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CALIBRATION OF CONTROL ROD SYSTEM OF THE X-10 REACTOR

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Jules S. Levin
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February 18, 1949

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Department of Reactor Science and Engineering
Brookhaven National Laboratory
Upton, N.Y.

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CALIBRATION OF CONTROL ROD SYSTEM ON X-10 REACTOR

Abstract

During the week of September 13 through September 17, 1948, experiments were performed on the Clinton X-10 reactor to determine the calibration of the number one and number two regulating rods, the number six shim rod, and the number seven safety rod. Absolute calibration of the regulating rods was obtained by allowing the cold pile to rise exponentially as a result of the partial withdrawal of one of the rods, while the relative effectiveness of various parts of the rods was obtained by introducing small increments of reactivity into the pile at full equilibrium power and observing the resultant power transient. The number six rod was calibrated by balancing with the number one and number two rods during a constant power run which started with the reactor in a cold condition. The value for the number seven rod was obtained by balancing against the number one and number two regulating rods during a run at full power with the reactor in temperature equilibrium. The results obtained for the entire rods were as follows:

Number one regulating rod	211 ± 42 inhours
Number two regulating rod	184 ± 14 inhours
Number six shim rod	235 ± 30 inhours
Number seven safety rod	105 ± 30 inhours

where errors stated are the maximum deviation considered possible with the data obtained.

Calibrations along the entire length of the number one and number two regulating rods were also obtained.

A mathematical fit was attempted on the calibration curve for the number two regulating rod, and reasonably close agreement was obtained for a function of the form:

$$\text{inhours} = (.0141)\,(13.60)^2 \int_x^{196} \left[J_0\left(2.405\sqrt{\frac{(x-61)^2+(60)^2}{(135)^2+(60)^2}}\right)\right]^2 dx$$

where x is the position of the rod in inches out, where 0 inches out equals 200 inches in.

Introduction

In order to allow more accurately for discrepancies between theory and experiment in the initial operation of the Experimental Reactor at Brookhaven, it was thought advisable to know more about the discrepancies existing between calculated and measured values of the effect of the shim and regu-

[redacted]

lating rods on the X-10 reactor at Oak Ridge National Laboratories. In order to determine this, it was necessary to know the calibration curves of the regulating rods. Because no measurements of these constants had been made since 1945, and since the control charts used by the X-10 operations personnel had been developed for a radically different loading, it was decided that it would be worthwhile to obtain a new calibration of the entire control system of the X-10 reactor.

The experimental program at X-10, however, demanded that the reactor be kept up to power as much as possible, with the power level being disturbed as little as possible. It was, therefore, decided that any measurements to be made with a cool, shut-down pile would have to be made during the regularly scheduled shut-downs of the reactor. All other measurements would have to be made as nearly at constant power as possible.

At the suggestion of Dr. L.B. Borst, it was decided to obtain absolute calibration of a portion of each of the regulating rods by observing the exponential rise of the power level of the cold pile after withdrawing a portion of one of the regulating rods. Sensitivity curves for the regulating rods would then be determined at full power using a transient-response method. Calibration of one of the shim rods could be made by withdrawing the shim rod during the long temperature transient obtained by running an orginally-cold pile at constant power until temperature equilibrium was reached. This method was possible since it was believed that each of the shim rods, if left inserted in the pile, individually possessed sufficient reactivity to prevent the warm reactor from becoming critical.

Since one of the safety rods could be inserted into the pile without causing shut-down if the regulating rods were withdrawn an equivalent amount, it was decided that, if time allowed, one of the safety rods could be calibrated quite simply by means of lowering it into the pile and noting the resulting adjustment of the regulating rods needed to keep the pile at equilibrium. A more detailed description of the methods used on each of the sets of rods will be found further on in this report.

The authors wish at this point to express their appreciation for the generous assistance given them by Mr. L.B. Emlet, Mr. M.E. Ramsey, and Mr. F.W. Tench of the Oak Ridge National Laboratory, and by Dr. L.B. Borst and Dr. I. Kaplan of the Nuclear Reactor Project at Brookhaven National Laboratory.

Determination of Absolute Calibration Factor

On September 14, 1948, an exponential rise experiment was performed to obtain an absolute calibration factor for the number two regulating rod. A similar experiment was performed for rod number one on September 17, 1948. In both cases the procedure used was exactly the same. However, because of the nature of the shut-downs immediately previous to these experiments, the

temperatures of the various components of the pile differed for the two cases. Initial temperature for both experiments follow:

	Number One	Number Two
Graphite*	33° C	39° C
Metal**	38° C	51° C

Graphite temperatures were on long transients and did not change appreciably during the course of the experiments.

Immediately previous to the first experiment, the control rod positions were zeroed so as to agree with the readings on the selsyn indicators. These indicators were known not to drift appreciably during the period of time involved in these experiments.

Procedure used in the experiment on rod number two is given below. A similar procedure was used for the number one regulating rod.

1) During the shut-down preceeding the exponential rise experiment, the fans were kept on as much as possible so as to have the entire reactor as cool as possible for the experiment.

2) Previous to the actual start-up, one fan was turned off and the damper on the other was shut as far as possible to remove any effects due to cooling. The second fan was left running, though dampered, so that it could be cut in rapidly in case of any impending overheating of the metal.

3) With air flow essentially zero, the pile was left alone until both the metal and graphite came into temperature equilibrium. This was a matter of some twenty minutes to half an hour.

4) The pile was then brought to critical at the lowest power accurately read on the #1 (direct reading) galvanometer -- about 5.5 KW. This was done by withdrawing the safety and shim rods and placing number two rod in the center of its most sensitive region, and then withdrawing number one rod to approximately the critical position. Fine adjustment was made with the number two rod since it was more easily controlled. The pile period meter was used as an indicator of criticality, and appeared to be quite sensitive to small changes in pile reactivity. As soon as the precise critical position had been determined and noted, the reactor was shut down by inserting the number two rod without disturbing the setting of the other rods.

5) At this point, some ten minutes or more were let pass to let the metal cool down again to its equilibrium temperature.

* As recorded on Micromax recorder; points 7 & 8, located at the center of hole 20.

** As recorded on Micromax continuous recorder; point B, located in hole 1763, two feet west of center.

6) The number two rod was then withdrawn as rapidly as possible to a position some thirty inches beyond the critical position. All personnel were then requested to keep hands completely off of the controls. Readings of pile power were taken on the #1 galvanometer every five seconds, changing scales on the galvanometer so as to make continuous reading of the power level possible. The period of this galvanometer was 6 seconds and was considered small enough when compared to the pile periods chosen so that it did not introduce appreciable error in the resultant data. When the maximum desireable power was passed, the pile was shut down by manually tripping the #1 safety circuit. The damper on the running fan was opened, the other fan was turned on, and the pile was returned to normal operation.

The data obtained in this manner was then plotted with the log of pile power level as a function of time. In both cases, the data essentially fell on a straight line up to the point where metal temperature had been observed to start changing, at which point the experimental curve began to fall increasingly below the expected straight line. In the case of the experiment on the number one rod, the rise in metal temperature turned out to be sufficient to check the rise of the pile, and it was not necessary to trip the safety circuits.

The portion of the experimental curve well below the point where the temperature was observed to have any effect and above the point where accurate readings of the galvanometer were possible -- generally the region of 1 to 100 KW. -- was selected for use in obtaining the period of the pile. This generally comprised a time interval of about five minutes, or about sixty readings. A straight line was then fitted through the experimental points. On rod number two, fits were made both by eye and by using the method of least squares, but due to the consistency of the data the periods resulting from these two methods differed only by 0.29%. It was, therefore, decided that since such an error would not be significant when compared to the errors to be encountered in other phases of the calculations, the fit to the data for the number one rod would be made by eye. In the final calculations, the least squares value was used for the number two rod and the eye-fit value was used for number one. Because of the use of the least squares method of fitting a straight line to the number two rod data, a probable error for the variation of the experimental points about the fitted line could be computed by regular statistical methods, and is thus included here to give some idea of the reliability of the data.

From the slopes of the straight lines obtained from the experimental points, the pile periods were computed. Then, using the inhour formula:*

$$\text{inhours} = \frac{54}{\tau} + \frac{20.3}{\tau + 0.62} + \frac{204}{\tau + 2.19} + \frac{535}{\tau + 6.5} + \frac{2036}{\tau + 31.7} + \frac{787}{\tau + 80.3}$$

* Hughes et al., Physical Review, January 15, 1948

a value for the reactivity of the portions of the regulating rods involved was obtained. The periods and values of reactivity obtained were as follows:

	Number One Rod	Number Two Rod
Period (seconds)	66.29	50.05 ± 0.05**
Reactivity (inhours)	37.59	45.79
Portion of rod (inches)	56.1 to 77.95	43.18 to 73.0

It is particularly interesting to note that the periods obtained by these experiments are in agreement with the observed periods as indicated by the pile period meter during the performance of the experiments. It is also encouraging to note that the resultant exponential rise curves begin to deviate from the expected pure exponential at precisely the point where observation of the metal temperature recorder indicated that the metal temperatures were just beginning to rise.

Determination of Sensitivity and Calibration Curves for the Regulating Rods

The sensitivity curves on the number one and number two rods were obtained on the midnight to 8 a.m. shifts on the mornings of September 16th and 17th. This particular time of day was chosen because of the more stable operation of the reactor due to more nearly constant atmospheric conditions and because of the availability of the pile at this time for unusual operation.

