper illustrates the key aspects in determining N, and thereby TI, through a finite-array criticality analysis of packages using the steel-banded wooden shipping containers (SBWSCs)[5] that were designed for the shipment of unirradiated uranium ingots

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that are slightly enriched (1.25% U-235) uranium metal cylinders, 30.48 cm (12 in.) in diameter and 15.24 cm (6 in.) long, each weighing ≈ 176 kg (≈ 387 lb). Each SBWSC package considered in this paper contains two such ingots. The SBWSC is a relatively simple package to illustrate the approach; other fissile material packages may require more complex analysis.

II. PACKAGING REQUIREMENTS FOR CRITICALITY SAFETY

According to 10 CFR 71, criticality safety must be demonstrated for a package under normal conditions of transport (NCT) and hypothetical accident conditions (HAC). The hypothetical accidents consist of a sequence of events (e.g., vertical drops, fire, and immersion in water) that would damage the package. These events often represent the most limiting conditions for criticality safety analysis. Therefore, it is reasonable and conservative to assume that during a hypothetical accidental fire (at ≈ 800^{0}C for 30 min), all wooden containers in a shipment are burned and disintegrated (even though they will most likely be only charred), and that the uranium ingots are scattered and arranged in the most reactive configuration, with interspersed hydrogenous moderation and total water (30 cm) reflection, as required by 10 CFR 71.59. The task is therefore to determine the maximum number of ingots in this most reactive configuration that would remain subcritical with an adequate safety margin. Once the maximum number of ingots that remains subcritical under NCT and HAC is obtained, the number N can be determined, and the minimum TI for criticality control in a shipment can then be calculated easily according to Eq.1.

III. OPTIMAL LATTICE PARAMETERS FOR AN INFINITE ARRAY OF PACKAGES

Determination of the maximum number of ingots under the most reactive configuration requires two steps: a search for the optimal lattice parameters, i.e., pitch, axial gap, and moderator density, that would maximize the neutron multiplication factor k_∞ for an infinite-array of ingots in hexagonal lattices; and calculations of a finite-array arranged in a configuration with minimum neutron leakage. The continuous-energy MCNP-4.2 Code package[6] was used in the search for the optimal lattice parameters that maximize k_∞. In that search, we considered six axial moderator gap sizes (2 to 12 cm), five moderator (water) densities (0.1 to 1.0 g/cm^3), and eight lattice pitches (31.48 to 44.48 cm). A total of 240 (6x5x8) MCNP calculations were systematically performed to search for optimal values over the parametric spaces. Some of the calculated MCNP k_∞ and 1-sigma (σ) uncertainty results (based on 250,000 neutron histories) for lattice parameters near the optimal values are presented in Table 1.

For the given uranium ingot composition and geometry, the MCNP results in Table 1 showed that k_∞ is mainly influenced by the amount of water in the unit cell for the hexagonal configuration. Consequently, a loosely packed array (such as Case I523) with a large pitch (36.48 cm) and axial gap (10 cm) and low moderator density (0.3 g/cm^3) can have a mass ratio of fissile to moderator materials (≈ 35) that is similar to that of a tightly packed array (such as Case I332) with a smaller pitch (34.48 cm) and axial gap (6 cm) but higher moderator density (0.5 g/cm^3). Infinite-arrays with these two types of lattice parameters will have comparable k_∞ values (1.03883 vs. 1.02793). Thus, to determine the most reactive configuration for the finite-array, one must consider the effect of neutron leakage, as we shall see in the next section.

IV. MINIMIZING NEUTRON LEAKAGE IN A FINITE ARRAY OF PACKAGES

Because neutron leakage from a system reduces reactivity, the most reactive configuration for a finite-array of ingots must be one with a minimum surface-to-volume ratio that gives the smallest total surface area for neutron leakage. Therefore, a tightly packed array with a spherical enclosure and with total water reflection should minimize neutron leakage. Because our task is to determine the maximum number of ingots for the finite-array that is within the criticality safety limit, an iterative search is necessary to determine the size, i.e., the radius of the spherical enclosure as described below. For hexagonal geometry, each unit cell consists of the uranium ingot surrounded by the moderator (water), and the volume of the unit cell is

$$v = \frac{\sqrt{3}}{2} p^2 h \tag{2}$$

where p is the pitch (flat-to-flat) and h is the height of the unit cell. For N ingots in a finite-array, the volume of the finite-array is

