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LATTICE MEASUREMENTS ON TUBULAR FUEL ASSEMBLIES IN D_2O

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LATTICE MEASUREMENTS ON TUBULAR FUEL ASSEMBLIES IN D_2O

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ABSTRACT

Substitution measurements in the Process Development Pile (PDP) were used to determine bucklings and diffusion coefficients for D_2O-moderated lattices of tubular natural UO_2 fuel assemblies. Four types of assemblies were investigated at triangular lattice pitches of 9.33, 11.10, and 12.12 inches. Coolants within the different assemblies included D_2O, air, and mockups of H_2O fog and organic liquids.

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LATTICE MEASUREMENTS ON TUBULAR FUEL ASSEMBLIES IN D_2O

INTRODUCTION

Many of the designs developed in the course of the Savannah River investigations of heavy-water-moderated power reactors called for the use of tubular fuel assemblies of natural UO_2. These fuel assemblies represented a relatively new development, and little information was available on their operating characteristics. In particular, little or no normalizing data were available for the physics calculations(1) required within the computer program(2) used to optimize the reactor designs. To fill this need, lattice substitution experiments were undertaken in the Process Development Pile (PDP)(3) covering a range of fuel assembly dimensions, pitches, and coolants.

SUMMARY

Eight sizes of natural UO_2 fuel tubes were fabricated by vibratory compaction of the oxide to about 81% of theoretical density within aluminum sheath cans. These fuel tubes were then combined with aluminum housing tubes to make up the four sets of fuel assemblies illustrated in Figures 1 and 2. Three of the designs were especially suited for H_2O fog or D_2O cooling. The other design was intended for organic cooling. The effects of gas cooling (or of voids in the liquid coolants) were also studied in all assemblies.

Measurements were made by determining the change in the critical height of the D_2O moderator in the PDP when one to seven of the test assemblies replaced the central fuel assemblies in uniform host lattices of UO_2 rod clusters or of uranium metal tubes. Both two-region, two-group analysis and a one-group perturbation analysis of successive substitutions were used to determine the test lattice bucklings and, in the cases with coolant voids, the change in the vertical diffusion coefficient δD_Z produced by the voids. The measurements were made at triangular lattice pitches of 9.33, 11.10, and 12.12 inches.

Bucklings for the D_2O-cooled lattices ranged from 400-500 μB. Replacing the D_2O coolant with air reduced the bucklings by about 2%. Adding hydrogenous coolants reduced the bucklings by as much as 30%, with the buckling reduction being roughly proportional to the amount of hydrogen added to the assembly. These hydrogen additions ranged from 0.1 to 0.2 g/cc for the H_2O fog mockups to 0.57 g/cc for the organic coolant mockups.

The experiments indicated that the fractional change in the vertical diffusion coefficient $\delta D_z/D$ produced by coolant loss in these assemblies could be described by a single function $\delta D_z/D = 1.528v + 0.016v^2$ where v is the void-to-cell volume ratio. The measured anisotropy fractions were used in conjunction with calculations and copper poisoning experiments to translate the measured buckling changes into k_∞ changes resulting from coolant losses.

DISCUSSION

Test Fuel Assemblies

Eight sizes of UO_2 fuel tubes were fabricated by vibratory compaction of natural UO_2 powder within aluminum sheath cans. Six tube sizes, along with appropriate housing tubes, were used to make up three sets of assemblies suited for H_2O-fog or D_2O cooling. These assemblies are illustrated in Figure 1. The other two tube sizes were used with appropriate housing tubes to make up one assembly set, which was a mockup of the type of assemblies being considered at the time for a pressure-tube, organic-cooled lattice. This design is shown in Figure 2. The oxide densities in all of the fuel tubes were 80-82% of theoretical.

