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Criticality Safety Review of 2 ½-, 10-, and 14-Ton UF_6 Cylinders

B. L. Broadhead

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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

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ABSTRACT

Currently, UF_6 cylinders designed to contain 2½ tons of UF_6 are classified as Fissile Class II packages with a transport index (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, although not certified for transport with enrichments greater than 1 wt % because they have no approved overpack, can be used in on-site operations for enrichments greater than 1 wt %. The maximum ^{235}U enrichments for these cylinders are 5.0 wt % for the 2½-ton cylinder and 4.5 wt % for the 10- and 14-ton cylinders. This work reviews the suitability for reclassification of the 2½-ton UF_6 packages 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 10 CFR.71 criteria for Fissile Class I packages, and no TI is needed for criticality safety purposes; however, a TI may be required based on radiation from the packages. Similarly, the 10- and 14-ton UF_6 packages appear acceptable for a maximum enrichment rating change to 5 wt % ^{235}U.

1. 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 transport index (TI) of 0. The U.S. Department of Transportation (DOT) currently assigns a TI of 5 to such shipments. Based on a rigorous Japanese supporting analysis and a known conservative approach of the U.S. analysis, the shipment was permitted. This criticality review is meant to provide a rigorous U.S. analysis to determine the TI for 2½-ton UF_6 cylinder shipments.

The U.S. regulations governing the packaging and transportation of fissile radioactive materials are contained in the publication 10 CFR.71.[1] Under the current 10 CFR.71 regulations, packages are classified according to Fissile Class I, II, or III and a corresponding TI is determined for each package design. Fissile Class I packages (TI not assigned, but effectively equal to zero) can be transported in unlimited numbers without any criticality safety controls. Fissile Class II packages ($0.1 < TI \leq 10$) are normally limited to a cumulative TI (sum for all packages) of 50.[*] A Fissile Class III shipment (packages with a $TI > 10$) requires special arrangements for control of each shipment. Under proposed rule changes, the fissile class designations are discontinued, while the TI value ranges, $TI = 0$, $0.1 < TI \leq 10$, and $TI > 10$, are still used to prescribe controls during shipment. The discussions in this report use both the old and the new package designations where possible, with greater emphasis on the Fissile Class designations since the proposed regulations are not in effect at the time the report is written.

This criticality safety review focuses on three UF_6 packages currently in use: 2½-ton, 10-ton, and 14-ton UF_6 cylinders. Because of the varied nature of each cylinder's use, they are treated separately.

The goal of the first phase of this work is to provide a review of the suitability of the 2½-ton cylinder and overpack for a subsequent reclassification as a Fissile Class I ($TI = 0$) package. Currently, the 2½-ton cylinder with the overpack is classified as a Fissile Class II ($TI = 5$) package[2,3] for the purpose of transportation. While the maximum ^{235}U enrichment that can be placed in this cylinder is 5.0 wt %, shipments in excess of 1.0 wt % ^{235}U require the cylinder be placed in an

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[*] See Ref. 1 for definition of transport index.

overpack. The overpack design for the 2½-ton cylinder has been granted approval from the U.S. Nuclear Regulatory Commission (NRC) [Certificate of Compliance (CoC) 4909 and CoC 9196] and DOT (DOT 21-PF-1A and 21-PF-1B, referred to generically as the 21-PF-1). The technical results for the 2½-ton cylinder are presented in Sect. 3.

The second phase of 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 the new TI is for 5.0 wt % product. For the 14-ton cylinder, the impact of such a change should only be felt for on-site operations and only an assurance of criticality safety is needed. In physical terms, the 10-ton and 14-ton cylinders are very similar. Both cylinders have the same diameter, with the 14-ton cylinder being longer than the 10-ton cylinder. They are both limited to a maximum of 4.5 wt % ^{235}U. However, only the 10-ton cylinder has an approved overpack; thus, the 14-ton cylinder cannot be shipped with greater than 1.0 wt % enrichment. The 14-ton cylinder is therefore used primarily for on-site operations rather than for transport. The 10-ton cylinder and overpack (the Paducah Tiger) are classified as a Fissile Class I (TI = 0) package,[4] having received approval for transport from the U.S. Department of Energy (DOE) (DOE 6553, currently under renewal) and the NRC (NRC 6553). The methods used in the analysis for both phases of this work are described in Sect. 2. The technical results for the 10- and 14-ton cylinders are described in Sect. 4.

The amount of internal moderation is very important for all three 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 and the rigorous quality assurance used during package filling and preparation for transport. Therefore, a premise of no water in-leakage into the UF_6 cylinder is made for each of the above analyses.

2. ANALYSIS METHODOLOGY

2.1 ANALYSIS TOOLS

The criticality calculations necessary for this review were performed using the CSAS25 control program of the SCALE-4 computer system.[5] 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.

2.2 VALIDATION STUDIES

References 6–7 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 7 documents the updating of this validation effort for the SCALE-4 version of SCALE on the IBM mainframe at ORNL. 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. 7 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[8] such that 99.9% of the distribution of calculated k_{eff} will fall above the tolerance band with a 95% confidence level. The two curves shown in Fig. 1 give the least-squares fit and corresponding limit curve for the calculated k_{eff} values of the 51 benchmark critical experiments as a function of the average neutron energy group causing fission, AEG. The top curve represents the least-squares fit to the data, and the bottom curve gives the lower limit of k_{eff} such that 99.9% of the distribution of calculated k_{eff} values are within the tolerance band with a confidence level of 95%. This bottom curve, along with the range of AEG values for this problem, is used to establish the subcritical maximum k_{eff} value for this study.

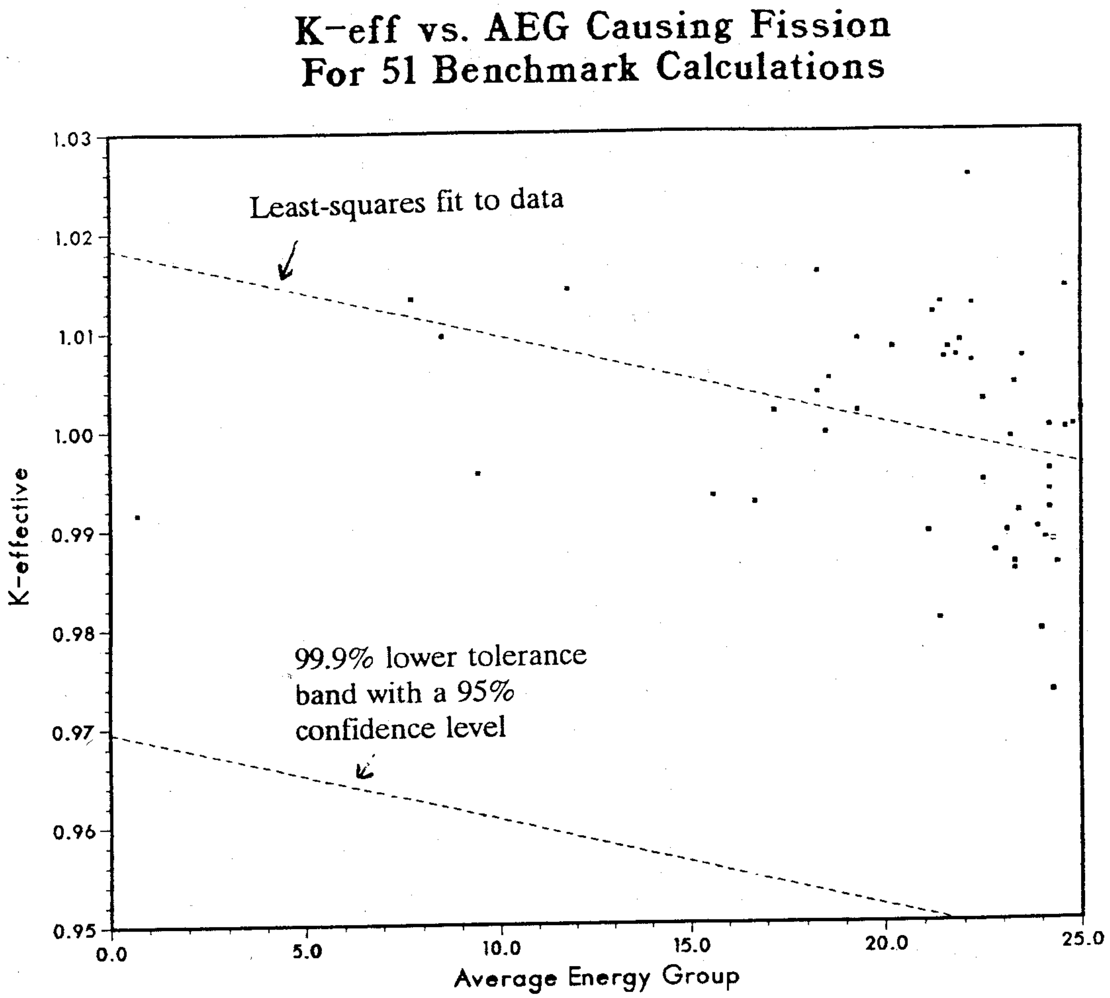

Fig. 1. k_{eff} versus average energy group causing fission (AEG) for 51 benchmark calculations.