$$V = Nv = N\left[\frac{\sqrt{3}}{2} p^2 h\right] \tag{3}$$

Assuming this finite-array of N ingots is enclosed within a spherical enclosure for minimum leakage, we can determine its radius R in the following manner. Because the volume of this spherical enclosure is

$$V = \frac{4\pi R^3}{3} \qquad (4)$$

so the radius of the spherical enclosure of a finite-array of N ingots is determined from its volume as

$$R = \sqrt[3]{\frac{3V}{4\pi}} \qquad (5)$$

where the volume V is calculated from Eq. 3 for N ingots in the finite-array. To determine the maximum allowable payload that is criticality-safe, a series of MCNP calculations was performed for various finite-arrays in spherical enclosures. The calculated k_{eff} and 1-sigma (σ) uncertainty values for these finite-arrays are used to derive the final adjusted neutron multiplication factor (k_{adj}). As indicated in Ref. 4, the acceptable upper limit for the adjusted neutron multiplication factor in transport certification has typically been 0.95. The final adjusted neutron multiplication factor (k_{adj}) has included the MCNP Code bias (0.00258) and uncertainty (0.006) obtained by the applicant from analyses of relevant critical benchmark experiments according to the formula

$$k_{adj} = k_{eff} + 0.00258 + 2\,(0.006^2 + \sigma^2)^{0.5} < 0.95 \qquad (6)$$

Using the optimal lattice parameters determined for the infinite-array analyses shown in Table 1, we performed a series of MCNP calculations for various radii of the spherical enclosures coresponding to the maximum number of ingots in the finite-array. The k_{eff}, 1-sigma (σ), and the derived final adjusted neutron multiplication factor (k_{adj}) for these finite-arrays are shown in Table 2. We performed three sets of finite-array calculations that correspond to 48, 56, 60, and 64 ingots, as shown in Table 2 for subcriticality confirmation. In the first set of calculations, we used the applicant's optimal lattice parameters (axial gap 3.15 cm, moderator density 1.0 g/cm^3, and lattice pitch 31.95 cm) and determined the maximum array size to be 56 ingots (see Case F7237). In the next two sets of calculations, we used our optimal lattice parameters (axial gap 4 cm, moderator density 0.9 and 1.0 g/cm^3, and lattice pitch 32.48 cm) and confirmed the maximum array size to be 56 ingots (see Cases F8237 and F9237). Among these 3 sets of calculations shown in Table 2, only the finite-array of 56 ingots gives $k_{adj} < 0.95$ under all optimal lattice parameters. Thus, based on the spherical enclosure for a finite-array, the maximum number of ingots per shipment that will satisfy the criticality safety limit is 56 ingots. The most reactive configuration is the one with the optimal lattice parameters of 32.48 cm pitch, 4.0 cm axial gap, and 0.9 g/cm^3 moderator density.

V. TRANSPORT INDEX FOR CRITICALITY CONTROL

According to 10 CFR 71.59, 2 x N damaged packages of uranium ingots are required to remain subcritical under the most reactive configuration. Thus, for 56 ingots with 2 ingots per package, 2 x N = 28 packages, therefore N = 14. By definition,

$$TI = \frac{50}{N} = \frac{50}{14} = 3.6 \qquad (7)$$

Accroding to 10 CFR 71, for an exclusive-use vehicle, the sum of the transport indexes of all packages per shipment should be < 100. Therefore, for these uranium ingots, the maximum number of packages M that can be safely transported in a shipment is determined as

$$M = \frac{100}{TI} = \frac{100}{3.6} = 27 \qquad (8)$$

i.e., 27 packages, or 54 of these uranium ingots, can be transported per shipment in an exclusive-use vehicle. In comparison, the SARP applicant established a TI of 4.1, based on a reduced finite-array of 48 such ingots to assure subcriticality with an extra safety margin under normal and hypothetical accident conditions. We performed three more MCNP calculations using optimal lattice parameters to confirm the subcriticality of such shipment; the results are included in Table 2 (see Cases F7777, F8888, and F9999). Thus, we have clearly shown that the reduced payload of 48 ingots is indeed subcritical with an extra safety margin.