The housings for the assemblies shown in Figure 1 were designed so that the D_2O moderator could be introduced into the coolant channels to simulate D_2O coolant. The D_2O in one or more coolant channels could then be remotely expelled by helium pressure, so that void coefficient and diffusion coefficient studies could be made during a single reactor run. Only two of these fuel assemblies (ABCD and B'C' in Figure 1) were used for H_2O fog coolant studies. In these experiments D_2O was excluded from the coolant channels, which were filled with expanded polyethylene, $(CH_2)_n$, to mock up hydrogen atom concentrations equivalent to that of the fog. Two polyethylene densities were used averaging 0.145 and 0.070 g/cc over the coolant channels. The innermost channel in both types of assemblies was air-filled during the polyethylene measurements.

The organic coolant used in the studies with the assembly shown in Figure 2 was "Dowtherm"* A, which is a eutectic mixture of 27% diphenyl and 73% diphenyl oxide. The channel between the pressure and calandria tube mockups was air-filled during the organic coolant experiments.

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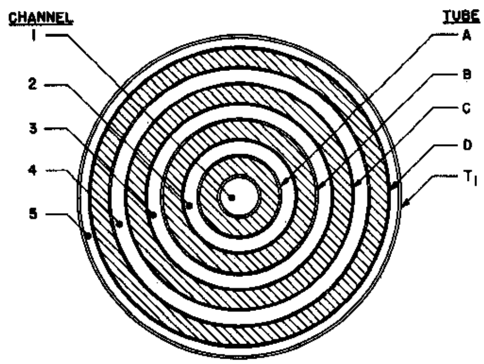
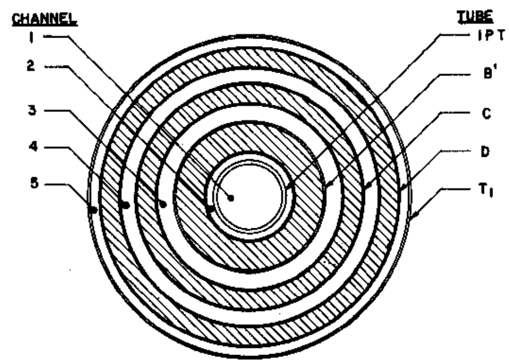
* Trademark of Dow Chemical Co.





Tube	OD clad, in.	ID clad, in.	Material	UO_2 density, g/cc
A	1.12	0.50	UO_2	8.90
B	2.10	1.48	UO_2	8.85
C	3.08	2.46	UO_2	8.87
D	4.06	3.44	UO_2	8.90
T_1	4.38 (OD)	4.30 (ID)	6061 Al	
IPT	0.97 (OD)	0.89 (ID)	1100 Al	
B'	2.10	1.18	UO_2	8.93
C'	3.38	2.46	UO_2	8.87
T_2	3.70 (OD)	3.62 (ID)	6061 Al	

NOTE: All cladding - 0.030 in. thick, 1100 Al
ABCD oxide - 0.250 in. thick
B'C' oxide - 0.400 in. thick

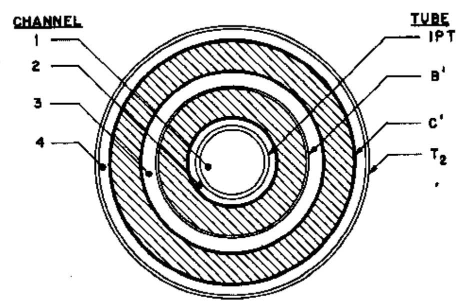
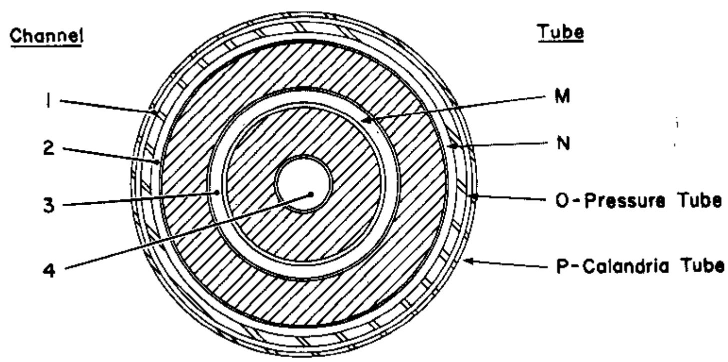