When the pile is in equilibrium, a small increment in the reactivity due to the slight removal of one of the control rods will cause the power level to rise. The temperature rise of the pile will, however, lag this power rise with the result that the power level will overshoot its equilibrium value, and will attain a peak value at the point where the temperature coefficient finally has an effect essentially equal to the increment given to the reactivity. At this point, since the temperature is still rising, the reactor power level will begin to fall, and will continue to fall until it again causes a sufficient change in the reactor effective temperature to start the power climbing. After two or three oscillations, the effect has been damped out sufficiently to be negligible. Actually the picture is somewhat complicated by the delayed neutrons which tend slightly to lower the height of the transient peaks and which cause the maximum to occur at a slightly earlier time. The theory of pile behavior under the above conditions is discussed in more detail in a memo to DuPont by Wheeler.

For small variations in the increment given the reactivity, the height of the transient peak is assumed proportional to the magnitude of the increment. Thus, by observing the transient response of the pile caused by small

** Probable error from least squares computation.

increments in control rod position for various points along the control rod, a sensitivity curve for the rod can be obtained. This method for calibration of control rods at full power was suggested by Dr. L.B. Borst.

Because of the small variations in power level occurring in these transient experiments, the #2 galvanometer was used. This galvanometer has a period of 14 seconds, which was again considered short enough to have no appreciable effect on the results. When used as a differential galvanometer on its second scale, full scale deflection either side of center on the #2 galvanometer was 250 KW. This made it possible to follow the transient response of the reactor with reasonable accuracy.

During these experiments a special technique was used on the cooling fan regulation. The current supplied to the two fans was kept constant in order that the same air-flow, in pounds per hour, would be cooling the reactor throughout the measurements. For reasonably small variations in atmospheric conditions, this would insure a uniform cooling effect.

In making the actual calibrations, the pile was first brought up to power and allowed to run for a sufficient time to produce virtual temperature equilibrium. Immediately preceding the experiment, all controls were left completely alone for a period of about ten minutes, until the various instruments indicated that the reactor was in a stable equilibrium condition. The rod being calibrated was then suddenly withdrawn a given increment -- from one inch to about fourteen inches, depending upon the sensitivity of the rod in that particular region. The withdrawal was made as rapidly as possible, with no effort being made to correct for overshooting or undershooting the desired distance, so that the reactivity increase was introduced in one motion of the rod, with no external variations in conditions once the single motion of the rod had been completed. The response of the pile was then followed on the #2 galvanometer, readings being taken every five seconds, until the reactor had passed its point of maximum power and had then reached the half-maximum point. In some cases, ten-second readings were continued for some time beyond this point in order to satisfy curiosity as to the shape of the curves.

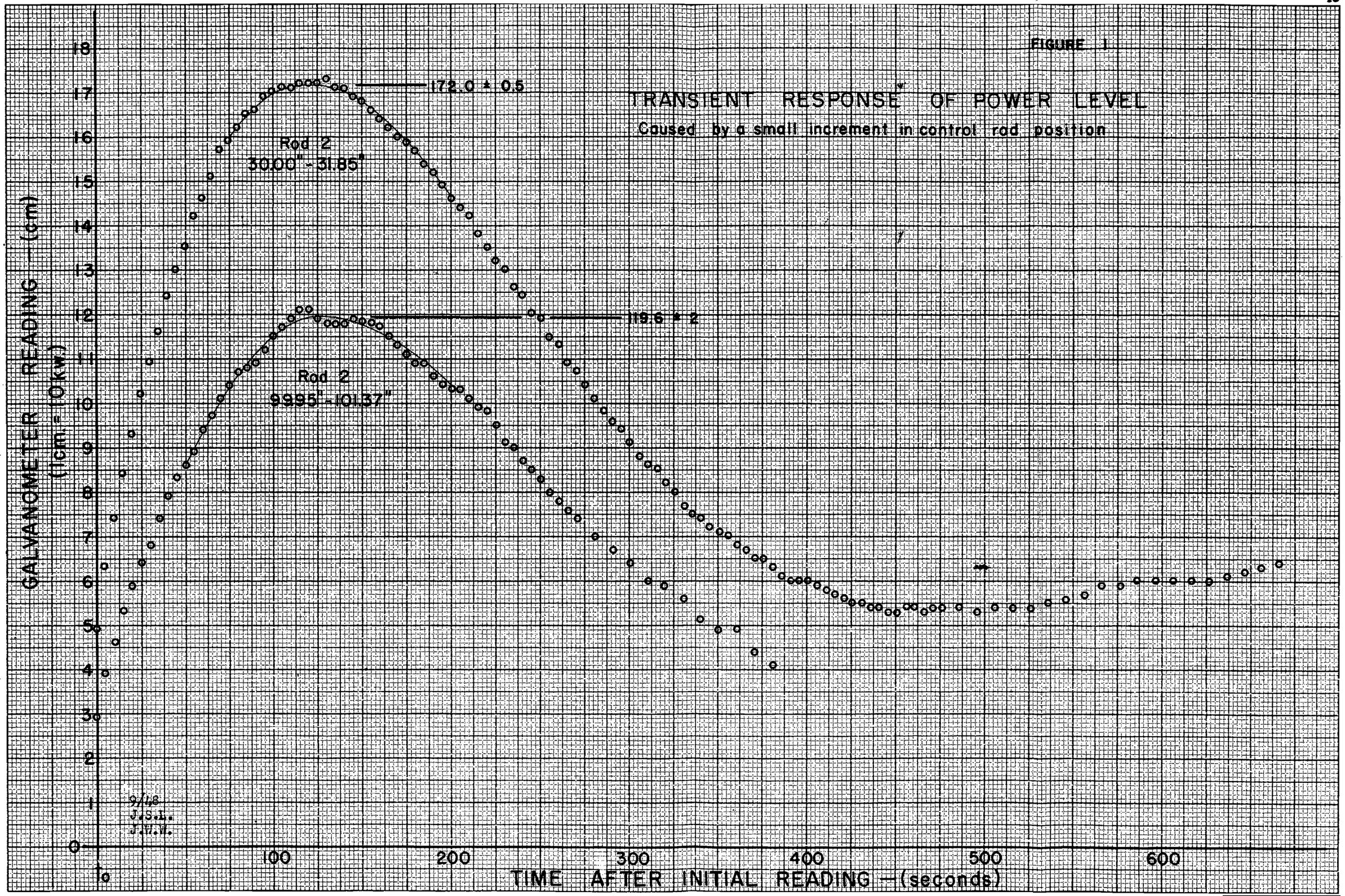
The data obtained in this manner was plotted with power as a function of time. Two curves typical of the transient response of the pile, presumably undisturbed by extraneous effects, are shown as examples. (Figure 1) Some of the curves, however, showed definite effects of outside influences, giving in some cases an extremely regular oscillation about the expected transient rise, and in other cases merely giving sudden breaks or jumps in the curves. Two curves showing the latter two phenomena are also included. (Figure 2)

The increments given the control rods in such measurements were all calculated so as to produce transient peaks of essentially the same magnitude, since if the transients could be predicted and controlled to produce peaks of equal height, any errors due to non-linearity of the relation between reactivity and peak height would have no effect on the calibrations. However, due to the

FIGURE 1

TRANSIENT RESPONSE* OF POWER LEVEL

Caused by a small increment in control rod position



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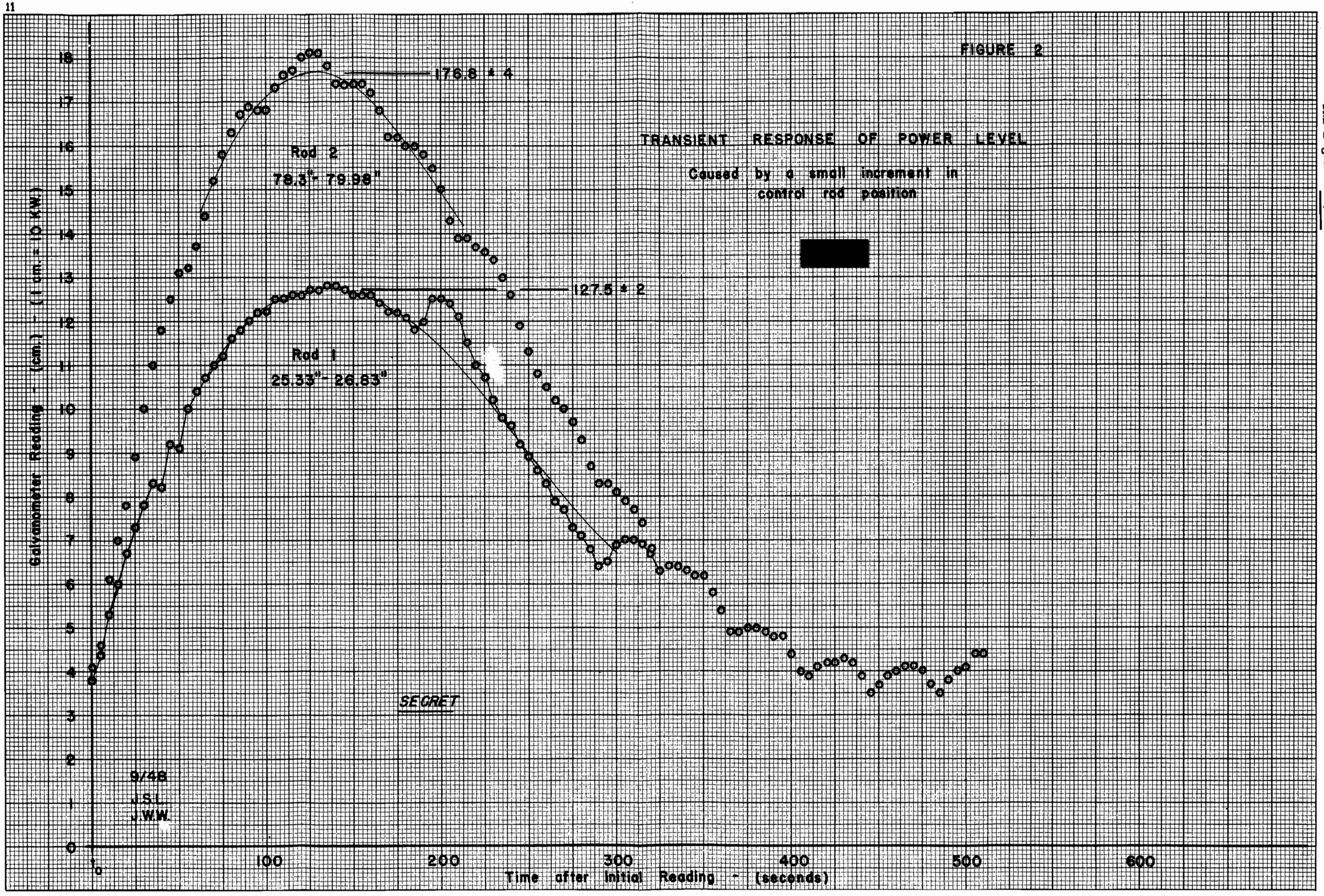

