Critical Reactor Laboratory

# Boron Coefficient of Reactivity
# Void Coefficient of Reactivity

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## ABSTRACT

The Boron coefficient of reactivity is negative and ranging from -12 ¢/g to about -85¢/g throughout the lattice. The void coefficient is negative and of the order -5¢/100cm$^3$ for large voids, and positive of the order +20¢/100cm$^3$ for small voids.

PURPOSE:

The purpose of measuring the Boron coefficient of reactivity is to calibrate the reactor with a 1/v absorber with a known cross section. Unknown cross sections of other 1/v absorbers can then be calculated in terms of the boron coefficient and the negative reactivity introduced by the new absorber.

The measurement of the void coefficient of reactivity is of both safety and experimental interest. Since the introduction of a void can affect the reactivity of the reactor, it is necessary to know the void coefficient to estimate the stability of the reactor with respect to void formation. Further, since samples might be placed in the reactor for cross section measurement, it is necessary to know the effect of adding a void (the sample) to accurately relate reactivity changes to a known cross section.

THEORY:

When an absorber is added to a critical reactor, the chain reaction will be damped since some of the neutrons ordinarily available to sustain the reaction will no longer be available. The degree to which the chain reaction is affected is determined by both the number of neutrons absorbed and by their importance in sustaining the chain reaction. From one group perturbation theory, the reactivity introduced by placing a small absorber of volume $V_p$ at the point $\underline{r}_o$ is:

$$\rho = - \frac{\Sigma_{ap} V_p \varphi^2(\underline{r}_o)}{J \int_v \Sigma_f \varphi^2 dV}$$

That is, the reactivity is weighted by the square of the flux at the point. This shows that the reactivity addition of a small absorber is greatest where the flux is largest. Of course there is actually an energy dependence of both flux and cross section at this point, and although it could be accounted for using two group perturbation theory, this dependence can be neglected for the following reasons.

1. The cross section of Boron is much smaller than at thermal energies.
2. The reactor is over moderated and the thermal flux could probably be assumed to be much larger than the fast flux.
3. The fast adjoint flux is smaller than the thermal adjoint flux, and is therefore less important in determining reactivity changes.

The conclusion then, is that the one group formula is sufficient for analysing the effects of absorber.

When a void is placed in a critical reactor it can affect the reactivity in three ways.

1. It removes moderator, therby hardening the spectrum.
2. It removes absorber from the reactor, a positive effect.
3. It changes the diffusion coefficient, increasing the leakage. This effect can be seen by examining the one group per-

turbation formula:

$$\rho = - \frac{\int_v \delta D (\nabla \phi)^2 dV}{\nu \int_v \Sigma_f \phi^2 dV}$$

It can be seen that changes in the diffusion coefficient are weighted by the square of the flux gradient at the point. In this case the largest void coefficient would occur near the edge of the reactor or near control rods, where the gradient is very steep.

Changes in reactivity due to removal of absorber by the void can be treated using the one group formula discussed above under Boron.

To examine the effects of a void on the moderating properties of the system, two group theory is necessary. Although it is difficult to say anything about magnitudes, any spectral hardening should add negative reactivity (to a thermal reactor) since it essentially removes thermal neutrons which are more effective in sustaining the chain reaction than are fast neutrons.

PROCEDURE:

To obtain the Boron coefficient of reactivity, a Nylon tape 55.85 cm by 5.8 cm was placed on the fifth plate of a given fuel element. The tape was impregnated to 1mg/cm$^2$ with natural Boron. The tape was placed on the least reactive side of the fifth plate, it being felt that this position was most representative of the average neutron distribution in the element. The tapes are thin enough so that no shadowing occurs and also have moderating properties similar to water. The difference between a reference critical position and the critical position of rod 4 after the Boron was added was used to determine the reactivity worth of the Boron as a poison. (This is essentially the same procedure as in the temperature coefficient determination.) This was done for each of the 6 stationary rod positions in the quadrant. For element 44, the boron was attached in a 3in by $2\frac{1}{4}$ in strip to a central stringer. The Boron coefficient was determined as before for each of a succession of axial positions in the element.

The void coefficient of reactivity was determined in each element by placing 3 strips of polystyrene between fuel plates 8-9, 4-5, 1-2, of the particular element. These positions were chosen in an attempt to obtain the average void coefficient of the elment. After the voids were in place, the difference between the new critical position and a reference was used to obtain the reactivity addition. To determine the actual void coefficient this number was divided by the actual amount of void in the polystyrene. This was done for each of the 6 stationary fuel elements in the quadrant. For element 44, a small piece of polystrene approximately 2" square was centered at different axial positions along a stringer placed in the center of the element. The reactivity worth of the void at thesespoints were measured as before.

