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MEASUREMENT OF THE BREEDING RATIO AND ITS COMPONENTS IN ZPPR ASSEMBLY 4, PHASE 1

Measurements to check calculations of breeding ratio were performed on Phase 1 of ZPPR Assembly 4[1] as part of the Demonstration Reactor Benchmark Program.[2]

Assembly 4 corresponds roughly in size and composition to a 300 MWe oxide-fueled LMFBR. Figures 1 and 2 depict the reactor. The core height was 91.4 cm, and the total core volume was 2318 liters. The outer core/inner core ^{239}Pu enrichment ratio was 1.479. Phase 1 represented an end-of-cycle configuration (but with no simulation of fission products or fissile buildup in the blanket). No control rods were present in the system: The nineteen control rod positions contained sodium and stainless steel characteristic of the rod-out composition.

1. The Measurement Technique

Writing the breeding ratio in terms of the quantities measured,

$$BR = \frac{{}^{28}c/{}^{49}f + \langle\bar{\alpha}\rangle_{40}\, I_{40}}{\langle 1 + \bar{\alpha}\rangle_{49} + \langle 1 + \bar{\alpha}\rangle_{41}\, I_{41} + \langle 1 + \bar{\alpha}\rangle_{25}\, I_{25}} \quad . \qquad (1)$$

I_x is the ratio of the total fission rate of isotope x to ^{235}Pu. ^{28}c and ^{49}f are the reactor-integrated ^{238}U capture and ^{239}Pu fission rates, respectively. The α are spectrum-averaged capture to fission ratios, and the brackets denote reactor-averaging.

In Assembly 4, ^{238}U capture accounts for about 98% of the numerator and ^{239}Pu absorption for about 95% of the denominator. Each term in Eq. (1) was measured, but the dominating first terms in both numerator and denominator were measured with particular care.

Detailed maps of the ^{238}U capture and ^{239}Pu fission rates were constructed from irradiations of a large number of foils. In the xy plane near the midplane, 177 ^{238}U capture and 119 ^{239}Pu fission determinations were made. Axial foil irradiations were made in ten different drawers, with a total of eleven foils of each type (^{239}Pu, ^{238}U, ^{235}U) in each of the ten drawers.

The detailed distributions within a drawer were decomposed into a smoothly varying component and a fine structure component. The smooth part was derived from the foil irradiations described above. To determine the fine structure, detailed foil irradiations were done in each type of cell (some cells were repeated with different types of adjacent drawer loadings). Thirty-eight of these detailed in-cell irradiations were done.

The experimental reaction rates determined from the combination of these measurements were then numerically integrated over each reactor region. These results along with the reactor integrals are shown in Table I.

At the reactor midplane, the radial distribution of $(1 + \bar{\alpha})$ was obtained for ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{235}U. For ^{239}Pu, measurements were also made in the axial direction. The spatial variations in the $(1 + \bar{\alpha})$ values are much smaller than for the capture or fission rate, so fewer points were required to obtain a good core-averaged value.

The reactivity-reaction rate technique was used for the $(1 + \bar{\alpha})$ measurement.[3] This measurement essentially measures a relationship between $\bar{\alpha}$ and $\bar{\nu}$. Using ENDF/B-III values for ν, the results for $<1 + \bar{\alpha}>_{49}$ (the reactor-averaged value) for ^{239}Pu, were higher than calculated values by 2.5 ± 3.7%. Table I gives the core-averaged values for $<1 + \bar{\alpha}>$, and the experimental results for the breeding ratio.

All the effects identified as affecting reactor-averaged values were included in the data reduction, with two minor exceptions. First, in measuring the fine-structure, the foils were placed roughly at the mid-height of the drawer. The cell top and bottom has an appreciable stainless steel concentration (due to the drawer bottom, and the matrix tube materials). There is a small "edge-effect" on reaction rates, most notably for ^{238}U capture. From Monte Carlo calculations, mentioned later, it was estimated that this effect would cause the measured breeding ratio to increase by less than 1%. Second, the determination of the in-fuel distribution was made in an enriched uranium, rather than plutonium-uranium, fuel plate. From Monte Carlo calculations the estimated effect was to lower the measured breeding ratio by about 0.5%. Because the two effects are small and tend to cancel, they were ignored in the data reduction.

