Atomic Energy of Canada Limited

THE POISONING OF NRX PILE

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by

W. H. WATSON

Chalk River, Ontario
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SUMMARY

The experimental methods used to study the poisoning of the NRX reactor are described and the operation of the reactor in relation to these methods is reviewed for the period February to September 1948.

Xenon Poisoning

The growth transients of weak poisoning indicate that about 13% of the xenon produced has a half life close to twenty minutes. It is believed that this is Xe-135* which is produced by a short-lived chain of fission products. The remainder of the xenon poisoning is due to I-135 having a half life of 6.65 hours. The experimental results are consistent with the thermal neutron cross-section of 3.0×10^6 barns.

The equilibrium critical height as a function of power has been followed to 20 MW. The xenon poisoning can be represented as

$$\Delta k = \frac{0.0284}{1 + \frac{8.33}{W}}$$

W is the reactor power in megawatts. Corrections have been made for the temperatures of the X-rod cooling water and of the moderator, loss of reactivity due to power and the production of plutonium and the creation of samarium poison. The results agree surprisingly well with the first order perturbation calculation based on (1) applied to the reactor with a critical height of 230 cm when unpoisoned.

Samarium Poisoning

After 300 MWD of operation the change in critical height of the reactor was followed during a long shutdown until, when the xenon transient had died away it was evident that a stable poison had been produced. The loss of reactivity was 25% of that computed from the cross-section and fission yield of Sm-149. The loss is, of course, an upper limit. It is possible that part of it should be ascribed to material carried in the moderator and removable by distillation. No other poisoning was detected.

1. INTRODUCTION

This report is intended to give an outline of the knowledge gained from observing the poisoning behaviour of the NRX reactor during six months operation from February to September 1948. It is planned to present the detailed observations and analyses in separate reports. Since this is an interim report it will probably be simplest to present it chronologically and to indicate how present concepts have developed.

During the initial exploration of the reactor operation at powers up to a nominal 1MW, the effect of moderator temperature and of the loss of reactivity commonly attributed to Xe-135 had been measured approximately[2].

Early in February 1948 the reactor was to be operated after a lengthy shut-down so it was decided to examine these effects with great care.

The development of the experimental methods for measuring the critical height of the reactor during operation at steady power and during shut-down by means of transients is the work of A.G. Ward and D.G. Hurst.

The Operations Staff have made a major contribution not only in providing non-operational conditions for particular measurements, but also in the maintenance and calibration of instruments without which the experiment could never have been completed.

The author is indebted to H.H. Clayton for discussions and calculations on xenon poison based on several of his reports[1][4].

2. MEASUREMENT OF CRITICAL HEIGHT VS MODERATOR TEMPERATURE

In a reactor with a liquid moderator the effective multiplication factor may be controlled not only by inserting absorbing control rods but also by means of the amount of moderator. This, in fact, determines the size of the reactor, for the neutron density is relatively small at the top and bottom of the liquid where there is no good reflector. Since an absorber inserted in the pile distorts the flux distribution it was thought desirable to aim at operating the reactor with one control rod inserted as little as possible and to measure the reproduction factor by means of the moderator depth with the reactor critical, or by the moderator depth minus the excess height found by measuring the period required to double the flux, with the reactor divergent. On account of the production of photoneutrons by γ-rays from fission products, the use of the reactor with a subcritical amount of moderator was, at the time most of these experiments were planned, judged to involve too many uncertainties. Our experience now proves that with adequate computing resources the convergent reactor can be managed if desired.

Based on experience in calibrating the control rods in terms of change in moderator depth[5] the experiment to measure the effect of temperature was planned as follows. The moderator was to be warmed in the storage tanks to 115°F then pumped to the calandria and circulated through the cooler without flow of cooling water. (It was in fact found desirable to circulate water through the cooler and to supply the water from an auxiliary heat exchanger by means of which its temperature could be regulated). The reactor would be operated at 4kW and, as the moderator cooled, its temperature would be observed as a function of the time. Meanwhile the weir box was to be gradually lowered in small steps, and the variation of the power measured by means of ion-chamber No. 108 (placed in the reflector opposite the middle of the calandria). The times were to be noted at which the ion current was stationary, and the reactor critical. This method was developed from experience in calibrating control rods.

It had been anticipated that the arrangement for setting and reading the weir box position would not be precise enough. Accordingly a separate apparatus for determining the moderator level was installed. This was soon found to be much less reliable than the weir box arrangement and was abandoned when it was found that the readings could be repeated by the weir box.

The weir box is a device for setting the level of the moderator in the calandria. If the level in the calandria is higher than that set by the weir box, it slowly lowers until equilibrium is attained. When the weir box is raised, the level in the calandria rises slowly, moderator being pumped up at 5 gpm by the special pump operating continuously for this purpose. The circulation of moderator to the cooler is at 140 gpm, and about 15 minutes are required to circulate the volume of moderator in the calandria.

The analysis of the weir box setting against time in relation to the observed oscillations of reactor power was carried through very carefully to take into account the delay in the response of moderator depth to a change in weir box position. In this way critical height was related to time and thence to the temperature of the moderator which was taken to be that given by the instrument E-5-T-40 indicating the temperature of the moderator entering the cooler.

Throughout these early experiments the X-rod assembly was cooled by the "40 lb" water supply at a temperature of about 34°F. This temperature was known to remain constant to within 1/2°F so it was not considered necessary to take it into account. Actually the results obtained in two separate moderator temperature runs differed significantly by an amount which was later explained by this cause. This fact has been mentioned in order to emphasize that good sensitivity was achieved. It is believed that so far as low power operation of the reactor is concerned the indication of critical height obtained by the method described is so reliable that every observable change exceeding 0.2 mm can be correlated with a change in the conditions of reactor operation.

The method described here for measuring the critical height of the reactor during nominal steady operation with control rods withdrawn was the basis of the method adopted in following the poisoning of the reactor at higher power. The weir box was set 1 or 2 mm above the critical position, and the power controlled by inserting a control rod which was then gradually withdrawn as the reactor became poisoned. The time at which the power reached a relative maximum with the control rod completely withdrawn was then noted as the time at which criticality was achieved for that particular setting of the weir box. It has been found possible to operate the reactor in this way as a routine by which critical height may be followed by an operator. This measurement is supplemented by observation of temperatures and X-rod header temperature (E-I-T-7 No. 1).

3. MEASUREMENT OF THE CRITICAL HEIGHT OF THE REACTOR BY TRANSIENT OPERATION DURING SHUT-DOWN

To observe the growth and decay of poison during shut-down following operation in which poison has been produced, it is desirable in determining the critical height to produce as little poison as possible. With the heavy water moderator in which photoneutrons are produced by the gamma radiation from fission products, steady operation at low power to measure critical height by the method described above is not possible immediately subsequent to high power operation. For a hundred-fold reduction in steady power level, several days must elapse on account of long-lived groups of photoneutrons. To overcome this difficulty, the period of the divergent reactor is measured during the transient growth of power to about one tenth of the operating power prior to shut-down. This method will now be described.

The critical height must be known fairly closely (to within half a centimeter) in order to get a good measurement. The weir box is set so that the moderator level is about 1 cm higher than critical and time is allowed for the transient disturbance of the moderator to die out (about half an hour). The shut-off rods are raised and then two of the control rods. The current in the ionisation chamber which is to be used to measure the growth of power is observed, to check that no error has been made in the estimate of excess reactivity to be expected when the remaining pair of control rods is withdrawn. This being confirmed, these are withdrawn as quickly as possible and the time when they have come to rest at 300 cm from the base of the calandria is noted. The times are noted at which the galvanometer indicates the same suitably chosen current with successively decreasing settings of the Ayrton shunt arrangement between the ion-chamber and the galvanometer. The shunt settings have been previously chosen so as to yield approximately equal time intervals between readings. The reciprocal (n) of the shunt resistance is then plotted semi-logarithmically against the time. From this plot, the period (T) for the reactor power to double is found in the following way. By trial a constant is found, which when added to n makes the plot a straight line the slope of which yields T.

The data for one transient chosen as an example are shown in Figure 1 together with the derived straight line the slope of which was computed to find T.

The justification of the foregoing procedure is as follows. If sufficient time has elapsed since the reactor was last operated, the photo-neutrons generated by γ-rays originating in nuclei derived from previous operation constitute a nearly constant source (S) of neutrons in the pile during the period transient. It is then easy to deduce (one-group model) that since

$$\frac{dn}{dt} = \frac{0.693\, n}{T} + S$$

$$\log \left(n + \frac{ST}{0.693}\right) = \frac{0.693\, t}{T}$$

In a series of measurements at low power the relation between T and excess moderator height (above critical) was found for a particular moderator depth. This can be applied at any other depth by remembering that the period is determined by excess k, so excess heights are proportional to dh/dk^2 which is nearly proportional to the cube of the critical height at which the measurement is made (see Sec. 5 below). The treatment has been justified in our experience. For a good measurement, T should lie between 100 and 200 seconds.

