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Section V

H. W. Newson, Section Chief

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ION CHAMBER FOR CONTROL AND OPERATION OF CLINTON HIGH FLUX PILE

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F. C. Armistead

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ION CHAMBER FOR CONTROL AND OPERATION OF CLINTON HIGH FLUX PILE

I. Introduction

The proposed Clinton high flux pile will have such an excess reactivity built into it and will have such a short neutron generation time (characteristic of the pile materials) that dangerously rapid changes in the power level will be possible. The control problem in this pile is more difficult than in previous piles, and demands upon the control equipment are greater than heretofore.

The Clinton low flux (graphite) pile is controlled and operated essentially on the basis of information registered on a galvanometer connected to a differentiating ion chamber (CP-782) and this chamber lies inside the pile shield against the reflector. In starting the pile up the first step is to withdraw the control rods until the power is such that the galvanometer begins to move perceptibly. A careful operator would detect this at no lower than 100 watts (or 1000 watts in the event the ion chamber were non-differentiating -- See data in Section III). From this level on up to normal operating power of approximately 4×10^6 watts the pile power level is "in sight" of the operator. That is, there is a range of 4×10^4 (or only 4×10^3 for non-differentiating chamber) covered by the one instrument on which pile operation and control principally depends. Such operating practice is permissible with a slow-moving pile, yet in the new pile it would be extremely risky. If one waits for the new pile to come "into sight" at some intermediate level, it may come into sight climbing so rapidly that it becomes dangerously high before controls can be actuated. For such a pile the operator needs a greatly

increased range of power level detection; preferably the range would be such that it would extend from the normal operating level down through the lowest level at which the pile may be when the operator wishes to start up again. The desired practical range is shown below (end of Section III) to be 10^5, which is 2.5 times the range normally covered by the graphite pile instrument used as a differentiating chamber and 25 times the range when used non-differentiating.

The lowest power considered detectable is that at which the ion current that measures pile power is as small as the ion current due to β and γ activity of the pile and ion chamber. Alternatively, in the case where the ion chamber is used as a differential chamber, with β and γ-induced currents almost completely bucked out, leaving only the neutron-induced current to be read on the boron coated side, the lowest power considered detectable is that at which the ion current due to neutrons is as small as the net remaining current due to pile and chamber activity after the best practical balance of these has been attained by chamber design.

The problem of increasing the effective range of the ion chamber is attacked on two lines: (1) extend the top of the range by increasing the absolute sensitivity of the instrument, i.e., amperes ion current per neutron flux unit, and (2) extend the bottom by decreasing the magnitude of the induced activity in the chamber components.

II. Determination of the Desired Practical Range: the Job Specifications

The desired practical range is determined on the following basis. The top of the range is fixed by the operating level of the proposed pile. The bottom of the range is the level the pile will have dropped to after a shutdown by the time the operator wishes to start up again. Of the various conceivable sequences of operation at the time of a shutdown and re-start-up, that one is assumed here which gives the lowest level from which it will frequently be necessary to re-start the pile.

There are two notable factors involved in the stopping and re-starting of such pile as this will be: (1) the time variation of the photo-neutron source strength, P, as a result of decay of γ emitters, and also (2) the time variation of the multiplication factor k_{eff}, as a result of poison concentration, chiefly Xenon.

Xe^{135} has an exceedingly large neutron-capture cross section. It is continually being produced in a pile by the decay of $Iodine^{135}$ which is produced as a fission product. Xenon is also continually being removed in a pile both by its own radioactive decay and by the neutron-capture processes. The amount of Xenon poison will rise immediately after a shutdown since it is still being produced by decay of the stored up Iodine, yet it is not being "burned up" as fast by neutrons. The amount of Xenon poison will decrease again, however, when the Iodine is so depleted that Xenon decay proceeds faster than the Xenon production by Iodine decay. The Xenon will grow to a concentration such that it will kill more reactivity than the pile has, even with all the rods out. The duration of this dead period is expected to be from approximately 1 hour until approximately 2 days after shutdown, except in the case of replacing part of the old active material, in which case a proportionate amount of the poison would be removed also. All intentional shutdowns will probably be accompanied by a replacement of much of the old active material.

