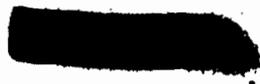


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Section IV

L. B. Borst, Section Chief

FINAL REPORT

OPERATING CHARACTERISTICS OF A CHAIN-REACTING PILE

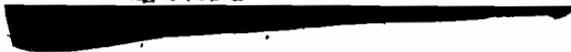
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ABSTRACT

The operating characteristics of the Clinton pile have been studied. The "best" values of these characteristics are tabulated below.

Barometric Coefficient	-0.4 inh/mm Hg
Operating Metal Temperature Coefficient (Operating temperature distribution)	-0.3 inh/°C
Operating Graphite Coefficient	-0.8 inh/°C
Operating Total Coefficient (Operating temperature distribution)	-1.1 inh/°C
Metal Temperature Coefficient (Uniform temperature)	-0.4 inh/°C
Graphite Temperature Coefficient (Uniform temperature in vacuum)	-1.9 inh/°C
Overall Temperature Coefficient (Uniform temperature in vacuum)	-2.3 inh/°C
Xenon Poisoning Coefficient	25 inh/1000 kw

The best value of the yield times cross section for Xe^{135} is $\gamma^{\infty} = 18.5 \times 10^{14}$ barns. Assuming a fission yield of 0.059 the Xe^{135} cross section is 3.1×10^6 barns.

OPERATING CHARACTERISTICS OF A CHAIN-REACTING PILEIntroduction

A chain reaction established within a moderated uranium system will show a variation in reactivity depending upon its environment. A graphite moderated pile in communication with the atmosphere will show a barometric effect due to changes in nitrogen concentration within the reacting medium. Variations in the temperature of the reacting system will produce variations in reactivity. Changes due to change in relative humidity are extremely small and are not easily measured.

A unit from which appreciable power is withdrawn will show the same sort of phenomena, but these will greatly influence the dynamics of the reacting system. Temperature changes will not be uniform, but will depend on total power output and position in the pile. The unit considered in this report is the Clinton Laboratories pile. It consists of a 24 foot graphite cube with a uranium rod lattice. Cooling is accomplished by an air stream flowing over each rod. Throughout most of this work the operating power was about 4000 kw, the maximum metal temperature 250° C, the pressure drop through the cooling air channels, 12 inches water (2.2 cm Hg.).

There are, in addition to variations due to environment, self-induced variations due to the chain reaction itself. Fission products formed from the reaction will presumably produce a loss in reactivity. Xe¹³⁵ has been previously reported as a significant poison. Attempts to detect other poisons have led to no positive results.

As normally operated using the maximum metal temperature as the control point, transients due to heating of the metal and graphite are not easily interpreted. Diurnal variations in inlet air temperature cause periodic variations in operating level and reactivity. It is therefore not easy to analyse operating data to obtain values characteristic of the unit. Under ideal conditions starting with a cool rested pile (from which the Xenon has decayed) and operating at constant power with constant inlet air temperature and constant barometric pressure, the pile will show the following transient:

$$\Delta inh = PA(1-e^{-Mat}) + PB(1-e^{-Mbt}) + CP \left[\frac{1}{\lambda_{Xe}} (1-e^{-\lambda_{Xe}t}) - \frac{1}{\lambda_I} (1-e^{-\lambda_I t}) \right]$$

where

P is the power output,

A and B are constants depending on the rate of heat transfer to the coolant,

M is the rate of flow of the cooling air,

a and b are constants depending on the rate of heat transfer to the coolant, the heat capacity of the metal and of the metal and graphite respectively,

C is a constant depending on the Xenon distribution in the pile and the Xenon cross section,

λ_{Xe} and λ_I are the Xenon and Iodine decay constants respectively.

The first component will be due to the rise in metal temperature. This factor shows a half-period of 1.5 min when the power is 4000 kw and the air flow is 10^5 c.f.m. After this time the metal will come to a heat flow equilibrium with the graphite with which it is in contact. The heating of the graphite will now be the controlling element as shown by the second factor. Its half period is about 3/4 hours. Thermal equilibrium will be 90% complete in 7 hours. The third transient is due to the formation of Xenon¹³⁵. In 72 hours this will have reached 99% of saturation. No longer term transients have been observed.

The Barometric Coefficient

The method used to measure this coefficient was to find times when the operating pile was thermally stable and there was a considerable change in air pressure.

In one case the barometer changed 5.8 mm in 6 hours, which is about as large as has been observed. Although the central metal showed no significant temperature change in this case, the graphite temperatures, which were known, dropped by a small amount. These temperatures were averaged weighting according to the square of the neutron density at each point. The average dropped 3° C. This change was taken to be representative of the average pile temperature, even though the central metal did not follow the trend. (The pile was being operated to keep the central metal temperature constant). During this run the Xenon concentration was at saturation so no correction had to be made. A slight air pressure correction had to be made because of small change in flow rate.

Date: 5-8-45

	12:30 A.M.	5:30 A.M.	7:30 A.M.
Pressure inside pile at approximately the center	721.4	724.2	727.2 mm of Hg
Pressure Change	0	2.8	5.8 mm of Hg
Inhour value of rod motion (Motion was into pile)	0	-1.0	-1.3 inhour
Average Graphite Temp.	101.0	99.3	98.0° C
Temperature Correction (with coefficient of $-1.3 \frac{\text{inh}}{^\circ\text{C}}$)	0	2.2	3.9 inhour
Reactivity change due to bar.	0	-1.2	-2.6 inhour
Barometric coefficient		- .43	- .45 $\frac{\text{inhour}}{\text{mm Hg}}$

In this case, the increase in reactivity due to temperature drop was greater than the decrease in reactivity due to air pressure rise. (The temperature correction is subtracted from the reactivity change due to rod motion).

