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MICHIGAN MEMORIAL PHOENIX PROJECT

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EVALUATION OF SOLID BORON STAINLESS STEEL SHIM-SAFETY RODS FOR THE FORD NUCLEAR REACTOR

ANN ARBOR MICHIGAN

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Evaluation of Solid Boron Stainless Steel Shim-Safety Rods for The Ford Nuclear Reactor

EVALUATION OF SOLID BORON STAINLESS STEEL SHIM-SAFETY RODS FOR THE FORD NUCLEAR REACTOR

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EVALUATION OF SOLID BORON STAINLESS STEEL SHIM-SAFETY RODS FOR THE FORD NUCLEAR REACTOR

I. INTRODUCTION

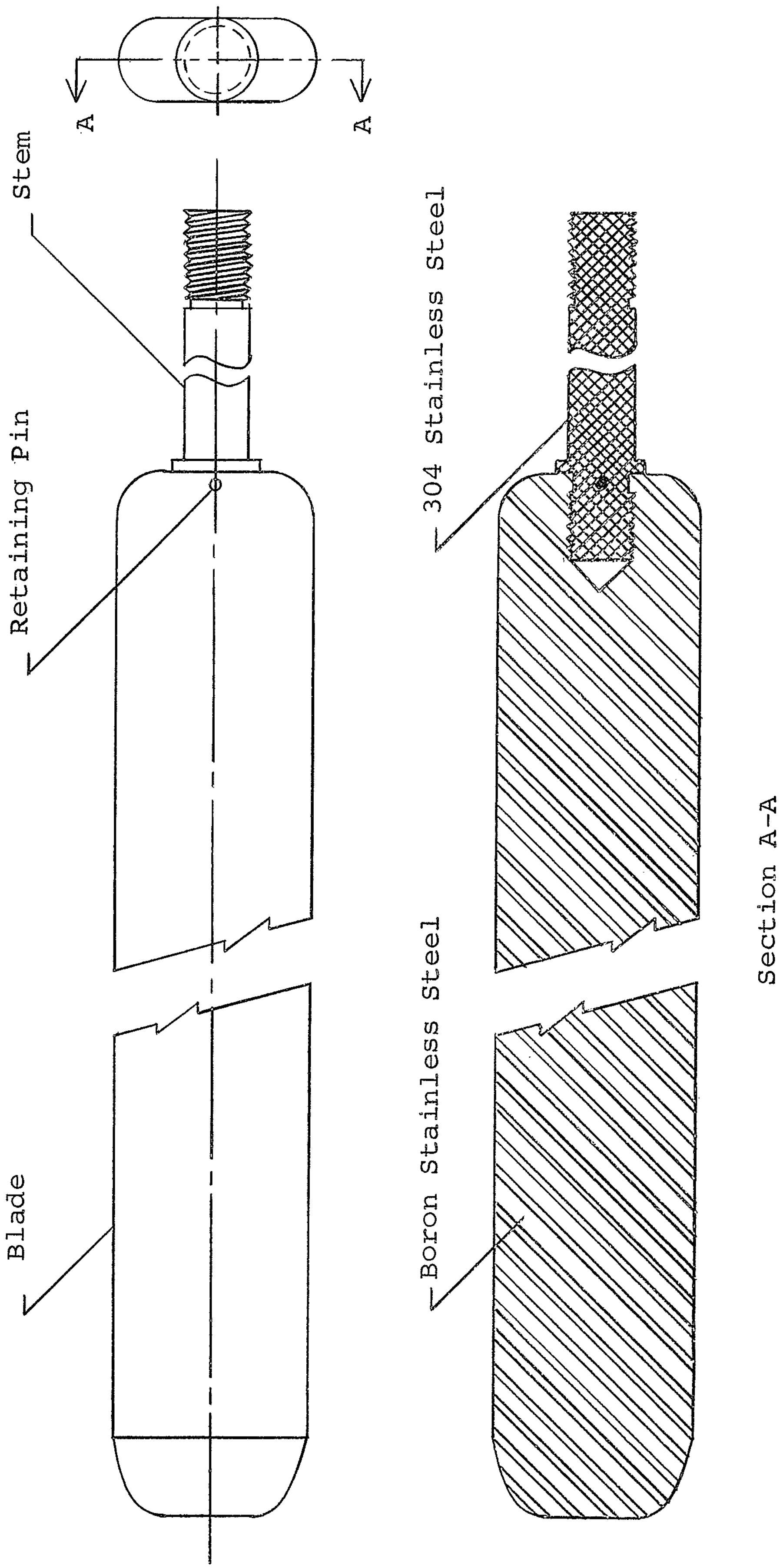
Off gassing from boron carbide powder filled shim-safety rods has been observed at the Ford Nuclear Reactor (FNR) and other facilities.[1,2] One boron carbide filled safety rod in the FNR swelled to such an extent that it jammed in its special control fuel element. An investigation indicated that a small hole permitted pool water to leak into the rod and that the hole was capable of self-sealing. The water inside the rod dissociated into gaseous hydrogen and oxygen and produced a sufficient pressure to expand the aluminum casing of the rod.

In an attempt to prevent future jamming incidents, a program was initiated at The University of Michigan's Phoenix Memorial Laboratory to design and to evaluate new shim-safety rods for use in the Ford Nuclear Reactor. Three solid rods made from stainless steel containing 1 1/2 per cent by weight natural boron were procured. These rods were fabricated according to FNR specifications by a commercial organization experienced with casting such material. During the evaluation of the performance of these rods, emphasis was placed on the determination of the reactivity worths.

II. DESCRIPTION OF SHIM-SAFETY RODS

Solid shim-safety rods were considered desirable for three reasons: they would not be subject to deformation from internal pressures; they would be more rugged than the boron carbide filled rods; and they would be heavier than the boron carbide rods. The additional weight would result in faster release of the rods from their electromagnets and would, therefore, provide shorter response times under emergency shut down conditions.