2. Analysis of the ZPPR Assembly 4 Breeding Ratio

Cross sections specifically for the plate-geometry critical assembly were generated using the ETOE/MC^2-I/SDX codes,[4,5] and diffusion calculations were made in a variety of reactor geometries. Two-dimensional diffusion and three-dimensional spatial flux synthesis results were compared against a three-dimensional finite difference computation (using the VENTURE code).[6] Only small difference in calculated parameters were found. The variation in breeding ratio, for example, was 1.2% in total, with synthesis higher than the VENTURE result of 1.2615 by 0.54%, and two-dimensional diffusion 0.62% lower. The C/E for the breeding ratio was, for the VENTURE calculation, 1.076 ± 0.041. Agreement among the geometric models for reaction rate integrals, while quite close in the core regions, varied by up to 4% in the blankets. These data are summarized in Table II.

Of the 7.6% difference in the measured and calculated breeding ratio, 5.4% was due to an overprediction of the ratio of the reactor ^{238}U capture to ^{239}Pu fission. This discrepancy has been noted several times in the past in analysis of fast assemblies with ENDF/B Version-III cross-section.[7] Another 2.6% came from a low calculation of the ^{239}Pu absorption to fission ratio, for $<1 + \bar{\alpha}>_{49}$. The other terms contribute in a very minor way to the discrepancy.

3. Analyses of Discrepancy

To investigate whether the discrepancy is tracable only to the basic cross-section data, or whether the calculational methods could be at fault, a variety of auxiliary calculational checks were made.

i. First, infinite medium cell calculations of an inner core drawer arrangement were done using the VIM Monte Carlo code.[8,9] VIM generates an "exact" solution to the Boltzman Equation and its cross-section information is continuous in energy. While VIM is a relatively new code and its validation is therefore a continuing activity, two tests of VIM against experimental results, and one test against an MC^2-II calculation all produced good agreement. (Errors in both codes were identified and corrected as a result of these comparisons).

For comparison of VIM against MC^2-II, the ZPR-6 Assembly 7 benchmark homogeneous unit cell was selected. This cell is essentially the same as an inner core cell in ZPPR Assemblies 2, 3, and 4, but is homogenized for data-testing computational purposes. The VIM and MC^2-II results were in excellent agreement for all facets of the neutron balance. Slight discrepancies in ^{238}U and iron capture were found (tracable to minor differences in algorithms) in the two codes.

ii. A VIM calculation was also done of a measurement of ^{238}U capture in a composite $^{235}U/^{238}U$ fuel plate mockup of a standard Pu-U-Mo fuel plate in a special ZPR-6 Assembly 7 measurement. In this measurement the fuel plate was simulated by a packet of alternating enriched and depleted uranium foils, which were then counted to give the in-plate reaction rates. The experimental and calculated values for the shape of ^{238}U capture within the fuel plate were in good agreement. This verification of the VIM calculation for the simulated uranium fuel plate gives the confidence in the VIM calculations of the plutonium/uranium fuel plates, where in-plate measurements are not feasible.

iii. In ZPPR Assembly 2, several foils were placed in a central inner core drawer to study the in-cell fine structure. This inner core cell was identical to that in ZPPR-4. The comparison of experimental and VIM-calculated reaction rates and reaction rate ratios in the ZPPR-2 unit cell displayed excellent agreement in shape (Fig. 3).