BORON COEFFICIENT:

STRIP SIZE: 5.8 cm × 55.85 cm

STRIP AREA: 323.9 $cm^2$

NET BORON: 324 mg

| ELEMENT | REF. CRIT POSITION | BORON CRIT POS. | $\Delta\rho(¢)$ | ¢/g |
|---|---|---|---|---|
| 22 | 16.90 | 17.145 | -3.95 | -12.20 |
| 23 | 16.90 | 17.392 | -7.79 | -24.03 |
| 23 | 16.89 | 17.36 | -7.47 | -23.05 |
| 32 | 16.89 | 17.390 | -7.93 | -24.48 |
| 33 | 16.89 | 18.015 | -17.26 | -53.26 |
| 34 | 17.25 | 18.80 | -20.65 | -63.72 |
| 43 | 17.25 | 18.87 | -21.37 | -65.95 |
| 44 | * (SEE CALCULATION) | | | -85. |

ELEMENT 44

STRIP SIZE 3" × 2¼"

STRIP AREA 43.5 $cm^2$

NET BORON 43.5 mg

| AXIAL POSITION | REF. CRIT POSITION | BORON CRIT POS | $\Delta\rho(¢)$ | ¢/g |
|---|---|---|---|---|
| 0-3" | 16.835 | 16.95 | -1.89 | -43.54 |
| 3-6" | 16.835 | 17.20 | -5.90 | -135.60 |
| 6-9" | 16.835 | 17.41 | -9.15 | -210.30 |
| 9-12" | 16.835 | 17.49 | -10.36 | -238.06 |
| 12-15" | 16.795 | 17.40 | -9.65 | -221.83 |
| 18-21" | 17.17 | 17.37 | -3.11 | -71.59 |

## Void Coefficient:

Polystyrene Strips:

① .050" × 2.347" × 22.5625"
② .050" × 2.371" × 22.5625"
③ .050" × 2.384" × 22.5625"

Volume Introduced = 131.29 $cm^3$

Mass introduced = 13.84 g.

Net mass displaced = 131.29 g − 13.84 g = 117.45 g
corresponding to a loss of 117.45 $cm^3$ of $H_2O$

| Element | Ref. Crit Position | Void Crit. Pos | $\delta\rho$ (¢) | ¢/$cm^3$ (×100) |
|---|---|---|---|---|
| 22 | 16.726 | 16.921 | -3.25 | -2.77 |
| 23 | 16.764 | 17.120 | -5.83 | -4.96 |
| 32 | 16.726 | 17.062 | -5.55 | -4.73 |
| 33 | 16.713 | 17.233 | -8.46 | -7.20 |
| 34 | 16.760 | 17.135 | -6.12 | -5.21 |
| 34 | 16.764 | 17.123 | -5.87 | -5.00 |
| 43 | 16.760 | 17.320 | -9.02 | -7.68 |
| 43 | 16.764 | 17.400 | -10.18 | -8.66 |

### Element 44 –

Poly strip: .051" × 2.156" × 2.438" = 4.39 $cm^3$

$H_2O$ Displaced = 4.39 $cm^3$ (1 g/$cm^3$ − 0.105 g/$cm^3$) = 3.93 g
corresponding to a void of 3.93 $cm^3$

CALCULATIONS:

The Boron Coefficient of reactivity for element 44 was estimated by averaging the Boron coefficients for the axial positions by using Simpson's Rule. To do this an additional data point was generated at 15-18" by using a linear interpolation between the two adjacent data points ⟹

$-(221.83 + 71.59) \div 2 = -146.71$

| POSITION | ¢/g | $f_i$ |
|---|---|---|
| 1.5 | - 43.54 | $f_0$ |
| 4.5 | - 135.60 | $f_1$ |
| 7.5 | - 210.30 | $f_2$ |
| 10.5 | - 239.06 | $f_3$ |
| 13.5 | - 221.83 | $f_4$ |
| 16.5 | - 146.71 | $f_5$ |
| 19.5 | - 71.59 | $f_6$ |

$$S_7 = \frac{h}{6}\left[f_0 + 4(f_1 + f_3 + f_5) + 2(f_2 + f_4) + f_6\right], \quad h = 3$$

$$= -1530$$

Average for element = $-1530/18 = -85$ ¢/g

This of course neglects the fact that no data is available from 21-22 in, but it only reduce this by a small amount

DISCUSSION:

The first thing to be explained are the trends observed in the coefficients. As expected from the perturbation theory, the boron coefficient decreased in general with increasing radius. Some of the details are that the coefficient in element 43 is greater than in the supposedly symmetrical element 34. this is basically due to the fact that element 43 has a fuel plate adjacent to another fuel plate in element 44, whereas the fuel in 34 meets only moderator in 44. The coefficients in elements 32 and 23 are approximately the same since they do exhibit symmetry.