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inevitable errors in any such experiment, there is a good deal of variation in the magnitude of the transient rises. It has been assumed that since most of these lie within a reasonably close region, the transient height is directly proportional to the increment in reactivity given to produce the transient.

In deciding upon the maximum point reached by the power transient, it was necessary to draw smooth curves through the average of the points near the peak of the various curves rather than actually using the maximum value or trying to remove the breaks or oscillations in any manner. Since interpretation or correction of the irregularities in the curves was impossible aside from noting that they might be caused by some such thing as bubbles in the steam pipe in the pile, the peak values are undoubtedly influenced by these irregularities in some cases. Luckily, however, most of the jumps and breaks occur in such a position as to make it possible to determine the peak of the true curve upon which the extraneous effect is superimposed. In order to give some idea of the magnitude of the uncertainties involved in determining the maximum values of the transient peaks, the maximum and minimum values of peak height which could conceivably be gotten from the data were determined. The deviations of these extremes from the previously determined true value were then computed. The final result of peak height was then given as the presumably-true value plus-or-minus the greater of the two limiting deviations. In the sample curves included in this report, (Figures 1 and 2) typical smooth curves have been drawn through the peaks of the transients in order to show the method of selecting the maximum values of the transients. Sample values for the errors in these maxima are also indicated.

It must be remembered in further calculations that the errors stated are not standard deviations or probable errors, but represent instead the values outside of which it is felt the true value could not lie. In this manner they are somewhat similar to the so-called "limit of error" or similar to the limits determined by using two or three standard deviations. However, since the exact statistical interpretation would be highly arbitrary in its origin, it was decided to handle the errors obtained as mathematically absolute limits rather than as statistical quantities. In this manner, any statement of errors would be an overestimate of the actual statistical error.

Errors in determining control rod position were considered to be plus-or-minus one in the last place of the reading. Using these errors and the errors in transient-peak height, the errors in control rod sensitivity in kilowatts per inch were calculated.

It was noticed on both of the days on which the calibrations were made that as the sun began to come up and the air temperature began to change, the behavior of the pile was not at all consistent and anomalous results were obtained. It is important to note here that the anomalous results obtained by repeating at dawn certain points taken about midnight do not prove that the data was not reproduceable, since certain points taken on the number two rod on September 16th were repeated when opportunity permitted on the 17th --

long before dawn -- and the results obtained (triangular points on Figure 4) fell well within the errors of the results of the previous night. It was, therefore, felt wise to ignore all data taken after conditions started changing in the morning and to consider only those points which were taken during the relatively constant conditions prevailing roughly between midnight and five o'clock.

The sensitivity in kilowatts per inch as a function of control rod position was plotted for both the control rods. Both of these plots are reproduced in this report. (Figures 3 and 4) The square points on the plot for the number two rod are the anomalous points taken as morning approached and were disregarded in drawing the curves. Data on the number one rod is not as significant as that on the number two rod due to a smaller number of points and to a larger scatter.

The area under these sensitivity curves corresponding to the portions of the rods withdrawn during the exponential rise experiments was then determined. From this a scale factor relating kilowatts per inch to inhours per inch was determined. Scale factors were as follows:

Rod number two	$0.0141 \pm 0.0005 \frac{\text{inhours/in.}}{\text{kw/in.}}$
Rod number one	$0.0154 \pm 0.0016 \frac{\text{inhours/in.}}{\text{kw/in.}}$

The agreement between these two values indicates that the rather arbitrary sensitivity curve drawn for the number one rod was somewhat low, but that the true value for the curve does lie somewhere between the two limits which were established.

The errors in the fit to the exponential rise turned out to be so small as to be negligable compared to the errors in the sensitivity curve, thus simplifying the calculation of the errors in the scale factor.

Finally, the sensitivity curves were integrated, the error curves being treated as separate curves during the integration, so that essentially for each rod three integrations were performed. The resultant calibration curves show inhours as a function of rod position. (Figures 5 and 6) The errors plotted as dotted lines on these curves are the average of the positive and negative deviations obtained from the integration, and are thus limits beyond which the true value probably could not lie. Again these errors have no definite statistical significance beyond indicating the possible deviations of the true value to a confidence interval of something like ninety percent rather than the confidence interval of fifty percent associated with the more-usually-stated probable error. Calibration curves for both control rods are included in this report.

It is interesting to note differences existing between these curves and previous curves for the same rods. Primarily, both of the new curves are higher valued at every point. Old and new values for the entire regulating

[redacted]

