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CRITICALITY SAFETY REVIEW OF 2½-, 10-, AND 14-TON UF_6 CYLINDERS

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ABSTRACT

The U.S. regulations governing the packaging and transportation of UF_6 cylinders are contained in the publication 10CFR71 [1]. Under the current 10CFR71 regulations, packages are classified according to Fissile Class I, II, or III and a corresponding transport index (TI). UF_6 cylinders designed to contain 2½-tons of UF_6 are classified as Fissile Class II packages with a TI of 5 for the purpose of transportation. The 10-ton UF_6 cylinders are classified as Fissile Class I with no TI assigned for transportation. The 14-ton cylinders are not certified for transport with enrichments greater than 1 wt % since they have no approved overpack. This work reviews the suitability of 2½-ton UF_6 packages for reclassification as Fissile Class I with a maximum ^{235}U enrichment of 5 wt %. Additionally, the 10- and 14-ton cylinders are reviewed to address a change in maximum ^{235}U enrichment from 4.5 to 5 wt %.

Based on this evaluation, the 2½-ton UF_6 cylinders meet the 10CFR71 criteria for Fissile Class I packages, and no TI is needed for criticality safety purposes. Similarly, the 10- and 14-ton UF_6 packages appear suitable for a maximum enrichment rating change to 5 wt % ^{235}U.

INTRODUCTION

The 2½-ton UF_6 cylinder is currently in wide use for both national and international transport of UF_6. Use across national boundaries necessitates licensing and certification activities within each country of transport. Recently, the Japanese attempted to arrange a shipment of 2½-ton UF_6 cylinders with an assigned TI of 0. The U.S. Department of Transportation currently assigns a TI of 5 to such shipments. Based on a rigorous Japanese supporting analysis and a conservative U.S. analysis, the shipment was permitted. This criticality review provides a rigorous U.S. analysis in support of a TI=0 rating for 2½-ton UF_6 cylinder shipments. In addition, this work assesses the impact on both the 10-ton and 14-ton cylinders of a change in maximum ^{235}U enrichment from 4.5 wt % to 5.0 wt %. Specifically, for the 10-ton cylinder, the question to be addressed is, what is the new TI for

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5.0 wt % product? For the 14-ton cylinder, the impact of such a change should only be felt for onsite operations since the lack of an approved overpack limits its transport to ^{235}U enrichments of 1 wt % or less.

The amount of internal moderation is very important for these cylinders since a single cylinder is critical given sufficient moderation. Subcriticality is maintained through the use of moderation control, both by limiting the H/U ratio to 0.088 and assuring the cylinder is a "leak-tight" container. The justification of a "leak-tight" container is based on the physical and chemical characteristics of UF_6 under transport conditions. Therefore, a premise of no water in-leakage into the UF_6 cylinder is made for each of the above analyses.

ANALYSIS METHODOLOGY

Analysis Tools

The criticality calculations necessary for this review were performed using the CSAS25 control program of the SCALE-4 computer system [2]. The functional modules executed by this program include BONAMI, NITAWL-II, and KENO V.a. The neutron cross sections used in this project were obtained from the SCALE 27-group ENDF/B-IV criticality library. Both the cross-section library and the SCALE-4 system are publicly available from the Radiation Shielding Information Center (RSIC). At Oak Ridge National Laboratory (ORNL), the SCALE-4 system is maintained under configuration control on an IBM mainframe. The SCALE 27-group library validation is discussed in the next section.

Validation Studies

References 3—4 provide a basis for the validation of the analytic tools used for this project. The original validation effort applied to an early SCALE-3 version of the CSAS25/KENO V.a system on an IBM 3033 computer system. Reference 4 documents the updating of this validation effort for the SCALE-4 version of SCALE. Both validation efforts used the SCALE 27-group ENDF/B-IV cross-section library. This latest version was used to perform the calculations in this study.

