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**APPROACH TO CRITICAL AND CALIBRATION EXPERIMENTS
IN THE
PLUTONIUM RECYCLE CRITICAL FACILITY**

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IN THE PLUTONIUM RECYCLE CRITICAL FACILITY

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APPROACH TO CRITICAL AND CALIBRATION EXPERIMENTS IN THE PLUTONIUM RECYCLE CRITICAL FACILITY

I. INTRODUCTION

The Plutonium Recycle Critical Facility (PRCF) is designed for investigations of reactor phenomena associated with either D_2O or H_2O moderator.

This report describes the initial approach to critical experiment and power level, control rod, and moderator level calibration experiments which were conducted in the PRCF when it was moderated with D_2O . Results of measurements of the longitudinal and radial flux distribution are included in a section separate from the power calibration. A section on control rod calibration presents the results of integral and differential worth measurements as measured by positive periods. A section on moderator level calibration presents the integral and differential worth of moderator level changes between 93 and 105 in. In a few cases the experimental results are compared to analytical results using three group diffusion theory.

The reactor is critical at a moderator level of 105 in. with 25 UO_2 fuel clusters surrounded by 30 Pu-Al fuel clusters at an 8 in. lattice spacing. Diffusion theory adequately describes the spatial distributions of the thermal neutron density. The maximum flux in the reactor is 4.6×10^8 neutrons/cm² sec at 100 w total power. The control rods are worth approximately 2 mk. The moderator level coefficient of reactivity is 0.16 mk/in. at 105 in.

II. FACILITY DESCRIPTION

The PRCF reactor vessel is a right circular cylinder 6 ft in diameter and 9 ft high. The side of the vessel is covered with 0.020 in. thick cadmium. The top of the vessel is covered by a top plate or grid. This grid is divided into

two parts, an inner and an outer template. The inner template is constructed so that it can be changed independently of the outer template. For loading studies which require heavy water moderator, the fuel elements are supported by both parts of the top grid. Since light water systems are characteristically smaller in radius and height than the D_2O systems, these loadings will occupy the region of the inner template. The fuel elements, in this case, will be supported by a bottom template which in turn hangs from the outer template.

The reactor configuration that is used for the D_2O moderated experiments is shown in Figures 1 and 2. Figure 1 shows the vertical position of reactor components relative to zero moderator level. This zero moderator level occurs at an elevation corresponding to -25 ft, 10 $\frac{7}{8}$ in. Figure 2 shows the radial position of reactor components.

FIGURE 1

Vertical Position of Reactor Components
(Positions are in in. and are relative to zero moderator level.
The CR, SR, VTM, and HTM represent control rods, safety
rods, vertical traverse mechanism and horizontal traverse
mechanism, respectively.)

FIGURE 2
Radial Position of Reactor Components

The fuel elements used in the experiments reported here are 19 rod clusters of natural UO_2 and 19 rod clusters of Pu-Al.^(1, 2, 3) Each fuel rod is 223 cm long and has a 0.0762 cm thick Zircaloy-2 cladding surrounding a core of 1.28 cm diameter. The plutonium fuel rods contain an alloy of 1.82 wt% plutonium in aluminum. Nominal values for the plutonium isotopic composition by weight are 93.97% Pu^{239} , 5.58% Pu^{240} , 0.44% Pu^{241} , and 0.014% Pu^{242} .

III. INITIAL APPROACH TO CRITICAL EXPERIMENT

The objective of this experiment was to achieve criticality with a two zone loading of UO_2 and Pu-Al fuel elements, with control and safety rods in their most reactive positions (withdrawn), and with the moderator level at 105 in. The reactor loading was first taken critical at a moderator level of 93 in. Subsequent adjustment of the loading resulted in criticality being achieved at 105 in. as required. The temperature of the moderator was ~ 25 C during these experiments.

The fuel arrangement which was expected to be critical was a central array of 25 UO_2 fuel elements and an annular array of 30 Pu-Al fuel elements. This estimate was made using data from the PRTR startup tests.⁽⁴⁾ Allowance was made for an increase in reactivity because of process tubes, shroud tubes, and helium gas gaps which occur in the PRTR but not in the PRCF. Likewise allowance was made for a loss in reactivity because of the safety rod voids and control rod poison which was present in the PRCF and not in the PRTR. The estimate was also corroborated by calculations made assuming three group diffusion theory.

The initial approach to critical was monitored with two BF_3 chambers connected to the PRCF instrumentation and six auxiliary BF_3 chambers and instrumentation. The radii and heights of the chambers are given in Table I. The multiplication data obtained are listed in Table II for all counters except Counters 4, 6, and E, which were not always in operation and a complete set of data is not available from them.

TABLE I

POSITIONS OF COUNTERS USED IN MULTIPLICATION MEASUREMENTS

Counter Number	Identification	Location	
		Radius, in.	Height from Zero Moderator Level, in.
1	1 2 in. BF_3 #5	12.20 F3	80.0
2	1 4 in. BF_3 #3	8.60 F2	30.0
3	1 4 in. BF_3 #4	13.45	60.25 (HFM)
4	1 2 in. BF_3 #3	3.46	60.25 (HFM)
5	1 4 in. BF_3 #2	4.62 F1(VFM)	67.0
6	1 2 in. BF_3 #6	4.62 F1(VIM)	54.0
PROF SCALER C	BF_3	33.75 C	53.63
PROF LCRME	BF_3	33.75 E	53.63

TABLE II

MULTIPLICATION DATA

The control rods are out, the neutron source is in, and the moderator level is at 105 in.

Loading Number	Number of Fuel Elements Loaded		Inverse Multiplication for Counter				
	UO_2	Pu-Al	1	2	3	5	C
0	0	0	100.00	100.00	100.00	100.00	100.00
1	7	0	66.5	79.7	54.1	73.9	33.5
2	13	0	56.4	74.7	30.8	53.3	73.2
3	19	0	49.8	67.9	41.3	46.5	72.2
4	25	0	42.32	53.35	32.70	39.7	66.6
5	25	3	13.32	40.0	12.59	--	42.90
6	25	2	16.49	43.5	13.3	13.03	44.74
7	25	5	7.43	31.23	7.63	3.5	33.33
8	25	6	6.19	25.0	5.79	6.91	29.93
9	25	8	4.346	21.13	4.608	3.279	26.32
10	25	12	3.01	15.13	2.91	3.40	20.24
11	25	15	2.02	11.11	1.97	2.26	15.47
12	25	18	1.45	8.34	1.395	1.61	11.65
13	25	21	0.849	5.176	0.812	0.945	6.903
14	25	23	0.573	3.434	0.527	0.63	4.91
15	25	25	0.361	2.344	0.344	0.395	3.13
16	25	27	0.266	1.700	0.245	--	2.50
17	25	29	0.134	0.829	0.117	0.133	1.21

Typical inverse multiplication plots are shown in Figure 3. Curve A is the average of the data in Table II for Counters 1, 3, and 5, whose behavior was very similar. Curve B is the data from Counter 2. The addition of Pu-Al elements to the less reactive loading of UO_2 fuel elements causes the initial increase of multiplication to be more rapid than subsequent loadings. Thus, the multiplication curves underpredict the critical number of fuel elements. This fact is corroborated by Curves C and D, which have been calculated using three groups of neutron energies and diffusion theory.⁽⁵⁾ Curves C and D differ only in that 24 mk and 27 mk, respectively, were assumed for the worth of the control and safety rod region.