The cell-averaged reaction rates, normalized to a single point in the cell, were calculated well by VIM. For ^{238}U capture, the measurements gave 0.9215 (ZPPR-2) and 0.9159 (ZPPR-4) versus a VIM value of 0.9197. For $^{239}Pu(n,f)$, the measured value in ZPPR-2 was 0.991, versus the VIM result 0.995. Thus the calculated cell-averaged correction factors were in good agreement with the measured numbers that were used in experimental data reduction.

iv. In summary, it appears that the 5.4% overprediction of ^{238}U capture to ^{239}Pu fission is due primarily to the ENDF/B Version-III data. No major source of error was identified in the SDX/MC^{2}-II cross-section generation. Similarly, the 2.6% underprediction of $\langle 1 + \bar{\alpha} \rangle_{49}$ may also be due to nuclear data, although here the experimental uncertainty is very much greater.

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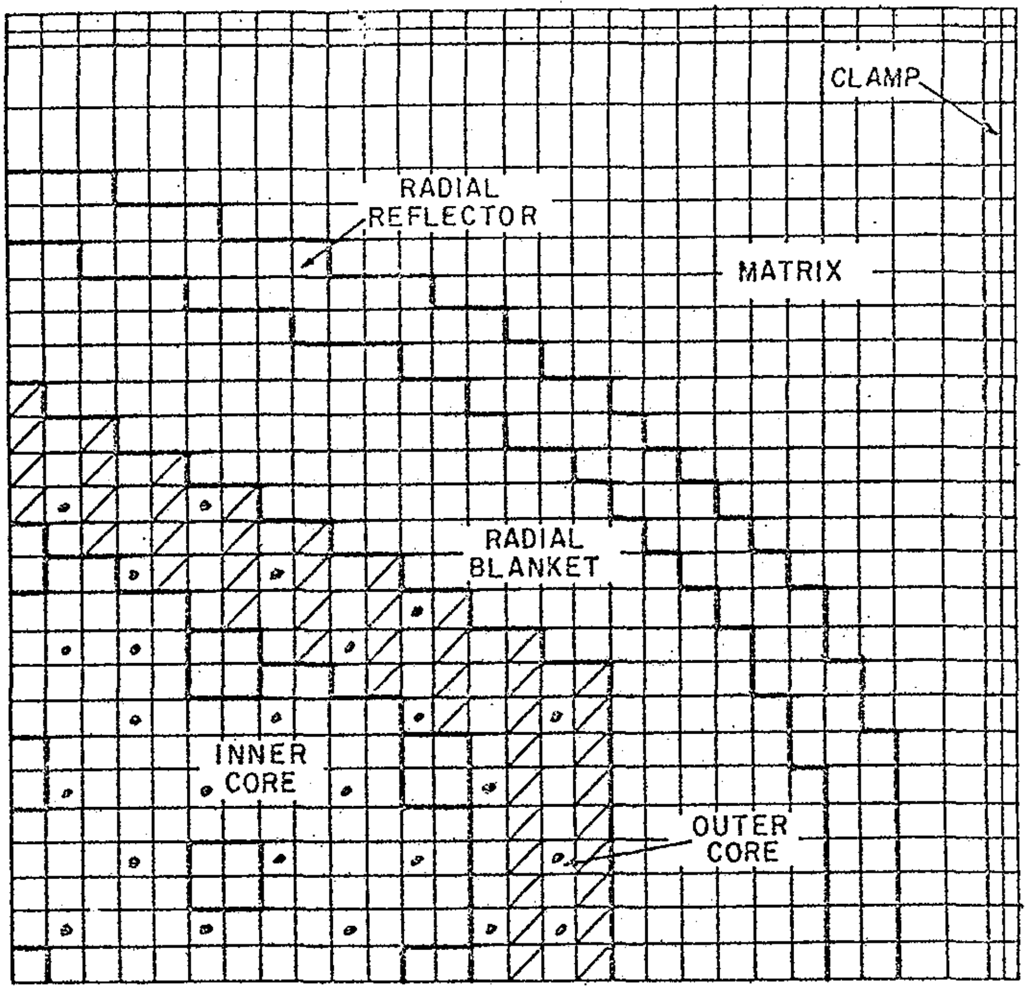

Sodium filled control rod position

Double-fuel column drawer, outer core

Spiked drawer (two fuel columns)

Fig. 1. Midplane Diagram of ZPPR Assembly 4, Phase 1.