In a lengthy numerical treatment of delayed and photoneutrons in relation to reactor kinetics the theoretical counterpart of the relation between T and excess height has been worked out from the data supplied by B.W. Sargent based on measurements in ZEEP, published American figures, and with an allowance for the different X-rod diameter in the NRX pile. In the instances for which calculations were made, the reactor was supposed to have been operating continuously for a long time at fixed power then shut down for an hour with shut-off rods or control rods inserted after which, for a certain assumed excess reactivity, the transient growth of power resulting was computed. The succeeding transient an hour later was likewise calculated. The theoretical curve relating T and δk agrees adequately with the experimental results for starting transients. These covered the range of doubling period 20 to 200 seconds.

Further, a typical transient has been calculated on the basis of the same data, and when submitted to the same treatment as the experimental observations in the period transient, yielded a period in excellent agreement with that deduced for the excess k assumed.

It is felt, therefore, that the procedure described is well founded. There are, however, two points of practical importance which should be mentioned. The ion chamber measurement was adopted, because of its convenience and reliability, only after a long and careful study of many transients made with several neutron counters and two ion-chambers.

Secondly, this simple method is not useful when the transient passes 100 kW, for the reactor loses reactivity due to heating of the uranium and due to the early production of xenon poison. The poisoning of the reactor subsequent to the transient can be calculated and constitutes only a minor effect even for transients to 1 MW.

4. REVIEW OF REACTOR OPERATION IN THE COURSE OF THIS WORK

For reference in explaining the sources of experimental information on the poisoning of NRX reactor it is useful to present an outline of what has been done.

On Feb. 3 and 5 the effect of changing the temperature of the moderator was measured at 4 kW. In the ensuing week the technique of measuring the reactor period to determine critical height was established.

On February 12 a 10 hour poisoning transient at nominally 1 MW was run, critical height being measured by the method of Sec. 2. After shut-down the critical height was measured (Sec. 3) by hourly period transients to 1 MW for the first 24 hours, thereafter to 100 kW until the critical height had decreased to its initial value 84 hours later. Unfortunately the 10 hour transient was interrupted by a 2 hour shut-down due to a trip of the reactor occasioned by the leakage of cooling water entering delay tank No. 1 directly to delay tank No. 2 thus actuating the radioactivity monitoring trip. In addition to this complication of the power-time graph during the run, another unexpected one occurred. This was due to the fact that the rod with its X-rod assembly cooled by "40 lb-water" lost reactivity in the course of reaching power, thus causing a marked drop (20%) in power before recovering its intended value when more moderator had been added to the calandria. These two disturbances of the power added greatly to the labour of calculating the poisoning to be expected. It was guessed that the loss on reactivity referred to was due mainly to warming the uranium. Accordingly experiments were at once undertaken to measure the loss of reactivity produced by raising the temperature of the X-rod assembly.

It was arranged to circulate hot water through the X-rod assembly and to measure critical height as the system cooled. Corrections for moderator temperature were applied. This experiment, which caused misgivings in advance as to the possible prevalence of leakage from the X-rod seals, was successfully carried through on Feb. 24. The magnitude of the effect observed is such that the change in temperature of the Ottawa River water from close to freezing point in midwinter to over 70°F in early September produces a loss of reactivity in summer operation represented by 4 or 5 cm in critical height with the calandria nearly full.

These experiments having been completed, it was planned to measure the growth of poison during continued operation at 1 MW (nominal)

and to follow subsequently the increase of critical height whenever possible during the operational approach to full power. Since "175 lb" water cooling of the X-rod assembly had to be put in service it was necessary to re-investigate by a separate experiment the prompt loss of reactivity due to power. This was carried out in the following way. With the reactor running steadily at 2 MW, and steady critical height, the moderator level was raised so as to bring the reactor to equilibrium under No. 3 control rod at a suitably chosen position. The control rod was inserted rapidly to decrease the power to a predetermined fraction of 2 MW and then withdrawn so as to keep the power steady at the new value. By extrapolation to the instant of the transient drop, the change in control rod setting characteristic of the known change in power level was found. From the calibration of the rod under the conditions of the experiment the equivalent change in moderator height and hence in k was known. Several transients of this type were measured. The prompt loss in reactivity is proportional to the power.

When the operating power had been raised by steps over several weeks to what was believed to be 5 MW, advantage was taken of the shut-down required to prepare for continued operation at full power, and the differential thermometer system E-I-T-10 was overhauled. This instrument purported to give the rise in the temperature of the cooling water due to operating the reactor and its performance had been questioned.

When the reactor was started up May 13th at 5 MW as judged by the total heat produced, it was quite obvious that the neutron flux measured by several instruments around the reactor was noticeably lower than it had been during operation prior to shut down. By careful weighing of all the evidence, including radioactivity of the cooling water and poisoning of the reactor, it was now concluded that prior to May 10 the nominal 1 MW was 1.4 MW.

The reactor power was raised in steps to 10 MW and maintained for several days until the critical height had become steady. Then after a few days intermittent operation, the power was raised to 12 MW and remained so for nine days. It had been intended to observe the decrease in critical height at 1 MW immediately following the high power operation. However, an enforced shut down on May 31 to remove a blistered X-rod prevented the measurement of the decay transient during the first 24 hours. From June 1 to 4 the critical height was followed at 1 MW. Then, since the moderator level had become steady it was decided to shut down and follow the critical height by period transients to 100 kW. This was done until June 23 when the reactor was "cold" and no change in critical height (temperature effects being allowed for) had been detected for some days. Reactor maintenance was then carried out and just prior to operating continuously at 10 MW a high power transient was run on June 30.

The experiment consisted of measuring the critical height and setting the moderator level so that the excess reactivity would be removed by the prompt poisoning of the reactor due to increase in power during the transient. The reactor power would therefore grow to a maximum. It was measured as a function of the time during six hours. Corresponding temperature measurements were made. The maximum in power (5-1/4 MW) was reached in 34 minutes, the starting doubling period was 113 secs. This transient has now been analysed.

On July 1 the reactor was started up at 10 MW and a record of the increase in critical height was obtained. Profiting by previous experience in this operation, it was arranged that the power as determined by heat production should be kept constant. The ion-chamber connected to the galvanometer at the control desk served only to operate the reactor over short periods; as the reactor poisoned and the moderator depth had to be increased, the setting of the potentiometer bias was changed so that the zero of the null instrument corresponded to the desired heat output instead of a particular current in the ion chamber. Since the moderator depth was increasing, the flux at the ion chamber corresponding to constant heat production would change first because the size of the reactor core was growing and secondly because the position of the maximum of the flux distribution was correspondingly being raised. Hence the ion chamber does not yield a current proportional to the power; it is sensitive to the extent to which the reactor is poisoned.

On September 1, after the satisfactory operation of the new catalyst in the recombination unit had been proved at 10 MW, the power was raised to 14 MW and the corresponding equilibrium setting for the weir box was established. It was estimated that it would be just possible to operate steadily at 20 MW with the calandria full, so it was decided to observe the poisoning at 20 MW. After running for 40 hours but before the critical height had levelled off, it was decided to drop the power to 10 MW in order to reduce the production of deuterium. The change in power was effected gradually in 1-1/2 hours; thereafter, the reactor was observed to poison and the moderator level was gradually raised to the limit. Poison continued to grow and the reactor was no longer critical. The power dropped practically linearly with time. The control and shut-off rods were kept withdrawn and at low level the flux was observed on the power-measuring ionisation chamber. The descent of the flux to its minimum was noted and thereafter its growth to 10 MW. The course of the phenomenon in time was roughly in accord with an elementary calculation.

5. ANALYSIS OF POISON MEASUREMENTS AND PRELIMINARY RESULTS

The detailed analysis of critical height measurements in relation to poisoning depends essentially on the conversion of differences in height into differences in the multiplication factor k. So long as we are dealing with changes in height within a comparatively small range the conversion is not important for the kinetic analysis, but it is when differences of height have to be compared at markedly different moderator depths such as occur in poisoning at 10 MW for example. One is dependent in the first place on the analysis of flux distributions in the reactor at low power. In the second place the effect of the reflector must be taken into account in some simple way, otherwise the complication of calculation becomes prohibitive.