2.3 ANALYSIS OVERVIEW

The Fissile Class I regulations in 10 CFR.71.57 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 used in this study begins with an infinite array model of 2½- and 10-ton UF_6 cylinders in their overpacks. 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 (see Refs. 2-4 for a discussion of protective packaging performance), the resulting curve of k_{eff} versus water density spans both the accident and normal conditions. The range of possible water densities is physically 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. This range of possible water densities is bounded by the use of void to full-density values.

For the 14-ton cylinders, a similar approach was used in which the UF_6 cylinders were modeled with variable density interstitial water moderation. Cylinder-to-cylinder spacing was set at the same value as the 10-ton cylinder because both cylinders have the same diameter.

If the k_{eff} values remain in the subcritical region for an infinite array with all possible water densities, then both accident and normal conditions of criticality safety for Fissile Class I have been met. Additional array calculations with the overpack present can then be used to assess the change in k_{eff} from the array results with no overpack. Calculations of single cylinders without overpacks and with infinite water reflection are used to provide calculational 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. A triangular pitch array is possible only for the 2½- and 14-ton cylinders, since the 10-ton cylinder has a square overpack. However, pitch reduction cases were evaluated for all three cylinders to verify the expected lack of sensitivity to cylinder-to-cylinder spacings. Portions of the k_{eff} versus water density curve corresponding to near-peak conditions were regenerated for all three cylinder sizes 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) because 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 shift somewhat.

2.4 SENSITIVITY STUDIES

The final set of calculations investigates temperature and fuel location effects. The temperature effects investigate the reactivity consequences of high UF_6 temperatures (corresponding to the fire test conditions) and low UF_6 temperatures (-40°C as required in 10 CFR.71.55 part d). The fuel location studies are necessary because the actual UF_6 configuration in each cylinder may vary. Thus, the most reactive fuel configuration must be determined. The configurations studied are shown in Fig. 2. The models are not drawn to scale, but simply to indicate the gross fuel location patterns. Models (a)—(c) each have approximately 40% void space. The fuel density for model (d) is reduced, such that all models have the same UF_6 loading. Model (c) represents the configuration due to the filling of a cylinder with liquid UF_6, which then cools uniformly from the outside with a corresponding decrease in volume. The resulting solid UF_6 typically has a void in the center. Model (a) represents the opposite configuration from model (c), and model (b) represents the fuel configuration expected from preferential cooling of UF_6 on only one side of the UF_6 cylinder. Model (d) approximates the low-density UF_6 fuel configuration. Experiments[9] have shown the most likely configuration to be a combination of model (b) and model (c), with the central void in model (c) shifted toward the cylinder edge slightly. Base case calculations were performed with model (c).

Additional calculations will investigate the reactivity effects of varying the UF_6 and moderator temperature during accident conditions. Temperature effects can be broken into density variations (both UF_6 and moderator) and resonance-capture variations. The density variations are accounted for in the fuel locations studies [e.g., model (d) above for low density UF_6] and the variable-water density calculations to obtain the optimal interstitial moderation. The resonance capture effects will be studied by performing three calculations, one at normal

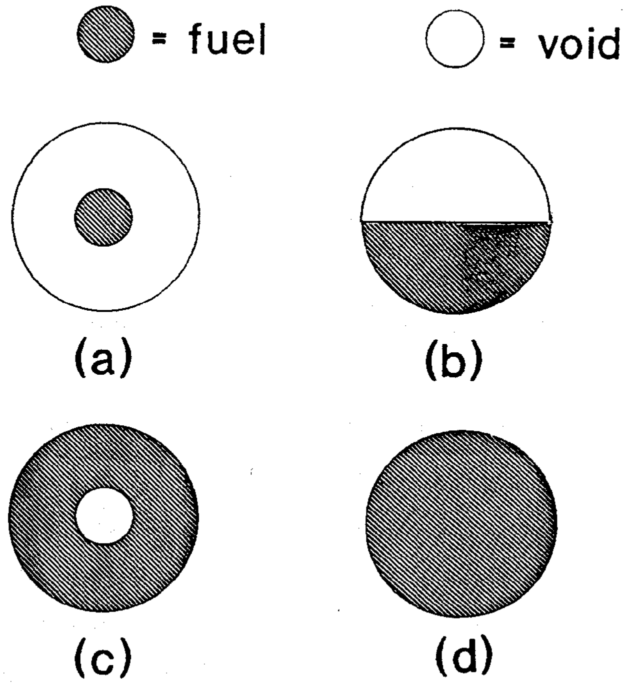

Fig. 2. Fuel locations analyzed to determine most reactive configurations for a constant mass.

temperature, one at elevated temperatures corresponding to an accident case, and one at -40°C as required in 10 CFR.71.55(d). A standard temperature of 20°C was used for the base case.

3. 2½-TON CYLINDER ANALYSIS

Phase I of the analysis evaluated the 2½-ton cylinder and its corresponding overpack, DOT 21PF-1, following closely the general description given in Sect. 2. This included the use of moderation control and the use of a "leak-tight" container to limit the hydrogenous material within the cylinder. The fuel region model was based on the fuel configuration shown in Fig. 2(c). An infinite array model incorporating an internal H/U ratio of 0.088 was then developed to allow the determination of the optimal interstitial moderation. In the 2½-ton cylinder model, the overpack is removed and replaced with variable-density water, while maintaining the same package-to-package spacing as a square-pitch array with the overpacks touching. The neglect of the overpack makes the results conservative (i.e., increases k_{eff}) because of the removal of neutron-absorbing materials. The variable-density water region allows for the determination of optimal interstitial moderation.

3.1 MODEL DESCRIPTION

The 2½-ton UF_6 cylinder model was developed from the actual cylinder and overpack dimensions contained in ref. 10. The steel cylinder radius was taken directly from the description in ref. 10. The curved lid and bottom surfaces of the cylinder were not modeled exactly; instead, the internal height of the cylinder cavity was determined from the volume as reported in ref. 10. The resulting model has a flat head and bottom rather than the actual curved one. The volume of the UF_6 inside the cylinder was obtained from the total UF_6 weight and a UF_6 density of 5.1 g/cm^3, as given in ref. 10. The inner radius of UF_6 [see model (c) in Fig. 2] 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 is shown in Fig. 3 and was 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 described above and shown in Fig. 3 is approximate due to the replacement of the overpack by variable-density water. The model shown in Fig. 4 corresponds to the 2½-ton cylinder in an overpack (DOT 21-PF-1). 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 model shown in Fig. 3 to be determined.

The materials contained in each region specified in Figs. 3–4 are described in detail in Tables 1 and 2. Table 1 presents each material, its total mass in the model, and its actual mass. Table 2 gives the material constituents and their respective atomic densities for completeness.

The models described above give the details for only one unit (i.e., a complete cylinder with and without its overpack). For infinite array calculations, these models were reflected on each of the six faces to represent an infinite array. No finite arrays were included in this study.

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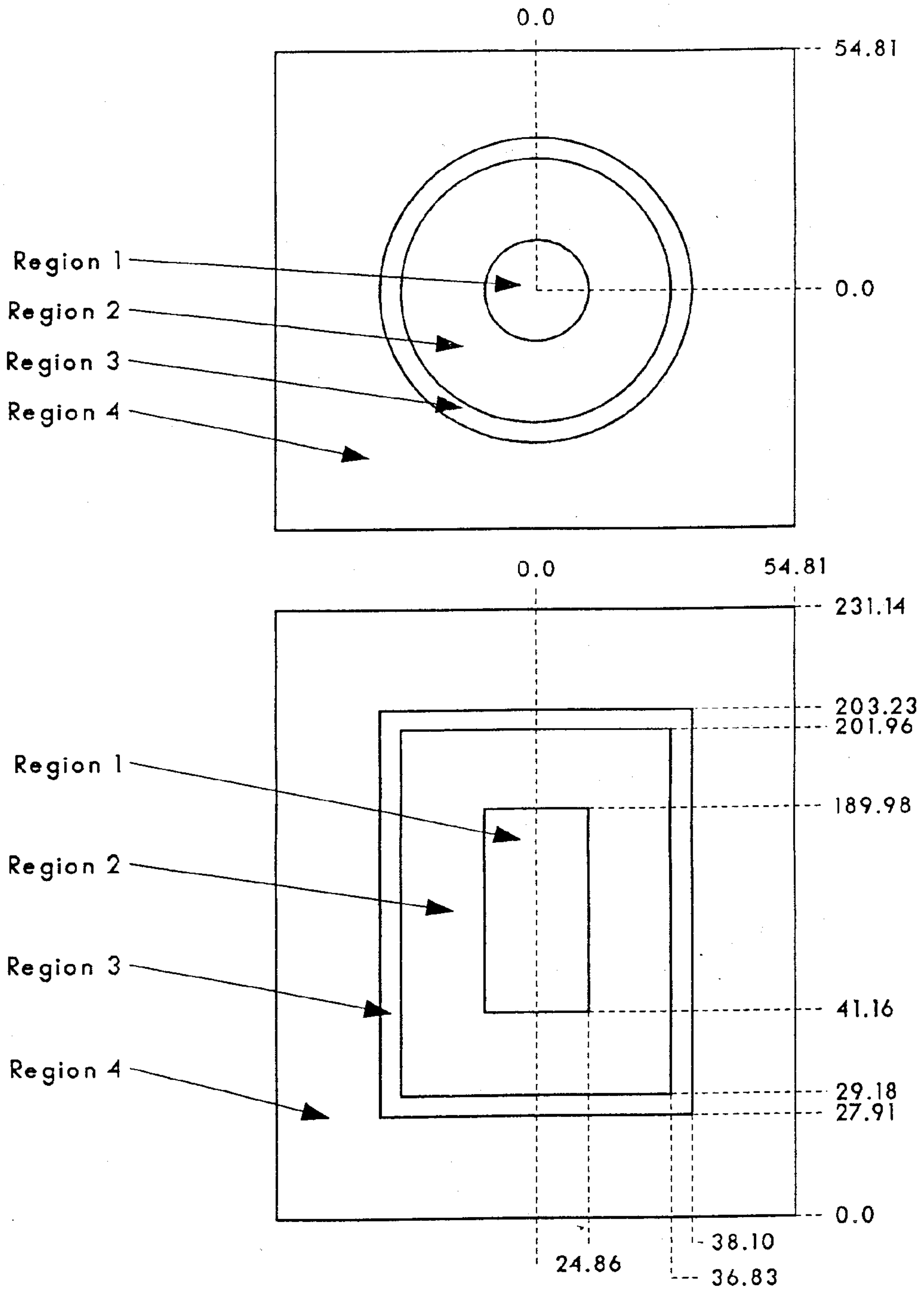