(1) Photo-neutron Effect

With both deuterium and beryllium there is a gamma-n reaction. The beryllium reflector of the proposed pile will therefore act as a neutron source to a degree determined by the gamma activity of the pile material. These photo-neutrons will maintain the power of the pile at an intermediate level for a considerable time after shutdown.

The calculation of the photo-neutron yield is made difficult by the lack of data specific to the particular problem. There is ample information (CP-3472, MonP-172) on the yield expectable from a D_2O - moderated reactor, and this is applicable only with uncertainty to a Be-reflected reactor. Although, by virtue of the lower energy threshold for the Be reaction than for the D reaction, there is (CP-3472) 3.3 times as great a photo-neutron yield expected in Be as in D, there remains the serious question as to how greatly this gain is offset by (i) the greater relative leakage from a photo-neutron source which surrounds the multiplying medium than from a source which is within the multiplying medium and (ii) the loss of gammas by absorption in the ordinary water of the Be reflected reaction. However, on the assumption that the D_2O moderated reactor is closely enough like the Be reflected one for the purpose at hand, the figures are given in Table I, Column 4, for the photo-neutron source strength at various times after shutdown. These figures are based on experimental constants (MonP-172) and calculations by means of the equation:

$$P\ \text{neut/sec} = \nu\ \text{neut/fiss} \times P\ \text{pile watts before shutdown} \times 3 \times 10^{10}\ \frac{\text{fiss/sec}}{\text{watt}}$$

$$\left[10^{-4} \times \left(189\, e^{-t/3.6s} + 5.93\, e^{-t/59.5s} + 2.03\, e^{-t/3.44m} + 0.975\, e^{-t/11.1m} + 0.600\, e^{-t/39.3m} + 0.676\, e^{-t/2.4h} + 0.0942\, e^{-t/6.3h} + 0.0298\, e^{-t/76h}\right)\right]$$

(2) Multiplication Effect

The actual rate of neutron production in a multiplying medium is greater than obtained from the neutron source alone by the factor $\frac{1}{1-k}$ the "multiplication". Due to the varying Xenon poison the multiplication factor k changes, and therefore the "multiplication" $\frac{1}{1-k}$ changes.

The Xenon poison effect* has been plotted as a function of time in Figure 1, showing the δk_{eff} of the sum of Xenon and Samarium poisoning at times up to 75 hours after shutdown, where the previous operating flux was 1, 2, and 4 times 10^{14} respectively. The values of k_{eff} shown in Column 3 of Table I, were obtained as follows:

k_{eff} = k_{eff} of cold pile with rods in $+\delta k_{eff}$ due to Xenon and Samarium

= $0.92 + \delta k_{eff}$ from Figure 1.

From column 6 of Table I we see that most normal situations can be covered by an ion chamber with a range of 10^5. The exceptions

---

* Note:

$$\delta k_{eff} = k_{\infty,o}\left[-\frac{f_o(N\,\sigma_a)^{Xe+Sm}/(N\,\sigma_a)^{25}}{1+f_o(N\,\sigma_a)^{Xe+Sm}/(N\,\sigma_a)^{25}}\left\{1-\frac{\ln k_{\infty,o}}{k_{\infty,t}}\frac{L_o^2}{M_o^2}\right\}\right]$$

where $k_{\infty,t} \simeq k_{\infty,o} = 1.6$

$f_o = k_{\infty,o}/\eta = 1.6/2.1 = 0.76$

$L_o^2 = 3.64\ cm^2$

$M_o^2 = L_o^2 + \tau = 3.64 + 64.2 = 67.8\ cm^2$

and $(N\,\sigma_a)^{Xe+Sm}/(N\,\sigma_a)^{25}$ at times after shutdown was obtained from a paper now in preparation by H. C. Schweinler.

are the special cases of nearly complete replacement of old active material at times 48 hours and 72 hours after shutdown. However, in these special cases it would be proper to consider the re-start-up as practically the same thing as an initial start-up and it would be necessary merely to exercise caution in bringing the k_{eff} up towards unity until such time as the power had increased by 10 or more into the range of the instruments.