FIGURE 3

Inverse Multiplication Curves from PRCF Startup

Curves A and B are experimental. The worth of the safety and control rod region was assumed to be 24 mk and 27 mk, respectively, for the calculated curves C and D.

The experimental curves are not continuous like the calculated curves because of the heterogeneity of elements being loaded at different radii. A heterogeneity also occurs within loadings at the same radius because of a difference in worth of an element near a control rod and one near a safety rod void. The calculations are based upon cross sections obtained from semiempirical studies of the results obtained at the startup of the PRTR.⁽⁴⁾ The nuclear parameters used in the calculations are listed in Table III. The regional radii and compositions of a lattice cell are shown in Figure 4. The radii and compositions of the annular regions which surround the central cell are listed in Table IV.

TABLE III

INPUT NUCLEAR PARAMETERS

The CR and SR are for control rod and safety rod channels

Material	D ₁ (cm)	D ₂ (cm)	D ₃ (cm)	Σ_{a1} (cm ⁻¹)	Σ_{a2} (cm ⁻¹)	Σ_{a3} (cm ⁻¹)	$(\nu\Sigma_f)_1$ (cm ⁻¹)	$(\nu\Sigma_f)_2$ (cm ⁻¹)	$(\nu\Sigma_f)_3$ (cm ⁻¹)	$\Sigma_s^{(1-2)}$ (cm ⁻¹)	$\Sigma_s^{(2-3)}$ (cm ⁻¹)	ν
UO ₂	1.700	0.9606	0.9155	0.00736	0.0335	0.1363	0.01591	0.00824	0.1800	0.0377	0.000983	2.46
Zr	1.727	1.059	1.282	--	--	0.0076	--	--	--	0.001316	0.0005316	--
D ₂ O	1.937	1.214	0.942	--	--	0.0001	--	--	--	0.0345	0.0136	--
Pu-Al	1.623	4.001	4.016	0.000357	0.0166	0.1226	0.000646	0.02404	0.2145	0.004868	0.0004279	2.84
Al	1.643	4.116	4.116	--	0.00087	0.0122	--	--	--	0.004667	0.0004625	--
Cd	1.937	1.214	0.942	--	--	0.100	--	--	--	0.0345	0.0136	--
24 mk CR & SR	2.078	1.350	1.049	--	0.00003	0.00204	--	--	--	0.0345	0.0136	--
27 mk CR & SR	2.078	1.350	1.049	--	0.00003	0.00230	--	--	--	0.0345	0.0136	--

FIGURE 4

Regional Radii and Compositions of a Lattice Cell

TABLE IV

ANNULAR REGIONS SURROUNDING THE CENTRAL CELL

Region Number	Outer Radius, cm	Composition
14	53.45	24 cells homogenized with Pu-Al in Fuel Regions 1, 5, and 9
15	56.455	3 cells homogenized with Pu-Al in Fuel Regions 1, 5, 9
16	59.4025	3 cells homogenized with Pu-Al in Fuel Regions 1, 5, 9
17	64.897	Region simulating three safety and three control rod channels
18	82.6417	23 cells homogenized with Pu-Al in Fuel Regions 1, 5, 9
19	83.3275	1 cell homogenized with Pu-Al in Fuel Regions 1, 5, 9
20	91.44	D ₂ O reflector
21	92.075	Aluminum tank wall
22	92.126	Cadmium sheet

The inverse multiplication data extrapolated to a total of 25 UO_2 and 31 1/2 Pu-Al fuel elements for the critical loading. Since all fuel channels were loaded with 25 UO_2 fuel elements and 30 Pu-Al elements, a UO_2 fuel element in Ring 4 was exchanged for a Pu-Al fuel element in Ring 8. This adjustment allowed criticality to be achieved with 25 UO_2 and 30 Pu-Al fuel elements as arranged in Loading 18 shown in Figure 5. The exchange was the movement of a Pu-Al fuel element from Position 517 to 313 and a UO_2 from Position 313 to 517 (Figure 2). The reactor was supercritical with this loading at a moderator height of 93.00 in. and a period of 50 sec (excess reactivity of 0.86 ± 0.02 mk) with all the control rods withdrawn.

The fuel loading was subsequently adjusted to the loading shown in Figure 6 to achieve criticality at a moderator level of 105 in. An aluminum guide tube, 5.0 in. OD with 1/8 in. thick wall and open at both ends was placed in Position 509. The Pu-Al was put back in Ring 8 and the UO_2 was put back in Ring 4 as previously loaded. Also the Pu-Al fuel elements in Positions 604, 210, and 713 were exchanged for UO_2 elements in Positions 705, 208, and 614, respectively. Although the latter exchanges occurred at the same radii and therefore no change in reactivity would be expected, the total excess reactivity of the loading was increased. This occurred because the Pu-Al elements were removed from control rod channels and positioned near safety rod channels. The flux near safety rods is increased relative to that near control rods when the rods are withdrawn because cadmium from the control rods is always present in the reactor (Figure 1). This fuel loading (Loading No. 20) was taken supercritical on a 40.0 sec period at a moderator height of 105 in. Control Rods 1 and 2 were fully withdrawn (6 in.) and Control Rod 3 was withdrawn 5 in. The total excess reactivity for Loading No. 20 with the control rods withdrawn and a moderator level of 105 in. was 1.36 ± 0.03 mk.

FIGURE 5
PRCF Loading No. 18

FIGURE 6
PRCF Loading No. 20

IV. MODERATOR LEVEL COEFFICIENTS

Coefficients of reactivity for moderator level changes were measured as the loading was adjusted for critical levels between 93 and 105 in. The measurements are of use in determining values of excess reactivity and changes in moderator heights required to compensate for fuel changes. Period measurements taken in Fuel Loadings 18 through 21 were used for the calibration.