FIG. 1 CROSS SECTIONS OF TEST FUEL ASSEMBLIES
H_2O-FOG-AND D_2O-COOLED DESIGNS



Tube	OD clad, in.	ID clad, in.	Material	UO_2 density, g/cc
M	1.620	0.500	UO_2	8.83
N	2.930	1.890	UO_2	8.83
O	3.310	3.110	6063 Al	–
P	3.550	3.430	6063 Al	–

NOTE: All cladding - 0.030 in. thick, 1100 Al
M oxides - 0.50 in. thick
N oxides - 0.46 in. thick

FIG. 2 CROSS SECTION OF TEST FUEL ASSEMBLY
ORGANIC-COOLED DESIGN

Host Lattice Fuel Assemblies

All of the experimental measurements were made as substitution studies with the test fuel assemblies replacing fuel assemblies from a uniform host lattice loaded into the Process Development Pile (PDP)[3], a D_2O-moderated critical assembly 16 feet 2-3/4 inches in diameter operating at moderator heights up to 15 feet. Two types of fuel assemblies were used to build host lattices. The fuel assemblies of the first host lattice, used for studies with the H_2O-fog- and D_2O-cooled test assemblies illustrated in Figure 1, consisted of 31-rod clusters of 0.50-inch diameter natural UO_2 rods. These clusters, which had been studied extensively in earlier investigations[4], are illustrated in Figure 3. The fuel assemblies of the second host lattice, used for studies with the organic-cooled test assembly illustrated in Figure 2 consisted of natural uranium metal fuel tubes 3.50-inch OD and 2.85-inch ID. These fuel assemblies illustrated in Figure 4 had also been investigated in earlier studies[5].

Nuclear parameters of the rod-cluster host lattices were well matched to the test lattices used, but the match was somewhat less satisfactory between the metal tubes and the organic-cooled fuel. Parameters of the host lattices are given in Table I. All host and substitution lattice measurements in these experiments were made at a moderator isotopic purity of 99.58 mol % and a temperature of 22°C.

TABLE I

Nuclear Parameters of Host Fuel Lattices

Fuel	UO_2 Cluster	UO_2 Cluster	U Metal Tube	U Metal Tube
Triangular lattice pitch, in.	9.33	11.10	9.33	12.12
B_m^2, μB	535 ±5[a]	525 ±4[b]	671 ±8[b]	558 ±7[b]
L^2, cm^2	118	176	125	234
τ, cm^2	138	131	124	122
p (resonance escape probability)	0.873	0.903	0.879	0.915