Prior to the completion of the analysis of vertical flux distributions at low power, the constant to be added to the weir box setting to yield the height (h_c) of the sine vertical flux distribution was taken to be 14 cm and the migration area 271 cm^2 - the value for the core. It is not known that this assumed constant difference to be added is at least 20.7 cm.* From "two-group theory" we can compute $\frac{d\kappa^2}{dh_c}$, κ^2 being the Laplacian of the reactor in which the real boundary conditions at the base and top of the core are replaced by the assumption that the neutron density vanishes at $z = 0$ and $z = h_c$, the former level being suitably chosen with respect to the calandria bottom. The reflector also is assumed infinite in extent. From a measurement of the reactor period and the delayed and photoneutron data, we can compute the value δ_e by which the effective multiplication constant k_e exceeds unity.

$$\delta_e = \frac{\tau_p}{T_e} + c\sum \frac{\mu_i \tau_i}{T_e + \tau_i}$$

0.693 T_e is the time required to double the power in a growth transient. As has been pointed out by Rumsey[6], τ_p in this formula should stand for the mean life of a neutron in the core plus reflector. Computed for NRX it turns out to be 1.077×10^{-3} sec. For $T_e > 100$ sec. only a minor correction is involved here in replacing T_c for the bare core by τ_p. Such measurements lead to $\frac{dk_e}{dh}$.

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* The figure to be adopted for this quantity is not yet finally settled; in this report the value quoted has been used.

In order to pass to the decrease in k_∞ which would exactly compensate an increase Δh in the depth of moderator, we must take into account the presence of the reflector in the manner indicated by Rumsey (loc. cit.). In effect we have to employ a fictitious value of M^2 different from that computed for the bare core (271 cm^2). The required value can be found by taking the ratio $\frac{dk_e}{dh} \Big/ \frac{d\kappa^2}{dh_c}$

Here are some values:

Δh cm	T_e sec	$\frac{dk_e}{dh} \times 10^4$ cm^{-1}	$\frac{d\kappa^2}{dh_c} \times 10^4$ cm^{-3}	"M^2" cm^2
1.15	155.8	4.82	1.53	316
1.65	99.8	4.83	1.53	-
1.12	-	4.30	1.375	312

The first two rows were obtained in February with a weir box critical setting of 219.91 cm; the last, in June with a critical setting of 228.45 cm.

For low power operation, the critical weir box setting in the vicinity of 220 cm gives

$$2.1 \text{ cm} = 10^{-3} \text{ in k or 1 milli-k}$$

This figure will be used in the future in place of the provisional 2.4 cm/milli-k which was adopted in February and used until the results of analysis made the better estimate possible.

In dealing with the fully poisoned reactor at 10 MW (weir box reading 269 cm) one naturally questions whether the boundary condition at the liquid surface is altered by the reduction of the height of the empty lattice above the moderator. Further, how should temperature corrections, determined for the unpoisoned reactor, be applied to the poisoned reactor which contains a considerably greater depth of moderator? This latter question arises quite apart from the temperature coefficient of the poison cross-section.

Since at the present time the representation of the radial distribution of flux in the unpoisoned reactor is unsatisfactory, the resolution of all of these matters is being postponed for they cannot be worked out correctly until the basic representation is improved.

In principle the proper treatment of a reactor with reflector requires at least two-group theory if the diffusion approximation is to be used. For a high flux reactor the size of which has to be increased by 20-30% to overcome the loss of reactivity due to poison, it is essential to have a good representation of the unpoisoned reactor, otherwise good numerical agreement with experiment cannot be expected. Perturbation theory can be applied to calculate the equilibrium critical height for known poisons at different power levels of steady operation, but the actual calculation required to represent poisoning in a high flux reactor may still turn out to be more involved than can be managed with our present computing resources.

The experimental programme has been arranged to cover different aspects of the matter.

(i) Studies of weak poisoning in which small changes in critical height take place. One observes the growth of poison during steady running at a low power (judged by perturbation of critical height) and the growth and decay of poison during shut-down after the chosen period of steady operation. The object of such measurements is to elucidate the scheme of processes by which the main poison is produced, to measure time constants and to estimate the cross-section of the main poison nucleus.

(ii) Measurement of growth of critical height to equilibrium for steady operation at successively higher powers. This is intended to lead to a good general description of xenon poisoning of the high flux reactor.

(iii) Observation of decay of critical height to its equilibrium value in shut-down after substantial operation at high power. This experiment was aimed principally at detecting poisoning by stable Sm-149. Since this poison builds up rapidly to an equilibrium independent of power, this experiment could be repeated only after charging the reactor with fresh uranium. It was also desired to detect any other poisons of long life (or stable), being produced.

(iv) Careful observation of the critical height over long periods of high power operation is intended to search for effects peculiar to a high flux reactor.

(v) The transient to high power was designed to reveal poisoning effects associated with short-lived substances. Problems arising from the destruction of poison by neutron capture in a high flux are minimised by the short duration of the main surge of power. It is now believed that the best way to perform this experiment is to pulse the power and observe the convergent reactor at a low flux instead of allowing the power to remain in the range dictated by the natural loss of reactivity due to the high power pulse.

On the basis of the analysis so far carried through, this method is by far the best one for studying how the xenon poison is produced. However, it requires precise calculation of delayed and photoneutron effects - a major computing task.

We shall now review these investigations.

Study (i)

Let us consider weak poisoning of the reactor in which the critical height is changed by a few centimetres. To a first approximation the amount of poison is measured by the amount x by which the actual critical height (corrected for temperature) exceeds that of the unpoisoned reactor. On the assumption that x is due entirely to Xe-135 of mean life T_2 (13.3 h) and that this substance is produced entirely from I-135 of mean life T_1 (9.5 h) the production of x may be represented by the pair of differential equations

$$\frac{di}{dt} = a_1 n - \frac{i}{T_1}$$

$$\frac{dx}{dt} = \frac{i}{T_1} - \frac{x}{T_2} - \gamma x n = \frac{i}{T_1} - \frac{x}{T_2'} \qquad 1$$

when n represents the reactor power, $a_1 n$ the rate of production of i, and $\gamma x n$ represents the destruction of poison by neutron capture. In steady power operation we may represent the decay of x in a single term x/T_2' where

$$\frac{1}{T_2'} = \frac{1}{T_2} + \gamma n \qquad 2$$

is a function of the power. When n corresponds to a flux of 1.4×10^{13} neutrons/cm^2 sec the rate of destruction of xenon by neutron capture is equal to the natural rate of decay outside the reactor and then $T_2' = \frac{1}{2} T_2$. It is obvious that in NRX with its high flux, the destruction of poison at high power is of major importance. Since the flux distribution is conditioned by the distribution of poison in the reactor, the rate of destruction of poison is dependent on the past history of operation. The amount of xenon present is likewise dependent on history not only from this cause but also because it is derived from a radioactive parent which is produced in the running of the reactor and which, by continuously transforming itself into xenon, produces poison during shut-down. The equations governing the growth and decay of x are then

$$\frac{di}{dt} = -\frac{i}{T_1} \qquad \frac{dx}{dt} = \frac{i}{T_1} - \frac{x}{T_2} \qquad 3$$

The solution of equation 3, when at $t = 0$ x and i have the initial values x_o and i_o respectively, is

$$i = i_o e^{-t/T_1}; \quad x = \frac{i_o T_2}{T_2 - T_1}(e^{-t/T_2} - e^{-t/T_1}) + x_o e^{-t/T_2} \qquad 4$$

By fitting the poison transient during a shut-down to an equation of form 4 we can compute the ratio x_o/i_o at the beginning of the shut-down and, of course, the mean lives T_1 and T_2 can be determined. The importance of the ratio x_o/i_o is that its value determines whether or not x may be expected to grow to a maximum before decaying. In fact, since the time to reach x_{max} is

$$t_{max} = \frac{T_1 T_2}{T_2 - T_1} \log_e \frac{T_2}{T_1\left(1 + \frac{x_o}{i_o}\frac{T_2 - T_1}{T_2}\right)} \qquad 5$$

we see that if

$$\frac{x_o}{i_o} > \frac{T_2}{T_1}$$

no maximum can occur in shut-down.

Since, when equilibrium has been attained in steady running at a fixed power, equation 2

$$\frac{x}{i} = \frac{T_2'}{T_1}$$

the poison should always grow initially in shut-down provided that the xenon is derived exclusively from iodine. If however, xenon is produced in sufficient quantity by an alternative process of short life there will be no increase in x after shut-down from operation at not too large a power.

This phenomenon was actually observed on June 4th in the shut-down from 1 MW operation. The clear indication of the time constant of the rapid production of xenon came from the high power transient of June 30. We now believe the mean life of the immediate parent to be 20 minutes and that about 13% of the xenon comes by this quick route. Since the poison Xe-135 is known to descend from the isomer Xe-135* of half life about 13 min., the most reasonable hypothesis is that the latter isomer is produced either directly in fission or is derived from a chain of short-lived products. Once this fact had been grasped the analysis of the first poison transient (Feb. 12) was repeated and the growth transient of the succeeding operation at nominal 1MW was recalculated. Notable lack of fit between theory and observation was then found to have disappeared.