The results are listed in Table V and presented graphically in Figure 7. The fuel loading is identified symbolically for each coefficient in Figure 7. The uncertainties in the coefficients are due primarily to uncertainties in the period measurements. The determination of uncertainties in period measurements is described in the Appendix. The effective fraction of delayed neutrons and the neutron lifetime which were used to convert periods to reactivity are 4.63×10^{-3} and 0.8 msec, respectively.⁽⁶⁾

Integration of the curve in Figure 7 results in the total reactivity change for a given change in moderator level. For a change in moderator level from level L to 105.25 in., the change in reactivity $\Delta \rho_L$ is given by

$$\Delta \rho_L = L(6.785 - 0.03150L) - 365.18 \text{ for } 99.7 \leq L \leq 105.25$$

and

$$\Delta \rho_L = L(5.652 - 0.02585L) - 308.38 \text{ for } 93.0 \leq L \leq 99.7$$

V. SPATIAL DISTRIBUTIONS OF NEUTRON DENSITY

Reaction rates of $1/v$ and non- $1/v$ detectors were used to determine the spatial distributions of the neutron density. The $1/v$ measurements were made with bare and cadmium covered BF_3 proportional counters. The counters traveled in tubes vertically in hole F-1 and horizontally at a height corresponding to a moderator level of 60.25 in. and midway between two parallel rows of lattice cells (Figure 2). Gold

TABLE V
MODERATOR LEVEL COEFFICIENTS OF REACTIVITY

<u>Loading Number</u>	<u>Period Number</u>	<u>Moderator Level, in.</u>	<u>Average Period, sec</u>	<u>Mean Moderator Level, in.</u>	<u>Moderator Level Coefficient, mk/in.</u>
18	1, 2, 3 04	93.000	51.600	92.875	0.85 ± 0.05
		92.752	77.800		
19	06 07	95.000	94.5	95.25	0.73 ± 0.06
		95.50	44.348		
20	09 10	101.0	237.	101.5	0.33 ± 0.03
		102.0	83.243		
20	11 12	102.0	86.416	102.5	0.33 ± 0.04
		103.0	44.074		
20	13 15	103.0	98.282	103.5	0.25 ± 0.03
		104.0	56.077		
20	15 16	104.0	56.077	104.5	0.20 ± 0.03
		105.0	39.097		
21	25 26	105.0	30.224	104.0	0.24 ± 0.02
		103.0	74.250		
21	26 27	103.0	74.250	102.7	0.29 ± 0.05
		102.4	113.442		
21	28 29	102.4	39.169	101.9	0.39 ± 0.03
		101.4	84.180		
21	29 30	101.4	84.180	101.3	0.4 ± 0.1
		101.15	108.417

FIGURE 7

PRCF Moderator Level Coefficient Versus Moderator Level

Loadings 18 and 21 are the same as Loadings 19 and 20, respectively, except for a guide tube added to the central fuel element positions.

foils were activated along these same tubes to obtain the reaction rate of non- $1/v$ detectors. The gold foils were calibrated in a known flux and used to determine the flux in the PRCF for a given level of irradiation.

A. Reaction Rates of BF_3 Chambers

The spatial distributions of $1/v$ reaction rates were measured with BF_3 proportional counters. One half inch diameter chambers were covered with 0.040 in. thick cadmium to measure the relative magnitude of the epithermal flux. Both ends of the cadmium were covered except for a $1/8$ in. diameter cable hole at one end which was the only nonabsorbing path. The covers were 8 in. long and the center of a chamber was placed $5 \frac{1}{2}$ in. from the hole to minimize the solid angle subtended at the cable hole. The bare chambers were $1/4$ in. in diameter. A pair of chambers, a $1/4$ in. bare and cadmium covered $1/2$ in. chamber, was placed 13 in. on centers in the vertical and horizontal traverse tubes. This separation placed the nearest end of the cadmium $6 \frac{1}{2}$ in. from the end of the $1/4$ in. BF_3 . This separation reduced the interaction of bare and cadmium counters to a negligible amount. The counting rates of the $1/4$ in. chambers were normalized to counting rates of $1/2$ in. chambers for calculation of cadmium ratios. This normalization was based upon calibrations obtained in a standard pile.

Spatial distributions of the total (bare) and epicadmium reaction rates in the vertical and horizontal directions are shown in Figures 8 and 9, respectively. Since these were measured with BF_3 proportional counters they represent distributions of neutron density. The agreement between thermal plus epithermal and epithermal density distributions in Figure 8 indicates equal bucklings for these groups of neutrons for the bare core. The end reflectors change the relative flux shapes near the core-reflector interface. The dashed curves in Figure 8 are cosine curves which best fit the points which are not affected by the end reflectors. The fits were made by the method of least squares and are described in Section VC.

FIGURE 8

Vertical Traverse with BF_3

Count rates from a bare 1/4 in. BF_3 and a Cd covered 1/2 in. BF_3 in hole F-1 are shown as dots . and circles o , respectively.

FIGURE 9

Horizontal Traverse with BF_3

Count rates from a bare 1/4 in. BF_3 and a Cd covered 1/2 in. BF_3 are shown as dots · and circles o, respectively.

The bare and cadmium covered counters have been calibrated to yield values of the cadmium ratio both horizontally and vertically. These values are shown in Figures 10 and 11. The BF_3 counters were calibrated in a standard pile and the calibration constant is 9.776. The constant converts a ratio of a 1/4 in. bare BF_3 count and 1/2 in. cadmium covered BF_3 count to a cadmium ratio. The solid curves in Figures 10 and 11 are "visual fits" to the experimental data. Figure 10 shows a constant cadmium ratio except near the top of the fuel where the effects of the D_2O reflector are present.

FIGURE 10

Cadmium Ratio of BF_3 in Hole F-1

The ratio of interpolated bare to experimental Cd covered count rates and the ratio of experimental bare to interpolated Cd covered count rates are shown by circles o and dots ·, respectively.

FIGURE 11

Cadmium Ratio of a BF_3 Counter Versus Horizontal Position

The ratio of interpolated bare to experimental Cd covered count rates and the ratio of experimental bare to interpolated Cd covered count rates are shown as circles $\circ$ and triangles Δ , respectively. The Ratio of experimental bare to experimental Cd covered count rates are shown as dots $\cdot$.