(a) At 99.68 mol % D_2O
(b) At 99.59 mol % D_2O

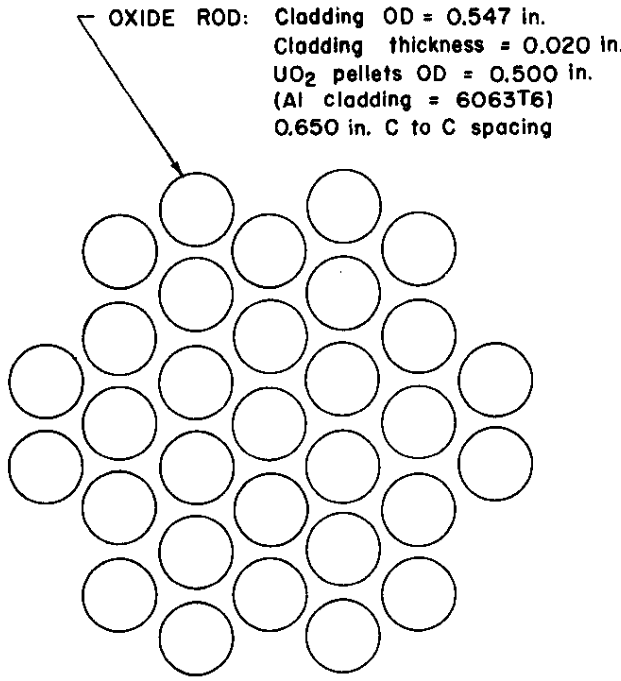
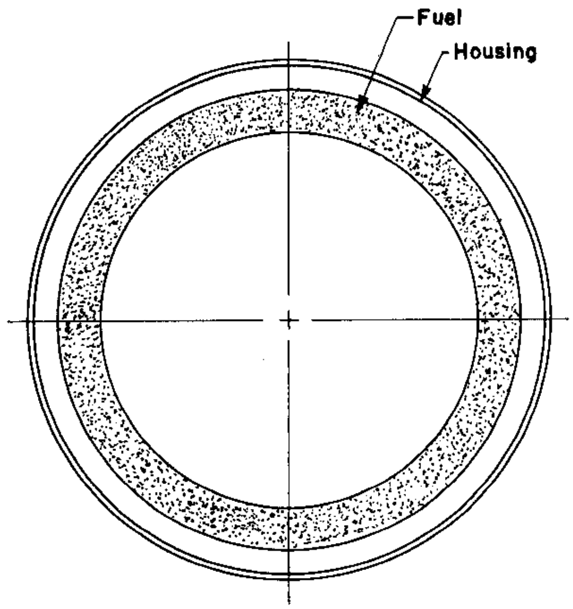


FIG. 3 UO_2 ROD CLUSTER HOST FUEL ASSEMBLY



Tube	OD, in.	ID, in.	Material
Fuel	3.500	2.860	Natural U
Housing	4.000	3.900	Al (6063)

FIG. 4 METAL TUBE HOST FUEL ASSEMBLY

Buckling Measurements

Buckling measurements were made at triangular lattice pitches of 9.33, 11.10, and 12.12 inches with test assemblies replacing one or more of the central seven host lattice fuel assemblies. The measurements were performed using two substitution techniques[6]. The first technique involved substituting all seven test assemblies in the center of the host lattice, measuring the vertical buckling in terms of the critical moderator height and a measured vertical extrapolation distance, and solving the two-group, two-region critical equations for the test lattice buckling.

The second technique, developed from one-group perturbation theory[7], utilized successive substitutions of one, three, and seven assemblies in the center region. The changes in buckling measured with respect to the changes in critical moderator height from the one-region host (or reference) lattice, the statistical weights of the test regions, and the ratio of one-group diffusion coefficients of the two regions provide data for extrapolating to the difference in buckling between one-region loadings of the host and test lattices. The formula used for the extrapolation (for the simplified case of equal diffusion coefficients in all regions) was

$$\frac{B^2 - B_1^2}{W_3 + \frac{1}{2} W_2} = \delta B^2 \frac{W_2}{W_3 + \frac{1}{2} W_2} + (B_3^2 - B_1^2) \qquad (1)$$

$$\delta B^2 \equiv B_2^2 - \frac{B_3^2 - B_1^2}{2} \qquad (2)$$

where B^2 is the measured vertical buckling in the mixed lattice, the subscripted values of B^2 are the critical vertical bucklings for pure individual regions, and the W values are calculated radial statistical weights for each of the regions. The pile regions are identified as (1) the reference lattice, (2) the mixed lattice encompassing the region in which the mixed and test lattice fuel assemblies are immediately adjacent to each other, and (3) the test lattice. This formula gives rise to a straight line plot with a slope equal to δB^2, the difference between the mixed lattice buckling and the average of the host and test lattice bucklings. It has an intercept equal to the difference between the host and test lattice bucklings.