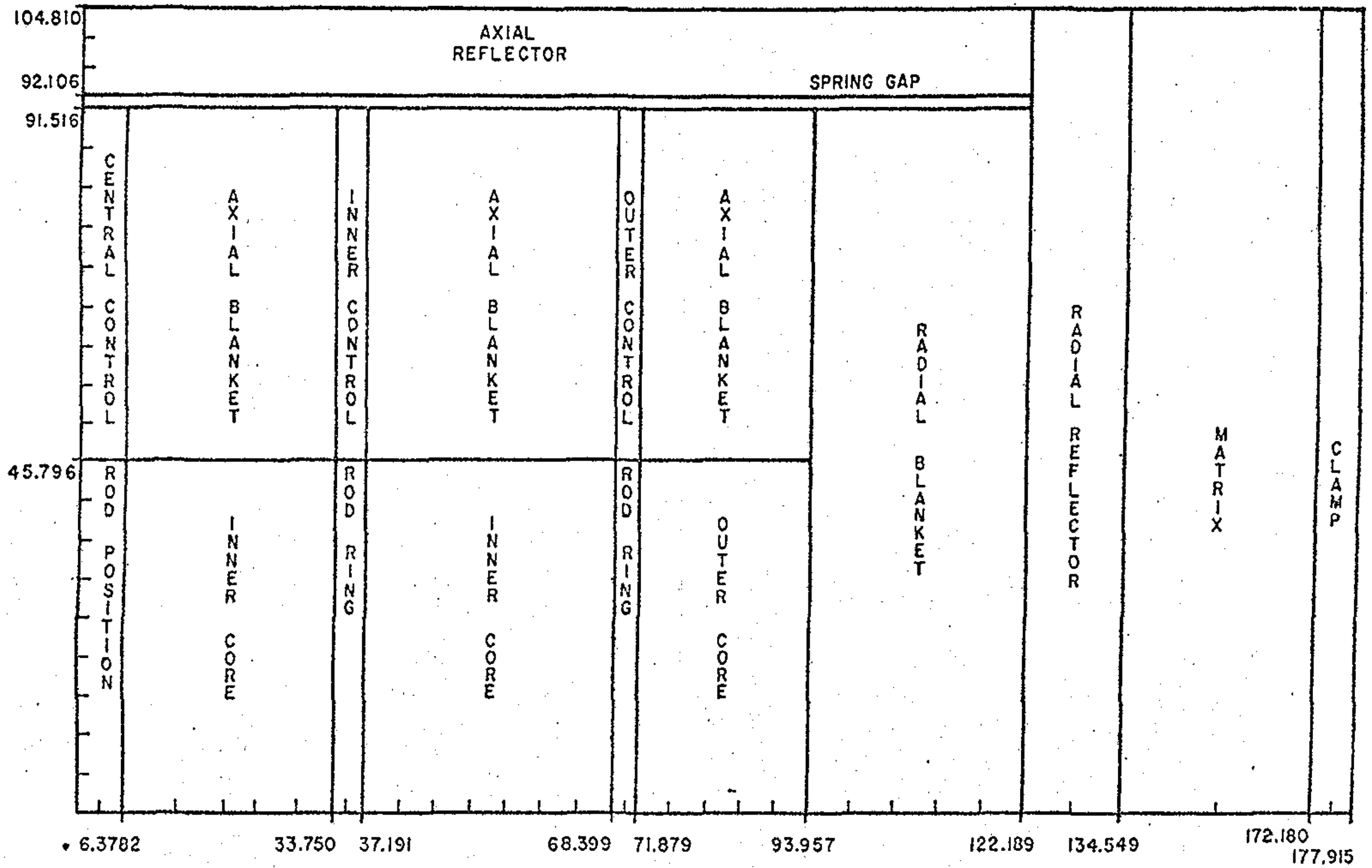

Fig. 2. rz Model of ZPPR Assembly 4, Phase 1

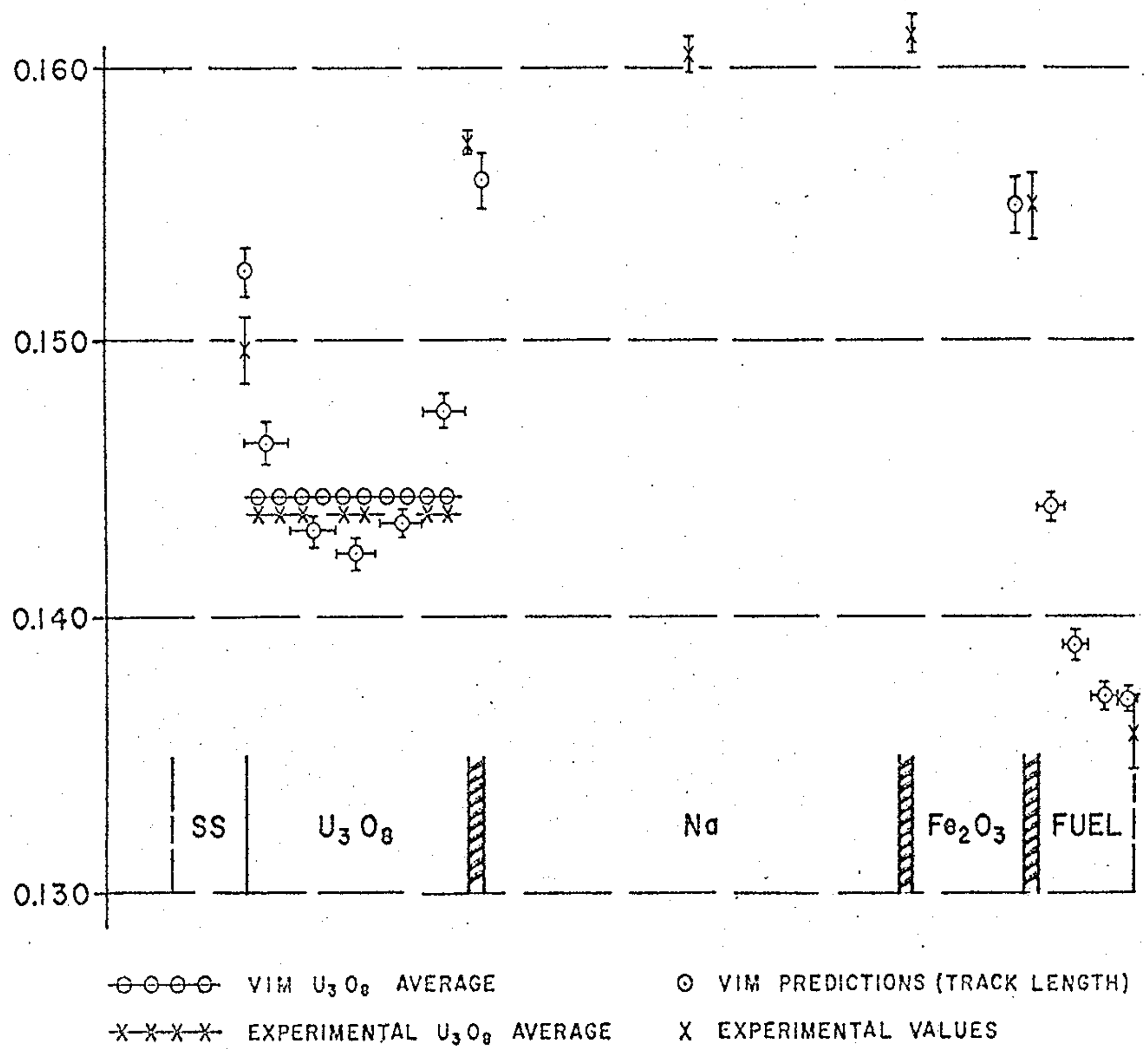

Fig. 3. $^{238}U(n,\gamma)$ Inner Core Cell Reaction Rate

TABLE I. Summary of Reactor Integrals and Breeding Ratio

Quantity	Region	E ± σ	Calculation[a] / Experiment
$<1+\bar{\alpha}>_{49}$[b]	Total	1.298 ± 0.049	0.975
$<1+\bar{\alpha}>_{41}$	Total	1.185 ± 0.094	0.994
$<1+\bar{\alpha}>_{25}$	Total	1.317 ± 0.037	1.019
$<\bar{\alpha}>_{40}$	Total	1.089 ± 0.073	1.002
I_{41}	Total	0.0214 ± 0.0012	0.984
I_{25}	Total	0.0282 ± 0.0013	1.020
I_{40}	Total	0.0289 ± 0.0012	0.950
^{238}U Capture	Inner Core	0.4925 ± 0.0022[c]	1.054
	Outer Core	0.2203 ± 0.0009	1.080
	Axial Blkt.	0.3526 ± 0.0025	1.043
	Radial Blkt.	0.4971 ± 0.0029	1.049
	Total	1.5625 ± 0.0045	1.054
^{239}Pu Fission	Inner Core	0.5702 ± 0.0025[c]	1.006
	Outer Core	0.4298 ± 0.0020	0.991