B. Reaction Rates of Gold Foils

The spatial distributions of non- $1/v$ reaction rates were measured with gold foils. A vertical and horizontal traverse were taken using 0.500 in. diameter by 0.006 in. thick gold foils. The activity measurements of the foils in each traverse were decay corrected to a common time and normalized to a monitor foil located near the center of the assembly. The vertical traverse is shown in Figure 12 and the horizontal traverse is shown in Figure 13.

The relative fluxes were converted to absolute fluxes by irradiating gold foils in a known thermal flux in a standard pile. A bare and a cadmium covered foil were symmetrically located near the source in the pile. The foils

FIGURE 12

Vertical Traverse with Gold

The foils were 0.006 in. thick x 1/2 ft OD and were placed relative to zero moderator level in Loading 20. The curve is the cosine fit to the data points between 17 and 85 in.

FIGURE 13

Horizontal Traverse with Gold

The foils were 0.006 in. thick x 1/2 in. OD and were placed relative to the center of the HTM in Loading 20.

were irradiated to within 92% of saturation. In measuring the activities of the irradiated foils the same counting systems were used as in the counting of the activities of PRCF foils. Thus counter efficiencies were absorbed into the calibration factor.

The specific activities which resulted from the standard pile irradiation were computed from the foil activities. The specific activities in conjunction with the value of the thermal flux in the standard pile and the absorption cross section for gold⁽⁷⁾ allowed the calibration factor to be calculated.

The specific activities were computed also for the two monitor foils irradiated in the PRCF. The calibration factor was applied to each of the two activities converting them to a value of the flux in which the foil was irradiated.

The monitor foil for the horizontal traverse was located at a moderator height of 60.25 in. and 3.46 in. radially from the center of the reactor. The absolute thermal flux corresponding to this position was $(6.2 \pm 0.2) \times 10^7$ neutrons/sec-cm².

The monitor foil for the vertical traverse was located at a moderator height of 56.0 in. and 4.62 in. radially from the center. The absolute thermal flux corresponding to this position was $(6.8 \pm 0.2) \times 10^7$ neutrons/sec-cm².

The maximum thermal flux for the irradiation in Loading 20 occurs at a moderator level of 51.94 in. and 4.62 in. radially and is equal to $(6.9 \pm 0.2) \times 10^7$ neutrons/cm²-sec. The current from the differential galvanometer was nulled during the irradiation when the voltage divider read 0.989 times the bucking voltage of 4.998 v and the Doubling Switch was at 2⁸. The operation of the galvanometer is described in the discussion of Period Measurements (page 41). The meter readings from Log Channels No. 1 and No. 2 were 3.9×10^{-1} . The readings from Linear Channels No. 1 and 2 were 59 x 1.5 and 44 x 1.5, respectively. All PRCF chambers including the galvanometer chamber are located at a radius of 33.75 in. and vertically at a moderator height of 53.63 in.

C. Calculated and Observed Distributions

The experimental reaction rates have been compared to those which are expected in the PRCF. The vertical distributions have been compared to cosine functions. The horizontal and vertical spatial effects have been compared to radial and vertical distributions calculated using one dimensional diffusion theory with three energy groups of neutrons.

The vertical distributions as determined by gold foils and BF_3 counters are compared in Figure 14. The spatial distributions as measured with bare and cadmium detectors have been fit by a function of the form

$$\varphi = P_1 \cos P_2 (H - P_3).$$

The P_1 is a normalization constant, P_2^2 is the vertical buckling B^2 , H is the height of the detector in terms of moderator level, and P_3 is the line of symmetry of the cosine function. The fitting was accomplished by the method of least squares using the program GLEX.^(8, 9) The parameters for the cosine function which best fit the data are listed in Table VI. The curves are shown in Figures 8 and 12 as dashed lines. The effect of the top and bottom reflectors are demonstrated by the deviation of the data points from the dashed lines.

The deviations are described by diffusion theory as shown in Figure 14 by the solid curve. The curve is the result of a calculation of the flux in a D_2O reflected slab reactor. The geometry of the slab is equivalent to the vertical geometry of the PRCF and the cross sections are the homogenized cross sections of Table III. In the reflector regions, the cross sections are those of D_2O homogenized with Zircaloy-2 or aluminum as required because of the Zircaloy-2 at the end of the fuel elements and the aluminum present in the PRCF reflectors. The aluminum occurs because of a grid plate in the bottom reflector and because of support beams for the top template. In the calculation, the slab reactor was reflected successively by regions of 8.6% Zr + 91.4% D_2O , 4.3% Zr + 90% D_2O + 5.7% Al, 88.6% D_2O + 11.4% Al, and 100% Al for the top reflector, and by 8.6% Zr + 91.4% D_2O , 100% Al, 8.6% Zr + 91.4% D_2O , 100% D_2O , and 100% Al for the bottom reflector.

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The vertical distributions are symmetric about the center which occurs at a height corresponding to a moderator level of 50.6 or 51.9 in. as determined by the BF_3 chamber or the gold foils, respectively. The centers of the distributions should be equal to ~ 52.6 in. which is $1/2$ of the height of the moderator level for the measurements. Since this is corroborated by the gold foil data and not the BF_3 data, it is suspected that the position calibration of the BF_3 chambers was low by ~ 1.3 in. This is reasonable since the calibration depends on knowing where the effective centers of the chambers are and since the gold foils could be positioned more precisely than the chambers.

The total vertical buckling and the buckling for neutrons with energies above the cadmium cutoff was found to be $1.45 \times 10^{-4} \text{ cm}^{-2}$ and $1.41 \times 10^{-4} \text{ cm}^{-2}$. This is compared to values of $B_1^2 = B_2^2 = 1.975 \times 10^{-4} \text{ cm}^{-2}$ and $B_3^2 = 1.348 \times 10^{-4} \text{ cm}^{-2}$ which have been used in the diffusion theory calculations for the fast or epithermal bucklings and the thermal bucklings, respectively. For values of the slowing down areas τ_1 , τ_2 , and L^2 of 57.8, 96.1, and 163 cm^2 the total vertical buckling which is assumed for the calculations is $1.65 \times 10^{-4} \text{ cm}^{-2}$.