Table II summarizes the measured bucklings. For the test fuel assemblies illustrated in Figure 1 the listed bucklings are averages between the two-group and substitution analyses, which

TABLE II

Test Lattice Bucklings[a]

Assembly[b]	Triangular Lattice Pitch, in.	D₂O- or Air-Filled Assemblies: Channels Air Filled	D₂O- or Air-Filled Assemblies: Material Buckling, μB	"Fog" Cooled Assemblies[c]: Polyethylene Density in Coolant Channels, g/cc	"Fog" Cooled Assemblies[c]: Material Buckling, μB	Organic-Cooled Assemblies[d]: Nominal H_2 Concentration, g/cc	Organic-Cooled Assemblies[d]: Material Buckling, μB
ABCD T_1	9.33	None	392	0.145	349		
		2,3,4,5	399	0.070	373		
		All	401				
	11.10	None	440	0.145	389		
		3	449	0.070	424		
		2,3	454				
		2,3,4,5	459				
		All	458				
IPT B'C' T_2	9.33	None	508	0.145	462		
		3	514	0.070	484		
		2,3,4	503				
		All	500				
	11.10	None	465	0.145	428		
		3	471	0.070	452		
		4	466				
		3,4	473				
		2,3,4	476				
		All	476				
IPT B'CD T_1	9.33	None	403				
		2,3,4,5	404				
		All	406				
	11.10	None	447				
		3,4,5	461				
		2,3,4,5	462				
		All	463				
MNOP	9.33	All	467			0.56	340
	12.12	All	375			0.56	247

(a) 22°C, 99.58 mol % D_2O moderator.
(b) See Figures 1 and 2 for key to assembly designation.
(c) Innermost channel in each assembly air filled.
(d) Outermost channel in each assembly air filled.

agreed to within ±10 μB in a random manner. For the organic-cooled assembly only the successive substitution method was used owing to the mismatch with the host lattice. Differences in bucklings, for a given assembly and lattice pitch due to different coolant conditions, are accurate to within ±5 μB. Absolute bucklings are accurate to within ±10 μB for Figure 1 lattices and ±20 μB for the Figure 2 lattices. For the lattices having air-filled coolant channels, the radial diffusion coefficients and migration areas, used in the two-group analysis, were obtained from the δD/D measurements and calculations discussed in the next section.

$\delta D_z/D$ Measurements

The fractional changes in the diffusion coefficient in the vertical direction, $\delta D_z/D$, when D_2O was expelled from one or more coolant channels, were also determined using the one-group perturbation theory used for the successive substitution analyses. A single D_2O-cooled test assembly was placed in the center position in the PDP, and the pile was taken to criticality. The heavy water in one or more coolant channels was expelled in several steps by helium under pressure, the pile being held critical by changing the moderator height. The changes in critical moderator height and the corresponding percentage of the channel(s) voided provided data necessary to compute $\delta D_z/D_{z_1}$, where D_{z_1} is the one-group diffusion coefficient of the reference lattice. The equation used in the analysis was

$$\frac{B^2 - B_1^2}{W_{r_2}\, W_{z_2}} = \text{Constant} - B^2 \frac{\delta D_{z_2}}{D_{z_1}} \frac{U_{z_2}}{W_{z_2}} \tag{3}$$

where the values of B^2 and B_1^2 are as defined previously, W_{r_2} is the radial statistical weight of the test assembly.

$$W_z = \frac{\int_0^z \psi^2 \, dz}{\int_0^H \psi^2 \, dz} \tag{4}$$

$$U_z = \frac{\int_0^z (\nabla\psi)^2 \, dz}{\int_0^H (\nabla\psi)^2 \, dz} \tag{5}$$

z is the distance between the extrapolated top of the pile and the gas-D_2O interface in the test assembly, and H is the extrapolated pile height.

The $\delta D_z/D$ measurements were made at the 9.33- and 11.10-inch pitches for the fuel assemblies shown in Figure 1 with a variety of coolant channels and channel combinations empty of D_2O. The results of the measurements and of a corresponding set of calculations are plotted on Figure 5 as a function of the void-to-cell volume ratio "v". The measurements can be described reasonably well by a single function $\delta D_z/D = 1.528v + 0.016v^2$.