Other methods of getting the coefficient were tried. During thunder storms there are frequently sudden barometric changes which can be made use of if the pile is at thermal equilibrium. The method has the disadvantage that the changes are of so short duration that the power level is not likely to be exactly constant. There is also some question as to whether the interstices of the graphite follow the barometric change. An occurrence of this type at 12:30 P.M. on June 7, 1945, was examined and a coefficient of $-.1 \text{ inh/mm Hg}$ was obtained.

Another method is to measure the reactivity before and after starting the fans. This method has the disadvantage of a temperature change not only of the metal, but also of the air in the channels and probably in the graphite accompanying the pressure change. The determination of what is the average pile pressure with the fans operating also becomes important. The average pile pressure has been calculated as the total difference in pressure from the atmosphere to the exit face minus half of the pile differential. This is probably the best estimate considering the instruments available. A unit change in the average pressure measured in this way is approximately equivalent to a unit change in barometric pressure as far as the reactivity is concerned. The value obtained by a measurement of this type is $-.15 \text{ inh/mm Hg}$. This value is considered less reliable than the previous value because of the many uncertainties.

Three experimental evaluations were made of the magnitude of the Xenon poisoning during each of which the reactivity of the unit was followed for several days (described below). During these periods barometric fluctuations of a few millimeters occurred. These reactivity changes were most satisfactorily eliminated by assuming coefficients of -0.3, -0.5, -0.3 inh/mm Hg respectively.

The "best" value of the barometric coefficient is therefore thought to be -0.4, \pm 0.05 inh/mm Hg. The previously reported value (CP-1300) was .25 inh/mm Hg.

Temperature Coefficient

Introduction

The net result of an increase in the temperature of a graphite moderated uranium pile is a change in reactivity. This change of reactivity is due to the following terms

$$\Delta K = \Delta K_l + \Delta_p K + \Delta_t K + \Delta_h K$$

where the first term evaluates the reactivity change due to a change in neutron leakage from the pile, the second term gives the change due to Doppler broadening of U^{238} resonance levels, the third term, the leveling of neutron density at high temperature, the fourth, the contribution due to variation of η with neutron energy.

The mean free path of a neutron increases with temperature so that a larger fractional leakage will occur at high temperatures. This will produce a loss in K with temperature rise. The broadening of the U^{238} resonance ($E \sim 10$ ev) with temperature rise will cause greater resonance absorption and therefore a loss in K . The absorption and particularly the fission cross section of U^{235} deviate from the $1/V$ law so that at higher temperatures a smaller fraction of the total neutrons will be

absorbed by U^{235} . This will also produce a negative coefficient. At high temperature, on the other hand, the ripple in the neutron distribution in the lattice will become less pronounced because of the larger mean free path, so that K should increase if this factor could be evaluated alone.

Of the total coefficient described above, the leakage, leveling and η terms depend upon neutron energy and therefore vary essentially with the temperature of the moderator. The sum of these may therefore be evaluated by measuring the temperature coefficient due to a change in graphite temperature alone.

The resonance effect, on the other hand, is a function of metal temperature, and may be evaluated by measuring the metal temperature coefficient with the graphite held at constant temperature.

The errors in calculating the contributions of these various effects is such as to give no reliable estimate of the coefficient expected. An empirical evaluation has therefore been made for each pile erected. The Argonne and Clinton piles have both been found to have negative coefficients. At the Argonne it has been possible to change the whole pile temperature uniformly, and to observe directly the variations of reactivity with temperature. Because of the research and production commitments at Clinton it has not been possible to observe the effect in this manner except on two occasions. In the first instance, the pile was heated with artificially heated air (CP-1300) and a coefficient of $-0.75 \text{ inh}/^{\circ}\text{C}$ was observed. In the second instance, the pile cooled for several days, and the reactivity was followed. The temperature effect was mixed with Xe decay and barometric changes. These measurements are described below. Reactivity changes associated with variations in temperature are easily observed in

the pile operating at high power. These changes, expressed in terms of "operating" coefficients, involve non-uniform temperature changes, and must be converted to uniform coefficients.

An independent measurement of the metal temperature coefficient can be useful in the evaluation of Doppler broadening. This measurement can be made most satisfactorily by an analysis of the temperature transient at the time of pile start-up or shutdown.

Operating Temperature Coefficient

The change in reactivity of the pile at equilibrium per degree change in control metal temperature (in practice, the hottest slug) may be called the operating total temperature coefficient. It is the sum of the contributions due to changes in metal temperature, graphite temperature and nitrogen concentration. This coefficient was originally evaluated when the maximum permitted metal temperature was changed. The value of $-.58 \text{ inh}/^{\circ}\text{C}$ was reported in CP-1300.

Independent evaluations of the same coefficient were made based upon normal operating records. Periods of equilibrium operation were found during a three month interval characterized by similarity in all operating conditions except pile temperature. The limiting conditions were the following:

No shutdown nearer than three hours previous to the run.

All available temperatures constant during the three hours within $\pm 2^{\circ}\text{C}$.

Power level constant within $\pm 0.25\%$.

Inlet air temperature within $\pm 1^{\circ}\text{C}$, except in one case.

Exit air temperature within $\pm 3^{\circ}\text{C}$.

Amount of nitrogen in pile within $\pm 0.3\%$.

The amount of nitrogen in the pile was taken to be proportional to the average air pressure divided by the average air temperature (absolute scale). The average air pressure was assumed to be the barometric pressure minus half of the pile differential pressure, and the average temperature to be the average of inlet and outlet air temperatures.

Three sets of data were found for three different values of nitrogen concentration. From the rod positions at these times the differences in reactivity were calculated. These were corrected for the Xenon poisoning and from this and the central metal temperature the coefficients were calculated.