The code and cross-section validation performed in Ref. 4 consisted of determining k_{eff} for a series of 51 benchmark critical experiments. These benchmarks consisted of a full range of possible experiments including 11 highly enriched cases and 40 low-enriched cases. The resulting k_{eff} values were analyzed statistically to determine the single-sided, uniform width, closed-interval, lower tolerance band [5] such that 99.9% of the distribution of calculated k_{eff} will fall above the tolerance band with a 95% confidence level. This tolerance band can then be plotted as a function of the average neutron energy group causing fission (AEG). The range of AEG for the particular problem under consideration determines the subcritical maximum k_{eff} for that problem (see Ref. 5 for further details). The AEG values for this study ranged from 9 to 16 which corresponds to a subcritical maximum k_{eff} of between 0.953 and 0.961. For conservatism and convenience, the single value of 0.95 was chosen to be the subcritical maximum k_{eff} for this study.

Analysis Overview

The Fissile Class I regulations in 10CFR71.57 require that subcriticality be assured during both normal and accident conditions. The regulations for normal conditions require that an infinite array of packages with optimum interspersed hydrogenous moderation be subcritical. The regulations for hypothetical accident conditions state that for 250 packages with optimal moderation between the packages, subcriticality must be assured. The analysis procedure described below should yield conservative estimates of k_{eff} for accident and normal conditions.

The procedure begins with an infinite array model of UF_6 packages. The cylinder overpack is then replaced with variable-density water. The pitch or spacing between the cylinders in the array is determined by the overpack size. This pitch is such that the packages, if the overpacks were present, would touch. The removal of the overpack increases k_{eff} due to the removal of a neutron-absorbing interstitial material. The variable-density water region allows evaluation of a full range of moderation (from void to full-density water). In the absence of gross deformations in the geometry, the resulting curve of k_{eff} versus water density should span both the accident and normal conditions. The range of possible water densities should be bounded on the low end by dry, burned insulation and on the high end by flooded conditions after a fire test where the insulation could possibly saturate with water.

If the k_{eff} values remain in the safe region for all possible water densities, then both accident and normal conditions of criticality safety for Fissile Class I have been met. Additional calculations with the overpack model added can then be used to assess the change in k_{eff} from the previous results with no overpack. Calculations of single packages with infinite water reflection provide checks on some of the array results.

The arrays as described above were all modeled as square lattices. The use of a triangular pitch allows for a denser packing; however, the geometry is much more difficult to model in the computer code. Therefore, portions of the k_{eff} versus water density curve corresponding to near-peak conditions were regenerated assuming a 7% reduction in the cylinder-to-cylinder spacings (i.e., pitch). The 7% pitch reduction accounts for the difference in packing factors for the two lattices (0.79 for square pitch versus 0.90 for triangular pitch) since the cell volume varies as the square of the pitch. For these additional runs, the peak value of k_{eff} is not expected to differ from the previous runs. However, due to the differing interstitial volumes, the water density at peak k_{eff} is expected to vary somewhat.

Model Description

The 2½-, 10-, and 14-ton UF_6 cylinder models were developed from the actual cylinder and overpack dimensions contained in Ref. 6. The steel cylinder dimensions were taken directly from the description in Ref. 6. The curved lid and bottom surfaces of each cylinder were not modeled exactly; instead, the internal height of each cylinder cavity was determined from the volume as reported in Ref. 6. Each of the resulting models has a flat head and bottom rather than the actual curved one. The volume of the UF_6 inside each of the cylinders was obtained from the total UF_6 weight and a UF_6 density of 5.1 g/cm^3, as given in Ref. 6. The inner radius of UF_6 (see model for 2½-ton cylinder in Fig. 1) was then determined from the resulting volumes assuming a uniform UF_6 thickness on the sides and ends of the cylinder. The single cylinder model shown in Fig. 1 was spectrally reflected on each of the six faces for infinite array calculations. Also, the single unit calculations used this model with the variable-water density region replaced with an effectively infinite water reflector. Similarly, the calculation with a 7% reduction in the pitch (approximating a triangular pitch array) used the same model except the outermost dimension (i.e., the outer boundary of the variable-water density region) was reduced by 7%. The cylinder was assumed to be centered axially within the variable-water density region.