The results of this work are shown in Figures 2 and 3. The former presents the observations of the critical height during the 10 hour transient and the subsequent shut-down together with the theoretical curves. In the interval I the curve is computed from the data given below. In II the line is calculated on the assumption that no poison is produced by the transients used to measure critical height. The dotted line in III is fitted to the experimental data with iodine mean life 9.6 h and xenon mean life 13.2 h, and the discontinuity between the theoretical curves for II and III is consistent with what is expected from an estimate of the poison produced in the transient preceding it. The discontinuity between I and II is caused by the loss of reactivity due to power. In Figure 3 is shown the transient decrease in χ^2 in operation at 1.4 MW. It is seen that the experimental points follow the theroetical curve where we assumed that 13% of the poison comes rapidly from fission and do not follow the curves calculated on the assumption that all of the poison is formed from I-135.

The equation scheme according to which weak poisoning is calculated is

$$\frac{dx}{dt} = (a_2 n) + \frac{i}{T_1} + \frac{y}{T_3} - \frac{x}{T_2'} \qquad 6$$

$$\frac{dy}{dt} = a_3 n - \frac{y}{T_3} \qquad \frac{di}{dt} = a_1 n - \frac{i}{T_1}$$

where

$T_3 = 18.8$ min.

$a_1 = 7.17 \times 10^{-3}$ cm/min MW

$a_3 = 1.80 \times 10^{-3}$ cm/min MW

$a_2 < 0.2 \times 10^{-3}$ cm/min MW

Thus direct production of Xe-135 may be neglected.

We may compute the <u>effective</u> cross-section σ_x for the poison as follows

$$a_1 + a_3 = \frac{8.97 \times 10^{-3} \times 10^{-3}}{2.1} \text{ cm/min MW}$$

$$= 4.27 \times 10^{-6} \text{ cm/min MW}$$

Assuming f = 0.888[3]

$N_u\sigma_u = 1.32 \times 10^5$. (for 220 cm of moderator in the tank + 14 cm extrapolation above moderator)

$\frac{\sigma_f}{\sigma_u} = 0.55$

No. of fissions/sec/MW = 3.1×10^{16}

Xe-135 fission yield - 6.0%

$$\sigma_x = \frac{4.27 \times 10^{-6} \times 1.32 \times 10^5 \times 0.55}{3.1 \times 10^{16} \times 60 \times 0.06 \times 0.888}$$

$$= 3.13 \times 10^6 \text{ barns}$$

If $N_u\sigma_u$ is assumed to be 1.24×10^5 (no allowance for extrapolation)

$$\sigma_x = 2.94 \times 10^6 \text{ barns}$$

The results are in reasonable accord with the calculations in[4] where the perturbation of flux is represented and the perturbation averages are computed. Using $\sigma_x = 3.0 \times 10^6$ barns, Clayton's formulae give for 1.4 MW, $\Delta\chi^2 = 1.43 \times 10^{-5}$; the corresponding experimental result is $\Delta\chi^2 = 1.38 \times 10^{-5}$ with M^2 assumed equal to 312 cm^2.

The analysis of weak poisoning of the reactor can therefore be regarded as satisfactory. It may be well to remind the reader that the elucidation depended on allowance for the temperature of the moderator and for that of the incoming X-rod cooling water. It depended also on estimation of the power by subsequent direct calorimetric measurement of a higher power. Perhaps the most disconcerting element in the work was the estimation of the loss of reactivity associated with the steady running of the reactor. This loss is now known to be 0.15 milli-k/MW when the uranium rods are cooled with "40 lb." water supply and 0.73 milli-k/MW when the uranium rods are cooled with the "175 lb." supply. The latter figure was strikingly confirmed in the June 30 transient, for the loss of reactivity showed immediately in the growth of power and was proportional to it. Indeed it is this loss of reactivity which limited the maximum power attained in the transient. The xenon poisoning appeared significant only in the subsequent decay of reactor power.

Study (iii)

It has already been mentioned that we are reconsidering the basic representation of the reactor from which calculation must proceed in the theoretical prediction of the effect of Xe poison on the critical height. Further, the computations themselves are protracted even for the estimation of equilibrium heights at successively higher powers of operation.

Nevertheless, by comparing the change in κ^2 due to equilibrium poison as a function of power, with that computed from the change in critical height derived by perturbation theory[1] for a reactor somewhat smaller than NRX, we can try to assess the value of the theory. Of course, temperature changes must be allowed for. At low power it is possible to maintain the moderator temperature near 60°F but at 20 MW the equilibrium moderator temperature is 120°F when the incoming river water is at 63°F. The allowance has been made by converting changes in critical height in the unpoisoned reactor due to temperature into changes in κ^2 (assumed independent of the moderator depth)*. Secondly, one has also to allow for the production of Sm-149 which is a stable poison with fission yield 1.5% and cross section 5.3×10^4 barns. This poison comes from Nd-149 (half-life 1.7 h) through Pm (half life = 47 h). Thirdly, the enrichment of the reactor due to the production of plutonium is significant. Fourthly, at the highest power one might expect to detect the modification of the Xe cross-section due to the higher temperature of the thermal neutrons, but this effect would require very carefully controlled experimental conditions to establish it.

The Sm poisoning is noteworthy in that the stable or nearly stable poison observed in NRX after 300 MW days operation was much less than expected from the quoted fission yeild and cross section. It has been suggested that the cause of the low poison yield in that progress of the fission chain of mass 149 to stable Sm-149 is arrested in a long lived isomer of Sm-149. This hypothesis is being examined elsewhere. The following are the facts ascertained to date with NRX.

In the shut down-subsequent to 12 MW operation at the end of May it was observed that the critical height decreased in the transient characteristic of xenon decay to a constant level which was 4.60 cm above the level at Feb. 27th, when steady operation at 1.4 MW began, leading eventually to high power. Apart from the temperature of the X-rod assembly the conditions of reactor operation were identical when the two measurements were made. There had been no measurable change in the isotopic ratio for the moderator but loss of reactivity might have taken place due to foreign matter taken up by the moderator in the course of operation. The correction for the 17.5°F difference is 1.09 cm leaving 3.51 cm increase in critical height due to nuclear changes in the reactor. Due to Pu production the estimated gain in reactivity was 0.61 cm. Hence the stable poison produced in the operation of the pile up to May 31 was equivalent to 4.12 cm or to $\Delta\kappa^2 = 5.9 \times 10^{-6}$. In operation after July 1, for two months at 10 MW and thereafter for several days each at 14 and 20 MW

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* This procedure almost certainly overestimates the temperature correction, for part of the measured change in κ^2 due to change in moderator temperature is brought about by change in M^2. The corresponding fractional change in κ^2 is then the quantity which should transfer unchanged when the moderator depth is altered.

in succession, the equilibrium critical height was measured. If we compare ΔK^2 for 12 MW interpolated from these data with the corresponding ΔK^2 prior to May 31, both being corrected for moderator and X-rod assembly temperature, for the loss of reactivity due to power (0.0047 milli-k at 20 MW) and for Pu production we find that the earlier ΔK^2 exceeds the latter by 5.5×10^{-6}. That is, within the limits of experimental uncertainty, substantially the whole of the stable poison had been accumulated by the middle of June when the critical height was measured during the long shut-down.

Now the approximate representation of the production of Sm poisoning would, on the basis of fission yield and cross-section data only, be expected to follow the equations

$$\frac{dp}{dt} = -\frac{p}{T} + an$$

$$\frac{ds}{dt} = \frac{p}{T} - \beta sn \qquad 7$$

where p and s stand for the amounts of Pm and Sm respectively, measured in a system based on these equations and the poisoning effect of Sm, a is the rate of production of p per MW, $\frac{1}{T}$ is the constant $0.693/47\ hr^{-1}$ and β is the fractional rate of destruction of Sm per MW. The solution for the initially unpoisoned reactor operated at steady power is

$$s = \frac{a}{\beta}\left[1 - e^{-\beta nt} + \frac{\beta bT}{1-\beta nT}\left(e^{-t/T} - e^{-\beta nt}\right)\right]$$

The equilibrium loss of reactivity is independent of the power and is given by

$$\frac{a}{\beta} = \frac{yN_u\sigma_f\overline{\rho v}}{\sigma_s\overline{\rho v}} \times \frac{f\sigma_s}{N_u\sigma_u}$$

$$= fy\frac{\sigma_f}{\sigma_a} = 0.888 \times 1.5 \times 0.55\% = 0.73\%$$

y being the fission yield of the chain of mass 149

f is the thermal utilisation

We have therefore to compare the experimental result $\Delta K^2 = 5.9 \times 10^{-6}$ with the expected 2.35×10^{-5} i.e. only 25% of that expected appeared.