The calculated values of $\delta D_z/D$'s illustrate the importance of taking into account neutron streaming in the gas channels. This was done using the Benoist theory[8,9]. A model was chosen in which the materials on either side of a voided channel were homogenized. Values of $\delta D_z/D'$ were computed for fast neutrons

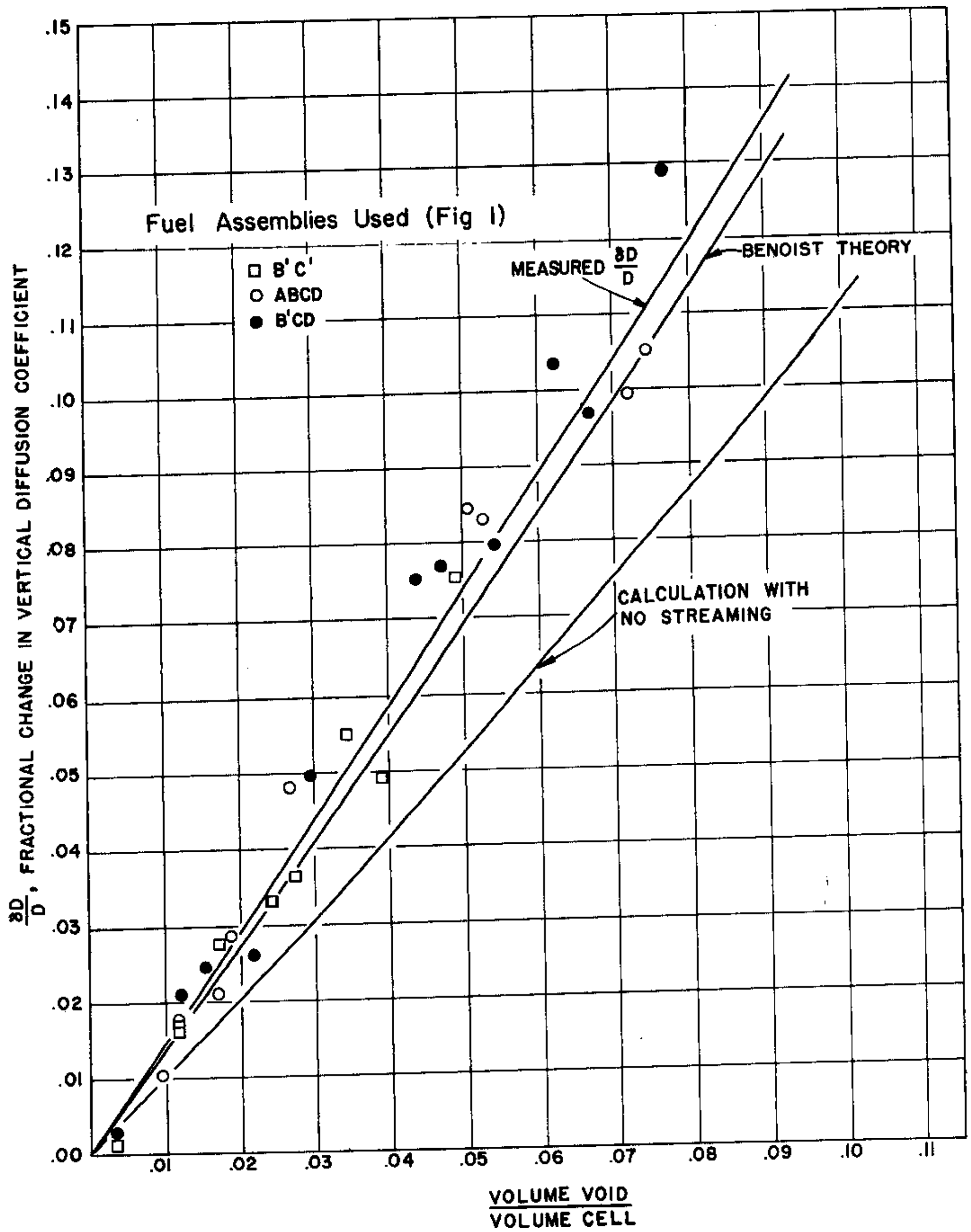


FIG. 5 CHANGE IN VERTICAL DIFFUSION COEFFICIENT ON VOIDING COOLANT CHANNELS IN D_2O-COOLED UO_2 FUEL ASSEMBLIES

only and single channel values were added to get the total change for all channels voided. Though in principle the calculations, like the measurements, are not single-valued functions of the void fraction, they were nearly so for these lattices and are shown that way. One reason the calculations slightly underestimate the measured changes is that the model used ignores reinforcement of streaming in several adjacent channels. However the reasonable agreement between calculations and measurements shows that this recipe is adequate for calculating changes in D for tubular fuel assemblies with small voided channels.

The value of $\delta D_r/D$ was also measured and calculated[9] for the B'C' assembly on the 11.10-inch pitch. The calculations agreed with the measurements, within the assigned error flags.

k_∞ Changes

The buckling changes due to expulsion of D_2O from the coolant channels of the B'C' and ABCD assemblies on the 11.10-inch pitch were converted to k_∞ changes by two methods. The first method depends on the anisotropic critical equation

$$k_\infty = (1 + \tau_z B_z^2 + \tau_r B_r^2)(1 + L_z^2 B_z^2 + L_r^2 B_r^2)$$

where z and r refer to vertical and radial directions in the pile.

$$\frac{\Delta k_\infty}{k_\infty} = \frac{k_\infty \text{ void}}{k_\infty \text{ no void}} - 1$$