The model shown in Fig. 2 corresponds to the overpack (DOT 21-PF-1) for the 2½-ton cylinder. Calculations performed with this model can be directly compared with those using variable water density at a water density which is equivalent to the hydrogenous content of the overpack. This comparison allows the change in k_{eff} for the approximate model to be determined.

The materials contained in each region specified in Figs. 1—2 are described in detail in Table I. Table I presents each material, its total mass in the model, and its actual mass.

Table I. Constituent material mass and density

Region	Shown in Fig.	Material	Density	Model mass (kg)	Actual mass (kg)
2½-ton results					
1	1	Void	-	-	-
2	1	UF_6	5.1	2,281	2,277
3	1	Steel	7.8212	495	635
4	1	Water / void	Variable	Variable	-
DOT 21-PF1					
13	2	Void	-	-	-
14	2	Steel	7.8212	80	NA
15	2	Phenolic foam	0.029	33	NA
16	2	Steel	7.8212	154	NA

ANALYSIS RESULTS

Calculational results are given below for single 2½-, 10- and 14-ton cylinders. Infinite array results with variable-density water replacing the overpacks are also presented for all three cylinders. Infinite array results with the overpack modeled are shown for the 2½- and 10-ton cylinders only. Additional results include fuel location and temperature sensitivity calculations. These calculations allow the quantification of reactivity effects of fuel movement inside the UF_6 cylinder and the effects of low and high fuel temperatures corresponding to accident conditions.

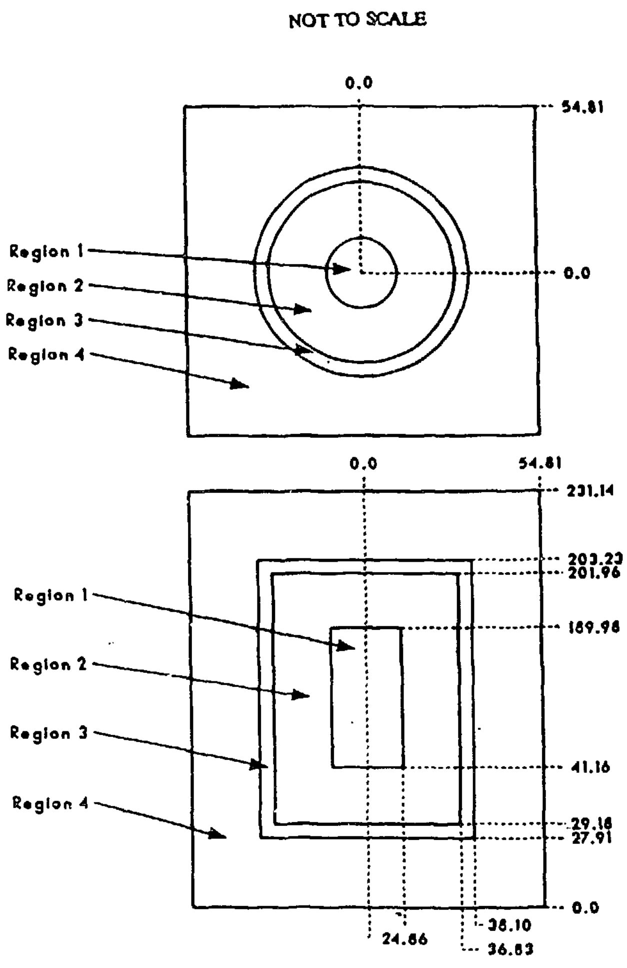

Fig. 1. Model for 2½-ton cylinder without overpack. (All dimensions in cm.)