The horizontal distributions as measured with gold foils and BF_3 counters are compared in Figure 15. The effect of the asymmetry of the loading (No. 20, Figure 6) is apparent in the figure. A hump in the curves appears at 20 in. SSW due to the void of the safety rod thimble (Position 206) and due to the higher concentration of Pu-Al fuel elements as compared to the NNE end of the traverse. Also, on the NNE side of the center, there is a flux depression caused by the cadmium of the control rod. The major asymmetry along the SSE-NNE line is due to the extra Pu-Al on the SSW side. This fact is corroborated by the traverses obtained in the PRTR where the only perturbation was one extra Pu-Al at one end of the traverse. (10) In the latter case the flux near the Pu-Al was enhanced by $\sim 29\%$ which is equivalent to the enhancement observed in the PRCF. The large depression observed at the center of the curves in Figure 15 is due to an aluminum guide tube, 5 in. in diameter with a $1/8$ in. thick wall, which is coaxial with

the central cell. Another effect is cell fine structure. On the NNE side of center there is a slight depression in the curve which represents the gold data. This depression is caused by a cadmium covered foil which was placed at Position 11.4 in. The depressions are propagated for about one lattice unit (8 in.) which is equal to a diffusion length for thermal neutrons in the loading.

FIGURE 15

Comparison of Bare Au and BF₃ Reaction Rates

The gold activity and BF₃ count rates are shown as circles $\circ$ and dots $\bullet$, respectively.

An unweighted average of the shape of the two halves of the horizontal traverse is compared in Figure 16 with the shape as computed assuming three group diffusion theory to be valid. The points which are plotted as experimental points are the average of the gold activity at corresponding points NNE and SSW of the center. The error flags represent the asymmetry of the two directions since if the ends of their error bars are connected the upper curve would be the SSE traverse and the lower curve would be the NNE traverse. The solid line is the result of the diffusion theory calculation.

The diffusion theory calculations were made using the code SWAP⁽⁵⁾ written for the IBM 7090. The code SWAP yields, as a portion of its output, the spatial distribution of the three group fluxes. Values of these fluxes which are listed in the output are proportional to values of the spatial distribution of the respective fluxes. The magnitude of a flux for one group of neutrons relative to those of the other groups have been determined experimentally.

The space-energy distribution of neutrons is assumed to have the form⁽¹¹⁾

$$\bar{\phi}(\vec{r}, E) = \gamma_3(\vec{r}) M(E, T_n) + \gamma_2(\vec{r}) \frac{\Delta}{E} + \gamma_1(\vec{r}) F(E) \quad (1)$$

The γ_3 , γ_2 , and γ_1 are the spatial distributions of the thermal, epithermal, and fission neutron groups, respectively, and

$\vec{r}$ = symbol of the space coordinates,

E = neutron energy,

T_n = effective temperature of the neutrons comprising
Group 3

$$\Delta = \begin{cases} 1 & \text{for } E \geq \mu k T_n \\ 0 & \text{for } E < \mu k T_n \end{cases}$$

and $\mu \approx 5$

The function

$$M(E, T_n) = E/(kT_n)^2 e^{-E/kT_n}$$

and $F(E)$ is the energy distribution of fission neutrons and not of concern in this discussion. The reaction rates of interest are those relative to the zero radius value, $A_B(o)$. They have been calculated with the expression

$$\frac{A_B^x(r)}{A_B^x(o)} = \frac{\int_0^\infty \sigma^x(E) F(E, r) dE}{\int_0^\infty \sigma^x(E) F(E, o) dE} = R_B^x(r) \quad (2)$$

where x refers to the detector isotope and $\sigma^x(r)$ to its activation cross section.

The ratio becomes

$$R_B(r) = \frac{\varphi_{s3}(r) + k \varphi_{s2}(r)}{\varphi_{s3}(o) + k \varphi_{s2}(o)} \quad (3)$$

where

$$k = C \left\{ \frac{D_{th}}{\frac{\sqrt{\pi}}{2} \sigma_o f} \left(RI_{ec} + \frac{RI_{es}}{D_{es}} \right) \right\}. \quad (4)$$

The φ_{s3} and φ_{s2} are respectively the thermal and epithermal fluxes as calculated with the SWAP code. The other parameters are defined as follows:

σ_o = microscopic activation cross section at 2200 m/sec

f = non- $1/v$ correction factor

$D_{th}(t)$ = average foil disadvantage factor for thermal Maxwellian neutrons
(ratio of surface flux to average flux in foil of thickness t)

$D_{es}(t)$ = average foil disadvantage factor for epithermal subcadmium neutrons

RI_{ec} = effective epicadmium resonance integral

RI_{es} = epithermal - subcadmium resonance integral.

The quantity C is a constant determined experimentally and relates the ratio $\frac{\varphi_3}{\varphi_2}$ of the actual thermal and epithermal fluxes to the ratio $\frac{\varphi_{s3}}{\varphi_{s2}}$ of those calculated by SWAP. The ratio $\frac{\varphi_{s3}}{\varphi_{s2}} \approx 1.672$ at $r = 11.7$ in. and therefore

$$C = 1.672 \frac{\varphi_2(11.7)}{\varphi_3(11.7)} \quad (5)$$

$$= 1.672 \frac{\frac{\sqrt{\pi}}{2} \epsilon_0 f}{RI_{ec} D_{th}} \left[\frac{CdR}{1.02} - 1 \right]^{-1} \quad (6)$$

where CdR is the value of a gold cadmium ratio at 11.7 in. This value was measured as 8.2 ± 0.2 for a 1/2 in. OD by 0.006 in. thick gold foil. Therefore

$$k = 0.237 \left\{ 1 + \frac{RI_{es}}{D_{es} RI_{ec}} \right\} = 0.272 \pm 0.008 \quad (7)$$

where $D_{es}^{(11)}$, $RI_{es}^{(11)}$, $RI_{ec}^{(11,12)}$ are 1.0466, 52 barns, and 333 barns, respectively, for the 0.006 in. thick gold foils. The value for RI_{ec} was obtained by using the data from Reference (12) to reduce the infinitely dilute resonance integral $RI_{ec} = 1553$ barns⁽¹¹⁾ to the effective resonance integral for a 0.005 in. thick foil. Then the data in Reference (11) were used to find the effective resonance integral for a 0.006 in. thick foil from that for the 0.005 in. thick foil. Thus

$$R_B^{Au}(r) = \frac{\varphi_{s3}(r) + 0.272 \varphi_{s2}(r)}{\varphi_{s3}(o) + 0.272 \varphi_{s2}(o)} \quad (8)$$

The plot of $R_B^{Au}(r)$ is shown in Figure 16 as the solid curve.

FIGURE 16

Calculated and Observed Au¹⁹⁸ Activity

The top of the error flags define the SSW traverse and the bottom the NNE traverse. The dashed line is an average experimental curve and the solid line is the calculated curve.