The material selected was 18-8 stainless steel containing 1 1/2 weight per cent natural boron. This boron concentration was considered to be acceptable in terms of rate of burnup since preliminary calculations indicated a shim rod lifetime of the order of 100,000 megawatt hours.[3] It was the purpose of this investigation to determine experimentally whether or not the boron concentration in the stainless steel rods would provide sufficient negative reactivity worths. Also, it was expected that this concentration would yield satisfactory metallurgical properties during the fabrication and use of the rods.[4] To make the new rods compatible with other mechanical components of the reactor, their shape and outside dimensions were made the same as the boron carbide filled rods. The new solid rod design is shown in Figure 1 on the next page. A sketch of a boron carbide filled shim-safety rod is shown in Figure 2 on page 4.



Solid Boron Stainless Steel Shim-Safety Rod

Figure 1

Boron Carbide Shim-Safety Rod

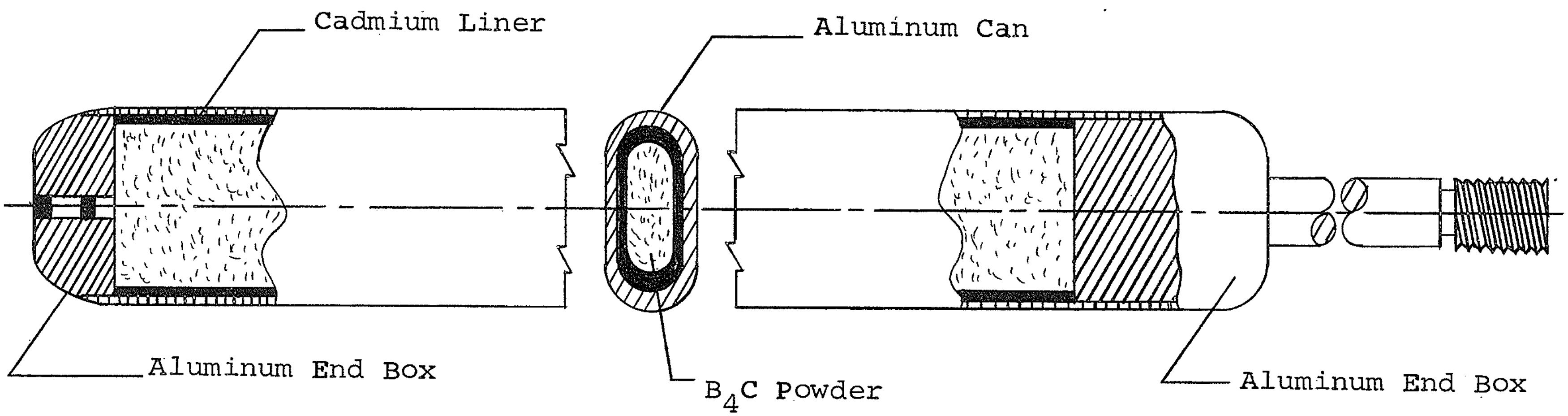


Figure 2

The boron carbide filled rods currently in use in the FNR are of the same design as those which experienced off gassing except that a cadmium liner was added to the interior of the rods as shown in Figure 2. Since these cadmium lined rods, which were readily available, had approximately the same reactivity worth as the unlined rods, they were considered acceptable replacements for the original rods.

Each of the 1 1/2 weight per cent natural boron stainless steel rods contains a total of 19 grams of the isotope B-10 and each of the rods filled with boron carbide powder contains a total of 101 grams of B-10 and a 2.4 pound liner of elemental cadmium. There was experimental evidence that the boron stainless steel rod worths would be approximately equal to the boron carbide rod worths.[4] An application of the reported data of Becker and Russell, however, indicated the boron stainless steel rods should be worth 16% less than the boron carbide powder filled rods.[5] This difference is attributed to epi-cadmium neutron absorption which is proportional to the boron concentration. Figure 2 shows that the poison is distributed throughout the boron stainless steel rods. The poison in the boron carbide filled rods is contained within the interior volume of the extruded aluminum tube and does not extend into the solid aluminum end boxes. Also, the interior surface of boron carbide filled rod is lined with cadmium. Since the rod positions are measured by the position of their associated rod drive mechanisms, this difference in poison distribution must be taken into consideration in the calibration of the rods. Assuming the same change in flux distribution as both types of rods are inserted, the differential worth curve of the stainless steel rod would be expected to peak before the peak of the differential worth curve for the boron carbide filled rods.

III. EXPERIMENTAL MEASUREMENTS

Prior to initiating this evaluation program, a facility license amendment was obtained from the AEC which authorized the installation of no more than one boron stainless steel safety rod in the reactor at any one time.

In the interest of safety, multiplication factors were measured for each of the three boron stainless steel rods using a subcritical fuel loading. For comparison, the same measurements were made with the boron carbide powder filled rods. The subcritical multiplication data was taken from two fission chamber pulse channels. For each shim rod lattice position, a boron stainless steel rod was found to be worth approximately 0.8 of its boron carbide counterpart. A summary of this data is given in Table 1.

Table 1

Subcritical Multiplication Factors

for

Boron Stainless Steel vs. Boron Carbide Filled Rods

Boron Carbide Powder Filled Rod

Serial Number	Run No.	Shim Rod Lattice Position	North Pulse Channel	West Pulse Channel
A-2	1	A	18.6	17.2
A-2	2	A	19.4	17.1
B-2	1	B	13.0	14.3
B-2	2	B	13.6	14.0
C-4	1	C	12.5	10.5
C-4	2	C	13.2	11.1

Solid Boron Stainless Steel Rod

Serial Number	Run No.	Shim Rod Lattice Position	North Pulse Channel	West Pulse Channel
7-61		A	13.2	12.05
8-61		B	11.2	11.8
9-61		C	10.4	9.5

A. Rod Worth Determinations by the Rod Drop Method

Rod worth determinations were made for all boron stainless steel and boron carbide filled rods employing the rod drop method and using post-neutron to pre-neutron density ratios given by F. Feiner and P. G. Klann.[6] The individual rods were dropped from the fully withdrawn position with the reactor at a power level of 1 kilowatt. Data for these measurements was taken from the Log N, Linear Level and Log Count Rate channels. The block diagrams of these channels are shown in Figure 3. A summary of the rod drop data is given in Table 2.