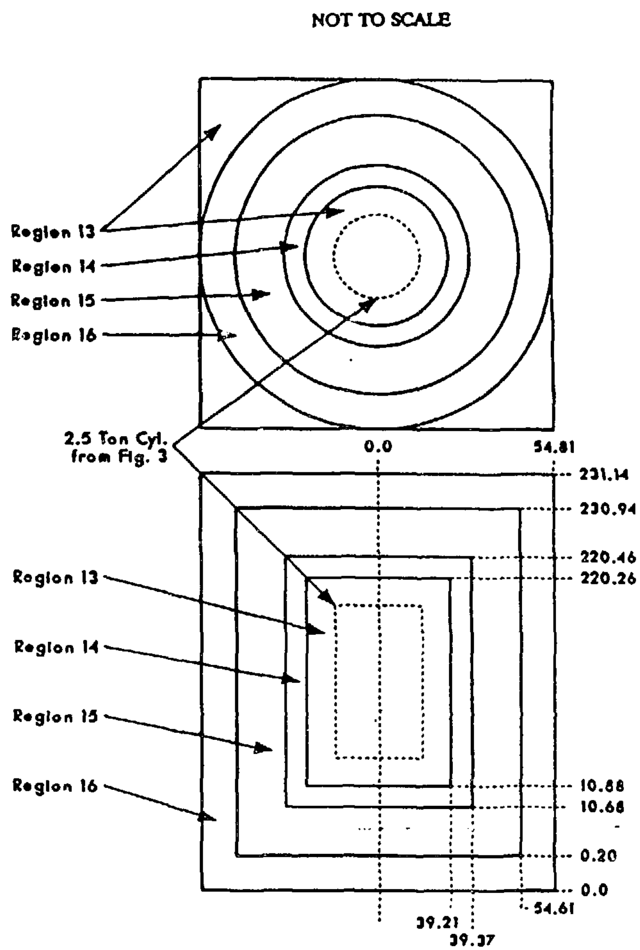

Fig. 2. Model for DOT 21-PF-1 overpack. (All dimensons in cm.)

Infinite Array Results Without Overpacks

A plot of the k_{eff} versus interstitial water specific gravity (SG) for the 2½-ton UF_6 cylinder is shown in Fig. 3. The k_{eff} values are plotted versus water SG for convenience; however, the corresponding water density at a SG of 1.0 is 0.9982 gm/cm^3 (water at 20°C, standard pressure). Thus, the abcissa label could be replaced with "water density." General features of the curve include a peaking of k_{eff} for low water SG, followed by a steep decrease with increasing water SG, and ending with a slight increase at near unity SG. The peak k_{eff} value of 0.817 ± 0.003 at a SG of 0.015 represents the point of optimum interstitial moderation. The rapid decrease in k_{eff} results for larger water SG indicates an overmoderated condition. The slight increase in k_{eff} at SG values near unity arises from a change in role of the water from a moderating material to a reflecting material.

Similar curves were also generated for the 7% reduced pitch case (associated with a triangular pitch). The original curve peaks at a slightly lower SG value (0.015) than the 7% reduced pitch case (0.020). However, the corresponding peak values of 0.817 ± 0.003 and 0.816 ± 0.002 are statistically indistinguishable. This is the expected behavior since the interaction between neighboring packages is governed by the total mass of moderating material. For differing separation distances, but equal masses, the densities (SG) should change while the k_{eff} values remain constant. The k_{eff} value of 0.817 should therefore represent a maximum for the 2½-ton cylinder for up to 2,277 kg of UF_6 at 5 wt %.

The same general trends seen for the 2½-ton cylinder are seen for the 10- and 14-ton cylinders. Generally, the curves peak for low water SG, followed by a steep decrease with increasing water SG, ending with a slight increase near unity SG. The peak value of k_{eff} for the 14-ton cylinder is 0.768 ± 0.002 for a water SG of 0.005. The 7% reduced case gives essentially identical results, 0.766 ± 0.002. For the 10-ton cylinder, the peak values are 0.769 ± 0.002 at a SG of 0.005 for the original radius and 0.763 ± 0.002 at a SG of 0.005 for the reduced radius.