Fig. 3. Model for 2½-ton cylinder without overpack. (All dimensions in cm.).

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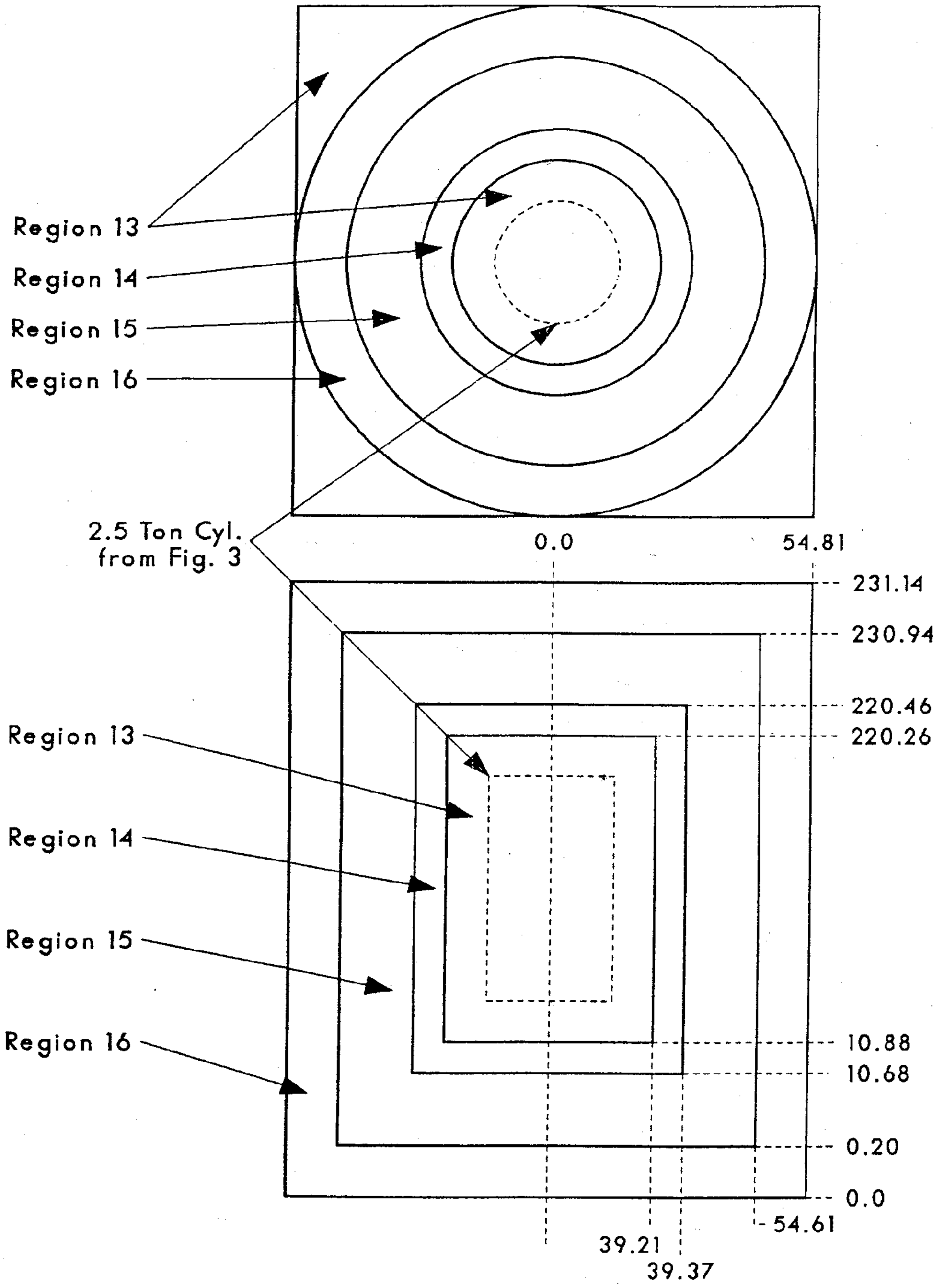

Fig. 4. Model for DOT 21-PF-1 overpack. (All dimensions in cm.)

Table 1. Constituent material mass and density (2½-ton cylinders)

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

Table 2. Constituent material number density data (2½-ton cylinders)

Region	Material/Reference	Density (g/cc)	Constituent	Atom density (atoms/b-cm)
2	UF_6 /ref. 10	5.1	^{235}U	4.4168E-4
			^{238}U	8.2860E-3
			F	5.3134E-2
			H	7.6800E-4
3, 14, 16	Carbon steel/ref. 5 SCALE standard composition	7.8212	Fe	8.3498E-2
			C	3.9250E-3
4	Variable-density water/ ref. 5 SCALE standard composition	0.9982*	H	6.6751E-2*
			O	3.3376E-2*
15	Phenolic foam/ ref. 11	0.029	C	5.9669E-4
			H	7.7981E-4
			^{10}B	1.0221E-5
			^{11}B	4.1465E-5
			Si	1.3680E-5
			Cl	2.4630E-6
			O	5.3063E-4

*Corresponds to full-density water.

3.2 ANALYSIS RESULTS FOR 2½-TON CYLINDER

Calculational results are given below for

1. infinite arrays with variable-density water replacing the overpacks (3.2.1),
2. an infinite array with the DOT 21-PF-1 overpack modeled (3.2.2),
3. a single 2½-ton cylinder surrounded by an effectively infinite water reflector (3.2.3), and
4. fuel location and temperature sensitivity calculations (3.2.4).

These latter calculations allow the quantification of reactivity effects of fuel configuration inside the UF_6 cylinder and the effects of low and high fuel temperatures corresponding to accident conditions. An overview of these calculations and their purposes are given in Table 3.

Table 3. Different types of calculations and their use in this study

Calculation type	Purpose
Infinite array with variable interstitial water density (without overpack)	
Original outer radius	Seek optimal interstitial moderation
7% reduced outer radius	Verify optimal conditions at different radius, estimate square-pitch versus triangular-pitch effects
Infinite arrays with overpacks modeled	Estimate change in k_{eff} due to neglecting overpack
Single unit, infinite water reflection	Meet regulatory requirement, consistency check on full-density water values from infinite array calculations
Temperature effects at near optimal conditions	Estimate temperature effects for accident conditions
Fuel configuration (see Fig. 2)	Identify most reactive fuel configurations

3.2.1 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. 5. 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 near unity SG. The peak k_{eff} value of 0.817 ± 0.003 at an 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 arise from a change in role of the water from a moderating material to a reflecting material.

Details of the region around the peak k_{eff} values are shown in Fig. 6. Here, the original curve for square lattice pitch is shown along with the curve for the 7% reduced pitch (associated with 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 %.

3.2.2 Infinite Array Results with Overpacks

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-ton cylinder with its overpack 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 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. 5 indicates that the cylinder overpack decreases k_{eff} by 0.15 Δk for the 2½-ton cylinder.

3.2.3 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 ± 0.003. This result is nearly identical with the SG = 1.0 value shown in Fig. 5. The single unit result is primarily used as an independent consistency check on the infinite array results.