B. Rod Worth Determinations by the Control Rod Comparison Method

In addition to three shim-safety rods, the FNR employs a non-borated stainless steel control or regulating rod. The control rod comparison method was used to determine the worth of both types of shim-safety rods. This method consists of comparing the total worth of the control rod with an incremental change in shim-safety rod position for a given core loading. The position of the shim rod being calibrated was adjusted until the reactor was as near as possible to a steady state condition. Thus, the reactivity assigned to the change in shim rod position was that of the total worth of the control rod. The control rod worth, determined by an independent

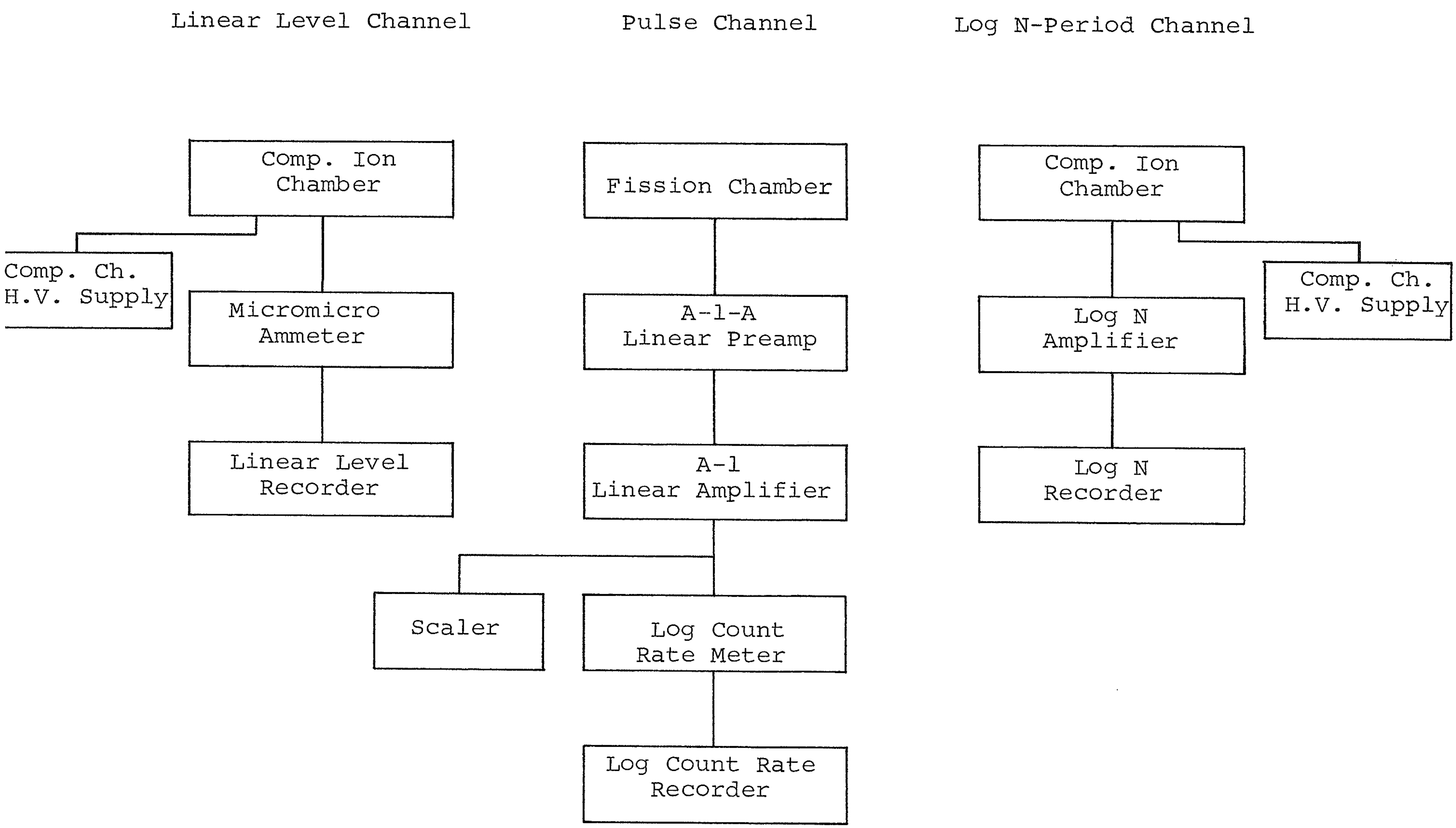


Figure 3

Instrument Block Diagrams

Table 2

Boron Stainless Steel and Boron Carbide Filled Rod Worths

in % $\Delta k/k$ Determined by Rod Drop Method

Boron Carbide Powder Filled Rod

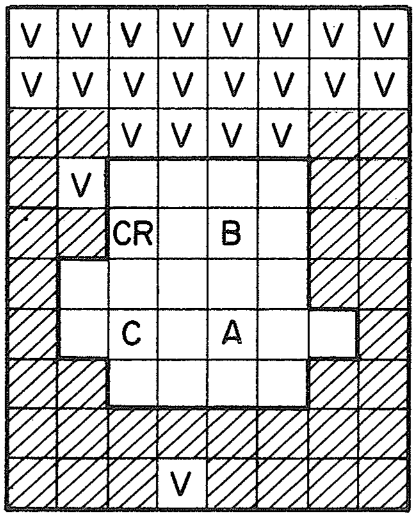
Serial Number	Run No.	Lattice Position	Core Loading	Log N Channel	Linear Channel	LCR Channel	Average % $\Delta k/k$
A-2	1	A	B	3.96	3.78	3.65	3.80
A-2	2	A	B	4.52	3.62	3.62	3.92
A-2	1	A	C	3.85	3.62	3.32	3.60
A-2	2	A	C	3.85	3.59	3.62	3.69
B-2	1	B	B	3.40	2.80	2.94	3.05
B-2	2	B	B	3.58	2.83	2.83	3.08
B-2	1	B	C	3.36	2.83	2.95	3.05
C-4	1	C	B	2.60	2.34	2.08	2.34
C-4	1	C	C	2.35	2.42	2.53	2.43
C-4	2	C	C	2.35	2.42	2.57	2.45