Infinite Array Results With Overpack

The previous infinite array calculations were all performed with models that replaced the overpacks with variable-density water. Additional calculations were then performed for the 2½- and 10-ton cylinders with overpacks to assess the degree of conservatism in the preceding results. These calculations, as before, were for an infinite array of these units. The k_{eff} value for the 2½-ton cylinder including the overpack is 0.655 ± 0.002. The effective water SG for this case is 0.01. Comparing these k_{eff} values with the values from Fig. 3 indicates that the cylinder overpack decreases k_{eff} by 0.15 Δk for the 2½-ton cylinder. The k_{eff} value for an infinite array of 10-ton cylinders including the overpacks is 0.547 ± 0.002. The overpack has an equivalent water SG of 0.05 which corresponds to a k_{eff} of 0.628 ±0.003 when the overpack is excluded, a difference of 0.08 Δk.

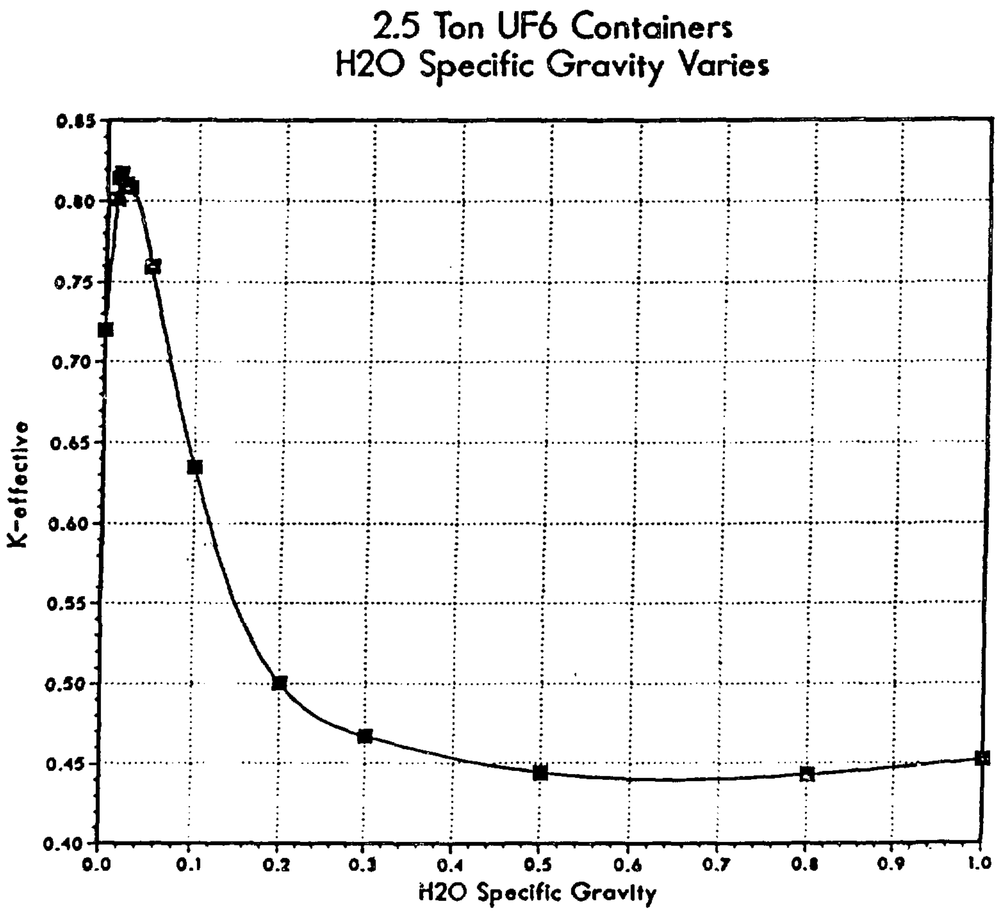

Fig. 3. Plot of k_{eff} versus water-specific gravity for infinite array of 2½-ton UF_6 cylinders (square-lattice, full-diameter model).

Single Unit Results

The single unit model for the 2½-ton cylinder consisted of the cylinder without an overpack, with an effectively infinite water reflector. This case should be essentially identical to the infinite array k_{eff} value with full-density water (SG = 1) because the water acts as an infinite reflector at full density. The single unit result is 0.453 $\pm$ 0.003. This result is nearly identical with the SG = 1.0 value shown in Fig. 3. The single unit result is primarily used as an independent consistency check on the infinite array results. Similar results were seen for the 10- and 14-ton cylinders.