VI. CONCLUSIONS

This paper illustrates a procedure for finite-array criticality analysis to ensure criticality safety of shipments of fissile materials in DOE-certified packages. After such a procedure has been performed, one can obtain the minimum transport index and determine the maximum number of fissile packages allowable in a shipment that meets the 10 CFR 71 criticality safety requirements. For the ingots chosen in this paper, our independent confirmatory analysis concluded that the transport index established by the applicant is very conservative and meets the subcriticality requirements with adequate safety margins under both normal transport and hypothetical accident conditions.

REFERENCES

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Table 1. Selected MCNP Results From Optimal Parameter Search for Infinite Arrays of Uranium Ingots

Selected MCNP Case	Lattice Parameters			MCNP Results 250,000 Histories		Moderator Mass	Fuel to Moderator Mass Ratio	Lattice Parameters Used for Finite-Array Analysis
	Gap	Moderator	Pitch					
	cm	g/cm^3	cm	k_∞	1-σ	g		
I133	2	0.5	36.48	0.96208	0.00129	3838	46	
I142	2	0.7	34.48	0.96636	0.00117	4108	43	
I151	2	0.9	32.48	0.97750	0.00120	3747	47	*
I224	4	0.3	38.48	0.99211	0.00124	3644	48	
I232	4	0.5	34.48	1.00824	0.00127	3964	44	
I241	4	0.7	32.48	1.01476	0.00125	4193	42	*
I251	4	0.9	32.48	1.01282	0.00129	5392	33	
I324	6	0.3	38.48	1.01980	0.00114	4414	40	
I332	6	0.5	34.48	1.02793	0.00110	4993	35	*
I341	6	0.7	32.48	1.01057	0.00112	5473	32	
I351	6	0.9	32.48	0.97086	0.00117	7036	25	
I424	8	0.3	38.48	1.03280	0.00123	5183	34	*
I432	8	0.5	34.48	1.01641	0.00119	6023	29	
I441	8	0.7	32.48	0.96939	0.00099	6752	26	
I517	10	0.1	44.49	0.98624	0.00116	2963	59	
I523	10	0.3	36.48	1.03883	0.00128	5069	35	*
I531	10	0.5	32.48	0.98849	0.00121	5736	31	
I617	12	0.1	44.48	1.01109	0.00123	3305	53	
I623	12	0.3	36.48	1.03265	0.00125	5760	31	*
I631	12	0.5	32.48	0.95434	0.00109	6650	26	

Table 2. Selected MCNP Results for Finite Arrays of Uranium Ingots

Selected MCNP Case	Number of Ingots N	Axial Gap cm	Moderator Density g/cm^3	Lattice Pitch cm	Sphere Radius cm	MCNP (250,000 k_{eff}	MCNP Histories) 1-σ	k_{adj}	Subcriticality Check $k_{adj} < 0.95$
Array Size Varied Using Optimal Lattice Parameters in SARP									
F7237	56	3.15	1.0	31.95	57.22	0.93378	0.00126	0.94862	yes
F7230	60	3.15	1.0	31.95	58.55	0.93538	0.00132	0.95025	no
F7231	64	3.15	1.0	31.95	59.82	0.93953	0.00123	0.95436	no
F7232	68	3.15	1.0	31.95	61.04	0.94242	0.00117	0.95723	no
Array Size Varied Near Optimal Lattice Parameters									
F8237	56	4.0	1.0	32.48	58.87	0.93299	0.00115	0.94779	yes
F8230	60	4.0	1.0	32.48	60.23	0.93437	0.00134	0.94925	yes
F8231	64	4.0	1.0	32.48	61.54	0.93483	0.00129	0.94968	yes
F8232	68	4.0	1.0	32.48	62.80	0.94006	0.00117	0.95487	no
Array Size Varied Near Optimal Lattice Parameters									
F9237	56	4.0	0.9	32.48	58.87	0.93487	0.00115	0.94967	yes
F9230	60	4.0	0.9	32.48	60.23	0.93619	0.00108	0.95096	no
F9231	64	4.0	0.9	32.48	61.54	0.94118	0.00099	0.95592	no
F9232	68	4.0	0.9	32.48	62.80	0.94192	0.00119	0.95673	no
Array Size Reduced to 48 Ingots in SARP									
F7777	48	4.0	0.9	32.48	55.92	0.92681	0.00113	0.94160	yes
F8888	48	4.0	1.0	32.48	55.92	0.92216	0.00122	0.93699	yes
F9999	48	3.15	1.0	31.95	54.35	0.92703	0.00101	0.94178	yes