FIGURE 3

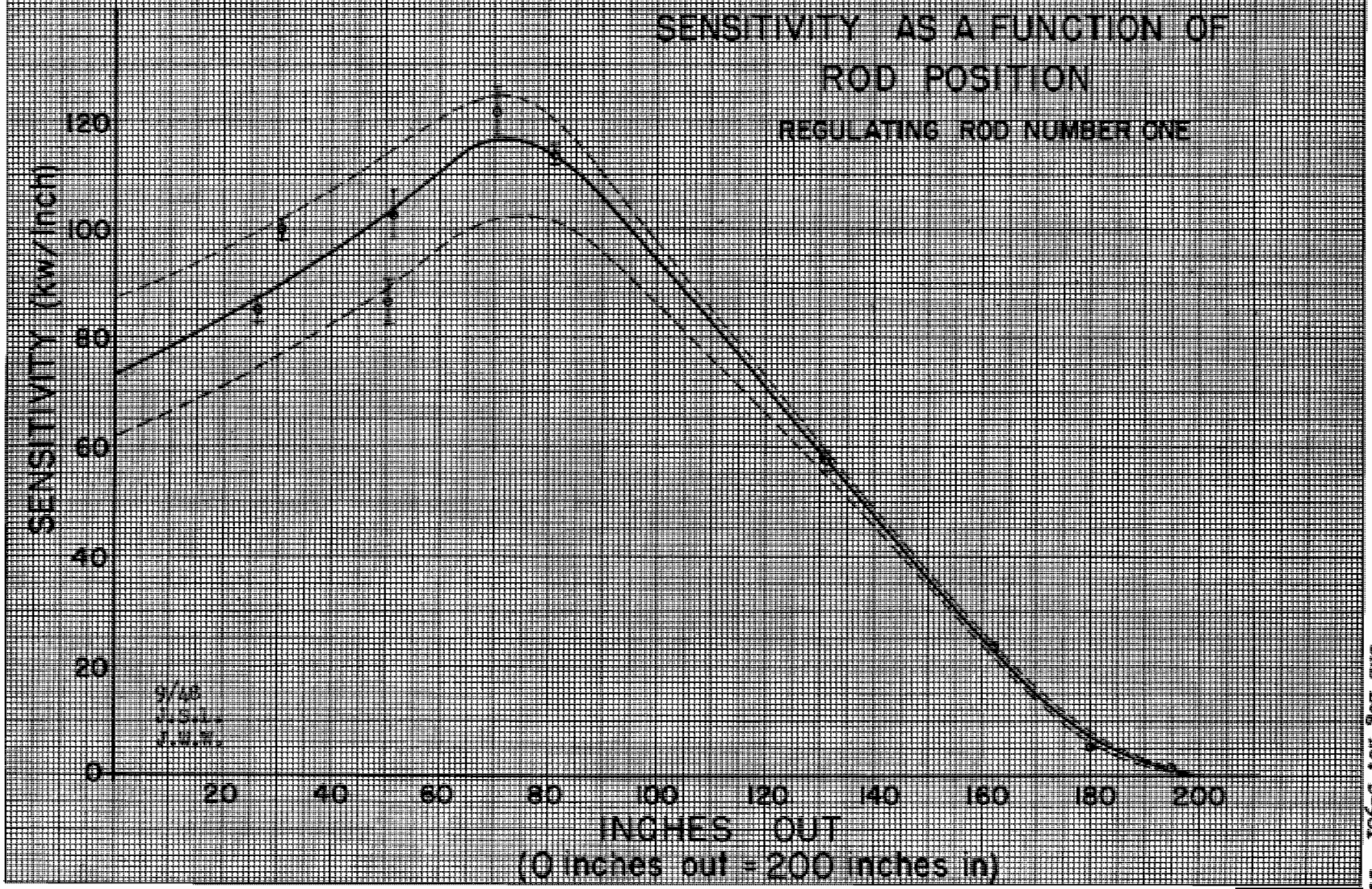

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FIGURE 4

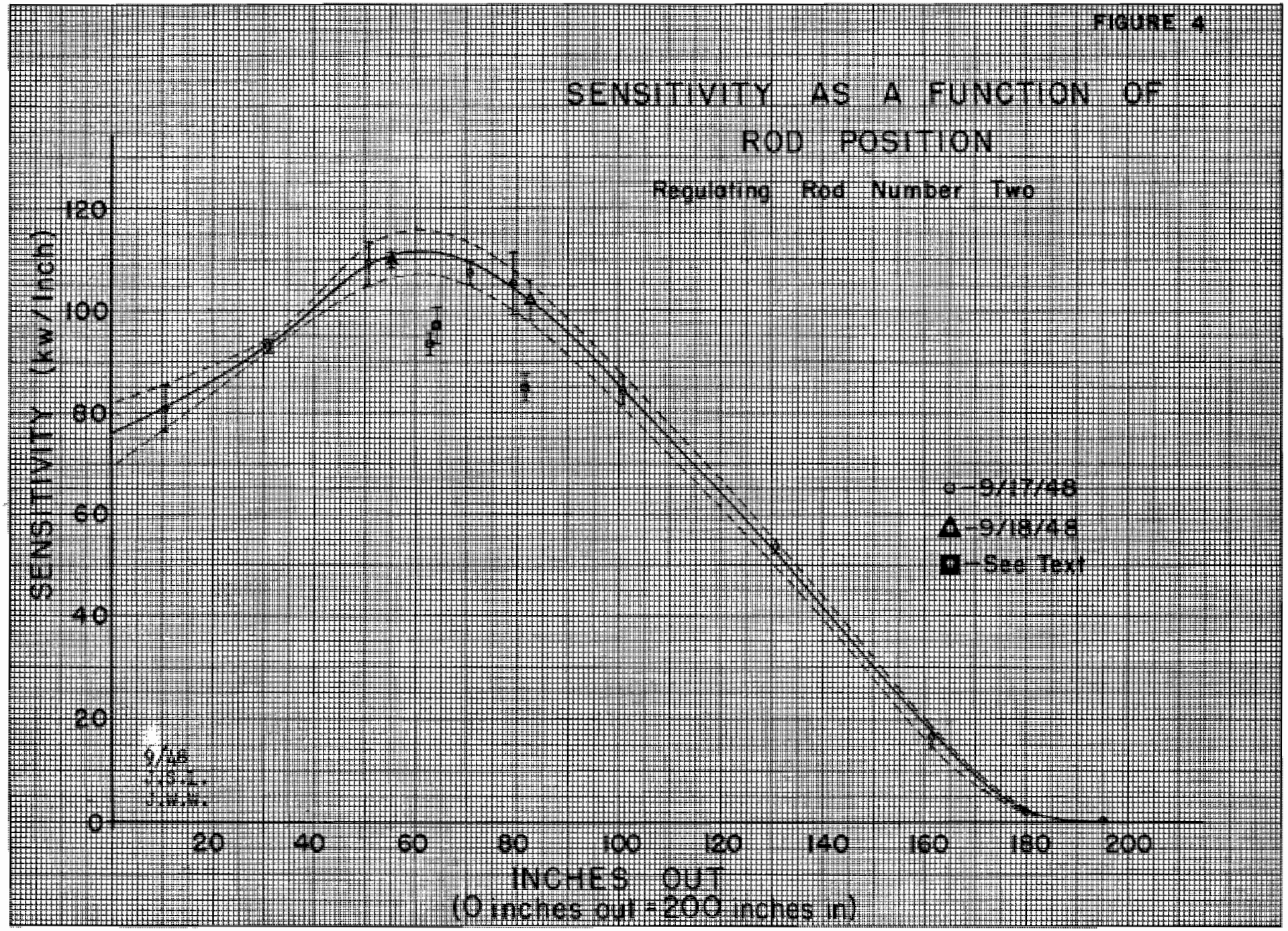

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FIGURE 5

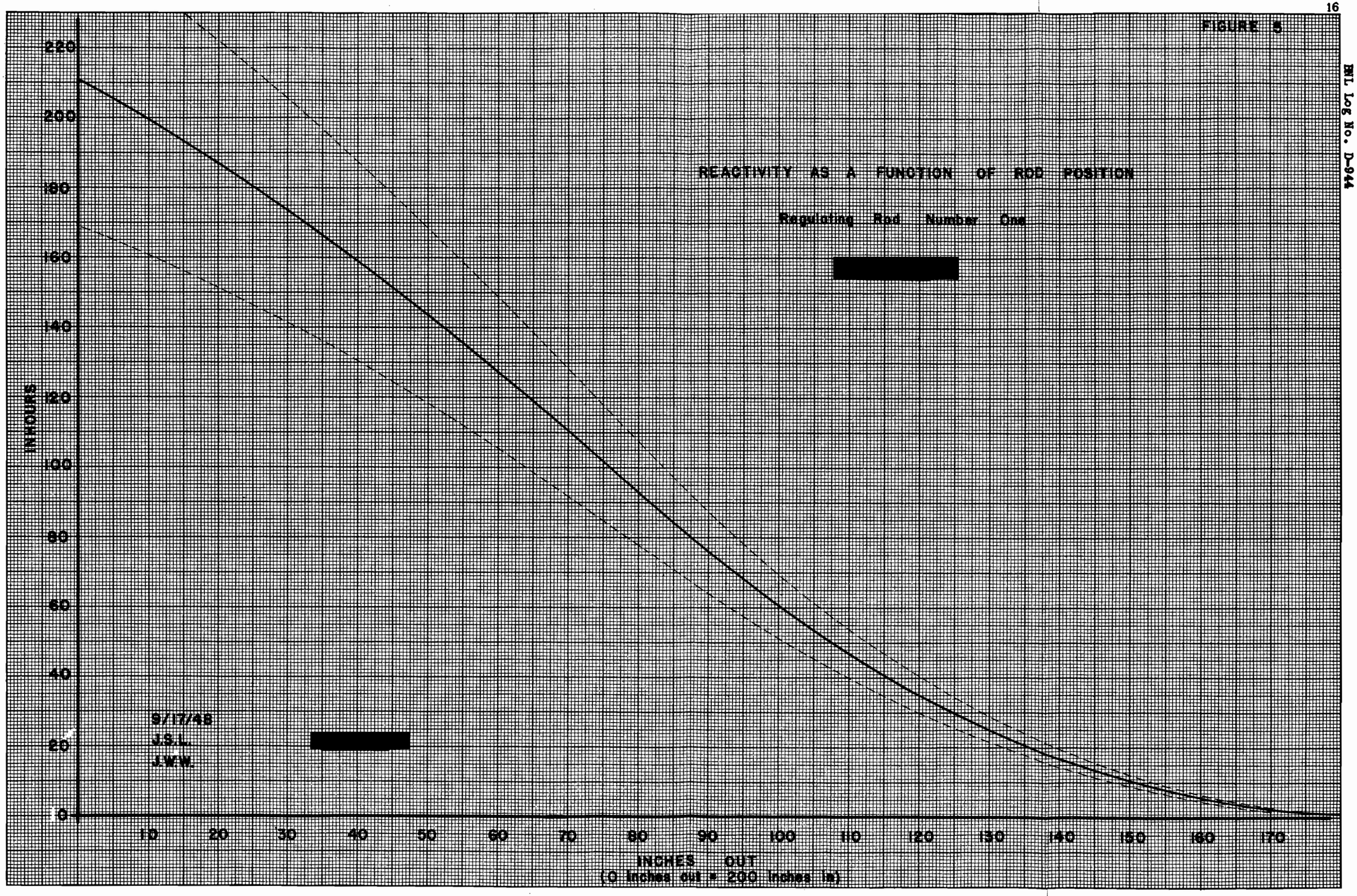

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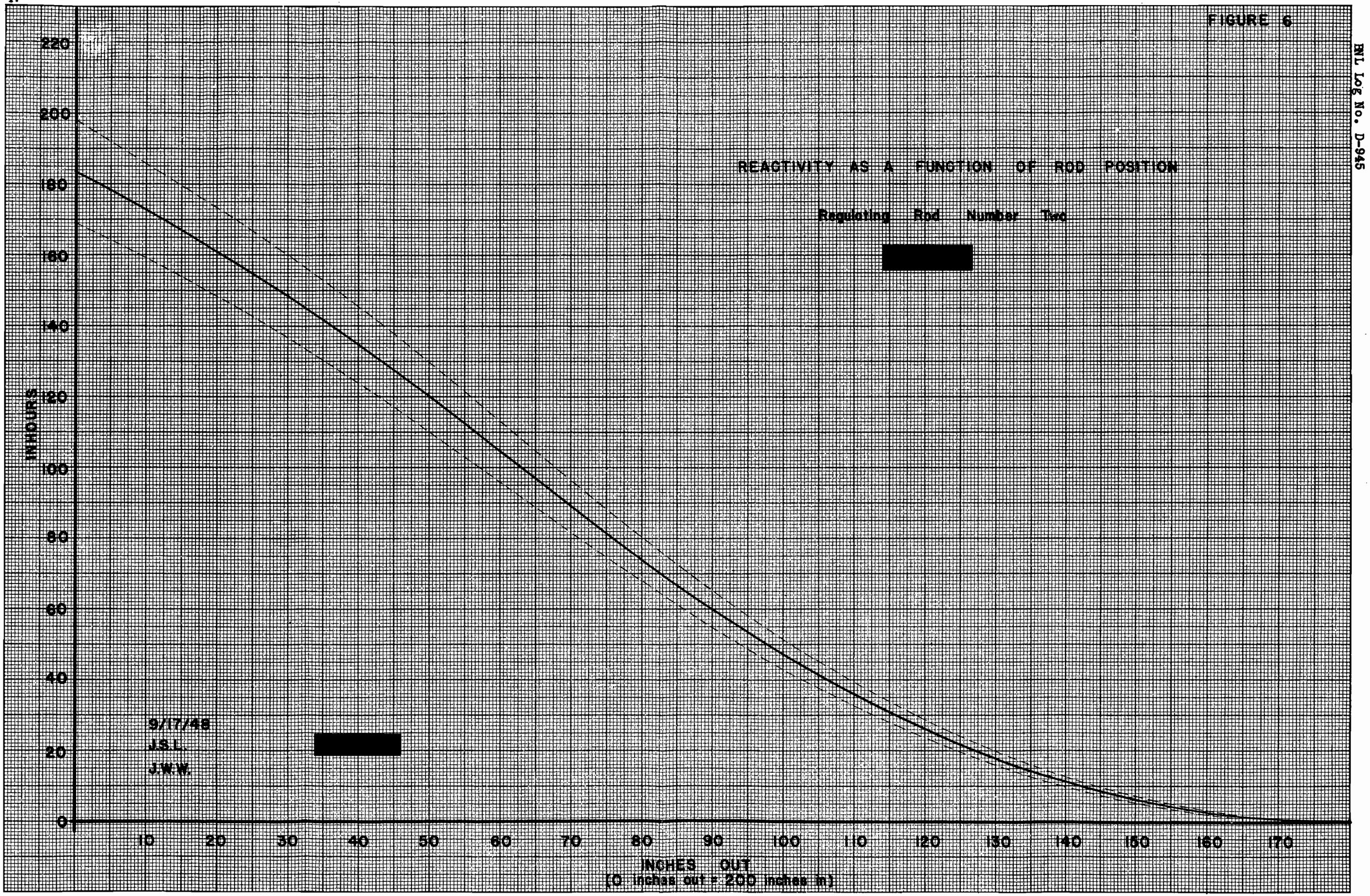
FIGURE 6


REACTIVITY AS A FUNCTION OF ROD POSITION
Regulating Rod Number Two
[redacted]
[redacted]
9/17/48
J.S.L.
J.W.W.
INHOURS
220
200
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
INCHES OUT
(0 inches out = 200 inches in)

rods (zero inches out) are as follows:

	Number One	Number Two
1945	186 inhours	145 inhours
This calibration	211 ± 42	184 ± 14

This is to be expected because of the increased, bowed loading of the pile. Bowing will extend the areas of high flux further toward the boundaries of the pile and thus the sensitivity of a control rod will be increased in the peripheral flux region.

Theoretically, with no control rod present, the region of maximum flux and thus greatest sensitivity should be at the center of the pile, a point about 56 inches out on the control rods. The calibration curves give the point of maximum sensitivity from 60 to 70 inches out, an effect due probably primarily to the effect of the control rod in shifting the neutron distribution during insertion, and also conceivably due in some part to the bowed loading.

Probably the most logical correlation that could be made would be a comparison of the control rod calibration curves with neutron traverses of the pile at about the same location as the control rod holes. Unfortunately, however, the only existant traverses of the X-10 pile were made while the pile was loaded in a radically different manner and would have little bearing on the present case. Should such a traverse be taken in the near future, it would certainly be desireable to compare the resultant curves with those obtained by calibration of the control rods.

An attempt was made to find a mathematical fit to the experimentally determined sensitivity and calibration curves for the regulating rods. Since the data on the number two rod was better than that on the number one rod, efforts were restricted to finding a satisfactory fit for the curves for the number two rod.

The functions considered for the sensitivity curve were of the form

$$A^2 \cos^2 \left(\frac{\pi}{2R} \sqrt{(x-x_o)^2 + a^2} \right)$$

and

$$A^2 \left[J_o \left(2.405 \sqrt{\frac{(x-x_o)^2 + a^2}{R^2}} \right) \right]^2$$

where x is the distance the rod has been withdrawn (0 inches out = 200 inches in)

x_o is the coordinate of the center of reactivity of the pile.