The anisotropic values of L^2, the thermal diffusion area, and of τ, the neutron age, were computed using the results of the $\delta D_z/D$ measurements and $\delta D_r/D$ calculations. The L^2 changes were obtained from the equation

$$\frac{\Delta L^2}{L_o^2} = \frac{\Sigma_{ao}}{\Sigma_a} \frac{\Delta D}{D_o}$$

where the "o" subscript refers to the water-filled assembly. The L_o^2's, Σ_a's, Σ_{ao}'s, and D_o were obtained from a code employing the P_3 approximation to transport theory. The τ changes were computed using

$$\frac{\Delta\tau}{\tau_o} = \frac{\Delta D}{D_o} \frac{1}{1 - \frac{\text{volume void}}{\text{volume cell}}}$$

where τ_0 was computed assuming that slowing down took place only in the moderator.

The second method depends on reducing to insignificance the $B^2 \Delta M^2$ term in the relation $\Delta k_\infty = M^2 \Delta B^2 + B^2 \Delta M^2$. This is done by poisoning the lattice to zero buckling with copper tubing placed within the fuel assembly coolant channels. This technique is described in detail in Reference 10. The anisotropy term, α, was determined from additional $\delta D/D$ measurements which included the copper in the assemblies.

The $\Delta k_\infty / k_\infty$ results are given in Table III.

TABLE III

k_∞ Changes Due to Expelling D_2O Coolant[a]

Assembly[b]	Channels[b] Air Filled	$\Delta k_\infty / k_\infty$, % 1st Method[c]	Co Poisoning Method[c]
B'C'	All	1.14	1.10
	2,3,4	0.84	0.85
	3,4	0.73	0.67
	3	0.57	0.44
	4	0.19	0.28
ABCD	All	1.87	
	2,3,4,5	1.77	
	2,3,4	0.94	
	3,4	0.58	

(a) All measurements made with fuel assemblies on an 11.10-inch triangular lattice pitch in D_2O at 99.58 mol % isotopic purity at 22°C.
(b) See Figure 1 for key to assembly designation.
(c) See text for explanation of different methods.

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