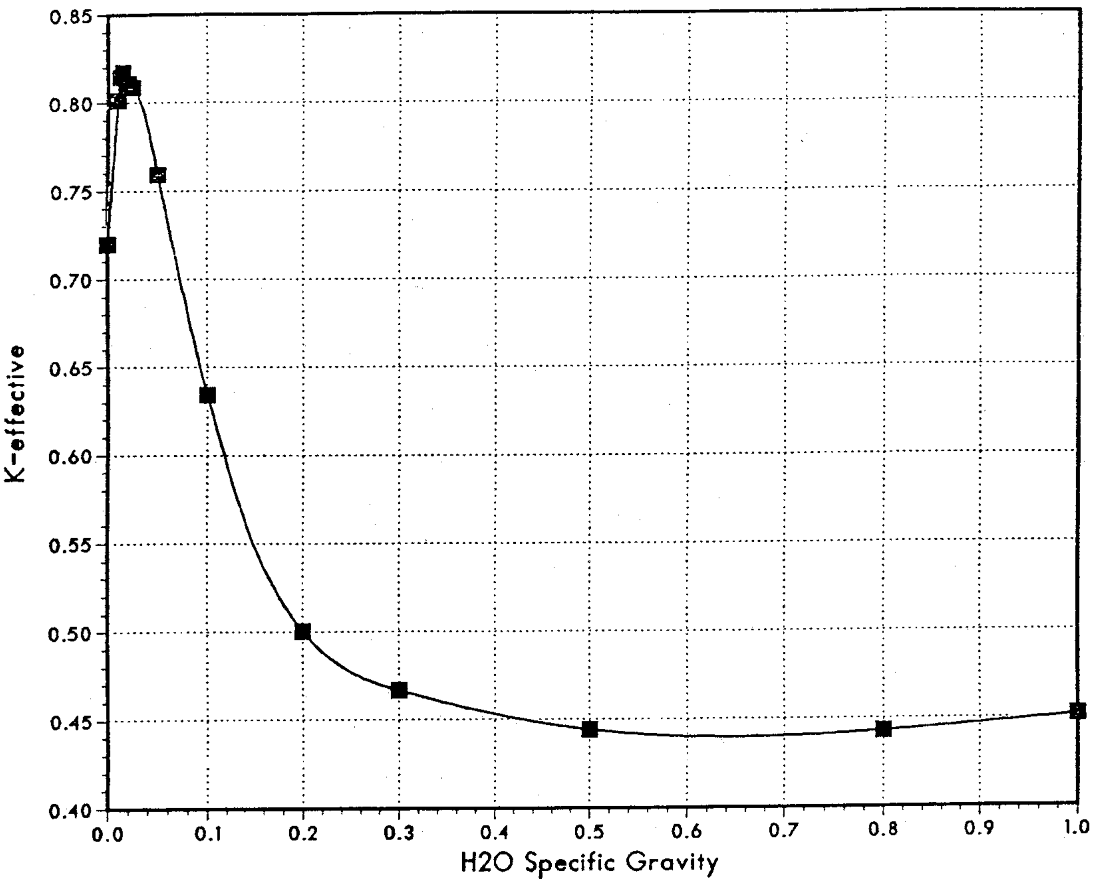

Fig. 5. Plot of k_{eff} versus water specific gravity for infinite array of 2½-ton UF_6 cylinders (square-lattice, full-diameter model).

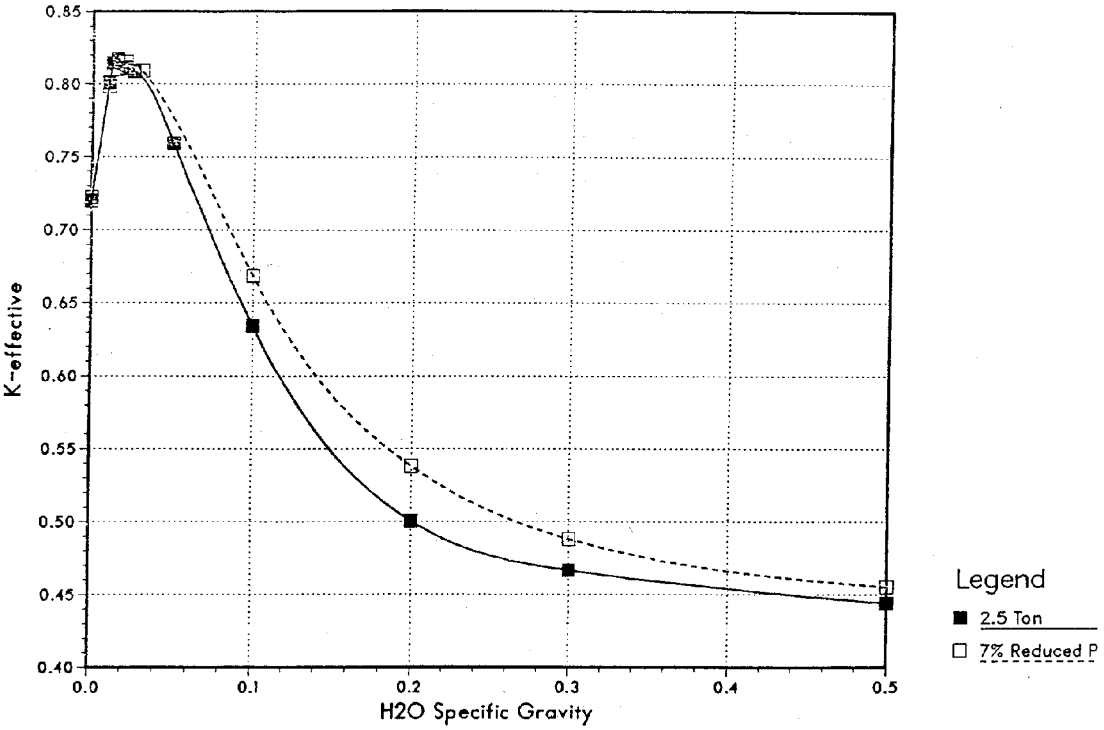

Fig. 6. Plot of k_{eff} versus water specific gravity for infinite array of 2½-ton UF_6 cylinders for original and 7% reduced pitch case.

3.2.4 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 (an 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 ± 0.002 and 0.818 ± 0.003, respectively. These values are equivalent to the base k_{eff} at 20°C of 0.817 ± 0.003. The temperature effects are thus extremely minimal.

The second sensitivity area investigated was that of fuel configuration. The infinite array model used for this study was the 2½-ton cylinder at a water SG of 0.02 (see Fig. 5). The fuel location studies analyzed all the cases shown in Fig. 2. 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 array results for cases a, b, c, and d are 0.774 ± 0.002, 0.782 ± 0.003, 0.811 ± 0.003, and 0.812 ± 0.003, respectively. Cases (c) and (d) are statistically indistinguishable when the standard deviations are taken into account and represent maximum reactivity conditions.

3.2.5 Validation Results

The complete set of supporting results for the plots shown in Figs. 5–6 are given in Table 4. In addition to the k_{eff} and water SG values, the table reports the AEG parameter values used for correlation to the lower limit of k_{eff} as discussed previously in Sect. 2.3. The values of AEG given in the table range from 9 to 16. Over this range, in Fig. 1 the lower tolerance limit (subcritical limit) falls between 0.953 and 0.961. For conservatism and convenience, the single value of 0.95 is chosen as the upper subcritical limit of k_{eff} for this study. Thus, the acceptance criteria for the calculational results presented above are the reported k_{eff} plus two standard deviations must be less than 0.95, and the AEG is within the range of 9 to 16.

3.2.6 Summary

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 ± 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 subcritical limit criterion at all interstitial moderation conditions. These k_{eff} values have been

Table 4. Tabulated results for various models of 2½-ton cylinders

Case	k_{eff}	Std. dev.	Water SG[a]	AEG[b]
Infinite array—square lattice pitch				
2½-ton results				
UF1	0.452	0.003	1.0	14.4
UF15	0.443	0.003	0.8	14.4
UF3	0.444	0.003	0.5	14.3
UF14	0.467	0.003	0.3	14.9
UF13	0.500	0.003	0.2	15.4
UF4	0.634	0.003	0.1	16.7
UF5	0.759	0.003	0.05	16.6
UF6	0.809	0.003	0.025	15.4
UF8	0.811	0.003	0.02	14.8
UF9	0.817	0.003	0.015	14.1
UF10	0.814	0.002	0.012	13.5
UF7	0.801	0.002	0.01	13.0
UF2	0.720	0.002	0.0	9.3
Infinite array—7% reduced pitch				
2½-ton results				
UF20	0.455	0.003	0.5	14.5
UF22	0.488	0.002	0.3	15.1
UF21	0.538	0.003	0.2	15.8
UF19	0.668	0.003	0.1	16.7
UF18	0.809	0.003	0.03	15.3
UF17	0.816	0.002	0.02	14.3
UF16	0.810	0.002	0.015	13.5
Overpack array results				
2½-ton results				
UF01	0.655	0.002	0.01	10.3
Single unit—infinite H_2O reflection				
2½-ton result				
UF59	0.453	0.003	1.0	14.4
Temperature effects				
2½-ton results				
UFT1 (65°C)	0.817	0.002	0.015	14.1
UF9 (20°C)	0.817	0.003	0.015	14.1
UFT3 (-40°C)	0.818	0.003	0.015	14.0
Fuel location effects				
2½-ton results				
UFA1 (Fig. 2a)	0.774	0.002	0.020	14.2
UFB1 (Fig. 2b)	0.782	0.003	0.020	14.3
UF8 (Fig. 2c)	0.811	0.003	0.020	14.8
UFF1 (Fig. 2d)	0.812	0.003	0.020	14.8

[a] Specific gravity.
[b] Average energy group causing fission.

shown to be insensitive to cylinder spacing and temperature effects. 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. These final calculations should be conservative due to the neglect of the overpack materials. The degree of conservatism in k_{eff} 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 10 CFR.71 criteria for Fissile Class I packages, and has a TI of zero for criticality safety purposes.