Study (ii)

The records of the critical height, the power of the reactor and the relevant temperatures have been maintained, together with that of other conditions which could affect reactivity. For studying the growth of critical height at steady power it is almost essential to have several consecutive days of steady operation, free from shut-down, the reactor being initially very weakly poisoned. While the effect of shut-down can be estimated approximately, the transient disturbance due to a shut-down, especially from high power, is detectable over about twenty-four hours and it is doubtful that sufficient precision can be attained to justify detailed treatment of data concerning frequently interrupted operation of the reactor.

To compute transient growth of critical height during poisoning, proper methods have not yet been worked out and there is not a large number of good series of measurements with which theory could be compared. On the basis of observations of poisoning at high power one can offer the approximate rule as to how the equilibrium height at a particular power is attained. A single exponential with half life about 8 hours can be used to estimate the transient by which critical height tends to its limiting value at a given high power.

The way in which the approximate equilibrium critical height depended on power is shown in Figure 4. It will be noted that the observations fall on two curves; the lower corresponds to observations prior to May 31 and the upper subsequent to July 1 when information was obtained for 10, 14 and 20 MW operation. The critical height of the reactor was 228.5 cm before operation at these powers; due to Sm poison and added J-rods this height was greater than the critical height of the unpoisoned reactor in February.

Using the relation between χ^2 and h(Figure 5) derived from two-group theory, these results may be used to compute the change $\Delta\chi^2_W$ in the Laplacian of the reactor core when the height levels off for the power W, temperature effects being allowed for in that we have to take into account the temperature of the moderator and of the incoming river water and to allow for the loss of reactivity proportional to the power which has already been mentioned. In addition, in order to compare with the theory of xenon poisoning, the small gain of reactivity due to plutonium production has been estimated and allowed for. The results are shown in Figure 6. We compare $\Delta\chi^2_W$ due to poison as a function of the power with $\Delta\chi^2_{oW}$ which would have occurred had there been no destruction of the poison by neutron capture. Let us introduce an effective poison life-time T_W such that

$$\Delta\chi^2_W = C(a_1 + a_3)\, T_W \qquad 9$$

where C is a constant to convert units.

Since $\Delta\mathcal{K}^2_{oW} = C(a_1 + a_3)\, T_2$ 10

we have

$$\frac{T_2}{T_W} = \frac{\Delta\mathcal{K}^2_{oW}}{\Delta\mathcal{K}^2_{W}} \qquad 11$$

and according to equation 2 this quantity should depend nearly linearly on W. In spite of the fact that the size of the reactor core increases with W it turns out that this linear relation is fairly closely followed (see Figure 7) and we may write

$$\frac{1}{T_W} = \frac{1}{T_2} + 9.0 \times 10^{-3}\ \text{W hr.}^{-1} \qquad 12$$

W being, of course in MW. Now in the limit of weak poisoning we may compute this coefficient of W as

$$\frac{F\sigma_x}{N_u\sigma_f} \cdot \frac{\overline{\rho v^2}}{\overline{\rho v}^2} = \frac{3.1 \times 10^{16} \times 3 \times 10^{-18} \times 3600}{1.32 \times 10^5 \times 0.55} \times 1.37 \times \frac{\pi^2}{8} = 7.7 \times 10^{-3}\text{hr}^{-1}/\text{MW}$$

(F = no. of fissions/hr MW) The figure 1.32×10^5 ($N_u\sigma_u$) is chosen to correspond to the size of the core of the unpoisoned reactor.

We reach therefore the empirical formula

$$\Delta\mathcal{K}^2 = \frac{AW}{1 + BW} \qquad 13$$

where $A = 1.09 \times 10^{-5}$ /MW

$B = 0.12$/MW

$$\text{or } \Delta k = \frac{0.0284}{1 + \frac{8.33}{W}} \qquad 14$$

and this formula agrees remarkably well with the results calculated by perturbation theory. It is not at all obvious why this simple result approximates the number given by elaborate calculation for it is natural to expect that in equation 13 W should be replaced by $\frac{Wh_o}{h_W}$ corresponding to the mean flux, h_o being the height of the unpoisoned core and h_W the height for power W. One is tempted to suggest that the poisoning is mainly produced in a region of substantially constant volume in which the mean flux is proportional to the power. This would be expected if the radial flattening in the core (which, it should be remembered, is actually contained

between two coaxial cylinders) were to take place towards the inside of the core thus compensating the longitudinal extension due to increased moderator depth.

In conclusion it may be remarked that the effect of the Xe resonance at 0.1 eV on the capture of thermal neutrons has been examined. For an assumed Breit-Wigner half-width $\Gamma/2 = 0.025$ eV the fractional increase in the thermal capture cross section due to a neutron temperature increase of 22°C is 7%. This range in neutron temperature is chosen because it is believed that the neutrons make on the average one collision in traversing the water sheath surrounding each X-rod and are thereby cooled to the average of the moderator and water-sheath temperatures. The figure of 22°C represents the range of this average in the experiments described. However, in order to deal with temperature effects on poisoning it would seem necessary to look into the matter in considerably greater detail. Since the xenon resonance occurs appreciably above thermal energies perhaps one should consider resonance capture as influencing the transfer of fast neutrons into the thermal range. Since the xenon is held in the uranium at different temperatures in different parts of the reactor, the distribution of xenon resonance escape probability should be introduced into the theory.

Study v:

In principle the method of analysing the transient growth and decay of the reactor power (n) is as follows. Since the poisoning produced in the transient is weak, we apply the method of representing it used in study (i). Let $\tau\epsilon n$ and $\tau\gamma x$ denote respectively the loss of reactivity proportional to the power and that due to the poison, τ being the mean life of a prompt neutron. Then the course of n is governed by

$$\frac{1}{n}\frac{dn}{dt} = -a + \frac{1}{n}\sum_{i=1}^{14}\frac{r_i}{\tau_i} - \gamma x - \epsilon n \qquad 15$$

where

$$a = \frac{c-\delta}{\tau},$$

δ being the excess reactivity deduced from its initial value by correcting for the temperature of the moderator during the transient; there was no variation of the temperature of the incoming river water. The delayed and photo-neutrons are represented by r_i which satisfy the differential equations

$$\frac{dr_i}{dt} + \frac{r_i}{\tau_i} = \frac{ck\mu_i}{\tau} n \quad (i = 1,2,\ldots.14) \qquad 16$$

τ_i being the mean life of r_i and μ_i the corresponding fraction of the delayed and photo-neutrons in this group.

The equations 16 are integrated numerically and the results applied to equation 15 to obtain the graph of $\gamma x + \epsilon n$ against n. In the initial rise during the first 20 minutes of the transient, this graph is straight. From its slope ϵ is deduced; consequently the dependence γx on the time can be inferred. The completion of the analysis consists in finding the constants a_1, a_2, a_3 and T_3 which fit the solution of equations 6 to the experimental curve. This process has shown that a_2 is very small, not exceeding 2% of the total rate of productions; T_3 is close to 20 minutes, and has yielded numerical values for a_1 and a_3 in the ratio already quoted.

REFERENCES

1. H.H. Clayton, "Application of the Perturbation Method in the Two-Group Diffusion Theory of Piles", Chalk River Report CRT-385, August 1948.

2. W.H. Watson, "Report on Fluctuation Search in Connection with NRX Pile Operation Commencing 15 Nov. 1947", Chalk River Report TPI-49 Official Use Only, January 1948.

3. H.H. Clayton, "Reduction of the Critical Height of the NRX Pile by Insertion of X-Rods into Shut-Off and Control Rod Positions", Chalk River Report CRT-386, August 1948.

4. H.H. Clayton, "Effects of Xenon Poisoning on NRX Pile", Chalk River Report TPI-42, Official Use Only, November 1946.

5. J.C. Duckworth, V.H. Rumsey, A.G. Ward and W.H. Watson, "Calibration of Control Rods", Chalk River Report PD-227, October 1947.

6. V.H. Rumsey, "On the Analysis of Experiments Involving the Kinetics of Piles with Reflectors", Chalk River Report AECL-105, Can J. Phys. 32, 435-449 (1954).