a is the vertical distance between the center of reactivity and the control rod.

R is related to the radius of the pile in such a way that the function goes to zero at a given value of x.

A is a normalizing factor.

Since it was known that the center of reactivity was not at the geometric center of the pile; that the flux distribution in the pile was not a pure cosine or Bessel function due to the bowed loading; and that the presence of the control rods further disturbed this distribution, the values of the parameters "x_o", "R", and "a" were determined primarily from the experimental data, with only secondary consideration given to the physical dimensions of the pile.

From the sensitivity curve, (Figure 7) "x_o" was taken to be 61 inches, the point at which this curve has its maximum. The geometric center of the pile was actually at x = 56 inches. Likewise, "R" was determined such that the function goes to zero at x = 196, the point at which the sensitivity curve drops to zero. "A", the normalizing factor, was taken so that the mathematical curve and the experimental sensitivity curves had the same values at "x_o". This left "a" as the only quantity which could be varied to adjust the fit. The vertical distance between the geometric center of the pile and control rod number two is 56 inches, however, since the geometric center of the pile and its center of reactivity do not coincide, "a" could take on various values, roughly of the order of 56 inches.

In fitting the cosine function, "a" was assigned values between 40 and 70 inches; however, none of the curves calculated gave satisfactory fits. Even when "a" was allowed to take on the extreme values of 0 and 100 inches, the fits were not improved. This appears to be due to the fact that the shape of the curve is very insensitive to the value of "a". It was concluded that no satisfactory cosine fit could be obtained.

The shape of the Bessel function fit was found to be much more sensitive to "a" and after a few attempts, "a" = 60 was found to give a good approximation to the experimental curves. Figures 7 and 8 show the fit of

$$\left[13.60\ J_o\left(2.405\sqrt{\frac{(x-61)^2+(60)^2}{(135)^2+(60)^2}}\right)\right]^2$$

to the sensitivity curve, and

$$(.0141)\ (13.60)^2 \int_x^{196} \left[J_o\left(2.405\sqrt{\frac{(x-61)^2+(60)^2}{(135)^2+(60)^2}}\right)\right]^2 dx$$

to the calibration curve, where 0.0141 is the experimentally determined factor relating KW/inch to inhours/inch.

In view of the perturbation of the neutron flux by the presence of the control rods, various poisons, and the bowed loading, it is surprising that such a good mathematical fit could be obtained.