4. 10- AND 14-TON CYLINDER ANALYSIS

Phase II of the analysis evaluated the 10- and 14-ton UF_6 cylinders in a very similar fashion to the 2½-ton analysis described in Sect. 3. The use of moderation control (with H/U of 0.088) and the assumption of a "leak-tight" container were again employed in the analysis of the 10- and 14-ton cylinders. The fuel region model was again based on the fuel configuration shown in Fig. 2(c). Infinite array models of the UF_6 cylinders with variable-density water interspersed were used to determine the optimal interstitial moderation. These infinite array models were analyzed with cylinder spacing corresponding to a square-lattice arrangement followed by a reduced-pitch square lattice to approximate a triangular pitch lattice arrangement.

4.1 MODEL DESCRIPTION

The calculational models of the 10- and 14-ton UF_6 cylinders (Figs. 7–8) were based on the physical descriptions given in ref. 10. Approximations were made in these models primarily in the head and bottom regions. These regions were modeled as flat, where the actual geometry was curved. The cylinder internal volume was conserved, while the amount of steel in the cylinder wall was underestimated for conservatism (steel is an absorber, the removal of which should increase k_{eff}). The UF_6 was assumed to adhere to the cylinder walls with a central void space as shown approximately in Fig. 2(c). For both the 10- and 14-ton cylinders, the void space was approximately 40%.

Calculations were performed for the models shown in Figs. 7–8 in three different ways. Single packages were analyzed with the models shown in Figs. 7–8 surrounded by an effectively infinite water reflector. Infinite array calculations were also performed by specifying reflective or mirror-type boundary conditions for each face of the single package models. The final type of calculation consisted of placing the single UF_6 cylinder models inside the 10-ton overpack (Paducah Tiger overpack) shown in Fig. 9. This calculation allows determination of the increase in k_{eff} when the overpack is removed.

The materials specifications for each region shown in Figs. 7–9 are described in detail in Tables 5–6. The materials number density, actual mass, and mass in the model are given for completeness.

4.2 ANALYSIS RESULTS FOR 10- AND 14-TON CYLINDERS

Calculational results are given below for

1. infinite arrays of these cylinders with variable-density water replacing the overpack (4.2.1),
2. an infinite array of the Paducah Tiger overpacks containing 10-ton UF_6 cylinders (4.2.2), and
3. single 10- and 14-ton UF_6 cylinders surrounded by an effectively infinite water reflector (4.2.3).

The infinite array calculations with variable-density water constitute the major portion of the analysis. These calculations allow the optimal interstitial moderation and, hence, peak k_{eff} value to be determined. The single package results are essentially a check on the array calculations since the array calculations for full-density interstitial water, and those for the single package with an effectively infinite moderator thickness, should be virtually identical. The calculations with the overpack modeled (only for 10-ton cylinder) allows the conservatism in the approximate model to be evaluated.

4.2.1 Infinite Array Results without Overpacks

Plots of k_{eff} versus interstitial SG for both the 10- and 14-ton cylinders are shown in Figs. 10–13. These k_{eff} values are plotted versus water SG for convenience; however, the corresponding water density at an SG of 1.0 is 0.9982 gm/cm^3 (20°C, standard pressure). Thus, the abcissa label could be replaced with "water density." 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

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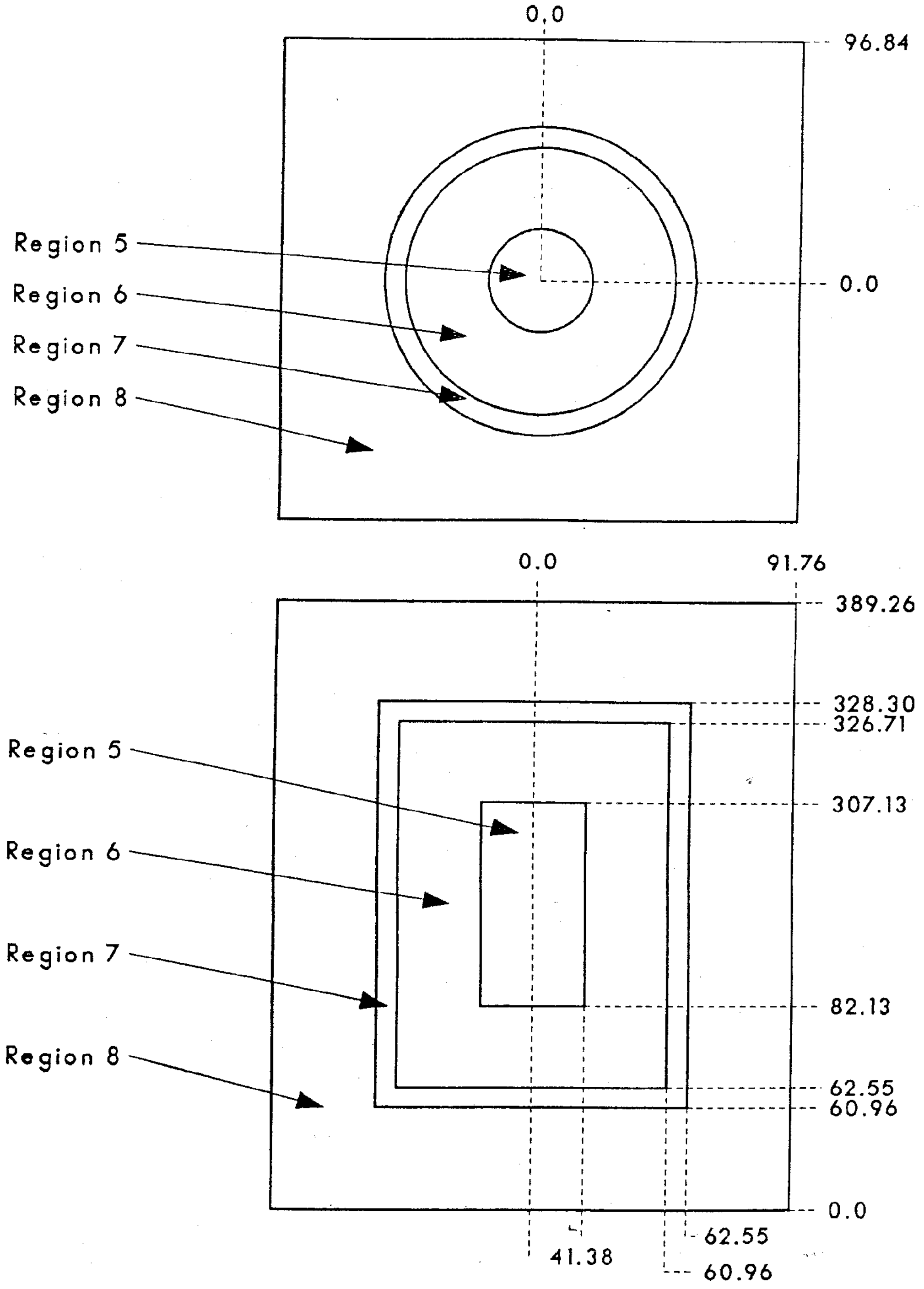

Fig. 7. Model for 10-ton cylinder without overpack. (All dimensions in cm.)