Case	Inhour Difference	Inhour (Xenon Correction)	Inhour Difference (Xenon Corrected)	Metal Temperature Difference °C	Operating Total Coefficient
I	29.02	10.0	19.02	28	$-.68 \frac{\text{inh}}{^{\circ}\text{C}}$
II	77.22	8.4	68.8	50	-1.38
III	62.98	9.4	53.6	50	-1.07

The lack of agreement in the coefficients is taken to mean that the conditions were not sufficiently stringent, but since any further reduction in tolerance would eliminate the data altogether, the method was abandoned in favor of the pile start-up method.

When the Clinton Pile was first put into operation, a series of calibration measurements were made. Among them was one of the temperature coefficients of the metal alone which gave a value of $-.66 \text{ inh}/^{\circ}\text{C}$ for the central slug. The experiment is described in detail in CP-1081, and is referred to in CP-1300 where the measurement is said to be subject to corrections - due to the fact that some heating of the graphite took

place and due to the better knowledge of the position of the active center of the pile. Later, as reported in CP-1300, metal temperature coefficient measurements were made under operating temperature distribution by shutting down the pile when at thermal equilibrium and taking criticals at low power as the fans cool the metal. The graphite cools very little while the metal cools to graphite temperature. Using this method the coefficient was determined to be $-.43 \text{ inh}/^{\circ}\text{C}$. From this result the coefficient for a uniform temperature change was calculated to be $-.72 \text{ inh}/^{\circ}\text{C}$.

A single pile start-up can be used to measure both the operating metal and the operating total temperature coefficient. If the pile is rapidly brought to some power level two temperature transients occur. First, the metal heating by itself with heat transfer to the graphite small, and then as the metal temperature becomes significant a transition to the second transient, where the graphite and metal temperatures rise together. The temperature distribution during this rise is essentially that of equilibrium conditions, so that the coefficient obtained from the rise is also the coefficient for equilibrium conditions.

In preparation for a start-up measurement the cooling fans are run for as long a period as possible during a shutdown to lower the pile temperature. With the fans running the power is brought up to 1 kw to establish the position of the #2 rod for constant power at that temperature. Since the #2 rod is most convenient for operation it alone is used for the measurements. Then the pile is brought up to full power and a log is kept of central metal temperature, #2 rod position, and the barometer reading for an hour or more. From the #2 rod calibration a conversion is made from rod position to reactivity. These values are corrected for changes in the Xenon concentration (correction usually about 4 inhours) and in air pressure (amounting to about 1 inhour).