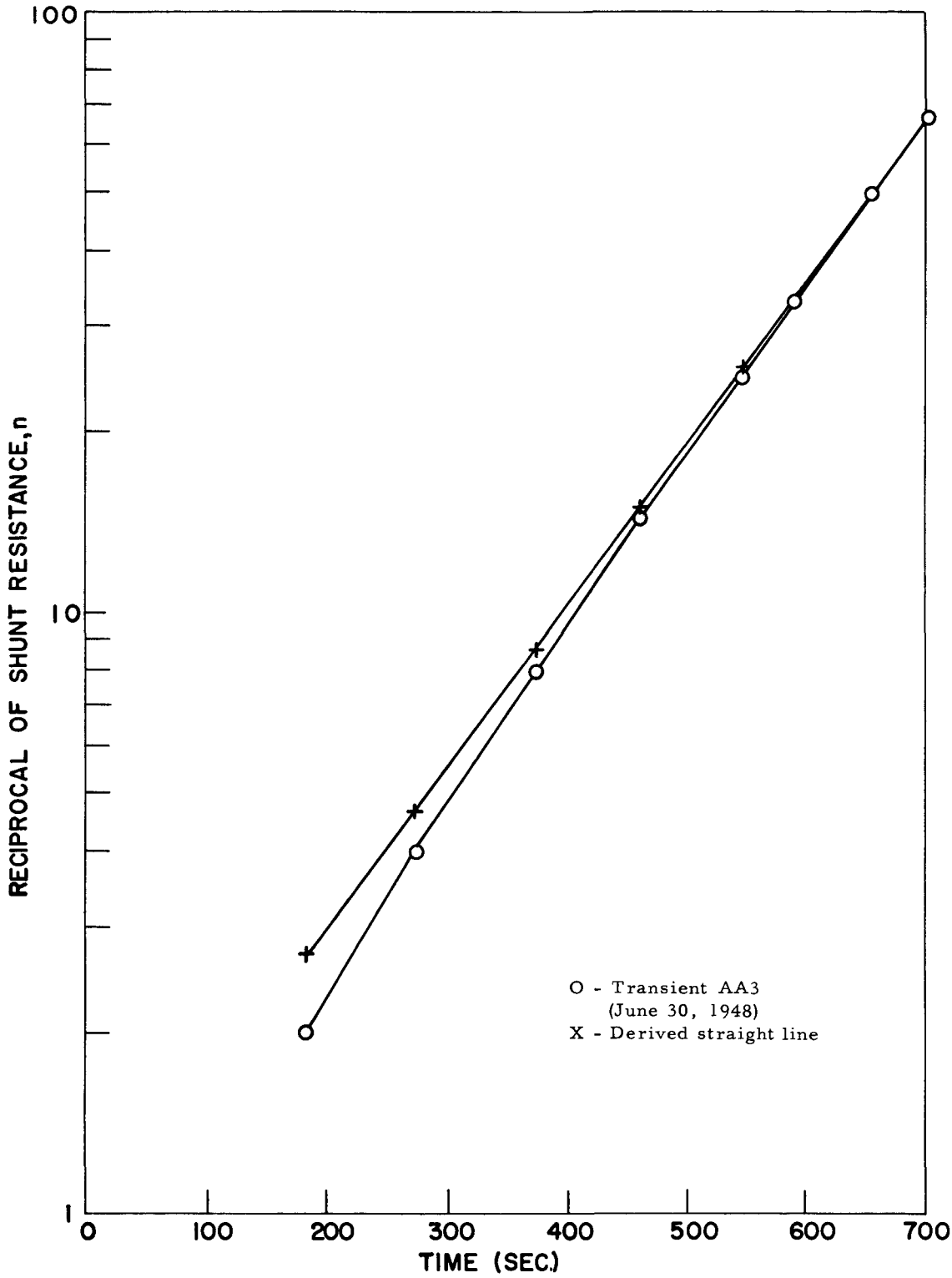

FIGURE 1

Reactor Period for Transient AA3 of June 30, 1948

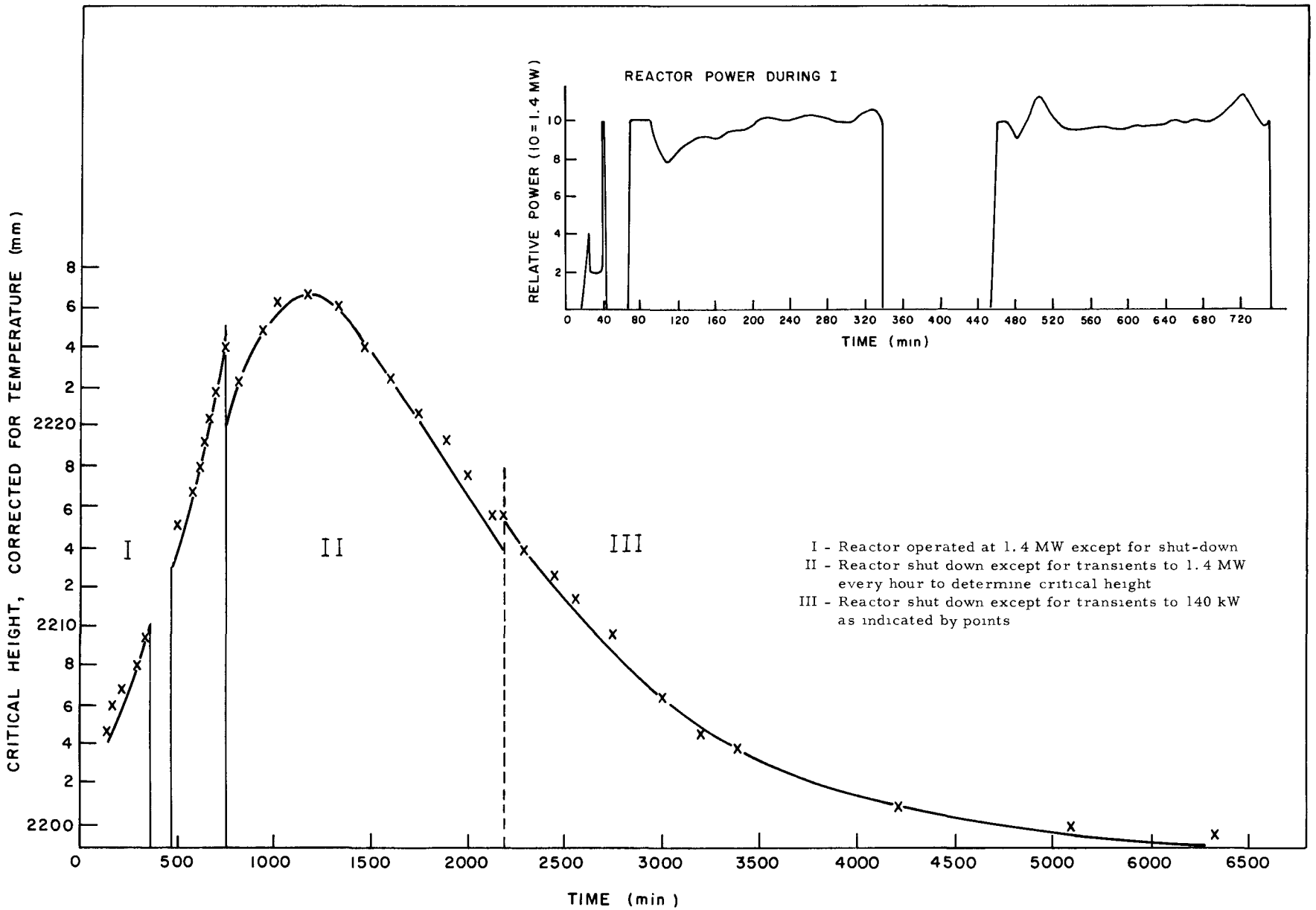

FIGURE 2

Critical Height During Transient of Feb. 12, 1948

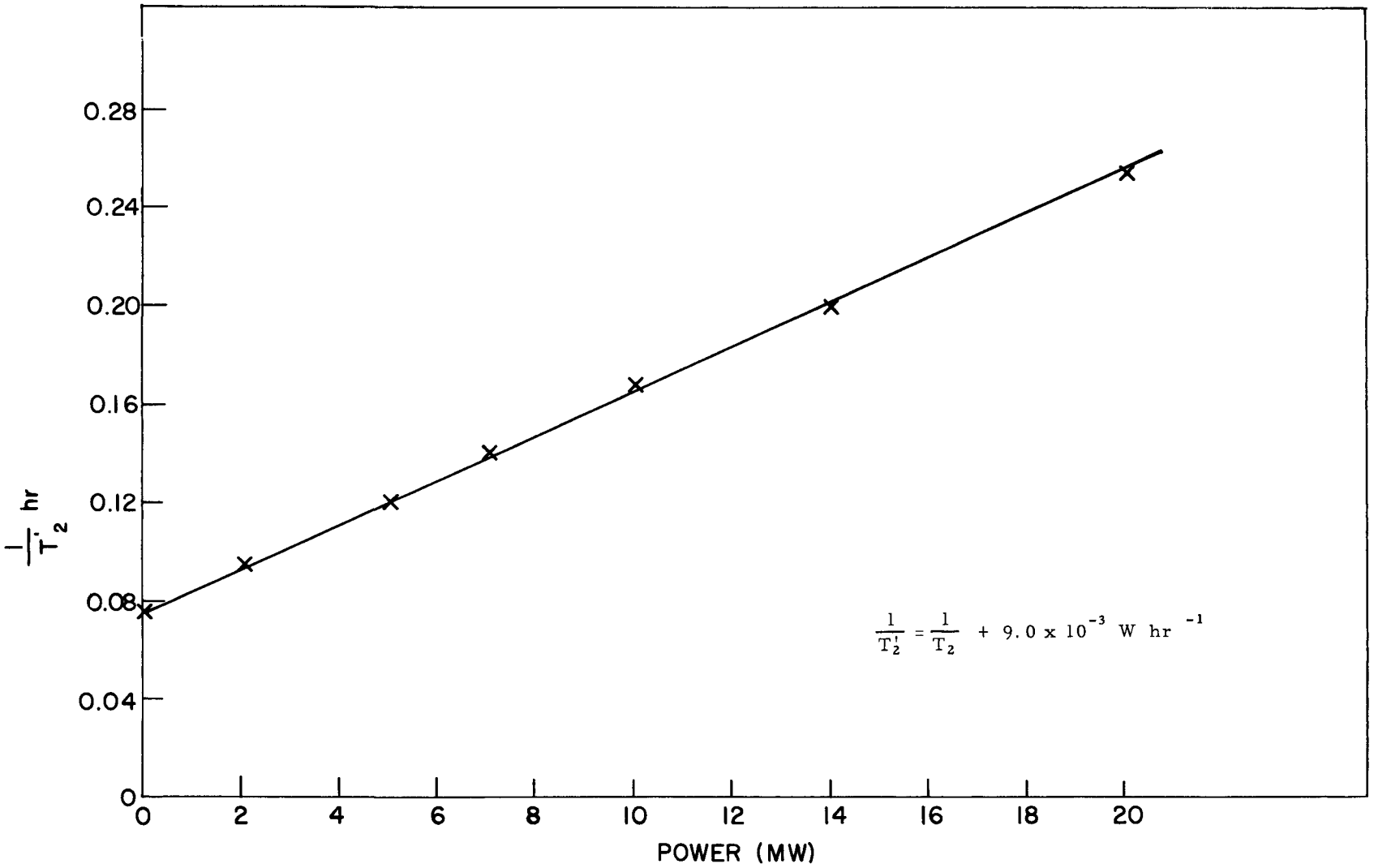