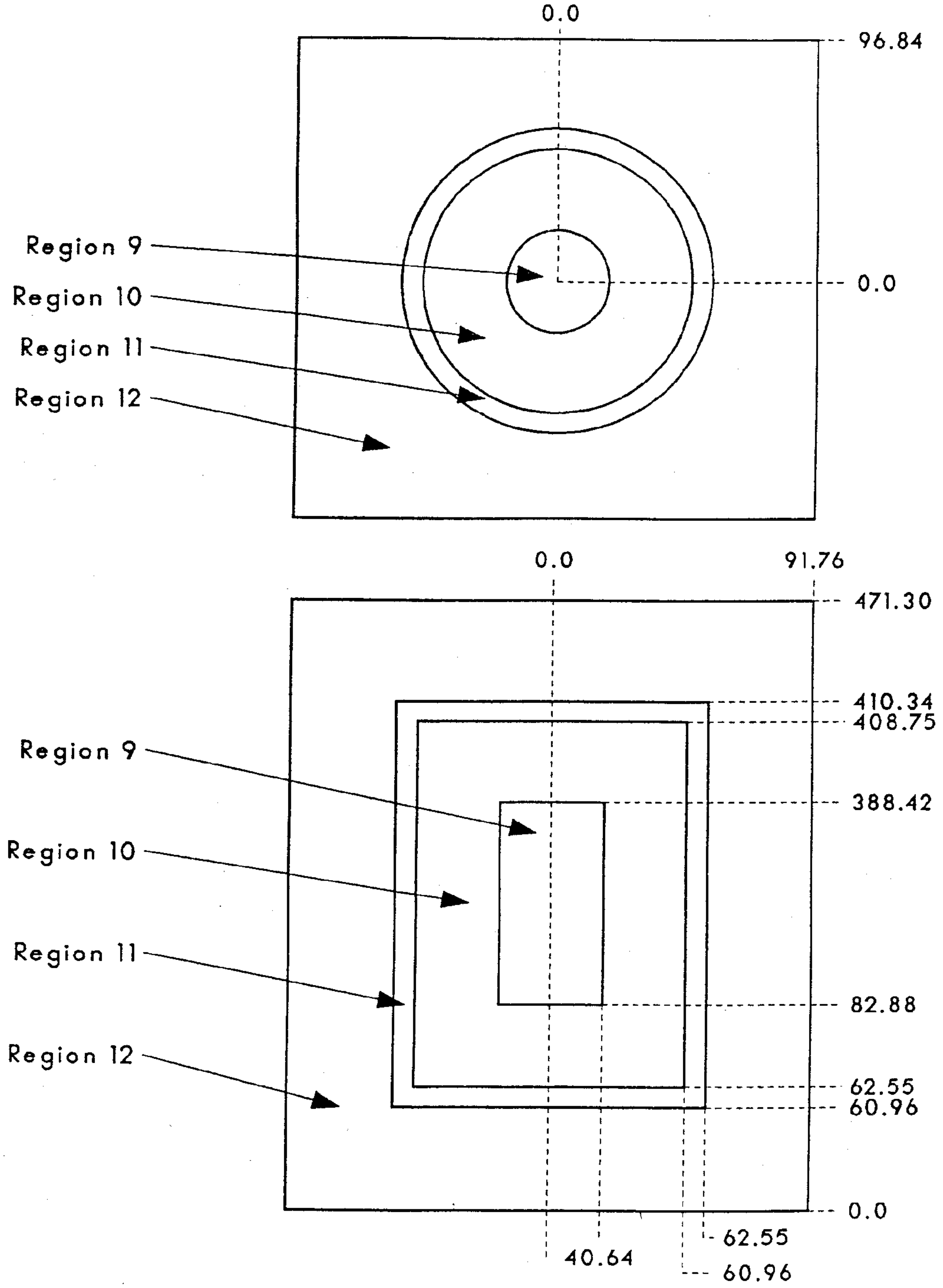

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Fig. 8. Model for 14-ton cylinder without overpack. (All dimensions in cm.)

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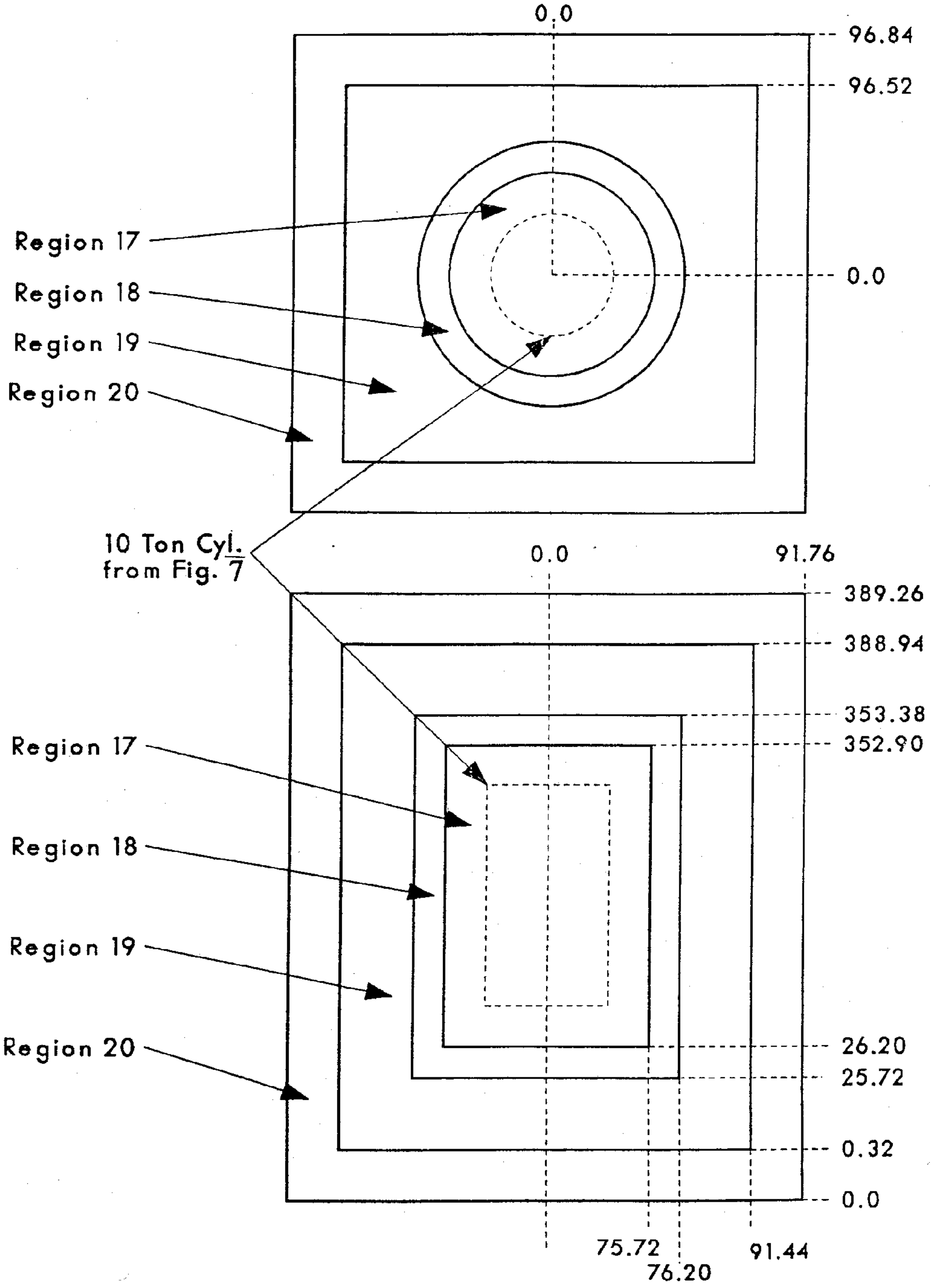

Fig. 9. Model for Paducah Tiger overpack. (All dimensions in cm.)

Table 5. Constituent material mass and density (10- and 14-ton cylinders)

Region	Shown in Fig.	Material	Density	Model mass (kg)	Actual mass (kg)
10-ton cylinder					
5	7	Void	-	-	-
6	7	UF_6	5.1	9,555	9,539
7	7	Steel	7.8212	1,580	2,041
8	7	Water or void	Variable	Variable	-
14-ton cylinder					
9	8	Void	-	-	-
10	8	UF_6	5.1	12,527	12,501
11	8	Steel	7.8212	1,976	2,359
12	8	Water or void	Variable	Variable	-
Paducah Tiger					
17	9	Void	-	-	-
18	9	Steel	7.8212	722	NA
19	9	Polyurethane	0.087	674	NA
20	9	Steel	7.8212	910	NA

Table 6. Constituent material number density data (10- and 14-ton cylinders)

Region	Material/Reference	Density (g/cc)	Constituent	Atom density (atoms/b-cm)
6, 10	UF_6/ref. 10	5.1	^{235}U	4.4168E-4
			^{238}U	8.2860E-3
			F	5.3134E-2
			H	7.6800E-4
7, 11, 18, 20	Carbon steel/ref. 5	7.8212	Fe	8.3498E-2
	SCALE standard composition		C	3.9250E-3
8, 12	Variable-density water/ ref. 5 SCALE standard composition	0.9982*	H	6.6751E-2*
			O	3.3376E-2*
19	Polyurethane foam/ ref. 4	0.08654	C	1.7750E-3
			H	3.5500E-3
			N	5.9200E-4
			O	1.1830E-3

*Corresponds to full-density water.

near unity SG. The peak value of k_{eff} (see Figs. 10–11) for the 14-ton cylinder is 0.768 ± 0.002 for a water SG of 0.005. In Fig. 11, curves of k_{eff} versus water SG are given for both the square-lattice pitch and a 7% reduced pitch. The 7% reduced case gives essentially identical results, 0.766 ± 0.002 versus 0.768 ± 0.002.

The results for the 10-ton cylinder are shown in Fig. 12, together with those for the 14-ton cylinder. These are shown together since the 10- and 14-ton cylinders are the same radius, only differing cylinder lengths. The overall trends of the 14-ton cylinder can thus be expected to duplicate those of the 10-ton cylinder. For the water SG values shown, the 10- and 14-ton curves are very similar. The 14-ton k_{eff} values are expected to continue to be slightly larger than those of the 10-ton values since for high water densities, the infinite array k_{eff} should approach the single unit k_{eff}. In Fig. 13, k_{eff} curves for the original radius versus a 7% reduced radius are given. The same characteristics as the 2½-ton and 14-ton cylinders are seen. Here, the peak values are 0.769 ± 0.002 at an SG of 0.005 for the original radius and 0.763 ± 0.002 at an SG of 0.005 for the reduced radius.