VI. ABSOLUTE POWER LEVEL OF PRCF

The absolute power level of a reactor is proportional to the total fission rate of the fissile material. Hence one must sum the product of the neutron flux and the fission cross section over all volumes which contain fuel. For a homogeneous right cylinder the power level P is given by

$$P = C \left[2 \int_0^{H/2} dz \int_0^R 2\pi dr \varphi(r, z) \Sigma_f(r) \right]. \quad (9)$$

The symbols used in this section are summarized in Table VIII at the end of the section. In Equation (9) the units of the quantity in the bracket is fissions per second and the constant C converts the fission rate to more familiar power units. The PRCF is a heterogeneous system and so Equation (9)

is replaced by the finite sum

$$P = C \left(\frac{2V_r}{BH} \bar{\phi}(0,0) \sum_{j=0}^8 \left\{ \frac{\phi(r_j,0)}{\bar{\phi}(0,0)} \Sigma_f(r_j) n_j \left[\sum_{i=1}^3 (m_i \phi_i / \phi_1) \right]_j \right\} \right) \quad (10)$$

using the definitions

$$\bar{\phi}(r,z) = \bar{\phi}(0,0) f(r) g(z) \quad (11)$$

$$2 \int_0^{H/2} dz g(z) = 2 \int_0^{H/2} dz \cos Bz = \frac{2}{B} \sin \frac{BH}{2} \quad (12)$$

$$2\pi \int_0^R r dr f(r) = \frac{V_r}{H} \sum_{j=0}^8 \left\{ \frac{\phi(r_j,0)}{\bar{\phi}(0,0)} \Sigma_f(r_j) n_j \left[\sum_{i=1}^3 (m_i \phi_i / \phi_1) \right]_j \right\}. \quad (13)$$

The result of the summation over i is a disadvantage factor accounting for the different average fluxes in the three rings of rods of a 19 rod cluster. The result of the summation over j is the individual fission rates summed over rings of clusters and the number of clusters per ring.

A. Disadvantage Factor

The value of disadvantage factor $\sum_{i=1}^3 (m_i \phi_i / \phi_1)$ was computed in two ways for a UO_2 cluster and a Pu-Al cluster. For each fuel cluster experimental data and analytical data were used. Ratios of bare Lu^{177} data obtained during the PRTR critical tests were taken as equivalent to the ϕ_i / ϕ_1 ratio since Lu^{177} is a good thermal neutron detector and the spectral index is relatively constant in the fuel. The theoretical values were calculated using diffusion theory and assuming three energy groups of neutrons. The results are listed in Table VII. The analytical and theoretical disadvantage factors agree within 5% and 1% for the UO_2 and Pu-Al fuel elements.

TABLE VII
DISADVANTAGE FACTORS FOR Pu-Al AND UO₂

	<u>Pu-Al</u>		<u>UO₂</u>	
	<u>PRTR^(a)</u>	<u>SWAP 3059</u>	<u>PRTR^(a)</u>	<u>SWAP 3058</u>
φ_1 / φ_1	1.000	1.000	1.000	1.000
φ_2 / φ_1	1.0165	1.0214	1.0185	1.0489
φ_3 / φ_1	1.0824	1.0952	1.0982	1.1880
$\sum_{i=1}^3 (m_i \varphi_i / \varphi_1)$	20.09	20.27	20.29	21.55
$m_1 = 1, m_2 = 6, m_3 = 12$			PRTR 20.19 $\pm$ 1 1/2%	
			SWAP 20.91	

(a) Reference (4), pp. 94-101

B. Relative Flux Per Ring

The radial distribution of the neutron density (Figure 16), as measured with gold foils placed on the Horizontal Traverse Mechanism (HTM) has been used in determining the flux ratio $\varphi(r_j, o) / \varphi(o, o)$. If one defined a cell disadvantage factor $F(r_i)$ (ratio of counting rate at the center of a cell to the counting rate at the traverse point in the cell) and counting rates $CR(r_j, o)$ from gold foils then the flux ratio is given by

$$\varphi(r_j, o) / \varphi(o, o) = \frac{F(r_j) CR(r_j, o)}{F(o) CR(o, o)} \quad (14)$$

It has been assumed that the energy distribution of neutrons is invariant in the lattice region. Cadmium ratio data which have been presented verify this assumption for a major portion of the system. The ratio $F(r_j) / F(o)$ is unity for like fuel elements if the counting rates are measured at similar positions in the two lattice cells of concern

The Lu^{177} and $\text{Lu}^{176\text{m}}$ data ⁽⁴⁾ which were obtained in UO_2 and Pu-Al cells during the startup of the PRTR have been used to obtain values of this ratio. Before the ratios were calculated the activation data which were obtained with bare foils were corrected for epithermal effects and neutron temperature effects for the $\text{Lu}^{176\text{m}}$ and Lu^{177} activities, respectively. The experimental data resulted in values of 0.63 ± 0.02 and 0.69 ± 0.01 for the ratio $F(r_j)$ for UO_2 and Pu-Al cells, respectively. The cell flux calculated using one dimensional diffusion theory resulted in corresponding values of 0.63 and 0.71. In the power calibration experiment a UO_2 fuel element was in the central position. Therefore $F(o)$ is the value of $F(r_j)$ for a region which contains UO_2 elements and the experimental value of 1.10 ± 0.04 is obtained for $\frac{F(r_j)}{F(o)}$ in a region which contains Pu-Al elements. The analytical value for the same region is 1.13 which agrees very well with the experimental value. To calculate the sum over j in Equation(10) the values 1.00 and 1.10 were used for UO_2 and Pu-Al regions, respectively

C Reduced Power Equation

The macroscopic cross sections $\Sigma_f(r_j)$ of the UO_2 and Pu-Al fuel rods are 0.0732 cm^{-1} and 0.0755 cm^{-1} , respectively. These values when combined with the results of previous sections result in a value of 54.10 for the quantities summed over j in Equation (10). Since $B^2 = 1.46 \times 10^{-4} \text{ cm}^{-2}$ and $\frac{V_r}{H} = 1.298 \text{ cm}^2$ the power Equation (10) can be reduced to

$$P = (3.67 \pm 0.15) \times 10^{-7} \phi(o, o) = k \phi(o, o) \quad (15)$$

where $\phi(o, o)$ is in neutrons/ cm^2 -sec. The value for k which is obtained if analytical values are used throughout the calculation is 3.79×10^{-7} .