FIGURE 7

Reactor Period as a Function of Power

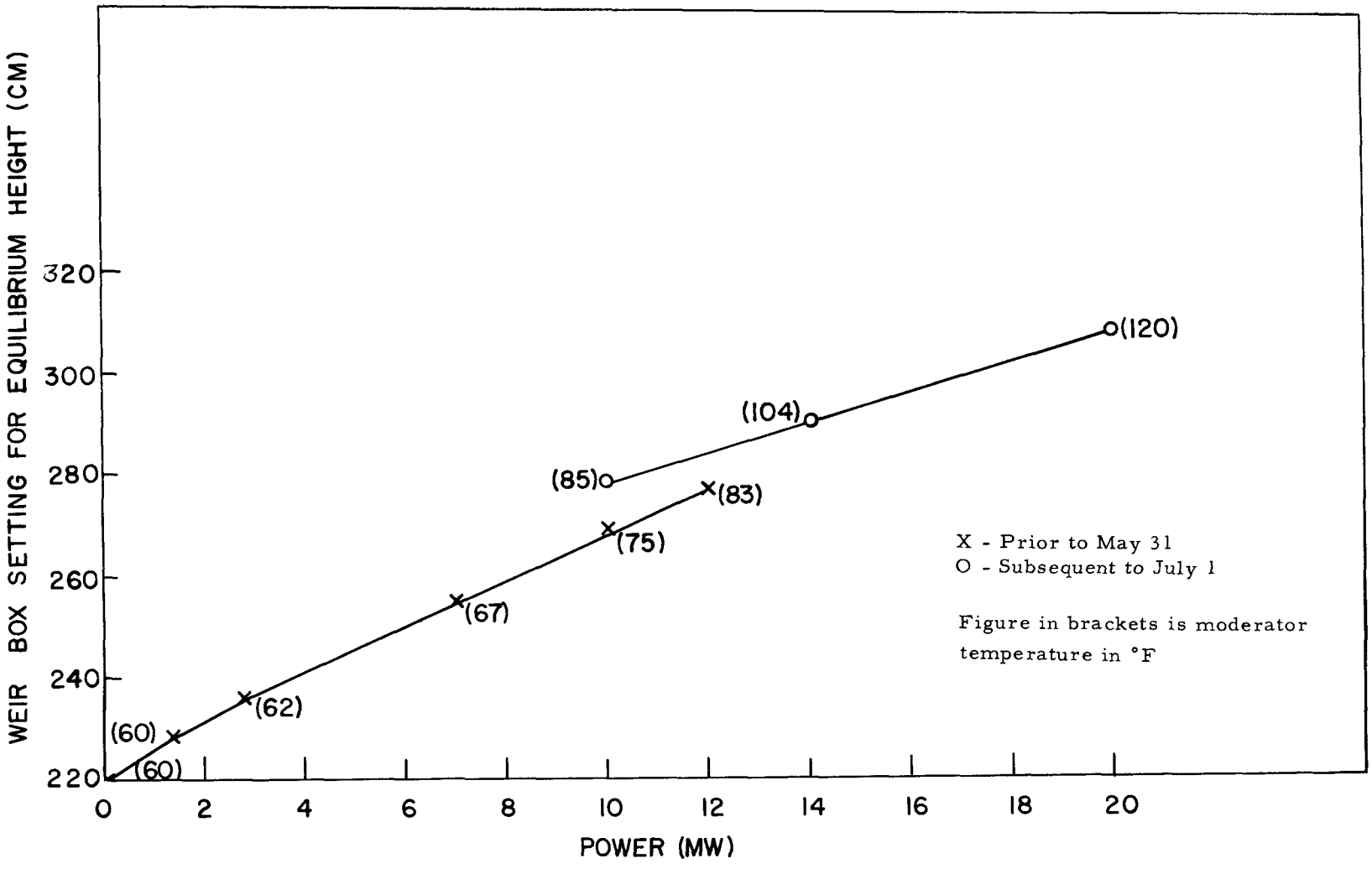

FIGURE 4

Equilibrium Moderator Level as a Function of Power

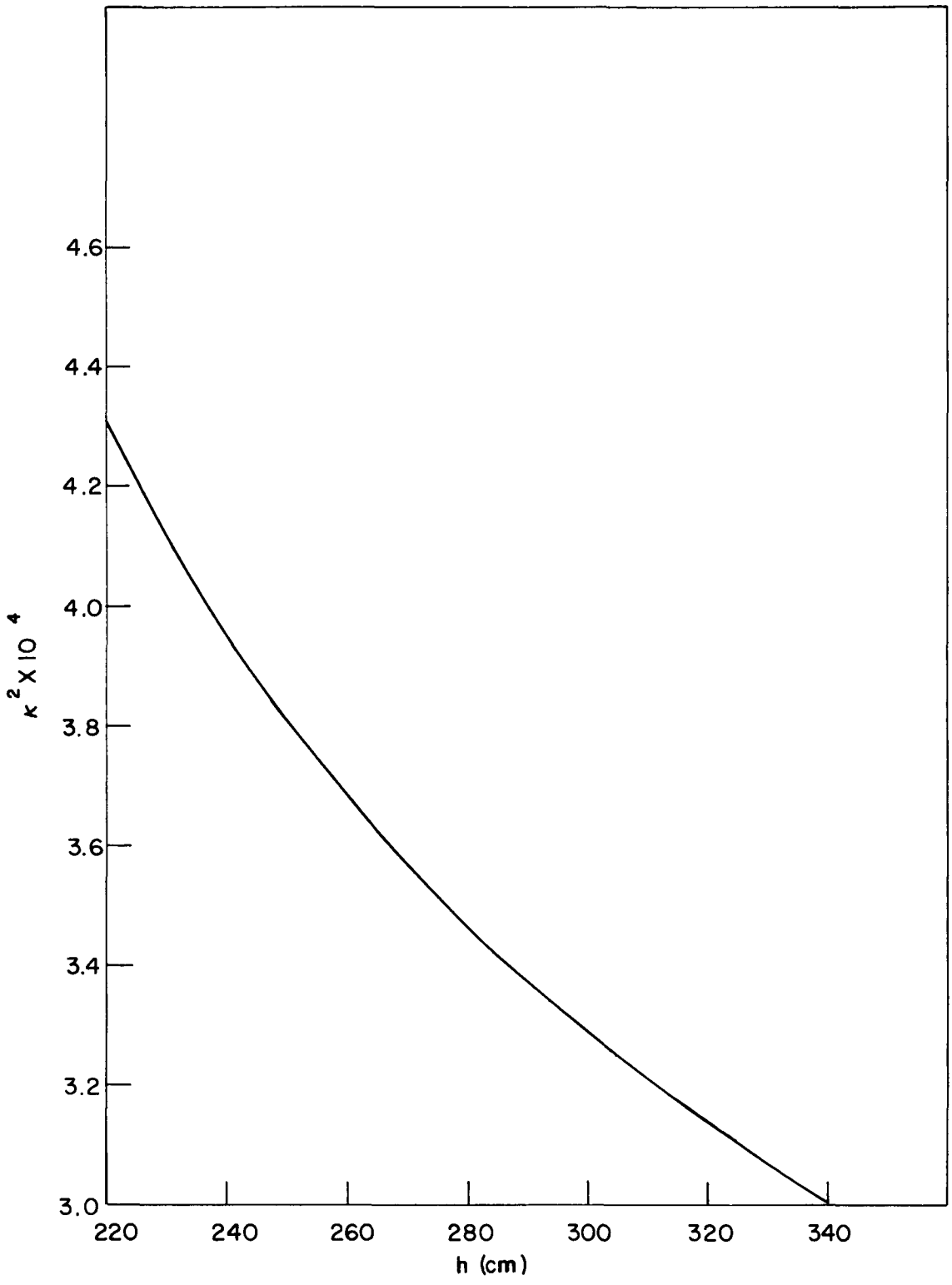

FIGURE 5