Solid Boron Stainless Steel Rod

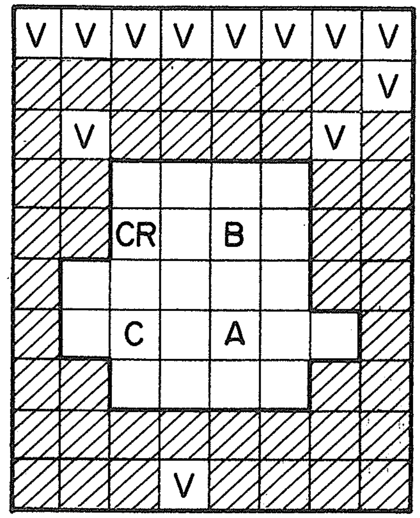
Serial Number	Run No.	Lattice Position	Core Loading	Log N Channel	Linear Channel	LCR Channel	Average % $\Delta k/k$
7-61	1	A	B	2.94	2.94	2.86	2.91
7-61	2	A	B	3.17	2.94	----	3.05
8-61	1	B	B	2.68	2.42	2.49	2.53
8-61	2	B	B	2.61	2.34	2.45	2.47
9-61	1	C	B	2.08	1.96	1.81	1.95
9-61	2	C	B	1.92	1.89	1.96	1.92

calibration using the pile period method,[7,8] was found to be 0.31% $\Delta k/k$. Integral worth curves were determined for the boron carbide rods and the boron stainless steel rods in the three shim rod lattice positions. These measurements were made using core loading C as shown in Figure 4. The resultant worth curves are displayed in Figures 5, 6 and 7.

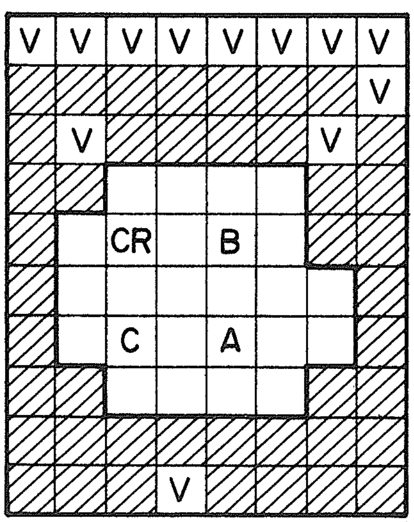
To establish a basis for comparison between the total worths measured by the rod drop and control rod comparison methods, it was necessary to establish the criteria for determining the total rod worth from the lower portion of the integral worth curves shown in Figures 5, 6 and 7. Since it was possible to generate the complete integral worth curve for the boron stainless steel rod in lattice position C (Figure 8), the effective differential worth curve peak was determined by halving the total rod worth as given by the complete integral worth curve and reading off the corresponding rod position at the half worth value. The total worths of the other two steel rods were then obtained by doubling their worth values at comparable positions determined from Figures 5 and 6. Since the individual total rod worths were in all cases of the same order of magnitude, the influence on the flux distribution during calibration was assumed to be the same for each rod.