4.2.2 Infinite Array Results with Overpacks

As stated earlier, only the 10-ton cylinder was analyzed with an overpack. This calculation, as before, was for an infinite array of packages with overpacks, 10-ton cylinder and Paducah Tiger overpack for this case. The k_{eff} value for an infinite array of 10-ton cylinders and overpacks is 0.547 ± 0.002. The overpack has an equivalent water SG of 0.05. By comparing the k_{eff} value at an SG of 0.05 in Fig. 12 (approximately 0.63) with 0.547, a difference of 0.08 Δk is seen. This represents a conservatism in the infinite array without overpack calculations.

4.2.3 Single Unit Results

The single unit models for the 10- and 14-ton UF_6 cylinders consisted of the cylinder without an overpack surrounded by an effectively infinite water reflector. These values are used primarily as an internal consistency check on the infinite array results for an SG of 1.0. The single unit results are 0.526 ± 0.002 and 0.533 ± 0.003 for the 10- and 14-ton cylinders, respectively. These two values are very nearly the same, as expected, since the 10- and 14-ton cylinders are very similar in size. Comparing the 14-ton single unit result with the k_{eff} at an SG of 1.0 in Fig. 10 also yields excellent agreement.

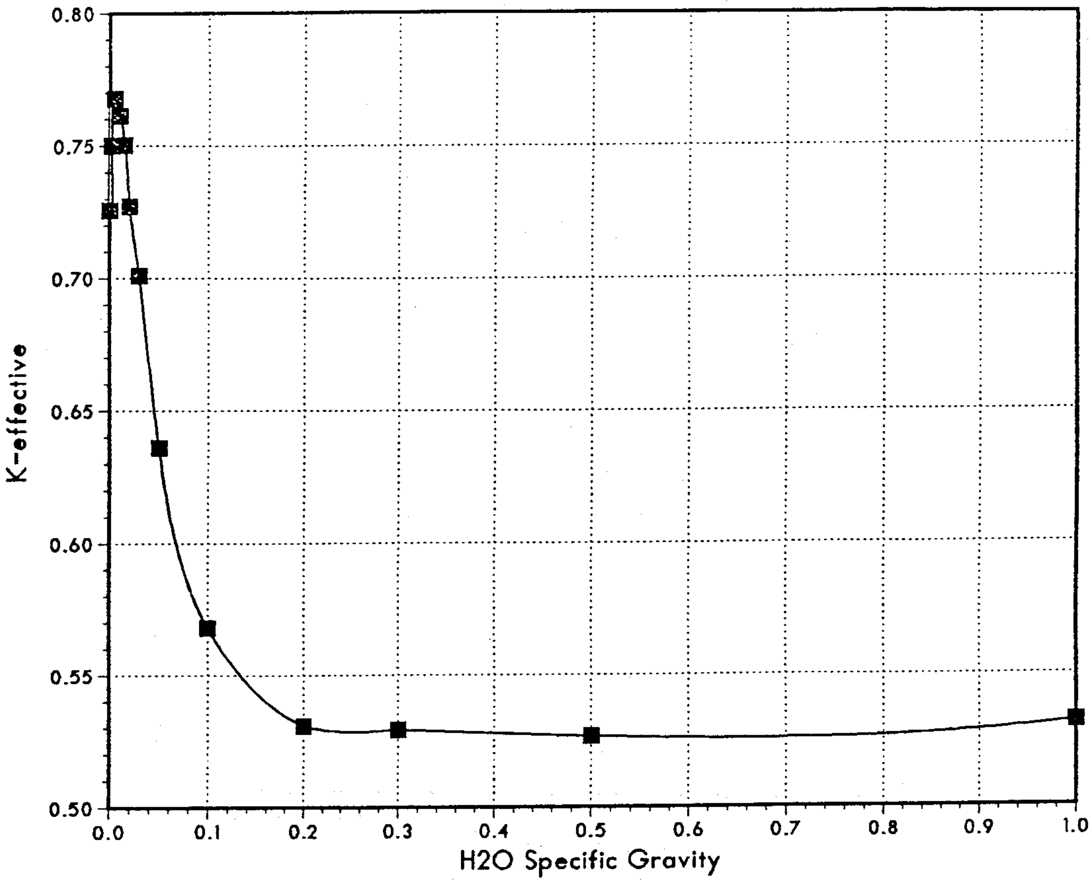

Fig. 10. Plot of k_{eff} versus water specific gravity for infinite array of 14-ton UF_6 cylinders (square-lattice, full-diameter model).

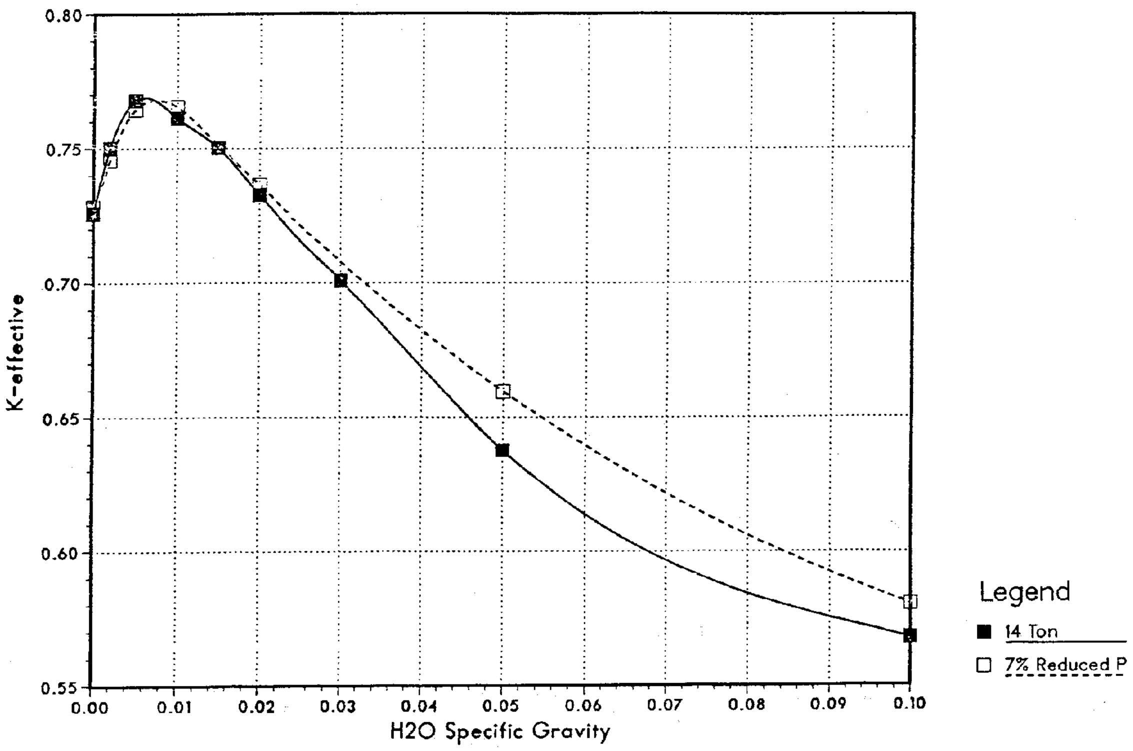

Fig. 11. Plot of k_{eff} versus water specific gravity for infinite array of 14-ton UF_6 cylinders for original and 7% reduced pitch case.