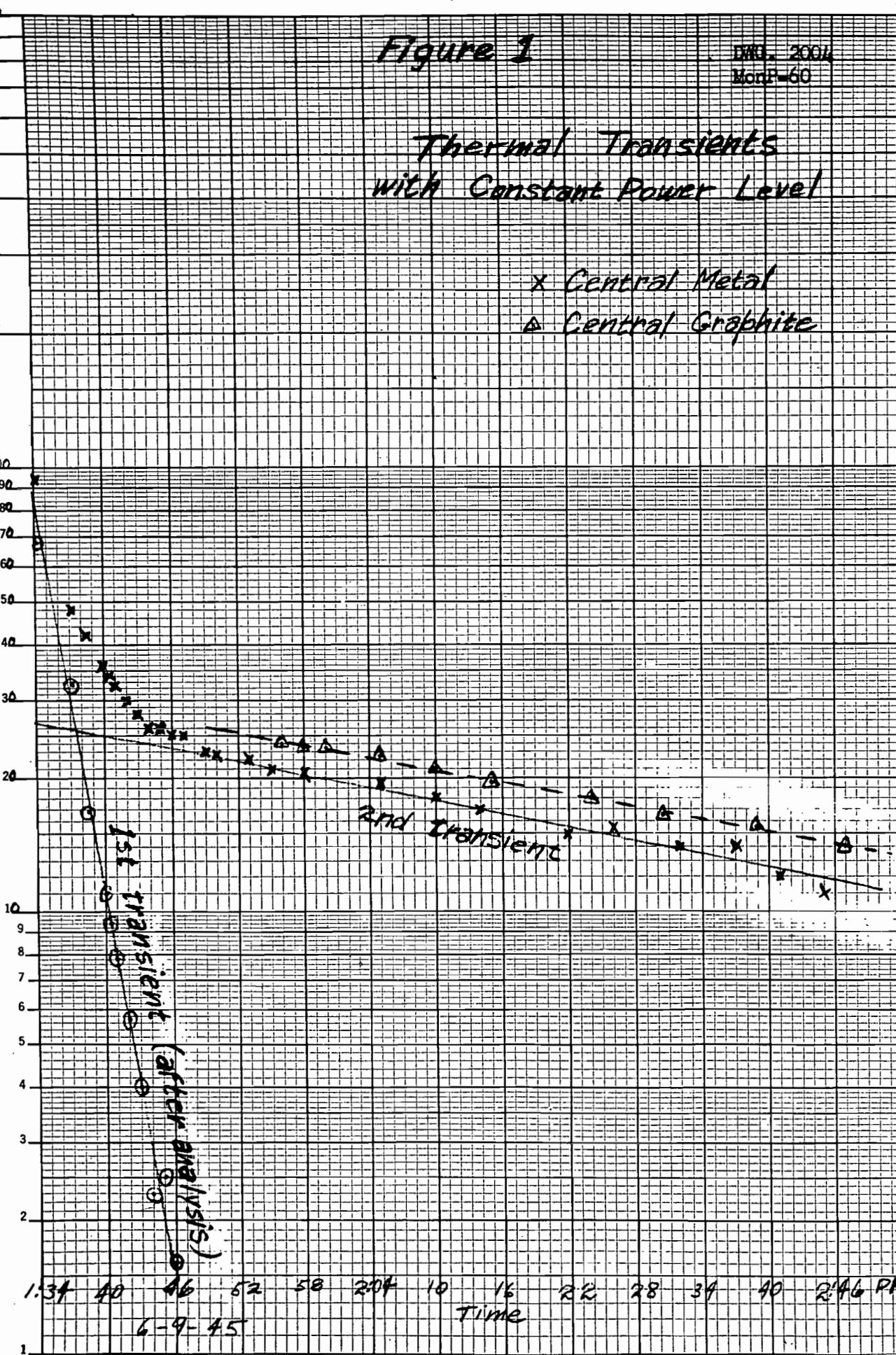
Figure 1

DRG. 2004
Mon P-60

Thermal Transients with Constant Power Level

x Central Metal
△ Central Graphite

Difference Between Equilibrium and Instantaneous Temperatures °C



1:34 40 46 52 58 2:04 10 16 22 28 34 40 2:46 PM
6-9-45
TIME

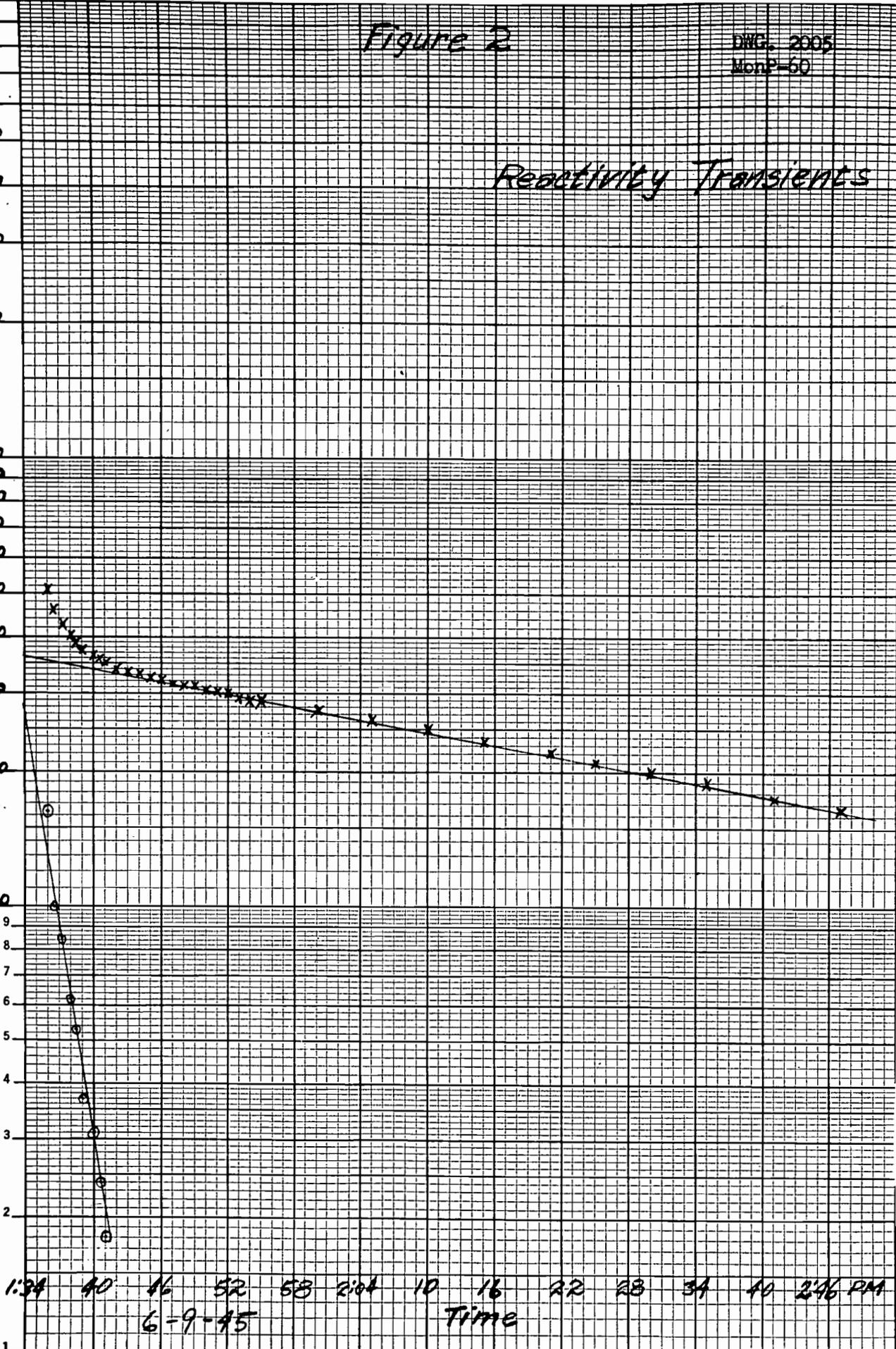
Figure 2

DWG. 2005
MonP-60

Reactivity Transients

Difference Between Equilibrium and Instantaneous Reactivities

- inhrs



1:34 40 46 52 58 2:04 10 16 22 28 34 40 2:46 PM
6-9-95 Time

A plot is then made as in Figures 1 and 2 of the difference between the instantaneous value of the hottest slug temperature and the equilibrium value for that power level, with the difference plotted as ordinate on a semi-log scale and time as abscissa on a linear scale. Since the pile power is not usually held constant until temperature equilibrium is attained, an equilibrium value is chosen which will make the second temperature transient appear as making a plot of reactivity against time. The temperature and reactivity curves when analyzed show two components, which are, respectively, parallel.

The two temperature exponentials as plotted here are each of the form $T - T_0 = P(1 - e^{-kt})$ where P, k, and T_0 are constants. P depends on the power level and the rate of heat transfer to the coolant, k depends on the rate of heat transfer alone, and T_0 is the initial temperature.