CORE LOADING A
EXCESS REACTIVITY = SUB CRITICAL



CORE LOADING B
EXCESS REACTIVITY $\approx 1\% \frac{\Delta K}{K}$



CORE LOADING C
EXCESS REACTIVITY $\approx 2\% \frac{\Delta K}{K}$

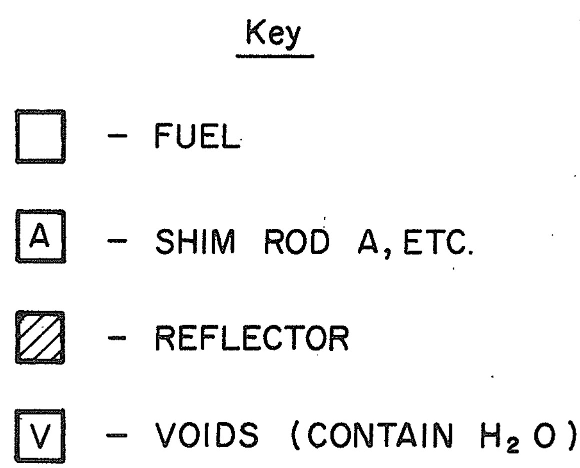


Figure 4

Reactor Core Loadings

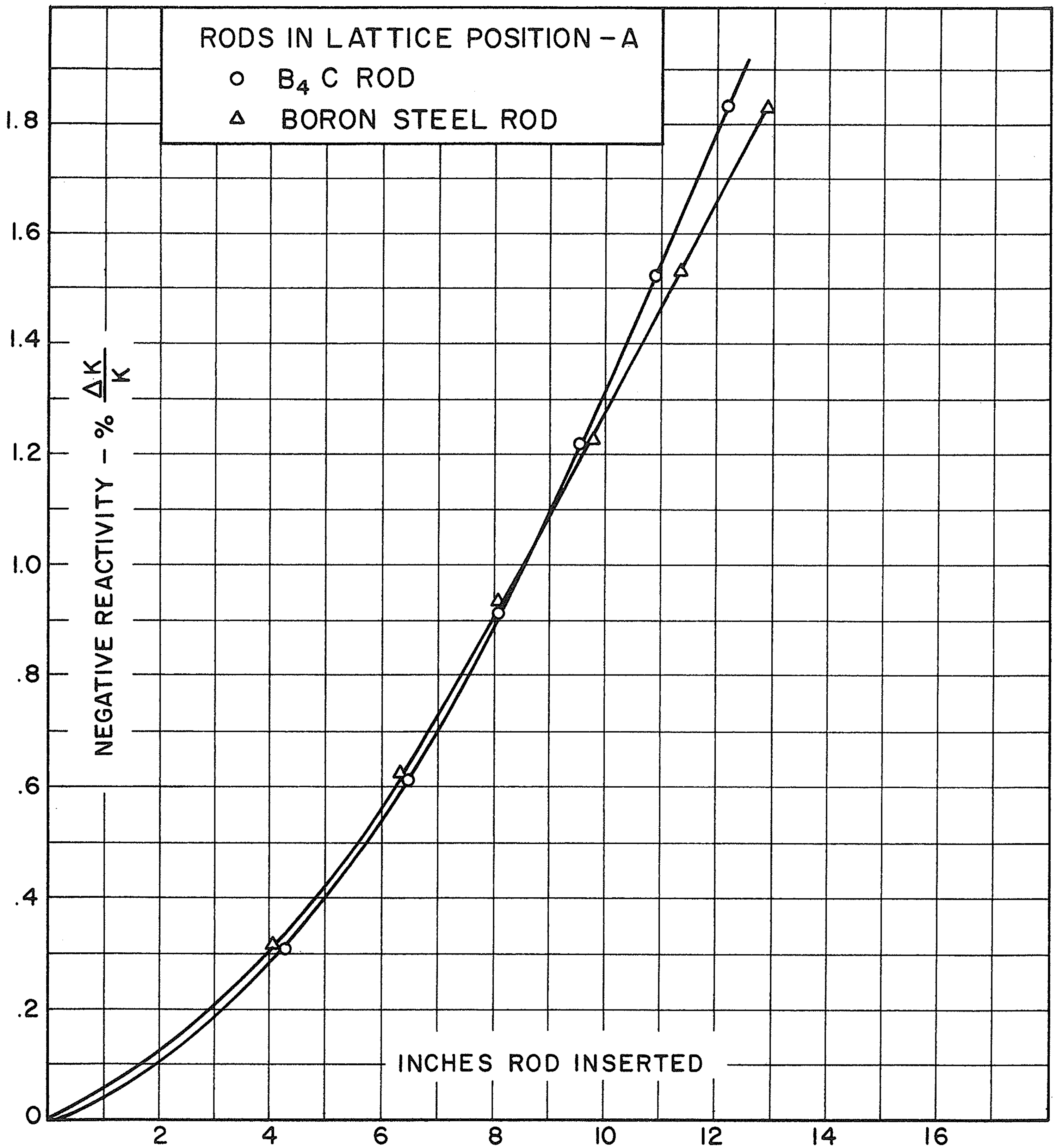


Figure 5

Integral Worth Curve

Lattice Position A

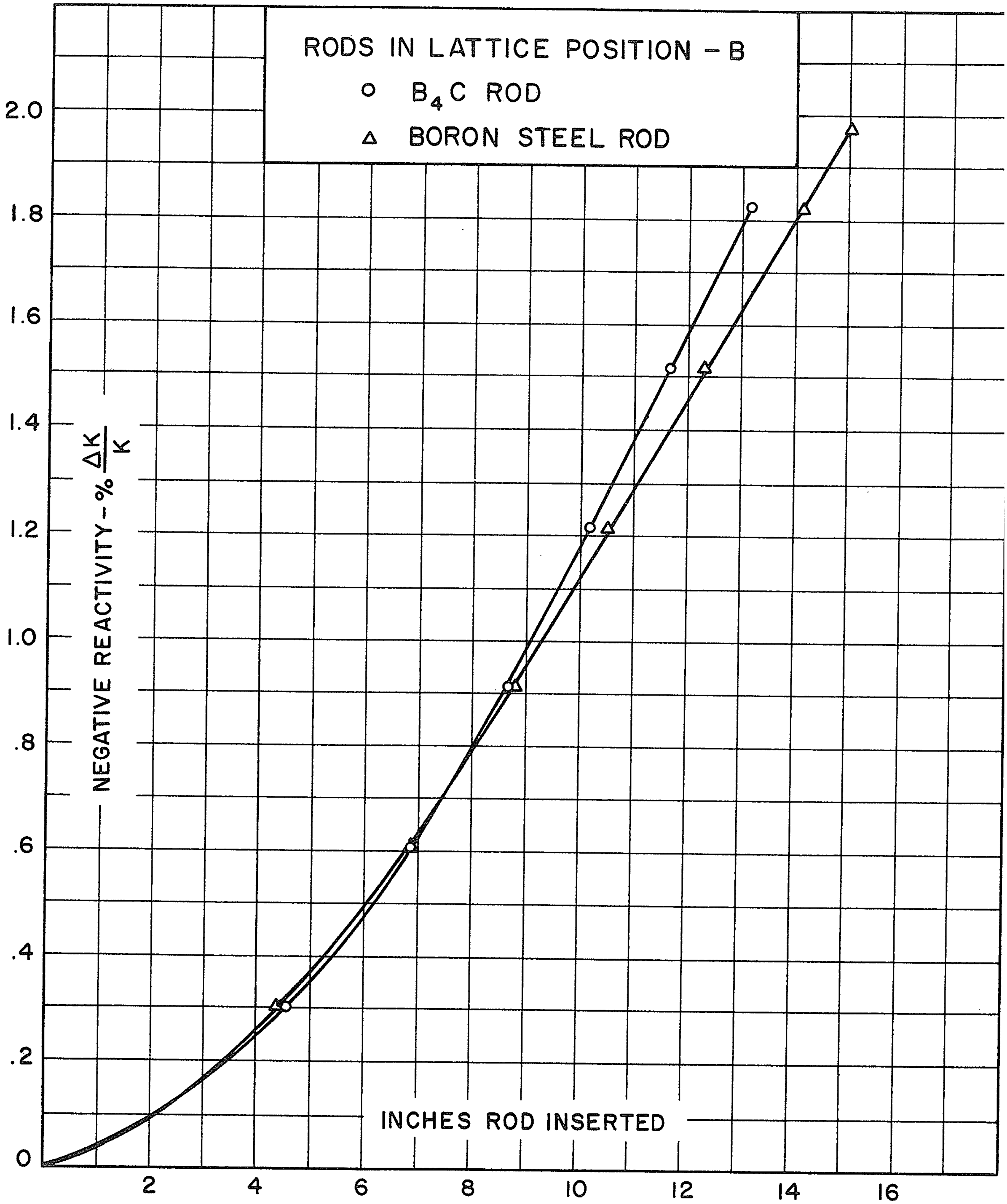


Figure 6

Integral Worth Curve

Lattice Position B

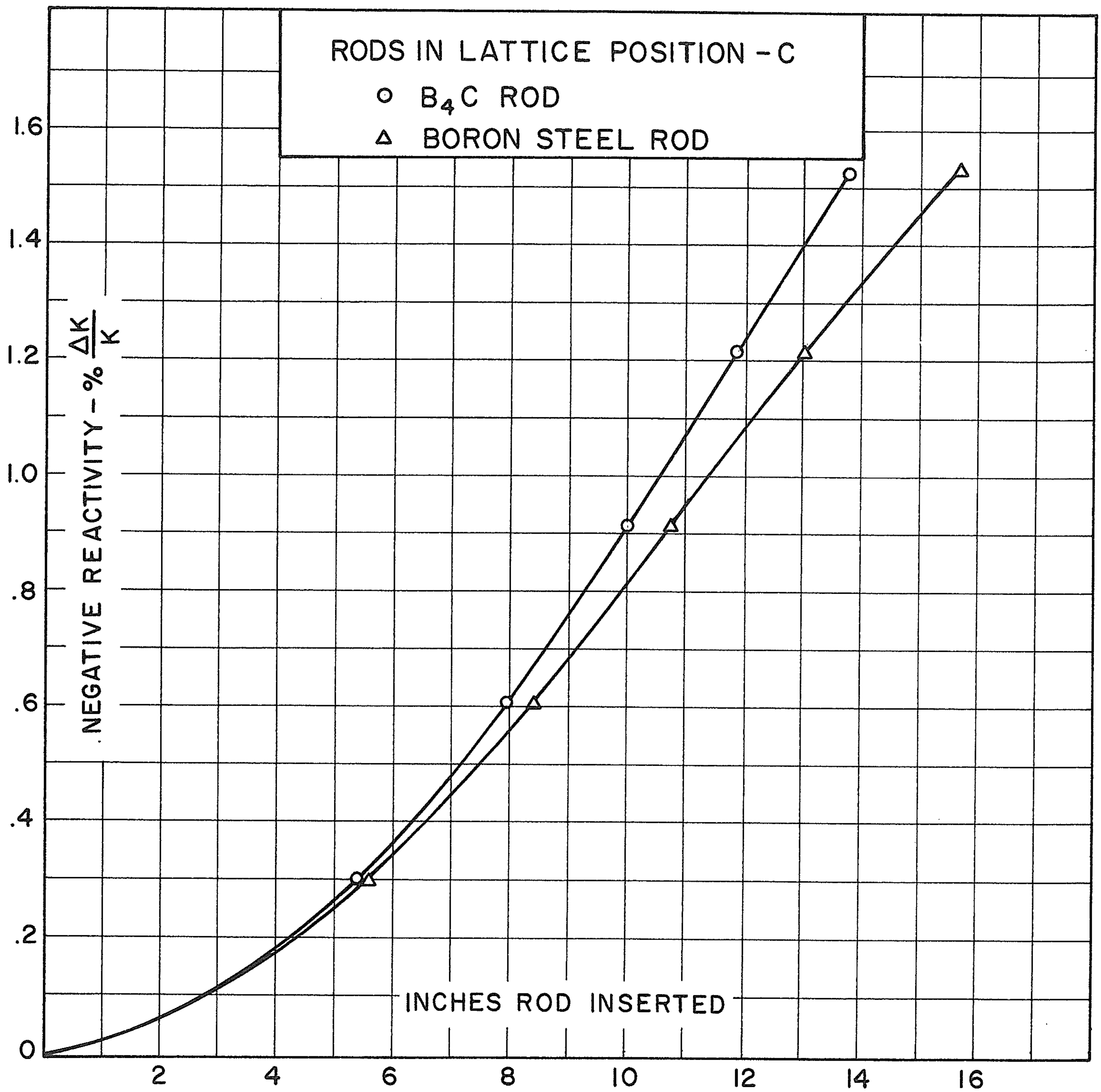


Figure 7

Integral Worth Curve

Lattice Position C

Figure 8 shows that for the boron stainless steel rod in position C twice the value of the rod worth when inserted 11.2 inches is equal to the total rod worth measured when fully inserted. Thus, if the same flux distribution is assumed for the other rods, the total worth of the boron steel rods for lattice positions A and B may be obtained by doubling the values of the respective integral curves when the individual rod is inserted 11.2 inches.

The worths of the B_4C powder filled rods may be similarly determined if the difference in poison distribution is taken into consideration. Because there is no poison in the lower inch of the B_4C powder filled rods, these rods must be inserted 12.2 inches in order to have the poison at the same position in the reactor core as that of the boron stainless steel rods when they are inserted 11.2 inches. Therefore, the rod worths at 12.2 inches are doubled to obtain the total worths of the B_4C powder filled rods. The results of these calculations are given in Table 4 of Section IV, Summary of Rod Worth Determinations.

C. Electromagnet-Rod Release Time Measurements

Since the boron steel rods weigh approximately 15 pounds in air and the boron carbide rods weigh approximately 7.5 pounds in air, it was expected that this increase in weight would result in shorter