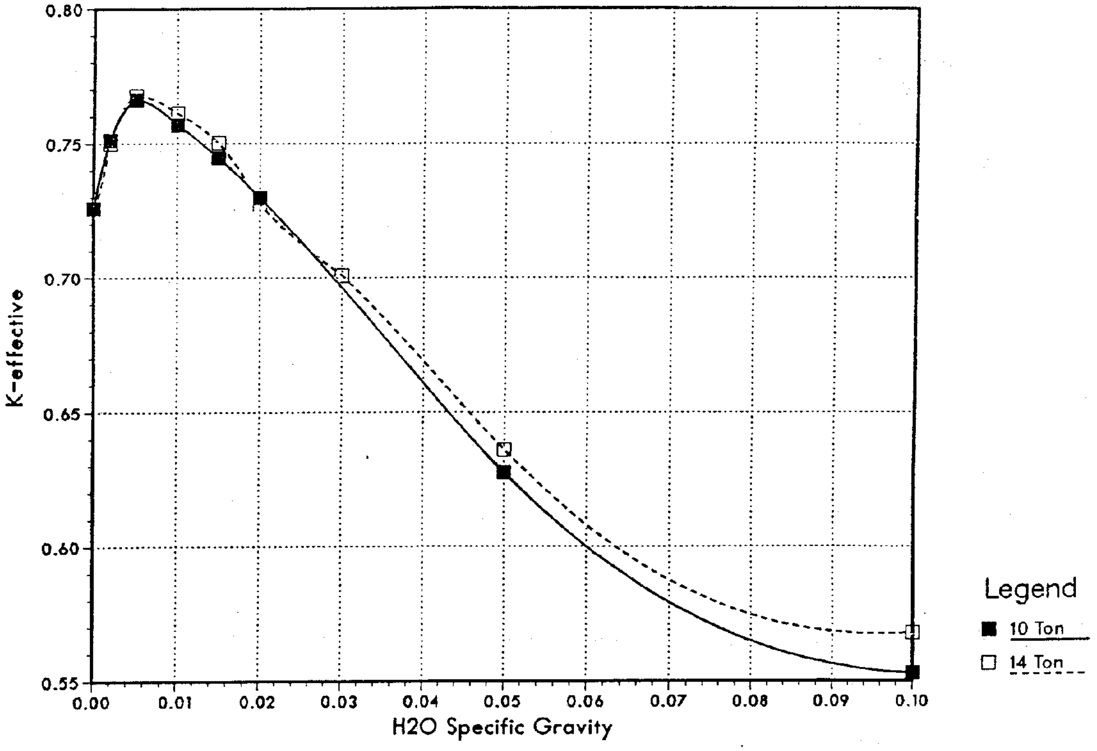

Fig. 12. Plot of k_{eff} versus water specific gravity for infinite arrays of 10- and 14-ton UF_6 cylinders (square-lattice, full-diameter models).

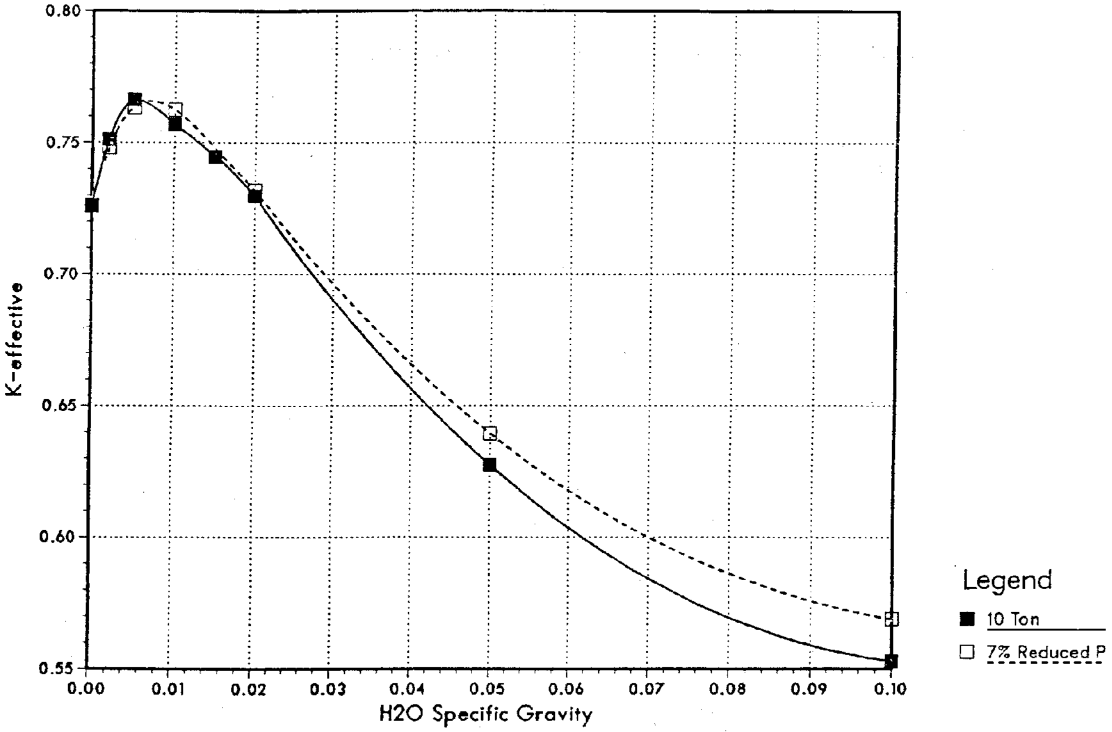

Fig. 13. Plot of k_{eff} versus water specific gravity for infinite array of 10-ton UF_6 cylinders for original and 7% reduced pitch case.

4.2.4 Sensitivity Results

The sensitivity calculations described in Sect. 3.2.4 for the 2½-ton cylinder were not repeated for the 10- and 14-ton cylinders. The conclusions for the 2½-ton cylinder included the insensitivity of k_{eff} to temperature effects. The peak cylinder temperatures for the 2½-ton and 10-ton fire tests were very nearly the same, assumed to be 65°C for this analysis. The extreme temperature of -40°C is specified by the regulations. Also, the normal condition temperature of 20°C was used for all other calculations for the 2½-, 10- and 14-ton cylinders. The similarity of cylinders and temperatures encountered should allow the temperature sensitivity conclusions from the 2½-ton analysis to be applied to the 10-ton analysis (the extreme temperature conditions apply only to cylinders with overpacks).

The fuel location sensitivity results generated in Sect. 3.2.4 should also be applicable to the 10- and 14-ton cylinders. Based on similar geometry arguments, the configurations with maximum k_{eff} should again be models (c) and (d). The geometry corresponding to model (c) was used in the analysis of both the 10- and 14-ton cylinders.

4.2.5 Validation Results

The complete set of supporting results shown in Figs. 10–13 are given in Table 7. The table reports k_{eff} values, water SG values, and AEG parameter values used for correlation to the lower safe limit of k_{eff} as discussed in Sect. 2.3. The values of AEG given in the table range from 9 to 14. Over this range, in Fig. 1 the lower tolerance limit (subcritical limit) falls between 0.953 and 0.961. For conservatism and convenience, the single value of 0.95 is chosen as the upper subcritical limit for k_{eff} in this study. Thus, the acceptance criteria for the calculational results presented above are the reported k_{eff} plus two standard deviations must be less than 0.95, the upper subcritical limit.

4.2.6 Summary

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 ± 0.002 and 0.769 ± 0.002 for the 10- and 14-ton cylinders, 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 subcritical limit criterion at all interstitial moderation conditions. These k_{eff} values should be insensitive to fuel location in the cylinder, cylinder spacing, and temperature

Table 7. Tabulated results for various models of 10- and 14-ton cylinders

Case	k_{eff}	Std. dev.	Water SG[a]	AEG[b]
Infinite array — square-lattice pitch				
10-ton results				
UF40	0.553	0.002	0.1	12.7
UF39	0.628	0.003	0.05	13.7
UF38	0.730	0.002	0.02	13.8
UF42	0.745	0.002	0.015	13.5
UF46	0.756	0.002	0.01	12.8
UF44	0.769	0.002	0.005	11.6
UF45	0.755	0.002	0.002	10.4
UF36	0.726	0.002	0.0	9.3
14-ton results				
UF23	0.532	0.002	1.0	11.7
UF24	0.527	0.002	0.5	11.5
UF25	0.529	0.003	0.3	11.8
UF26	0.531	0.003	0.2	11.6
UF27	0.568	0.003	0.1	12.5
UF28	0.636	0.003	0.05	13.6
UF29	0.701	0.003	0.03	13.9
UF32	0.727	0.002	0.02	13.5
UF33	0.750	0.002	0.015	13.3
UF31	0.761	0.002	0.01	12.6
UF34	0.768	0.002	0.005	11.4
UF35	0.750	0.002	0.002	10.2
UF30	0.726	0.001	0.0	9.2
Infinite array — 7% reduced pitch				
10-ton results				
UF58	0.569	0.003	0.1	12.9
UF57	0.732	0.002	0.02	13.6
UF56	0.762	0.002	0.01	12.6
UF55	0.763	0.002	0.005	11.3
UF54	0.748	0.002	0.002	10.1
UF53	0.726	0.002	0.0	9.3
14-ton results				
UF52	0.581	0.003	0.1	12.8
UF51	0.737	0.002	0.02	13.3
UF50	0.766	0.002	0.01	12.4
UF49	0.764	0.002	0.005	11.2
UF48	0.746	0.002	0.002	10.0
UF47	0.728	0.002	0.0	9.3
Overpack array results				
10-ton result				
UF02	0.547	0.002	0.05	11.2
Single unit —infinite H_2O reflection				
10-ton result				
UF60	0.526	0.002	1.0	11.9
14-ton result				
UF61	0.533	0.003	1.0	11.8

[a] Specific gravity.

[b] Average energy group causing fission.

effects. These final k_{eff} values correspond to an infinite array of optimal interstitially moderated cylinders. 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. 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 on-site operations.

These final calculations should be conservative due to the neglect of the overpack materials. The degree of conservatism has been estimated at 12% for the 10-ton cylinder.

Based on this evaluation, the 10-ton UF_6 cylinder with 5 wt % ^{235}U enrichment meets the 10 CFR.71 criteria for a Fissile Class I package with a TI of zero for criticality purposes; however, TI may be required based on radiation from the packages.

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