	Total	1.0 ± 0.0032	1.000

$$BR = \frac{{}^{28}c/{}^{49}f + <\bar{\alpha}>_{40} \quad I_{40}}{<1+\bar{\alpha}>_{49} + <1+\bar{\alpha}>_{41} \quad I_{41} + <1+\bar{\alpha}>_{25} \quad I_{25}}$$

$$= \frac{(1.5625 \pm 0.0186^{d}) + (0.0315 \pm 0.0025)}{(1.298 \pm 0.049) + (0.0254 \pm 0.0025) + (0.0371 \pm 0.0020)}$$

$$= \frac{1.5940 \pm 0.0188}{1.360 \pm 0.049} = 1.172 \pm 0.045$$

[a] Calculations from a three-dimensional VENTURE run with 28 energy groups.

[b] A value of 2.934 was used for $\bar{\nu}$ near the inner core center.

[c] Uncertainties are from counting statistics only. They do not include the $^{28}c/^{49}f$ relative calibration uncertainty of 0.9%.

[d] Contains all recognized uncertainties.

TABLE II. VENTURE/RZ/SYN3D Comparisons of ZPPR-4/1 Breeding Ratio Components

	VENTURE		RZ		SYN3D		Experiment
k_{eff}	0.9917		0.9963		0.9911		