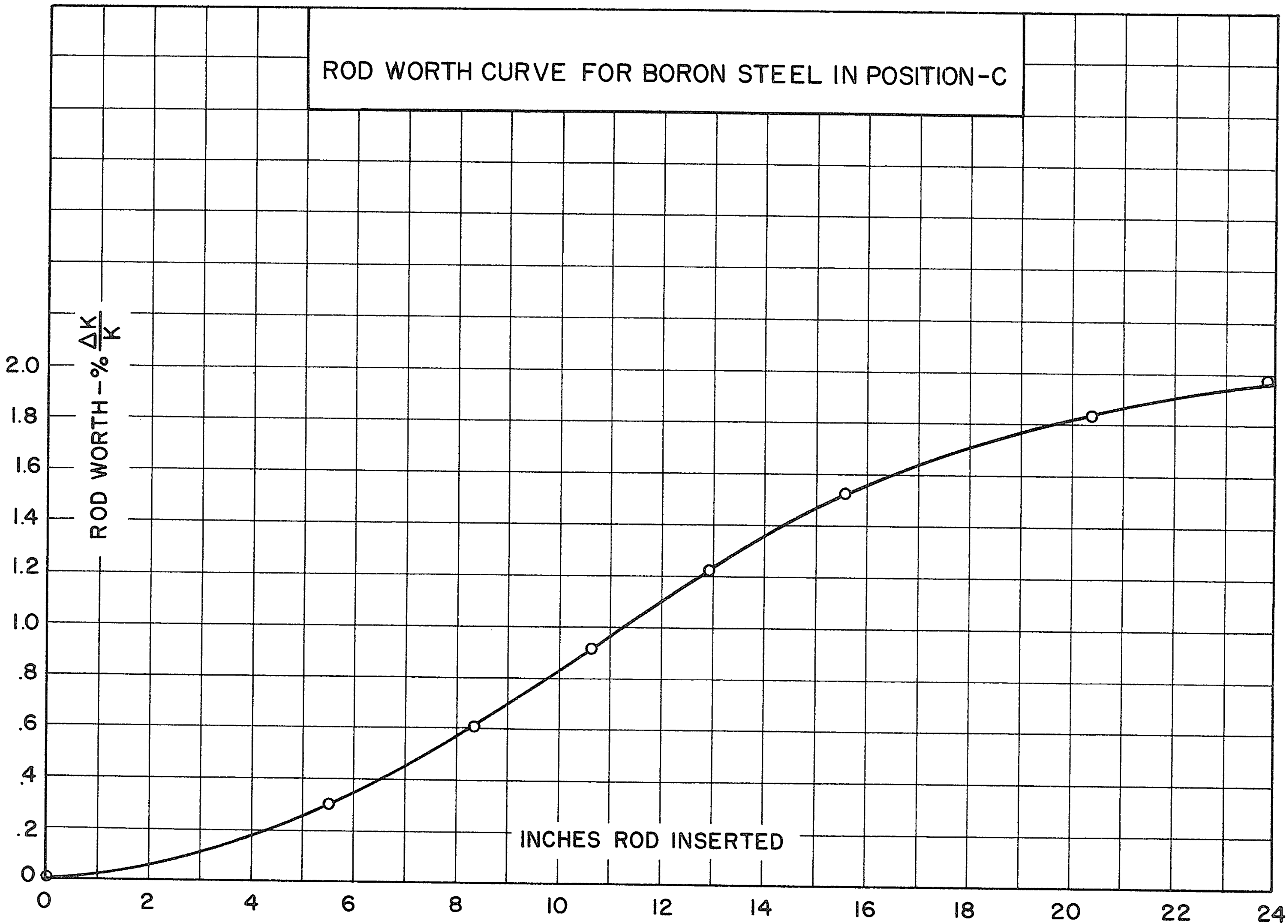


Figure 8

Total Integral Worth Curve Lattice Position C electromagnet-rod release times. Table 3 gives measurements which indicate that the release times for the solid rods average 12 milliseconds as compared to an average of 19 milliseconds for the boron carbide rods. Release time measurements were made by the method devised by L. C. Oakes at ORNL.(9)

Table 3

Electromagnet Currents and Rod Release Times for Boron Stainless Steel and B_4C Powder Filled Shim-Safety Rods

	Serial Number	Lattice Position	Current* (ma)	Drop Current (ma)	Release Time (m sec)
B_4C	A-2	A	50	15	18
Steel	7-61	A	60	25	11
B_4C	B-2	B	38	12	19
Steel	8-61	B	42	15	11
B_4C	C-4	C	52	18	19
Steel	9-61	C	53	21	14

*Release times were determined with maximum permissible currents. The magnitude of these currents are dictated by the characteristics of the FNR Safety System.

D. Radiographic Inspections

X-ray photographs taken of all the boron stainless steel rods indicated no detectable void formation or cracks in the steel castings following the rod calibrations and a drop testing procedure in which 10 drops were made from 100 per cent withdrawn positions.

IV. SUMMARY OF ROD WORTH DETERMINATIONS

Table 4 on the next page lists the worths of boron stainless steel and B_4C powder filled rods as determined by the rod drop and control rod comparison methods for core loadings B and C. These measurements were made with a pool water temperature of $80^{\circ}F$. The values listed under the rod drop method are averages of the runs listed in Table 2 and recorded by the Log N, Linear Level and Log Count Rate channels. The values listed under the control rod comparison method were determined by the procedure outlined in Section III.

Figure 9 shows a plot of the pertinent data from Table 4. Core loading C data is given for both methods for the B_4C powder filled rods. For the boron stainless steel rods, core loading C data is given for the control rod comparison method and core loading B data is given for the rod drop method. Limits are marked indicating a range of ± 10 per cent of each of the worth values as measured by the rod drop method. In each of the six cases the worth as determined by the control rod comparison method falls within this ± 10 per cent range.

Table 4

Boron Stainless Steel and Boron Carbide
Filled Rod Worths in % $\Delta k/k$

Boron Carbide Powder Filled Rod

Serial Number	Shim Rod Lattice Position	Core Loading	Rod Drop Method	Control Rod Comparison Method
A-2	A	B	3.86	----
		C	3.64	3.66
B-2	B	B	3.06	----
		C	3.05	3.27
C-4	C	B	2.34	----
		C	2.44	2.55

Solid Boron Stainless Steel Rod

Serial Number	Shim Rod Lattice Position	Core Loading	Rod Drop Method	Control Rod Comparison Method
7-61	A	B	2.97	----
		C	----	3.0
8-61	B	B	2.50	----
		C	----	2.68
9-61	C	B	1.94	----
		C	----	1.98