FIGURE 7

SENSITIVITY AS A FUNCTION OF ROD POSITION

Regulating Rod Number Two

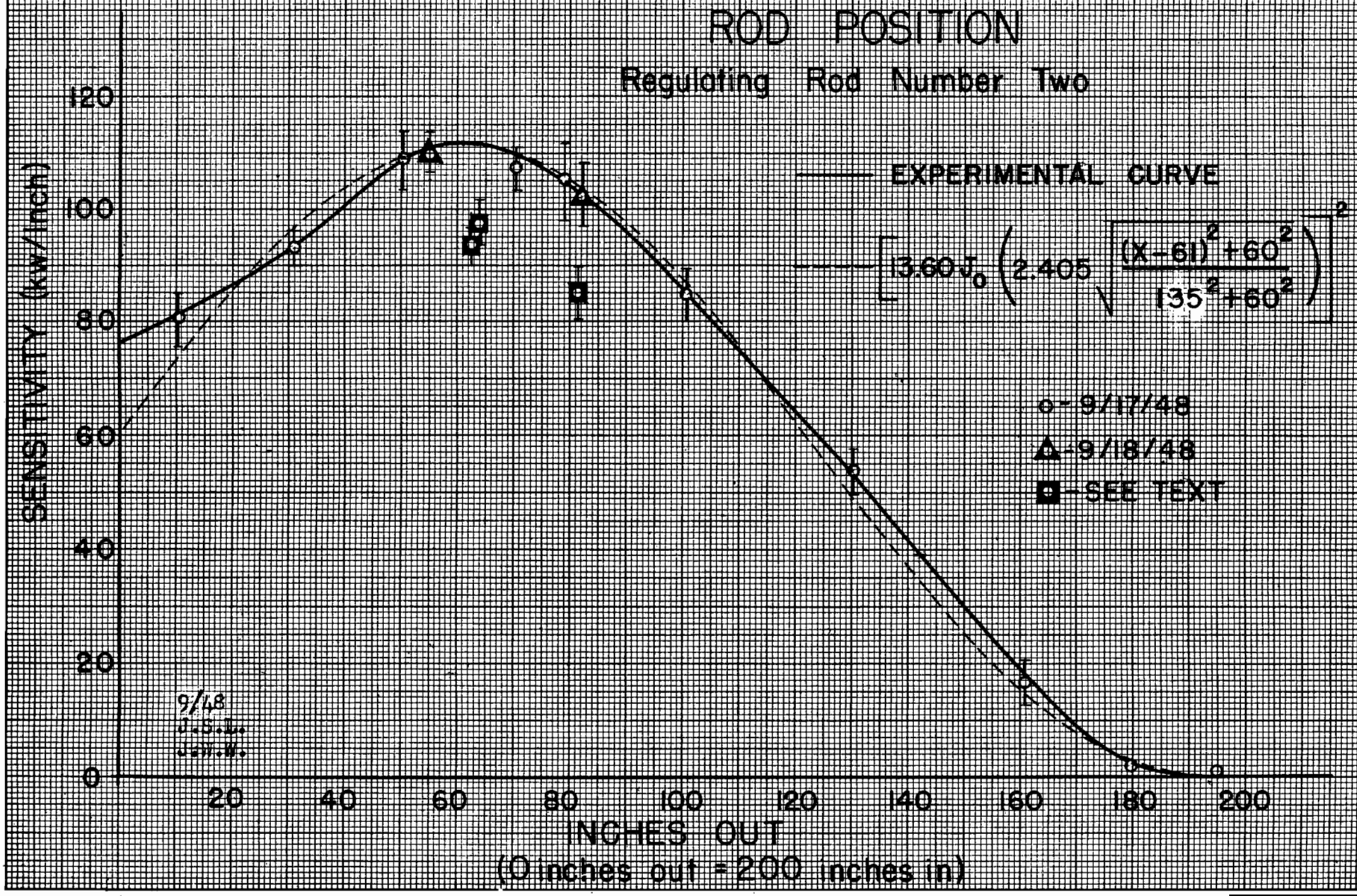
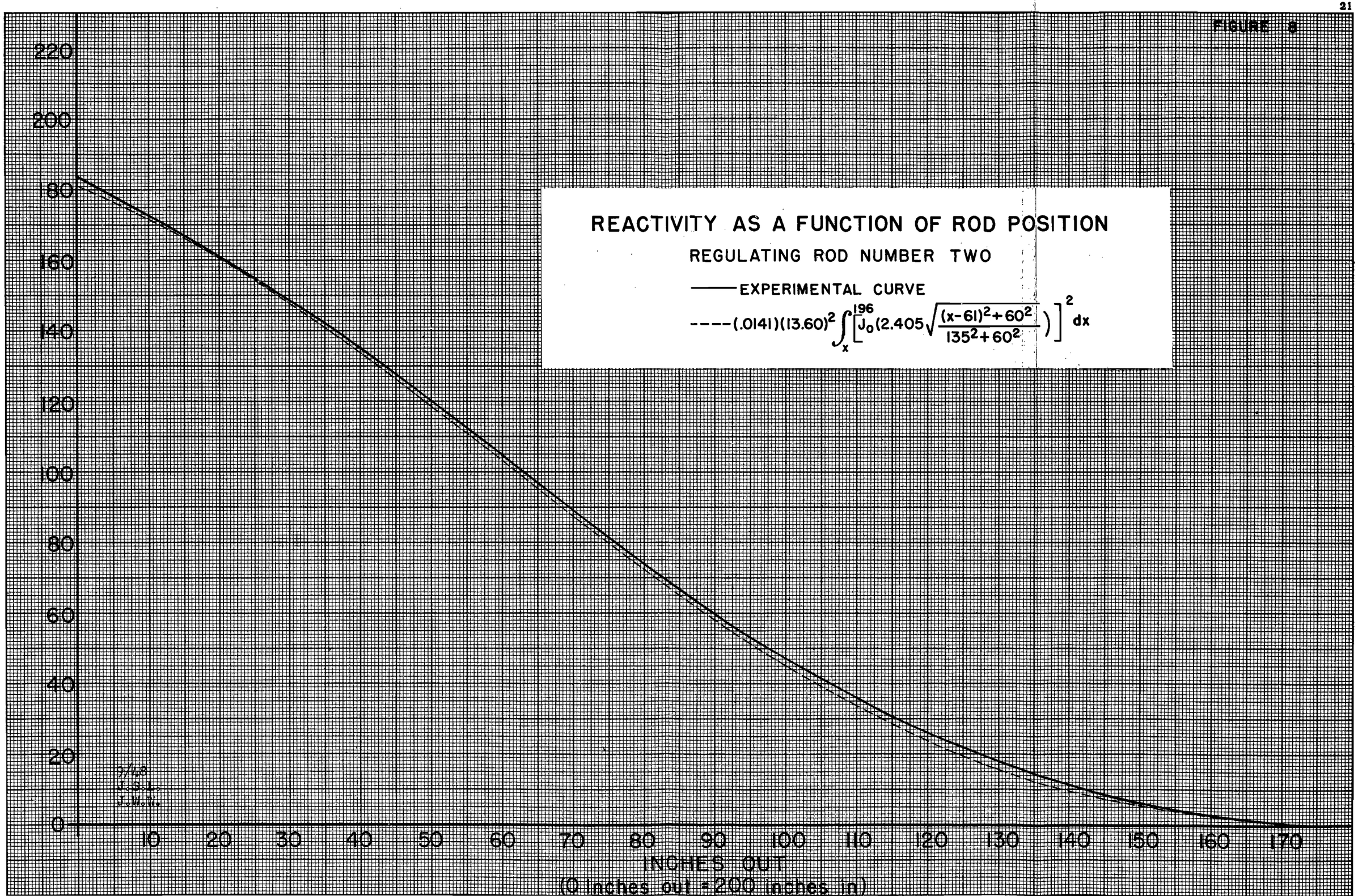


FIGURE 8



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Determination of Total Value of Shim Rod

On the graveyard shift on September 15th, the pile unexpectedly became available for use while still essentially cold. With both fans on full, and the number six shim rod all the way in, the pile was brought directly up to 3600 KW, using the number one and number two rods. Readings were taken, every seven or eight minutes, of graphite and metal temperatures, inlet and exit air flows and temperatures, rod positions, barometric pressure, and power level. The reactor was held at 3600 KW. as closely as possible for a period of about one hour, at which time, due to the increasing effect of the temperature coefficient, both the number one and number two rods became entirely withdrawn from the pile in the process of maintaining constant power. As soon as both rods were fully out, the number six rod was withdrawn from the pile and jogged, to be sure that it was out as far as it would go, the reactor power being held down to 3600 KW. by using the number one and number two rods. A maximum transient power of 4400 KW. was reached during the trade. The pile was then held at a constant power of 3600 KW. for another two and a half hours, with readings being taken on various instruments as before.

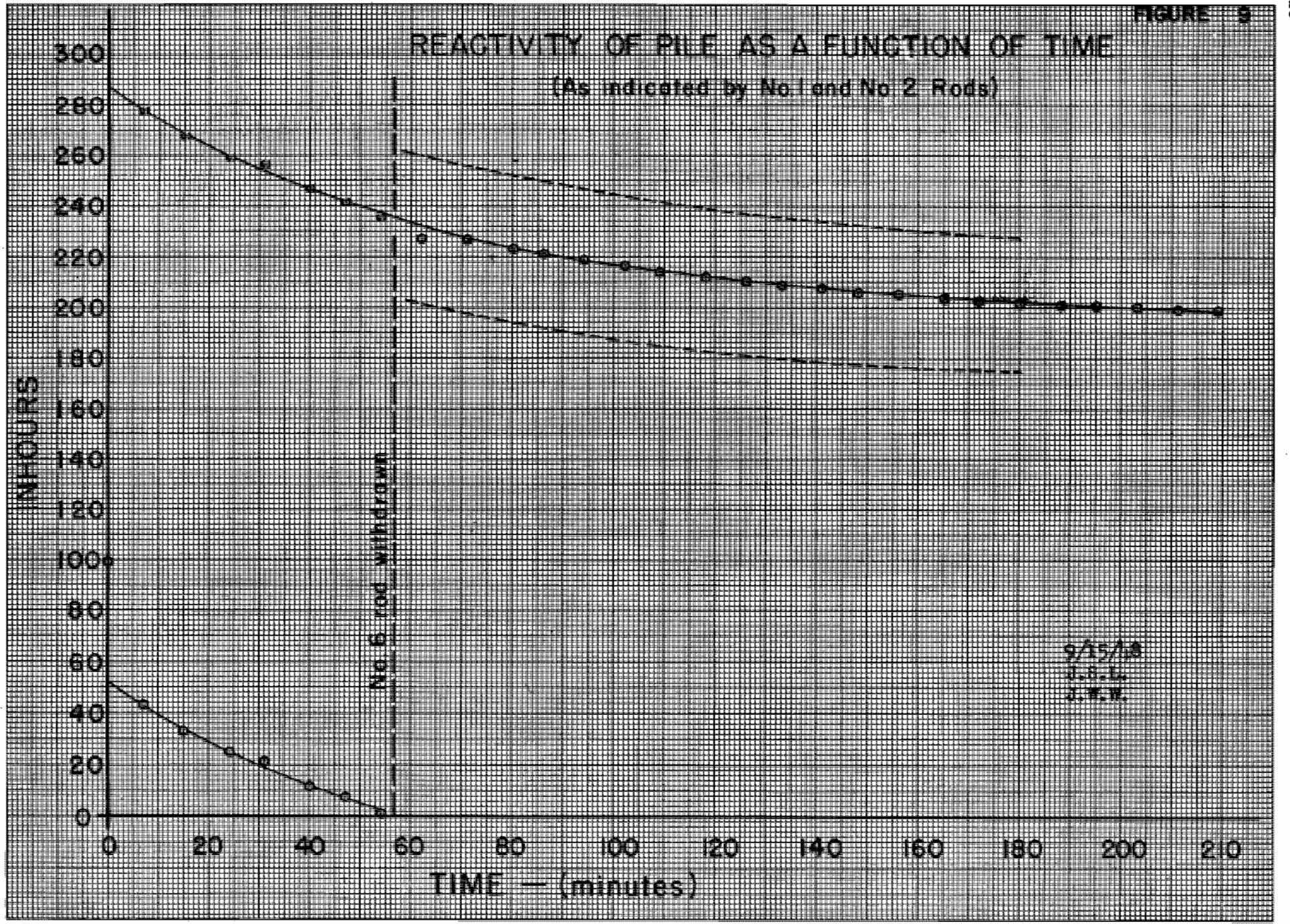
Using the calibration curves obtained for the number one and number two rods, a plot was made of pile reactivity in inhours, as indicated on the number one and number two rods, as a function of time. (Figure 9) This yielded two segments of curves separated by the value of the number six shim rod. Transposition of the lower segment upward by an amount of 234.5 inhours made the two segments continuous. Since the point of zero reactivity as indicated by the number one and number two rods is known essentially without error, the major errors in the value for the number six rod are in the inhour values to be read off the calibration curves for the two regulating rods. The error obtained is roughly a thirteen per cent error, lying between the ten per cent error in the calibration of number two rod and the twenty per cent error in the calibration of number one. The value of 234.5 $\pm$ 30 inhours is higher than the value of 211 inhours given in previous calibrations, which is quite to be expected due to the bowed pile loading.