On one run the data (as plotted in Figures 1 and 2) were as follows:

Time	<u>Metal Coefficient</u>	
	Temperature (from analyzed curve not from data curve)	Reactivity from analyzed curve
1:34 P.M.	81.0° C	27.0 inh
1:43	4:1° C	1.0 inh
	<u>76.9° C</u> Difference	<u>26.0 inh</u>

Operating Metal Coefficient -0.30 inh/°C

Time	Metal Temperature	Central Graphite	Reactivity
1:50 P. M.	22.4° C	25.9° C	30.3 inh
2:50 P. M.	<u>11.7° C</u>	<u>13.5° C</u>	<u>17.0 inh</u>
Difference	10.7° C	12.4° C	13.3 inh

Operating Total Coefficient = $\frac{13.3}{10.6} = -1.3 \text{ inh/°C}$ (10.7 x .3 = 3.2 inh due to metal temperature rise)

Operating Graphite Coefficient = $\frac{10.1}{12.4} = -.82 \text{ inh/°C}$ (10.1 inh due to graphite temperature rise)

To check the hypothesis that the graphite followed the same exponential, a plot was made of the difference between the instantaneous central graphite temperature and the equilibrium value on a log scale against time on a linear scale. The curve obtained was a straight line parallel to the metal temperature line. The values obtained from four runs of this type including the above gave the following results:

Date	Operating Metal Temperature Coefficient	Operating Total Temperature Coefficient	Operating Graphite Temperature Coefficient
6-9-45	-.3 inh/°C	-1.3 inh/°C	-0.8 inh/°C
7-23-45	-.3 "	-1.4 "	-1.0 "
9-21-45	-.15 "	-0.7 "	-0.5 "
12-6-45	-.2 "	-1.0 "	-0.8 "

The accuracy of the measurement depends to a large extent on the accuracy of the control rod calibration. The change in the control rod calibration as the pile heats up is a factor which has not been assessed. However, the fact that the two sets of high values were obtained on one region of the rod while the two sets of low values were obtained on another points to an error in control rod calibration. Occasional changes in metal loading and in the position of poisons are factors affecting rod calibrations.

No account has been taken of the thermal expansion of the air in the graphite so the operating coefficient is for metal, graphite, and air.

Metal and Graphite Coefficient

Certain coefficient measurements could not be classified as operating coefficients, because of different temperature distributions. During a low power run in October, 1944, when the decay of the Xenon was being

followed, corrections due to temperature changes fit the best when a temperature coefficient of $-1.3 \text{ inh}/^{\circ}\text{C}$ was used. This is reported in CP-2192. In this case (mentioned later in this report in the section on Xenon) the metal was at the temperature of the adjacent graphite. In another run of this type, February, 1945, a value of $-1.2 \text{ inh}/^{\circ}\text{C}$ gave the best results.

In two other measurements reported in CP-2222, the pile was allowed to sit after shutdown until the metal temperature dropped to graphite temperature. A critical was taken, the pile was cooled by the fans, and then another reactivity measurement was taken. The values of temperature coefficient obtained were $-1.1 \text{ inh}/^{\circ}\text{C}$ and $-1.5 \text{ inh}/^{\circ}\text{C}$. In a later run of the same type, a value of $-.9 \text{ inh}/^{\circ}\text{C}$ was obtained.

Temperature Coefficient Without Gradient

The temperature coefficient for the pile at uniform temperature was measured only once when the pile was heated overnight by radiators in the inlet air duct. The value observed as reported in CP-1300 is $-.75 \text{ inh}/^{\circ}\text{C}$.

Best Values based on the available data:

Operating Total Coefficient = $-1.1 \text{ inh}/^{\circ}\text{C} \pm .1$ (Temperature reference point at central or hottest slug)

Operating Metal Coefficient = $-0.3 \text{ inh}/^{\circ}\text{C} \pm .05$ (Temperature reference point at central or hottest slug)

Operating Graphite Coefficient = $-0.8 \text{ inh}/^{\circ}\text{C} \pm .1$ (Temperature reference point central graphite)
(no correcting for nitrogen)



Summary of Experimental Results

Coefficient	Value: Inh/°C	Per °C With Respect To:	Temperature Distribution	Metal Graphite Temperature Difference	Temperature Change Distribution	Remarks
Operating Total	-0.58	Hottest Slug	Operating	Operating	Operating	CP-1300
"	-0.68	"	"	"	"	Not pre- viously reported
"	-1.38	"	"	"	"	"
"	-1.07	"	"	"	"	"
"	-1.3	"	"	"	"	"
"	-1.4	"	"	"	"	"
"	-0.7	"	"	"	"	"
"	-1.0	"	"	"	"	"
<hr/>						
Operating Metal	-0.66	"	"	"	"	CP-1081
"	-0.43	"	"	"	"	CP-1300
"	-0.3	"	"	"	"	Not pre- viously reported
"	-0.3	"	"	"	"	"
"	-0.15	"	"	"	"	"
"	-0.2	"	"	"	"	"



Summary of Experimental Results (Continued)

Coefficient	Value: Inh/°C	Per °C With Respect To:	Temperature Distribution	Metal Graphite Temperature Difference	Temperature Change Distribution	Remarks
Operating Graphite	-0.8	Central Graphite	Operating	Operating	Operating	Not pre- viously reported
"	-1.0	"	"	"	"	"
"	-0.5	"	"	"	"	"
"	-0.8	"	"	"	"	"
Metal and Graphite	-1.3	All Points	"	Zero	Uniform	CP-2185
"	-1.1	"	"	"	"	CP-2222
"	-1.5	"	"	"	"	CP-2222
"	-0.9	"	"	"	Operating	Not pre- viously reported
"	-1.2	Average Pile Temperature*	"	"	"	"
Total	-0.75	All Points	Uniform	Zero	Uniform	CP-1300

* The average of available temperatures was obtained using the square of the neutron densities as weight factors.