κ^2 as a Function of Moderator Level

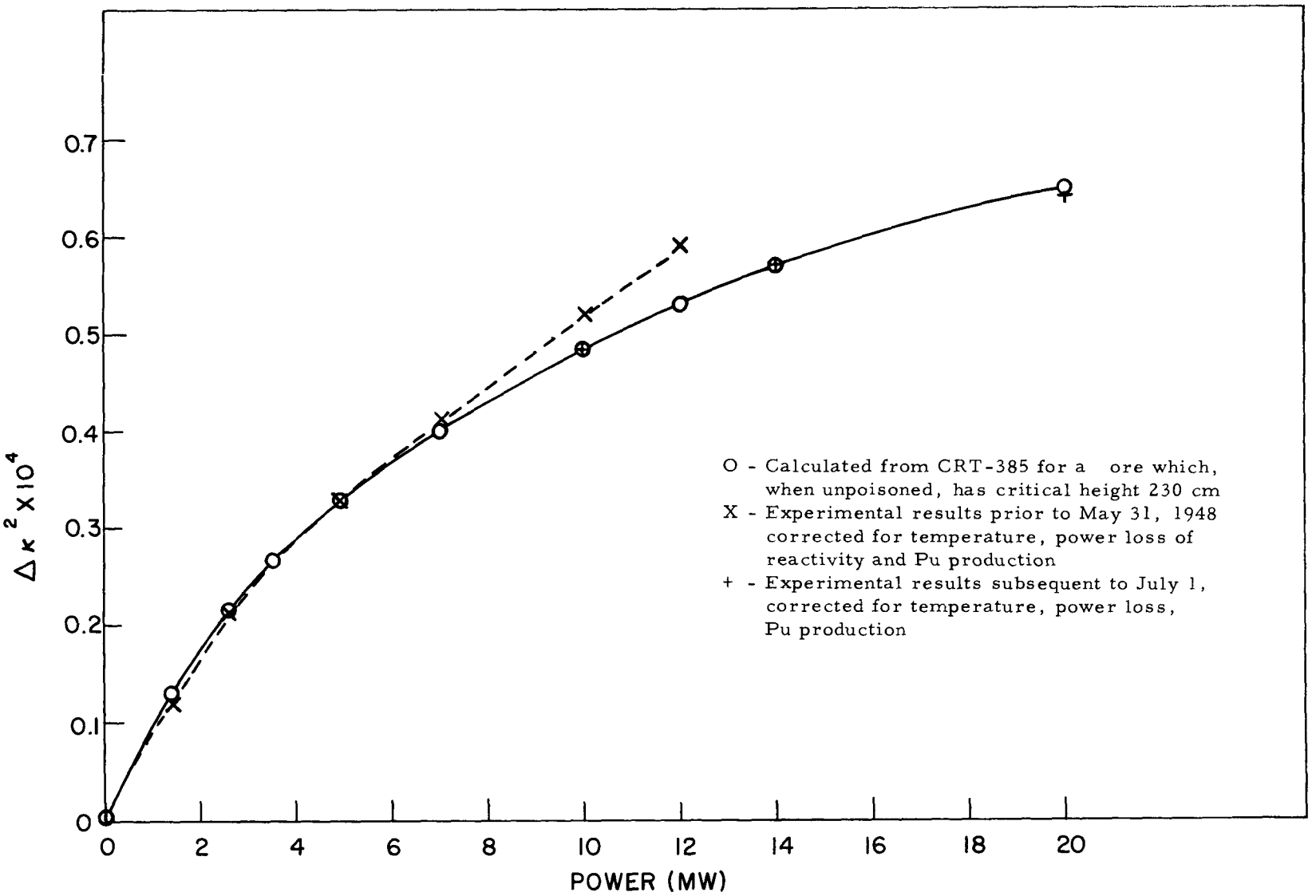

FIGURE 6

Change in Laplacian of NRX Due to Poisoning

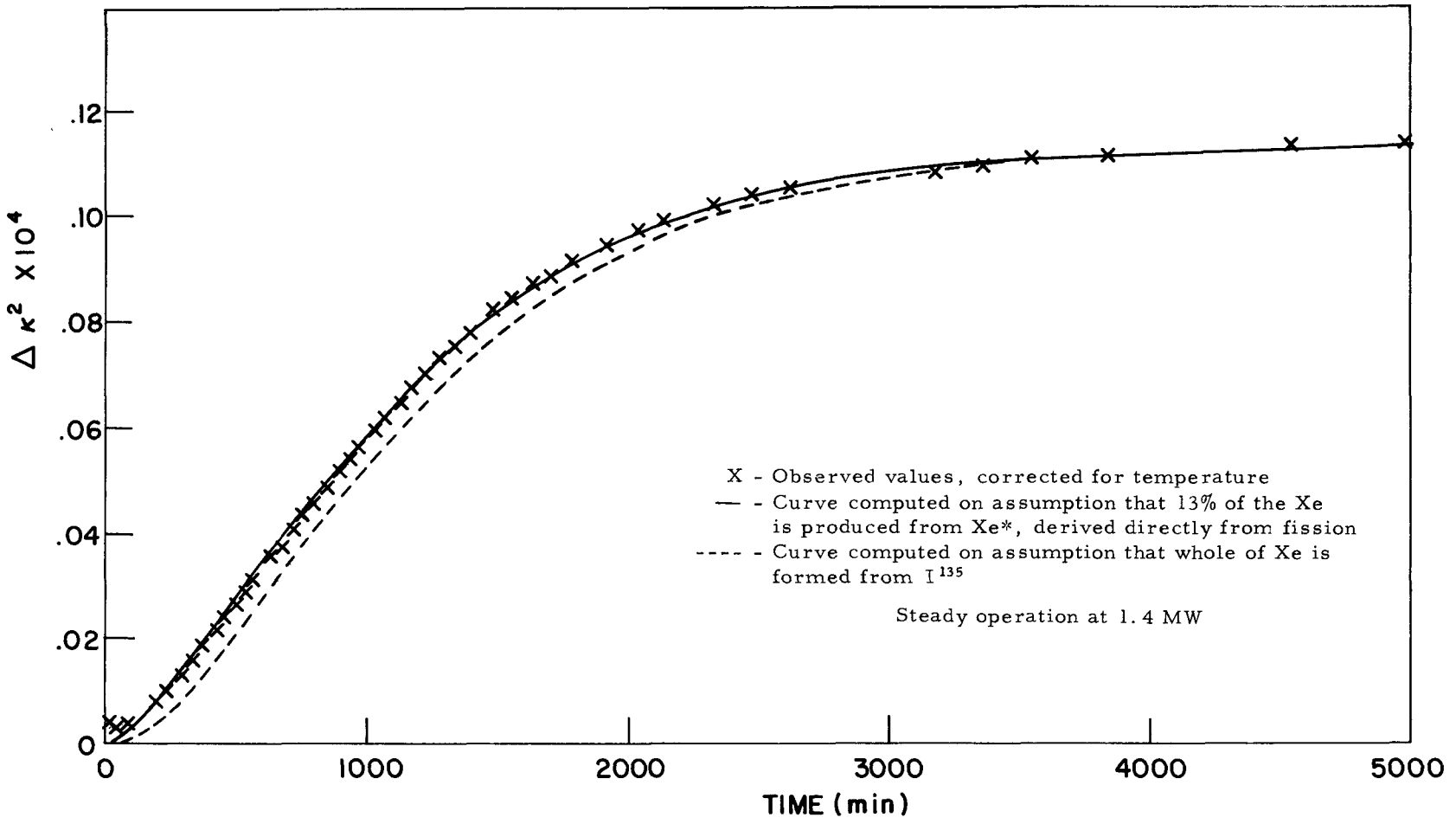

FIGURE 3

Growth of Critical Height Due to Xe Poison