D. Power Level of 100 Watts

When the meters of the Log Channels read 3.9×10^{-1} the maximum flux is $(6.9 \pm 0.2) \times 10^7$ neutrons/ cm^2 -sec at a moderator level of 51.94 in. and at a radial position of 4.62 in. (Section V B). The cell disadvantage factor for this position is 0.60 ± 0.02 which results in

$$\phi(o, o) = (4.1 \pm 0.2) \times 10^7 \text{ neutrons/cm}^2\text{-sec}$$

since $Z = 0$ corresponds to a moderator level of 51.94 in. The power level for this value of the flux is 15.1 ± 0.8 w. Thus, the Log Count-Rate Meter reads 8×10^5 at 0.010 w and at 100 w

$$\phi_{\max} = (4.6 \pm 0.3) \times 10^8 \text{ neutrons/cm}^2\text{-sec} \begin{cases} Z = 0.0 \text{ in.} \\ R = 4.62 \text{ in.} \end{cases}$$

Log #1 and #2 Meter = 2.6

Linear #1 Meter = 39 x 15

Linear #2 Meter = 29 x 15

Differential Galvanometer Null at

Bucking Voltage = 4.998 v

Voltage Divider = 0.410 x Bucking Voltage

Doubling Switch = 2^{12}

TABLE VIII

SYMBOL DEFINITIONS FOR EQUATIONS OF SECTION VI

Symbol	Definition	Units
P	Total Power	watts
C	Conversion Constant = 3.15×10^{-11}	watts/fission/sec
H	Total fuel rod length	cm
R	Radius of fuel core	cm
r	Radial distance	cm
Z	Height from midplane	cm
$\phi(r, Z)$	Spatial distribution of the neutron flux	neutrons/cm ² /sec
$\Sigma_f(r_1)$	Macroscopic fission cross section of fuel in ring 1	cm ⁻¹
$\phi(0, 0)$	Neutron flux at the center of the center rod of the central cluster	neutrons/cm ² /sec
f(r)	Radial component of neutron flux	
g(Z)	Vertical component of neutron flux	
B ²	Vertical buckling	cm ⁻²
V _r	Volume of a single rod of a cluster	cm ³
r _j	Radius of the j th ring of clusters	cm
$\phi(r_j, 0)$	Neutron flux at the center of the center rod of a cluster in ring j	neutrons/cm ² /sec
n _j	Number of fuel clusters in ring j	
m ₁	Number of fuel rods in the 1 th ring of a cluster = 1, 6, or 12	
$\bar{\phi}_1$	Average flux in the 1 th ring of cluster	neutrons/cm ² /sec
ϕ_1	Flux at center of the center rod of a cluster	neutrons/cm ² /sec

VII. CONTROL ROD CALIBRATIONS

The three control rods of the D_2O moderated PRCF have been calibrated by supercritical period measurements. The calibration was made in Fuel Loading No. 35 which is shown in Figure 17. The total travel of Control Rods No. 1 and 2 was calibrated in six equal increments of 1 in. per increment and Control Rod No. 3 was calibrated in 12 equal increments of 1/2 in. per increment.

FIGURE 17
PRCF Loading 35

Each control rod consists of a 1.000 in. OD with 0.088 in. wall aluminum tube which travels vertically inside a 1.315 in. OD with 0.055 in. wall aluminum tube. Both tubes are enclosed in a 1.660 in. OD with 0.140 in. wall aluminum thimble which is inserted in the moderator and filled with air. A control rod assembly is shown in Figure 18. The total travel of the inner cylinder from the "full in" position to the "full out" position is 6 in. Both cylinders have alternate 6-in. long regions on their outer surfaces, which are coated with 25 mil thick cadmium, as shown in Figure 1. The reactivity of the PRCF is increased by raising the inner cylinder so that its cadmium sections are shaded from thermal neutrons by the cadmium sections of the outer cylinder.

FIGURE 18
Control Rod Assembly

At the beginning of the calibration Control Rods No. 1 and 2 were in their out position (6 in.) and Control Rod No. 3 was in its in position (0 in.). The change in reactivity which resulted from withdrawing a 1/2 in. increment of No. 3 was determined by measuring the period before and after the change. The changes in reactivity from withdrawing 1 in. increments of No. 3 were determined after the initial 1/2 in. increment. When the periods became short and it was necessary to adjust the reactivity, Control Rod No. 2 was inserted and reactivity changes were determined for 1 in. increments of Control Rod No. 2. These calibrations were repeated until Control Rod No. 2 was completely in and No. 3 out. The same procedure was repeated with Control Rod No. 2 and No. 3 except that all increments were 1 in. for No. 3 also.

The reactivity values are tabulated in Table IX under Differential Worth. The sum of the individual increments appear under Accumulative Worth. The differential worth which is the reactivity resulting from an incremental change in position of a control rod divided by the length of the increment is plotted in Figures 19, 20, and 21. The value for a differential worth is plotted at the midpoint of the increment. In the same figures are plots of the integral or accumulative worth for each rod.

TABLE I
REACTIVITY VALUES

Control Rod	Position (in.)	Reactivity (k)	Period (sec)	Differential Worth (k/in.)	Accumulative Worth (k)
Control Rod No. 1					
Out	6	0.000	0.000	0.000	0.000
In	5.5	0.000	0.000	0.000	0.000
In	5.0	0.000	0.000	0.000	0.000
In	4.5	0.000	0.000	0.000	0.000
In	4.0	0.000	0.000	0.000	0.000
In	3.5	0.000	0.000	0.000	0.000
In	3.0	0.000	0.000	0.000	0.000
In	2.5	0.000	0.000	0.000	0.000
In	2.0	0.000	0.000	0.000	0.000
In	1.5	0.000	0.000	0.000	0.000
In	1.0	0.000	0.000	0.000	0.000
In	0.5	0.000	0.000	0.000	0.000
In	0.0	0.000	0.000	0.000	0.000
Control Rod No. 2					
Out	6	0.000	0.000	0.000	0.000
In	5.5	0.000	0.000	0.000	0.000
In	5.0	0.000	0.000	0.000	0.000
In	4.5	0.000	0.000	0.000	0.000
In	4.0	0.000	0.000	0.000	0.000
In	3.5	0.000	0.000	0.000	0.000
In	3.0	0.000	0.000	0.000	0.000
In	2.5	0.000	0.000	0.000	0.000
In	2.0	0.000	0.000	0.000	0.000
In	1.5	0.000	0.000	0.000	0.000
In	1.0	0.000	0.000	0.000	0.000
In	0.5	0.000	0.000	0.000	0.000
In	0.0	0.000	0.000	0.000	0.000
Control Rod No. 3					
Out	6	0.000	0.000	0.000	0.000
In	5.5	0.000	0.000	0.000	0.000
In	5.0	0.000	0.000	0.000	0.000
In	4.5	0.000	0.000	0.000	0.000
In	4.0	0.000	0.000	0.000	0.000
In	3.5	0.000	0.000	0.000	0.000
In	3.0	0.000	0.000	0.000	0.000
In	2.5	0.000	0.000	0.000	0.000
In	2.0	0.000	0.000	0.000	0.000
In	1.5	0.000	0.000	0.000	0.000
In	1.0	0.000	0.000	0.000	0.000
In	0.5	0.000	0.000	0.000	0.000
In	0.0	0.000	0.000	0.000	0.000