Calculated Coefficients For A Uniform Temperature Distribution

With the help of Messrs. Weinberg and Scalettar a calculation was made of some coefficients for the pile changing temperature uniformly. The average temperature in any slug channel was obtained by the formula

$$\bar{T}_M(z) = T_{M^0} \frac{\int_0^L z(z) M^2(z) dz}{\int_0^L M^2(z) dz} = T_{M^0} (.86)$$

where T_{M^0} is the metal temperature at the hottest point of the row,
 $z(z)$ is the temperature distribution as a function of position (z) in the row.

As an approximation in lieu of good data we took a sine function starting at zero at the beginning of the row of metal and reaching a maximum at 68 cm behind the center of the pile, which is the measured hottest point.

$M(z)$ is the neutron density distribution for which we took the sine function reaching a maximum at the center and zero at 50 cm beyond each end of the metal rows.

The average temperature along a diameter was obtained by a similar equation:

$$\bar{T}_M(r) = T_{M^0} \frac{\int_0^R R(r) M^2(r) r dr}{\int_0^R M^2(r) r dr} = T_{M^0} (.87)$$

where

T_{M^0} = temperature at $r = 0$ for some constant Z

$R(r)$ = radial temperature distribution function which was obtained from a cross sectional temperature plot

$M(r)$ = radial neutron distribution, taken to be $J_0 \left(2.4 \frac{r}{R - 50} \right)$

where

r = variable radius,

R = radius of metal loading, 50 cm is augmentation distance.

Multiplying the two together we get the effective average metal temperature.

$$T_{M \text{ ave}} = T_{M0} (.86)(.87) = .75 T_{M0}$$

where

$$T_{M0} = \text{Temperature of hottest slug.}$$

Then the metal temperature coefficient is

$$C_M = \frac{C_{M'}}{.75} = \frac{-.3}{.75} = \frac{-.4 \text{ inh}}{^{\circ}\text{C}}$$

where C_M is the coefficient for the metal with constant temperature rise over the pile, and $C_{M'}$ is the coefficient with operating temperature distribution.

If we assume the same temperature distribution relative to the hottest graphite point as was calculated for the metal, we have

$$T_G \text{ ave} = 0.75 T_{G0}$$

$$\text{Then } C_G = \frac{C^{\circ}G}{.75} = \frac{-.8}{.75} = \frac{-1.1 \text{ inh}}{^{\circ}\text{C}}$$

where C_0 is the graphite coefficient for a uniform temperature distribution and $C^{\circ}G$ is for an operating temperature distribution.

The assumption that the graphite temperature distribution is the same as the metal neglects the fact that the hottest point in the graphite is farther from the center of the pile than the hottest point in the metal. However, the error introduced is probably not greater than $0.1 \text{ inh}/^{\circ}\text{C}$. This value for graphite includes the contribution due to the variation in the nitrogen content of the graphite and channels.

$$P = RDT \quad dP = RDdT \text{ for constant density.}$$

Then

$$\frac{dP}{P} = \frac{dT}{T}, \text{ for } dP = 1 \text{ mm of Hg, } dT = \frac{T}{P} = \frac{^{\circ}\text{C}}{\text{mm Hg}}$$

Since a change of 1 mm of Hg produces 0.4 inh change in reactivity,

$$\frac{T}{P} = \frac{^{\circ}\text{C}}{.4 \text{ inh}}, \text{ and } \frac{^{\circ}\text{C}}{\text{inh}} = \frac{T}{0.4P}$$

an average pressure of 740 and average absolute temperature of 385 gives

$$\text{Nitrogen temperature coefficient} = \frac{\text{inh}}{^{\circ}\text{C}} = \frac{0.4 P}{T} = \frac{0.4 \times 740}{385} = 0.8 \frac{\text{inh}}{^{\circ}\text{C}}$$

The corrected graphite coefficient will therefore be

$$C_{G_N} = C_G - (\text{N}_2 \text{ correction}) = -1.1 - 0.8 = -1.9 \frac{\text{inh}}{^{\circ}\text{C}}$$

Then the calculated temperature coefficient of the lattice in vacuo for uniform temperature distribution is

$$\text{Total Temperature Coefficient} = -1.9 - 0.4 = -2.3 \frac{\text{inh}}{^{\circ}\text{C}}$$

Evaluation of Causes of Temperature Coefficient

From above

$$\Delta K = \Delta_1 k + \Delta_r k + \Delta_t k + \Delta \eta k$$

where $\Delta_1 k$ is the change in reactivity due to change in leakage, $\Delta_r k$ is the change due to Doppler broadening of U^{238} resonance, $\Delta_t k$ is due to the leveling effect of the neutron density at high temperatures, $\Delta \eta k$ is due to the variation in η with neutron energy.

In CP-478 Morrison evaluates the factors causing the temperature coefficient and gives an estimate of the temperature coefficient for a lattice with rods 1.6 cm radius, while the Clinton pile has rods of 1.4 cm radius. Assuming that this discrepancy will cause only small errors, a re-evaluation of $\Delta \eta k$ is made using Morrison's values of $\Delta_1 k$ and $\Delta_t k$, since $\Delta \eta k$ was stated to be the least reliable.