$\langle 1+\bar{\alpha} \rangle_{49}$, inner core	1.2751		1.2758		1.2750		
$\langle 1+\bar{\alpha} \rangle_{49}$, outer core	1.2523		1.2517		1.2522		
$\langle 1+\bar{\alpha} \rangle_{49}$	1.2654		1.2654		1.2652		1.298 ± 0.049
Breeding Ratio	1.2615		1.2537		1.2683		1.172 ± 0.045
	C	C/E	C	C/E	C	C/E	Experiment (E)
^{49}f (inner core)	0.5739	1.0065	0.5697	0.9991	0.5717	1.0026	0.5702
^{49}f (outer core)	0.4261	0.9914	0.4303	1.0012	0.4283	0.9965	0.4298
^{49}f	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
^{28}c (inner core)	0.5190	1.0538	0.5162	1.0481	0.5167	1.0491	0.4925
^{28}c (outer core)	0.2379	1.0799	0.2398	1.0885	0.2390	1.0849	0.2203
^{28}c (radial blkt.)	0.5215	1.0491	0.5128	1.0316	0.5418	1.0899	0.4971
^{28}c (axial blkt.)	0.3677	1.0428	0.3665	1.0394	0.3574	1.0136	0.3526
^{28}c	1.6461	1.0535	1.6353	1.0466	1.6550	1.0592	1.5625