Sensitivity Results

The temperature for all calculations thus far has been 20°C. The final set of calculations quantified the effects of temperature and fuel location on the k_{eff} results. The temperature effects were estimated by analyzing the 2½-ton cylinder at optimal moderation (a SG of 0.0150) with temperatures of 65°C, 20°C, and -40°C. The k_{eff} values for 65°C and -40°C are 0.817 $\pm$ 0.002 and 0.818 $\pm$ 0.003, respectively. These values are equivalent to the base k_{eff} at 20°C of 0.817 $\pm$ 0.003. The temperature effects are thus extremely minimal.

The second sensitivity area investigated was that of fuel location. The infinite array model used was the 2½-ton cylinder at a water SG of 0.02. The fuel location studies analyzed all the cases shown in Fig. 4. Case (c) is the fuel geometry chosen for all cases thus far. This geometry was chosen since it was a likely physical configuration and also was expected to be the most reactive. The results for cases a, b, c, and d are 0.774 $\pm$ 0.002, 0.782 $\pm$ 0.003, 0.811 $\pm$ 0.003, and 0.812 $\pm$ 0.003, respectively. Cases (c) and (d) are equivalent when the standard deviations are taken into account and represent maximum reactivity conditions.

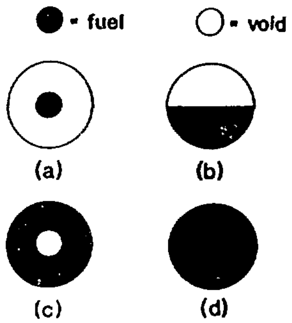

Fig. 4. Fuel locations analyzed to determine most reactive configuration for a constant mass.

SUMMARY/CONCLUSIONS

The maximum k_{eff} value for the conditions of optimal interstitial moderation with the premise of no water leakage into the UF_6 cylinder, has been shown to be 0.817 $\pm$ 0.003 for the 2½-ton cylinder with 5 wt % ^{235}U enrichment. Applying a 2σ safety margin yields a k_{eff}

value of 0.823. Since this is a peak value, the 2½-ton cylinder has a k_{eff} less than the 0.95 upper safety limit criterion at all interstitial moderation conditions. These k_{eff} values have been shown to be insensitive to cylinder spacing and temperature effects. The fuel has been shown to be in the most reactive configuration under the assumed conditions. This final k_{eff} value corresponds to an infinite array of optimal interstitially moderated cylinders; thus both normal and accident conditions for Fissile Class I have been met. The implication for accident conditions is that the UF_6 cylinder is protected by the overpack such that no appreciable damage to the cylinder occurs (i.e., will not leak). These final calculations should be conservative due to the neglect of the overpack materials. The degree of conservatism has been estimated at 20% for the 2½-ton cylinder.

Based on this evaluation, the 2½-ton UF_6 cylinder with 5 wt % ^{235}U enrichment meets the 10CFR71 criteria for Fissile Class I packages, and has a TI of zero for criticality safety purposes.

For the 10- and 14-ton cylinders, the maximum k_{eff} values for the conditions of optimal interstitial moderation with the premise of no water leakage into the UF_6 cylinder are 0.768 $\pm$ 0.002 and 0.769 $\pm$ 0.002, respectively. Applying a 2σ safety margin yields corresponding k_{eff} values of 0.772 and 0.773. Since these values represent peak reactivity, both the 10- and 14-ton cylinders have a k_{eff} less than the 0.95 upper safety limit criterion at all interstitial moderation conditions. Thus, the 10-ton UF_6 cylinder should meet both the accident and normal conditions for a Fissile Class I (TI = 0) cylinder with 5.0 wt % ^{235}U enrichment. The implication for accident conditions is that the 10-ton UF_6 cylinder is protected by the overpack such that no appreciable damage to the cylinder occurs. These results also indicate that the 14-ton cylinder should be able to accommodate an increase in enrichment from 4.5 wt % to 5 wt % for onsite operations.

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