For dimensions and location of the number six rod, see Appendix I.

Plots were also made of the log of reactivity, as indicated by the number one and number two rods, as a function of time, graphite temperatures as a function of time, metal temperatures as a function of time, and reactivity as a function of temperature difference between inlet and outlet air. None of these plots showed any characteristics which allowed useful conclusions to be drawn and were, therefore, discarded.

[redacted]

FIGURE 9



[redacted]

Determination of Total Value of Safety Rod

A procedure somewhat similar to that used on the number six shim rod was employed to determine the calibration of the number seven safety rod. With the pile in equilibrium at 3360 KW. readings were taken every three minutes of rod positions, inlet and exit air temperatures, metal and graphite temperatures, and power level. After several readings had been made, the number seven safety rod was inserted into the pile, the power being kept to the equilibrium level by means of the number one and number two rods. Readings were taken for about twenty minutes after the insertion, at which point the pile was considered to be again in equilibrium.

Because the pile was in an equilibrium condition rather than a transient condition, the resultant plot of inhours, as indicated on the number one and number two rods, as a function of time gave two segments of straight lines, except for slight transients immediately after the insertion of the number seven rod. (Figure 10) Because the calibration curves for the number one and number two rods had to be used in plotting the segments of the reactivity curve both before and after the insertion of the safety rod, there are errors inherent in both of the segments, rather than only in one of them as in the case of the shim rod. The displacement of the two line segments was 104.5 $\pm$ 30.3 inhours, or the value of the safety rod in terms of pile reactivity. Because of the nature of the methods used in the propagation of the errors in the various calibrations, it is believed that the value of the safety rod is much better known than the computed error would tend to indicate. However, the errors stated are the ones which were rigorously obtained by use of the methods outlined above.

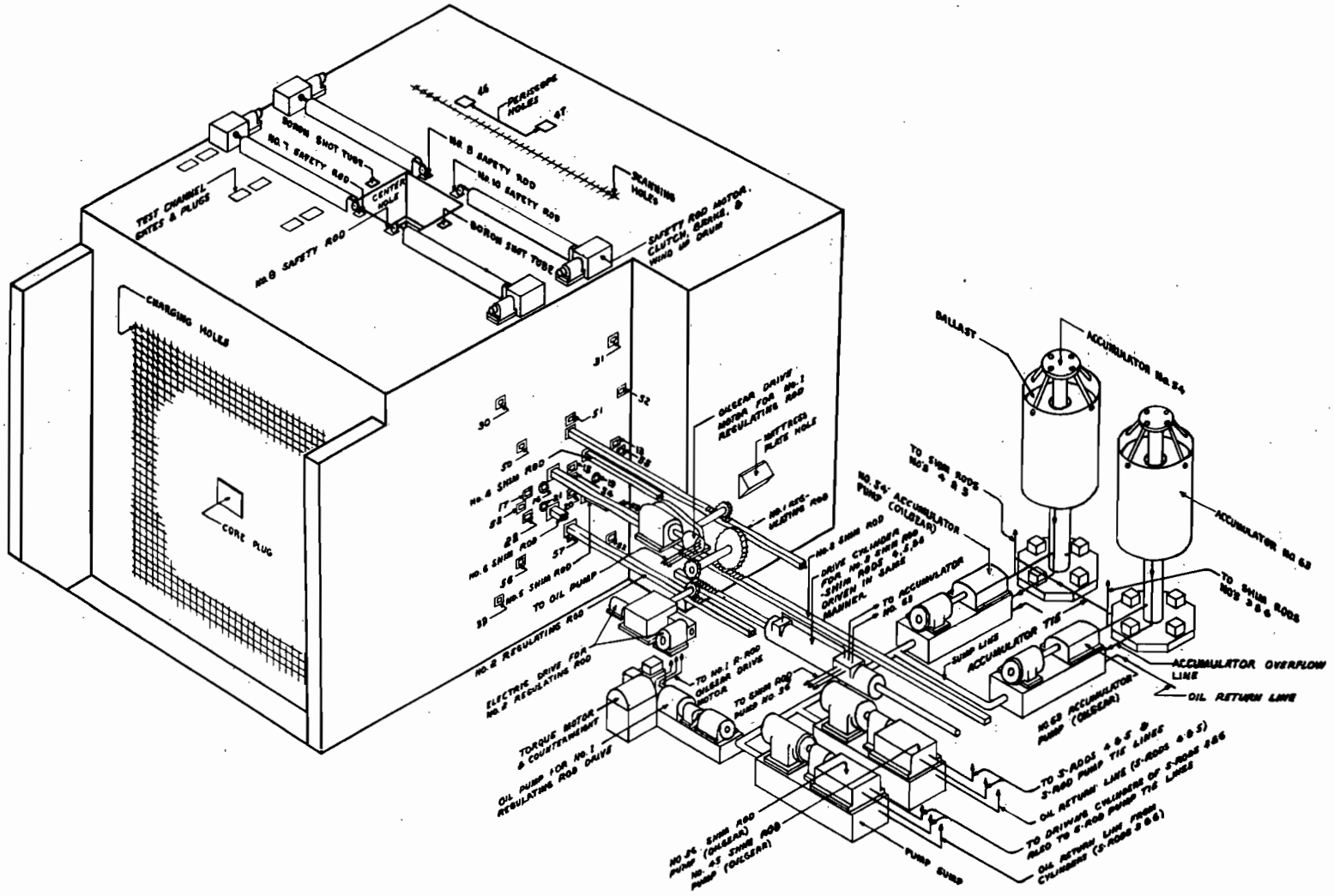
The value for the safety rod obtained by these calculations agrees well with the old value of 101 inhours when one considers the bowed loading of the reactor, which evidentally has caused an increase in the calibrated values for all the control rods.

APPENDIX I

Brief Description of X-10 Control System

The Clinton X-10 reactor is essentially a cube of graphite, twenty-four feet on an edge. The charging channels run east and west and are two-inch square holes spaced on eight-inch centers. The square array is essentially thirty-six holes by thirty-five holes, with the long side vertical.

The two regulating rods are constructed of 1 3/4-inch square, 19 foot long rods of 1.3% Boron steel and are used such that when the indicating selsyns show complete insertion (zero inches out) the rods penetrate the graphite structure to a depth of 200 inches. Although the regulating rods can be withdrawn from the pile more than 200 inches, it was noted that movement of the rods inside the shield has no effect whatsoever on the reactivity of the pile. The number one regulating rod enters the pile on the north side,