	Morrison	Our Value
Metal Coefficient = $\Delta_r k$	-1.3×10^{-5}	$-1.0 \times 10^{-5} = -.4 \text{ inh}/^\circ\text{C}$
$\Delta_1 k$	-2.7×10^{-5}	
$\Delta_t k$	$+4.6 \times 10^{-5}$	
$\Delta_\eta k$	-9.7×10^{-5}	-6.6×10^{-5}
Graphite Coefficient = $\Delta_1 k + \Delta_t k + \Delta_\eta k$		$-4.7 \times 10^{-5} = -1.9 \text{ inh}/^\circ\text{C}$
Total Coefficient = $\Delta_1 k + \Delta_t k + \Delta_\eta k + \Delta_r k = -9 \times 10^{-5}$		$-5.7 \times 10^{-5} = -2.3 \text{ inh}/^\circ\text{C}$

Xenon Poisoning

The inhour value of the Xenon poisoning was determined by calculating a theoretical curve for the relative amount of Xenon present and matching it to a reactivity curve corrected for other effects.

In order to calculate the Xenon concentration during a run the previous pile history has to be known, but not further back than 72 hours because the Xenon which was present at that time will have decayed to less than 1% of the original value.

The formula for the concentration at any time, t, is

$$N_{xe} = \frac{\lambda_I}{\lambda_I - \lambda_{xe}} \int_0^t k P(\tau) \left[e^{-\lambda_{xe}(t-\tau)} - e^{-\lambda_I(t-\tau)} \right] d\tau$$

where

λ_I = decay constant = 0.1050 hr⁻¹

λ_{xe} = decay constant = 0.0737 hr⁻¹

P(τ) = the power level in KW

k = proportionality constant

When used for calculation it is best expressed in this form for the concentration at any time t_n.