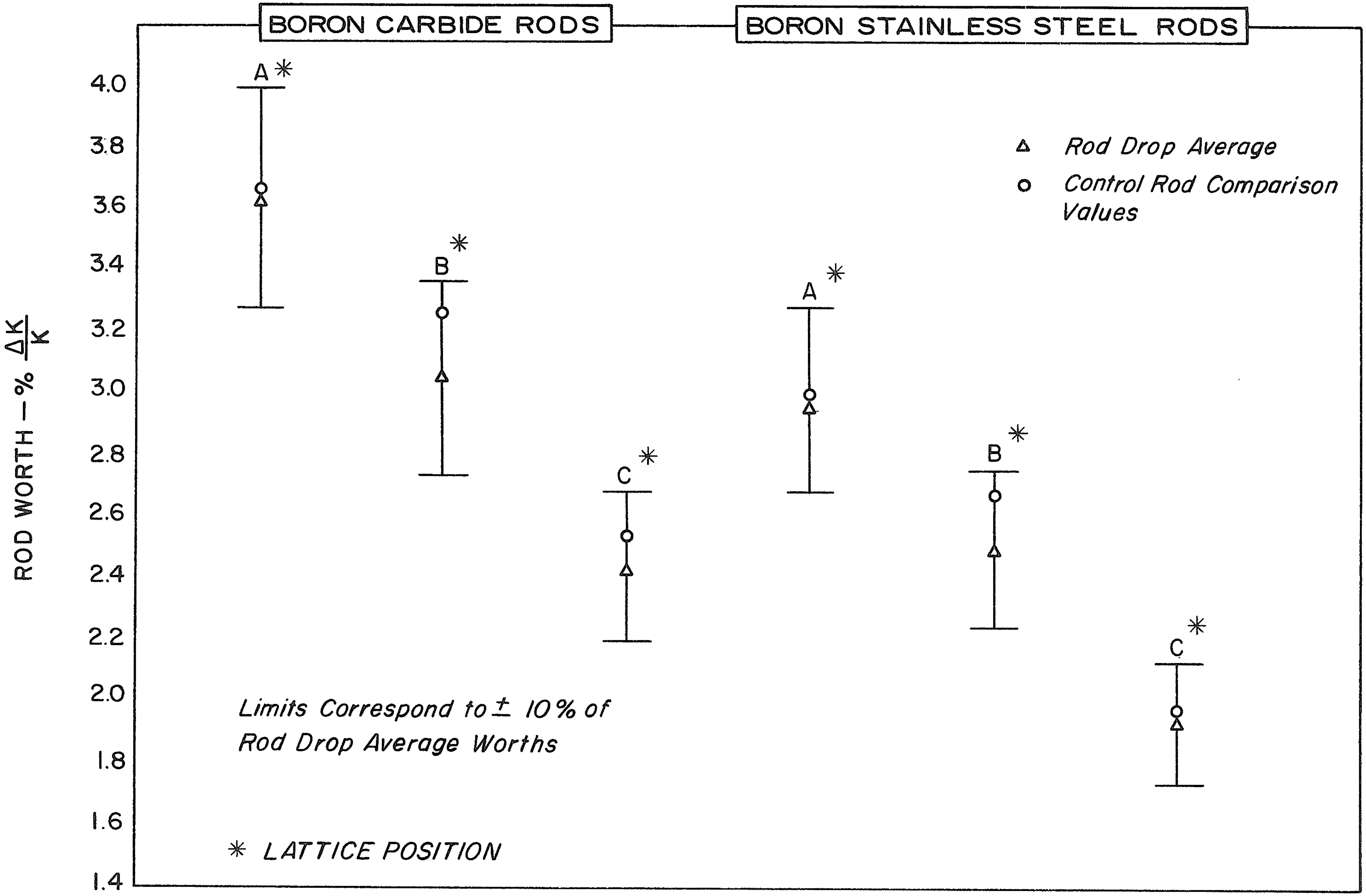


Figure 9

Shim-Safety Rod Worths by Rod Drop and Control Rod Comparison Methods

V. SUMMARY AND CONCLUSIONS

The worths of the 1 1/2 weight per cent boron stainless steel rods have been measured using the rod drop method and the control rod comparison method for each of the three reactor lattice positions. The total worth of the three rods was found to be -7.4% $\Delta k/k$ as measured by the rod drop method. Individual rod worths determined by the control rod comparison method agreed with the rod drop measurements within a range from 0 to +8%. The experimental determination of the total worth of the three rods was found to be reproducible within an overall uncertainty of $\pm$10%.

Taking an excess reactivity of +2.7% $\Delta k/k$ as authorized by the FNR Facility License, and the lower error limit of the three rods as -6.6% $\Delta k/k$, the use of the boron stainless steel rods would provide a shutdown margin of 3.9% $\Delta k/k$. This corresponds to a ratio of 2.4:1 for the total rod worth to the maximum excess reactor loading.

On the basis of reported results of the behavior of 2 per cent boron stainless steel rods in the EBWR,[10] it is anticipated that no significant metallurgical degradation from radiation damage will occur in low power (1-5 MW) research reactors such as the FNR. The life of the rods in the FNR should be limited by the depletion of boron rather than by metallurgical considerations. Using the method of T. J. Pashos, et. al.,[3] and a hot spot factor of 5.0, calculations indicate a total of 60,000 megawatt hours would be required to reduce the total shim rod worth to 5.4% $\Delta k/k$. This reactivity corresponds to twice the licensed excess reactivity for the FNR. Hence, after 60,000 megawatt hours of operation, the ratio of total rod worth to maximum core excess would be 2:1. Burnout of the boron over a period of several years will require periodic re-evaluation of the worth of the rods and eventual replacement.

Although the total worth of the boron stainless steel rods is 80% of that for the boron carbide powder filled rods, this worth still provides a 2.4:1 ratio of total rod worth to maximum permissible excess reactivity. Fabrication of the rods from solid material provides a rugged construction which offers a high degree of assurance that significant rod deformations will not occur. Because of the rugged construction, the boron stainless steel rods will provide a more dependable means of reactor shutdown and in this way will provide a greater degree of safety protection than we now have with boron carbide powder filled rods. It is, therefore, recommended that the existing rods in the Ford Nuclear Reactor be replaced by the boron stainless steel rods discussed herein.

VI. REFERENCES

1. C. W. Ricker, W. R. Dunbar, and J. B. Bullock, "Deformation of the Ford Nuclear Reactor Shim-Safety Rods", MMPP #110-2, Michigan Memorial Phoenix Project, The University of Michigan, December 1960.
2. USAEC Health and Safety Information, No. 129, September 21, 1961.
3. T. J. Pashos, G. D. Ritland, and J. L. Russell, Jr., "A Method for the Comparative Evaluation of Reactor Control Materials", GEAP-3344, April 13, 1960.
4. Private Communication: Diamond Power Specialty Corp., Lancaster, Ohio, to W. R. Dunbar, February 2, 1961.
5. R. A. Becker, and J. L. Russell, Jr., "Relative Effectiveness of Reactor Control Materials", GEAP-3201, p. 25, July 20, 1959.
6. A. Radkowsky, and J. R. Stean, eds., Naval Reactors Physics Handbook, Vol. 3, Chap. 5, September 1958.
7. J. F. Hogerton, and R. C. Grass, eds., The Reactor Handbook, Vol. I, AECD 5532, USAEC, April 1956.
8. R. A. Moor, J. C. Nance, and L. W. Perry, "GTR Rod Calibration", NARF 54-14T, March 30, 1955.
9. F. P. Green, ed., "Reactor Safety System Response", ORNL 2318, p. 13, February 14, 1958.
10. J. A. Thie, Nucleonics, 19, 60, (1961).