ROD CONTROL MECHANISM ~ CLINTON PILE

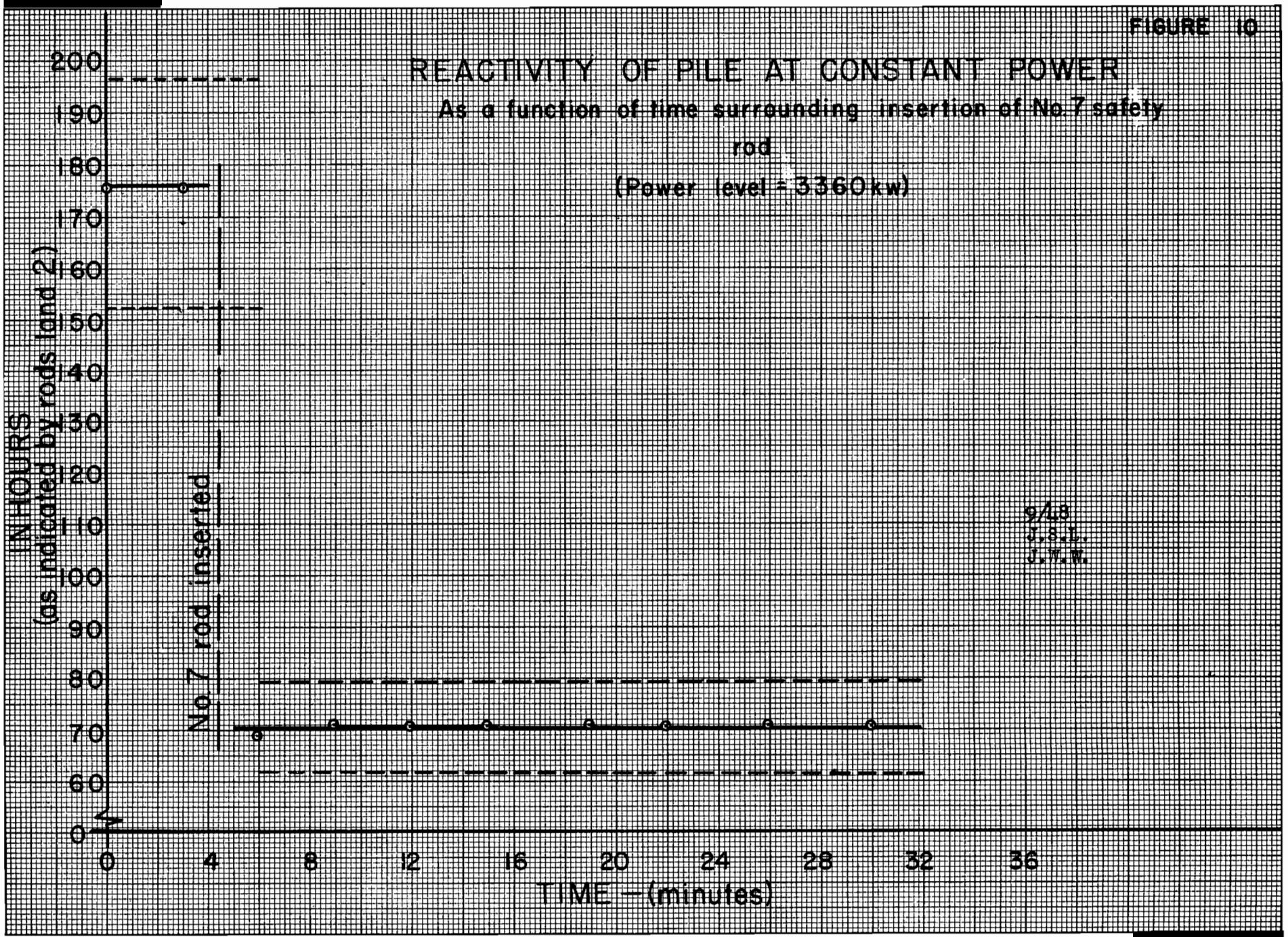
NUMBER THREE AND NUMBER FOUR SHIM RODS HAVE BEEN REMOVED FROM THE PILE PERMANENTLY.

FIGURE 10

REACTIVITY OF PILE AT CONSTANT POWER

As a function of time surrounding insertion of No.7 safety rod

(Power level = 3360 kw)



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J.W.W.

56 inches directly above the center line of the pile. This would mean that the number one rod lies between graphite channels 61 and 62. The number two rod enters the north side between graphite channels 75 and 76, 56 inches directly below the centerline of the pile. On the control panel, the positions of these rods are indicated by selsyns which can be interpolated to the nearest hundredth of an inch. Immediately before starting the calibration experiments, the selsyns were zeroed so as to agree accurately with the rod positions. Selsyn drift is known to be negligable over a period of a week or more.

The two shim rods enter the pile from the north face, two feet below the centerline of the pile and two feet to either side of the vertical axis of the pile, entering the graphite structure between holes 71 and 72. The number six rod is closest to the east face of the pile. Physically, they resemble the regulating rods, except that when fully inserted they extend 18 feet 8 inches into the graphite and when fully withdrawn are 4 inches outside of the graphite. In operation the shim rods are either completely withdrawn from the pile or are completely inserted. Indicating lights on the control board show the rod positions. Provision is also made for jogging the shim rods out to insure complete withdrawal.

The four vertical safety rods enter the top of the pile through access holes in the shield and extend through into the graphite. The four rods are arranged 2 feet 4 inches either side of the east-west centerline and 4 feet 2 inches either side of the north-south centerline. In this manner they enter the graphite between charging rows number 14 and 15, and between rows 21 and 22. When fully withdrawn the safety rods are completely out of the graphite structure, with their lower ends flush with the surface of the graphite. When inserted, the rods, which are eight feet long overall, extend above and below the centerlin e of the pile by four feet. The number seven rod is closest to the south-east corner of the pile. The four safety rods are constructed of 1.3% Boron steel rods, one and one half inches in diameter. In operation they are either fully in or fully out of the reactor.

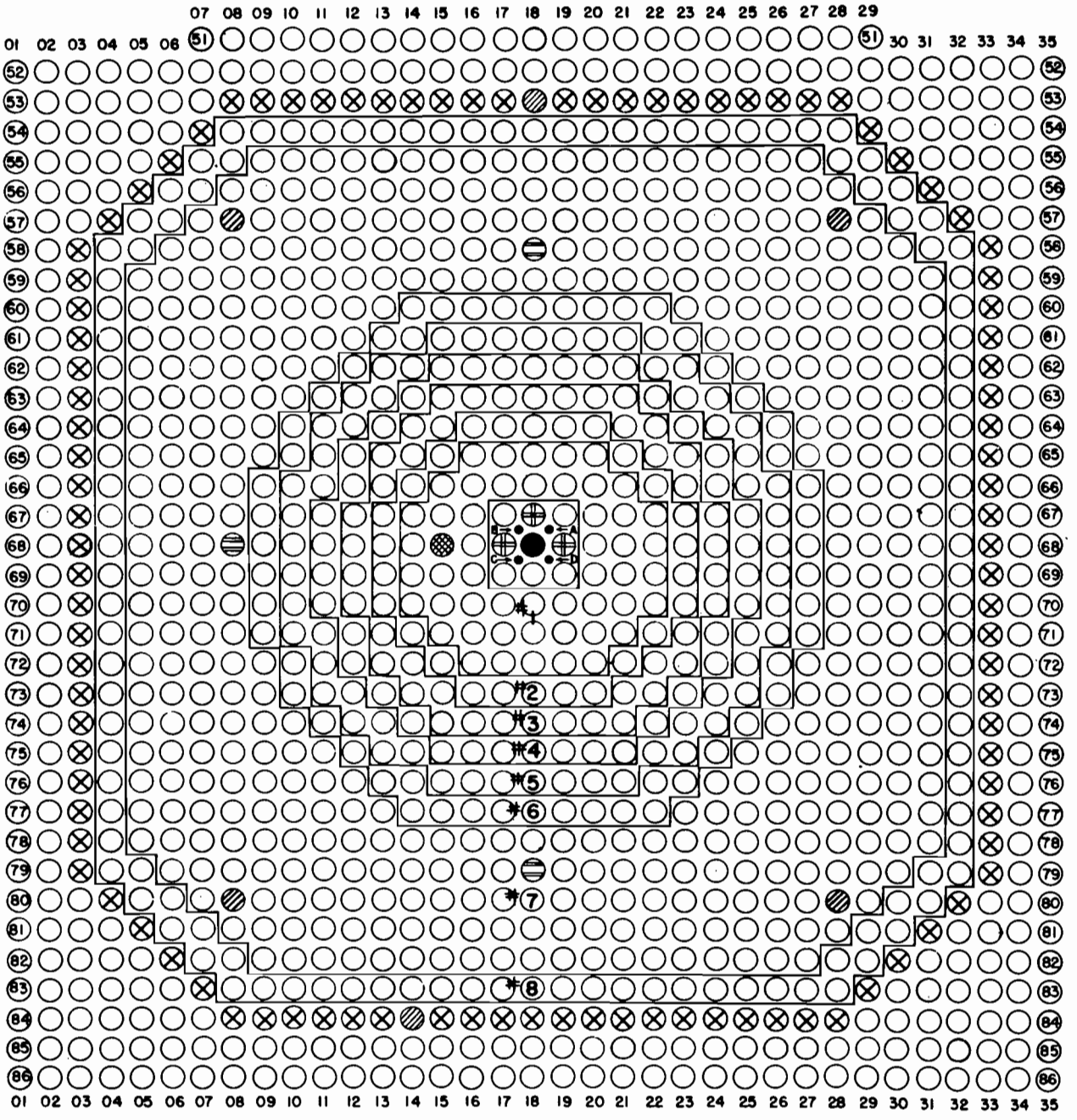
During the experiments described in this report, the reactor was loaded such that the first slugs of metal were 32 inches from the north and south faces of the reactor.

APPENDIX II

Loading Pattern of X-10 Reactor

The loading pattern of the X-10 reactor as of 14 September 1948, is given in the accompanying diagram. The location of special features such as doughnuts, myrnalloy slugs, gold, calcium nitrate, and the six thermopiles is shown as well. The loading is bowed, with smaller numbers of slugs in the center channels than in the ones nearer the outside rim.

[redacted]



LOADING as of SEPTEMBER 14, 1948

- SPECIAL THERMOPILE
- MYRNALLOY
- GOLD
- CALCIUM NITRATE
- DONUTS (7 slugs/row)
- EXPERIMENTAL

ZONE	NO. CHANNELS	NO. SLUGS	TEMP.
1	60	39	200-230°C.
2	26	43	200-240
3	42	47	200-240
4	38	47	200-250
5	58	47	190-240
6	54	47	150-190
7	438	54	90-190
8	114	47	90- below

[redacted]

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