The situation is somewhat different for the void coefficient. The most striking difference is the presence of a positive void coefficient in the center element 44. As reported previously, the entire reactor is over moderated, especially in this thermal column. The presence of a void in this lattice serves not so much to remove moderator as to remove absorber. A void here contributes to the chain reaction by reducing parasitic capture of neutrons in water. As for the boron coefficient, the remaining elements have negative void coefficients whose magnitude increases with decreasing radius. An interesting point however, is that element 43 has a void coefficient 50% larger than element 34, whereas the boron coefficient in 43 is only slightly larger than in 34. I think this is due to the method used to measure the coefficients. For Boron, the coefficient was measured using only plate 5, while voids were placed between plates 1-2, 4-5, and 8-9. The voids in element 43 have more fuel separating them from the thermal column than in element 34; one of the voids in 34 having only one plate between it and 44. If you consider the performance of voids in 44, you might guess that the negative effect of removing moderator in 34 is compensated by the positive effect of removing absorber, especially when so many moderated neutrons are available. This would mean that the void in 34 closest to 44 is ineffective. Now the fact that 34 has a void coefficient two-thirds the size of 43 is explainable since it effectively has only two-thirds the void.

One other item to consider in attempting to explain the results is the validity of applying perturbation theory to these experiments. Only small changes in absorbtion or diffusion can be considered and the gross properties of the system should be unaffected. These requirements would hold for the measurements made along the stringer for both Boron and void since only small changes were involved. The question is whether the measurements made along the other fuel elements involved small changes. The magnitude of the changes for Boron were about the same in both element 44 and the other elments, so this would be valid. The void coefficient however, exhibits quite different behavior, being small and negative in the stationary elements and small and positive in element 44. One could conclude that the void coefficient is always positive in element 44 since it has about the same magnitude as in the stationary elements. This is incorrect. Nevertheless, perturbation theory

is valid since the changes are small.

The possibility of drawing faulty conclusions is related to the way in which the measurements were made. There are two major competing effects in the void coefficient; the increase of leakage and the decrease of absorbtion. In element 44, the changes were so small that leakage could not compensate for the loss of absorber. For larger voids however, compensation would occur. Thus element 44 has a positive coefficient with respect to small voids and a negative coefficient with respect to large voids. Similar behavior can be expected in the six other elements of the quadrant. As the voids become smaller, the role of absorber becomes relatively more important, eventually exhibiting a positive void coefficient. This would not be as pronounced as in element 44 however, since the gradient in 44 is much smaller than elsewhere in the core. These predictions should be checked experimentally.

The only term of the six factor formula affected by the addition of a poison is the thermal utilization

The addition of a poison obviously reduces f. Calculation of f/f using this formula are two difficult, and calculations assuming a homogeneous reactor are worthless in determination of reactivity changes. Any material with a 1/v cross section, such as gold (below lev) could be used as a standard. An element with an energy dependence which can be corrected to 1/v could also be used. These include U-235, Cadmium, and Indium (below their resonances). The Boron 11 cross section is one-one thousnadth of the Boron-10 cross section. Thus non 1/v effects of Boron 11 would be negligible.


we want materials without resonances

The void coefficient is dependent on more terms of the six factor formula. By removing moderator fewer fast neutrons are thermalized and the resonance escape probability decreases. By removing moderator, more neutrons are allowed to leak out, decreasing the nonleakage probabilities. The thermal utilization increases since a void removes moderator which would otherwise absorb neutrons. The fast fission factor is so small in this reactor that no change would be noticeable from spectrum hardening.

The effect of a void is most pronounced where the flux gradient is largest. If a small void was placed near a control rod, the worth would be increased due to the flux distortion in the neighborhood of the rod. Of course a large void surrounding the rod would affect things differently. In this case the rod worth might be decreased if the rod were primarily a thermal absorber, since there would be fewer thermal neutrons.

The temperature coefficient experiment could also have been treated as a void experiment. The effect of temperature was principally to decrease the moderator density, but uniformly, instead of locally. Void coefficients are especially important in Boiling Water Reactors where they have a large feedback effect. The negative void coefficient aids the stability of the BWR significantly.