FIGURE 19

Calibration Curves for Control Rod No. 1

FIGURE 20
Calibration Curves for Control Rod No. 2

FIGURE 21
Calibration Curves for Control Rod No. 3

The curves of the differential and integral worths are not the same for all of the control rods. The rods were manufactured to be identical so any differences are attributed to differences in the total worth of a rod because of differing environments. The total worths were normalized and the data for the differential and integral curves replotted in Figure 22.

FIGURE 22

Normalized Calibration Curves of the Three Control Rods

Curves 1, 2, and 3 are the differential and integral curves for Control Rods 1, 2, and 3, respectively.

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APPENDIX

PERIOD MEASUREMENTS

Accurate determinations of reactivities in a research reactor depend on precision measurements of positive periods either for the measurement itself or as a means of calibrating a moderator level or control rod change which then is used as a secondary standard for the reactivity measurement. The conversion of periods to reactivity values is made using delayed neutron parameters and photoneutron probabilities ⁽⁶⁾ which result in the sum of the delayed neutron abundances $\beta_{\text{eff}} = \sum \beta_i = 4.63 \times 10^{-3}$ and a neutron lifetime of 0.8 msec, respectively. Uncertainties caused by an incorrect choice of delayed neutron parameters are discussed in Reference (6).

In systems moderated with heavy water, period measurements are more difficult to obtain than in H₂O or graphite systems due to long-lived delayed-neutron precursors from the D(ν , n)H reaction. Particular attention must be given to power level history because of fission product build up and decay and associated transients in the (ν , n) reaction rate. Another problem, common to period measurements in any system, is the accurate timing of consecutive measurements of a single period. The latter problem includes galvanometer linearity, shunt precision, ion chamber saturation, and operator uniformity. Operator uniformity pertains to the timing of doubling, e-folding, or tripling time measurements which involve human operations, e. g., the flipping of a switch as a galvanometer indicator sweeps past a null position. The integrated contribution of all of these problems to the loss of precision in period measurements is apparent in reproducibility tests.

Periods are determined from a series of doubling time measurements made as the power level of the PRCF rises from approximately 1.56 to 100 w. This flux rise yields six doublings of the initial flux and six corresponding time measurements. However, not all of the times are asymptotic doubling times because of long-lived delayed neutron effects. The

values of the last three measurements of the eight are statistically the same and have been averaged to obtain the asymptotic period.

The time for the flux to double is measured with an electronic clock that counts pulses from a 1000 cps oscillator which uses a tuning fork as a frequency standard accurate to 0.001%. The clock is started manually by the operator at the time a differential galvanometer indicator sweeps by its null position. The null occurs when a current I (Figure 23) from the ion chamber of Linear Channel No. 2 is equal to and opposite that I_c produced by a 5 v comparison voltage supply which is stable to $\pm 0.05\%$. A "doubling" switch R_D and $R_{D'}$ gives 16 discrete steps of factors of two (accurate to $\pm 0.05\%$) from a given null by keeping the voltage V produced by the ion chamber current less than or equal to the comparison voltage V_c . A voltage divider R_B (repositionable to $\pm 0.05\%$) determines at what power level or ion current the first null occurs. This is accomplished by adjusting the magnitude of the comparison voltage V_c . During a period measurement the bucking voltage is not changed but after a null occurs the voltage V caused by the ion chamber current is reduced a factor of two by the doubling switch. When the next null occurs the electronic clock is stopped and a second one is simultaneously started to within approximately ± 1 msec. The first clock is then started at the next null after being reset. This technique yields time measurements that are dependent, in that an error in the termination of one time measurement is an error in the opposite direction for the start of the next measurement. Thus, over a series of time measurements the errors on the beginnings and endings of the individual measurements cancel. The error on the average doubling time then comes from the error on the beginning and ending of the series which is averaged. Therefore, statistical uncertainty in the average doubling time is found by considering the uncertainty in the measurement of the total time for the last three doubling times.

FIGURE 23

Schematic Representation of the Galvanometer Doubling Circuit

Three doubling time measurements DT_i , $i = 1, 2, 3$ are made in consecutive time intervals t_1 to t_2 , t_2 to t_3 , and t_3 to t_4 . Each time t_i is selected by the operator, as the galvanometer indicates a null, with an uncertainty $\pm S$. Therefore, the DT_i are each uncertain by $\pm \sqrt{2S}$ and the average doubling time $\overline{DT}$ is uncertain by $\pm \frac{\sqrt{2S}}{3}$. The latter is so since the average doubling time is one third the time interval $t_4 - t_1$, which has an uncertainty of only $\pm \sqrt{2S}$ also. The value of S is found from a statistical evaluation of the average value of the DT_i . This calculation yields an uncertainty in DT_i of

$$S_{DT_i}^2 = \frac{3}{7} (DT_i - \overline{DT})^2 \text{ which as already stated is}$$

$$S_{DT_i} = \sqrt{2S}.$$

Normally, if the DT_i were independent,

$$\frac{S^2}{DT} = S_{DT_i}^2 / 3$$

and $\frac{S}{DT} = \sqrt{\frac{2}{3}} S$

rather than the smaller value of $\sqrt{2/9} S$ given above

The doubling times from a set of 25 period measurements were analyzed. The average value of $S_{DT} = \sqrt{\frac{2}{3}} S$ was found to be ± 0.22 sec over a doubling time range of 25 to 70 sec. This corresponds to reactivity uncertainties of ± 0.006 mk ($\pm 0.13\%$) to ± 0.0015 mk ($\pm 0.03\%$) for doubling time measurements of 25 sec to 70 sec, respectively.

In summary, the period is determined from the measured value of the time for the flux to increase by a factor of eight. The uncertainty is found from the standard deviation S_{DT_i} of the distribution of the three dependent measurements of the doubling time which make up the factor of eight

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