Figure 1 - Power Level before and during run

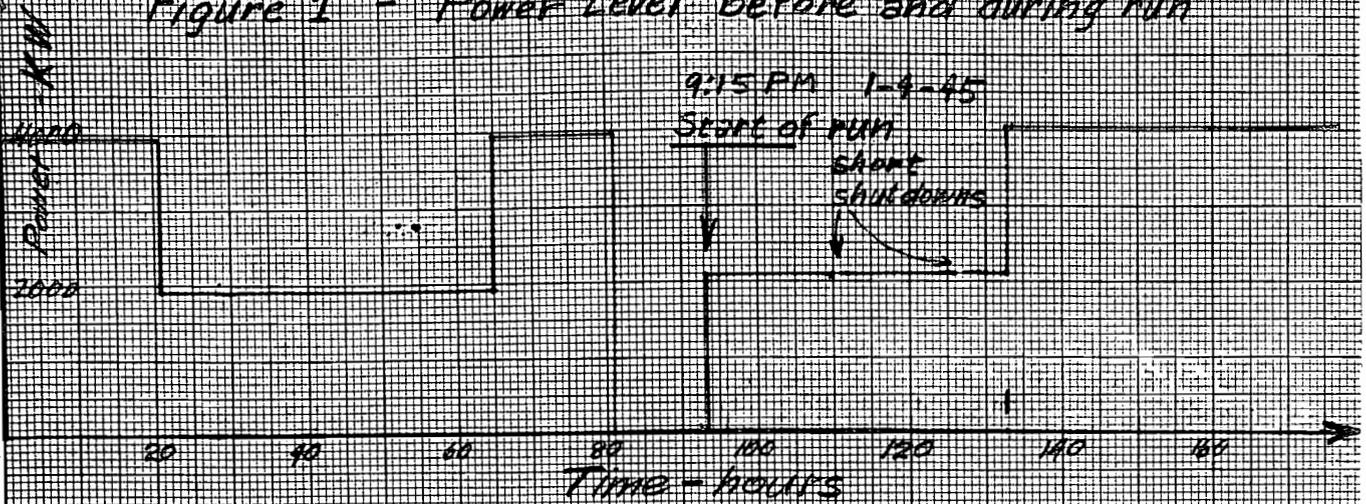


Figure 2 - Xenon Poisoning

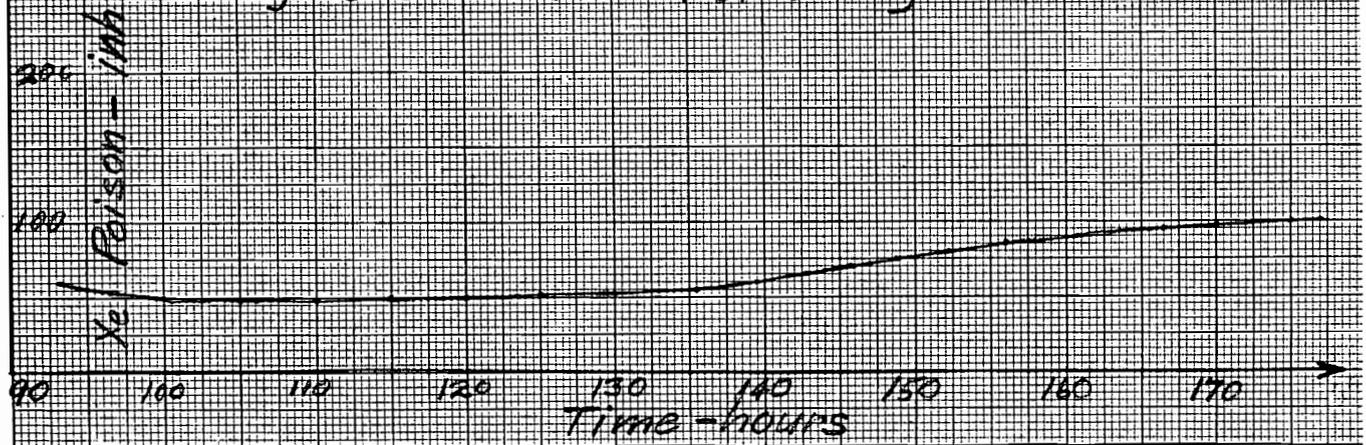
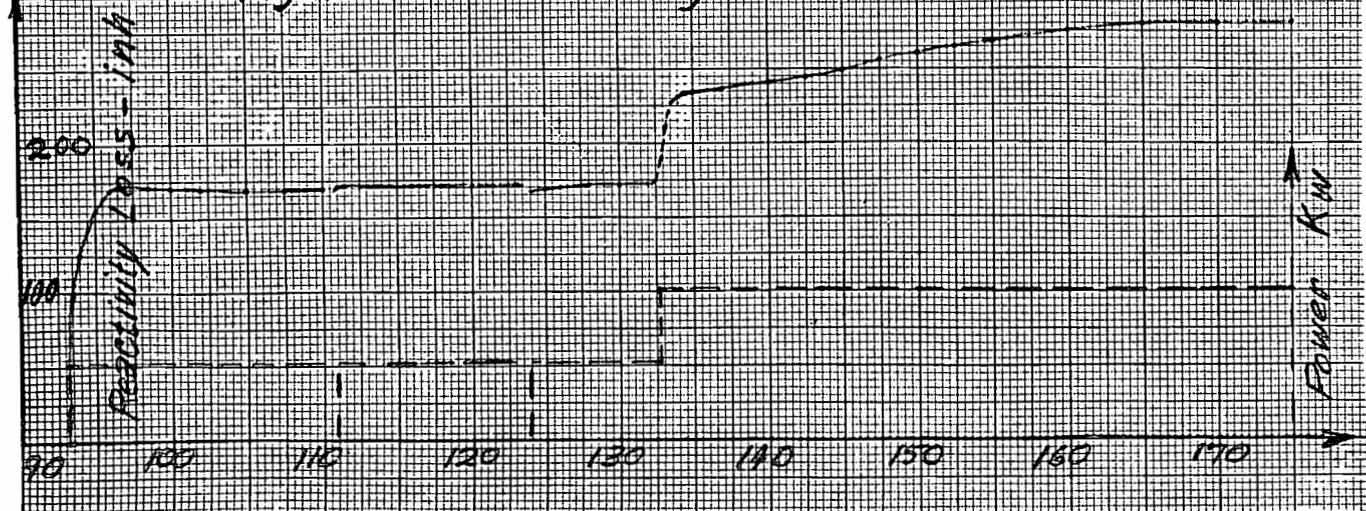


Figure 3 - Reactivity Loss



$$N_{Xe} = \frac{\lambda_I k}{\lambda_I - \lambda_{Xe}} \sum_{i=1}^{l=n} \left[P_i \left\{ e^{-\lambda_{Xe} t_n} \frac{e^{\lambda_{Xe} t_1} - e^{\lambda_{Xe} (t_1-1)}}{\lambda_{Xe}} - e^{-\lambda_I t_n} \frac{e^{\lambda_I t_1} - e^{\lambda_I (t_1-1)}}{\lambda_I} \right\} \right]$$

where P_i is the power level from $(t_1 - 1)$ until t_1 . We are indebted to Mr. Scalletar for setting up these equations.

In Figures 1 and 2 are shown the power levels of the period 1-4-45 to 1-8-45 and the resulting calculated Xenon concentrations. Experimentally, we plotted the reactivity loss of the pile as a function of time, getting the reactivity from the control rod positions and correcting this for barometric changes with a barometric coefficient of $-.3 \text{ inh/mm Hg}$. The curve, Figure 3, that we then obtained showed temperature and Xenon transients. Of the total run which lasted over four days, about 16 hours are occupied by temperature transients. These occur at the beginning, when the pile came to full power at 2000 KW, and again in the middle of the period when it changed to 4000 KW. Aside from these periods the reactivity curve showed a shape which could be matched by varying the ordinate of the calculated Xenon curve to the proper value. With this done we could read off the inhour value of the Xenon for any time. Since the 4000 KW run lasted for two days the saturation value was reached within 5%. At the end of that time the inhour value was 100.7. At complete saturation it would have been 106.2 inhours. The power level was 4040 KW, so the saturation value of the Xenon poisoning of the Clinton pile is 26 inh/megawatt.

This value corresponds to $\gamma \bar{\sigma} = 18 \times 10^4$ barns. Using γ to be .059, which is the sum of 0.056 for Xe^{135} from the I^{135} decay reported in CC-2219 and 5.6% of 0.056 = 0.003 reported as the independent fission yield of Xe^{135} in CC-3007, we obtain $\bar{\sigma}_{Xe} = 3.0 \times 10^6$ barns.

In the first evaluation of Xenon poisoning done in October 1944, and reported in CP-2192, 22.5 inh/megawatt was found to be the saturation poisoning, $\gamma_{\infty} = 16 \times 10^4$ barns and $\sigma_{Xe} = 2.7 \times 10^6$ barns, using $\gamma = 0.059$. During this run a barometric coefficient of -0.3 inh/mm Hg and a total operating temperature coefficient of -1.3 inh/ $^{\circ}$ C were used.

In another Xenon run, February 21, 1945, 25 inh/megawatt was observed as saturation Xenon poisoning, $\gamma_{\infty} = 18.5 \times 10^4$ barns, and $\sigma_{Xe} = 3.1 \times 10^6$ barns. Barometric coefficient of $-.5$ inh/mm Hg and total operating temperature coefficient of -1.2 inh/ $^{\circ}$ C were used satisfactorily. During this run the pile was shut down for four days and the Xenon decay was followed.

Longer Period Poison

The February 21, 1945, run which lasted four days was also analyzed for a possible longer period poison. The decay time of four days would make a decay of half-life of about a week most prominent. No effect was observed, and considering the accuracy of the measurements we can say that a poison of half-life of about a week and $\gamma_{\infty} = 2500$ would probably have been observed.

During the run of October, 1944, reported in CP-2192, a large amount of metal which had been in the pile three months or more was discharged and a change in reactivity which could be attributed to a long-lived poison from fission products was not observed.