Of course it would be desirable to have a range of 10^{10} to cover from operating source strength ($\simeq 10^{18}$n/sec) all the way down to a practical-sized external source ($\simeq 10^{8}$n/sec); however, it is primarily necessary only to cover the period of time just before the pile enters the irretrievable dead period, i.e., up to approximately 1 hour, and hence a range of $\simeq 10^{4}$, after shutdown. In that short interval there will be some haste to get an accidentally stopped pile back up to power again before it is too late, and the ion chamber must keep the pile power in sight of the operator during this time.

The above discussion considers the range that must be covered by the ion chamber in conjuntion with the power <u>level-control</u> equipment. On the chance that the <u>derivative control</u> equipment might make some greater demand upon the range of the ion chamber this problem has been analyzed; see Appendix I. Equation (9) of this Appendix gives S_r, the minimum permissible ratio of neutron amps to beta and gamma amps at the same neutron flux in terms of the operating conditions.

For the following conditions:

normal operating power = 3×10^{7} w.

dangerous (shutdown) power = 6.75×10^{7} w.

period of pile motion = 0.1 sec (assumed as a good figure, being 10 times as large as the fastest possible period and 1/10 as small as the likely periods which may occur as the result of operating accidents).

apparent period at which derivative control alarms = 1 sec.

time delay in control equipment = 0.1 sec.

It is shown in the Appendix that the minimum permissible ratio is

$$S_r \simeq 100.$$

To recapitulate and to write the job specifications: an ion chamber must be built which can give practical current readings through a range of at least 10^5 in the power level of a nuclear reactor and which will have $S_r \geq 100$; the practicality of the current readings should be determined on the basis of their being clearly distinguishable against the background of the uncompensated beta- and gamma - induced ion current that is due to the chamber's own activity. (To be on the safe side the criterion of practicality is based on use of the ion chamber in the non-differentiating way.)

[redacted]

III. How Well the Present G.E. Chamber Meets the Job Specifications

A fundamental assumption which is made in tests of the present G. E. chamber is that the range of the chamber (in the sense defined at the conclusion of the previous section) is independent of the power of the reactor. For example, if by testing in the X-pile we find that the chamber is usable from 3 MW down to 300 watts, then we conclude that in a 30 MW reactor it is usable only down to 3000 watts. In other words, the background current which fixes the lower end of the useful range is assumed proportional to the normal operating power. This seems reasonable since it is the neutron flux intensity at normal operation which determines the amount of background current from the pile and chamber activity.

The range of the G.E. ion chamber was measured as follows: a chamber which had been inside the shielding up against the graphite of the Clinton pile for a long period of time was removed outside the shielding, and the ion current due to its own activation was measured.

Neutron-induced ion current in chamber when pile was operating at 4×10^6 watts	4×10^{-6} amps
Beta-and gamma-induced non-differentiated ion current in chamber outside shield $\frac{1}{2}$ hour after removal (estimated to be 90% of value immediately after removal) ..	10^{-9} amps
Beta-and gamma-induced, imperfectly differentiated ion current in chamber $\frac{1}{2}$ hour after removal.....	$\sim 10^{-10}$ amps
Fluctuations in beta-and gamma-induced ion current in chamber $\frac{1}{2}$ hour after removal.....	5×10^{-12} amps

Thus the quantity S_r, of the previous section, $= \frac{4 \times 10^{-6}}{10^{-9}} = 4000$, which is amply larger than the required 100. Also the range of the chamber if used as a differential chamber would be 8×10^5 for perfect balancing of differential chamber or 4×10^4 for practically attainable balance, or 4×10^3 if used as a non-differentiating ion chamber. The last figure

is the range we are most interested in.

A range of at least 10^5 is required (see conclusion to Part II above) and only 4×10^3 is available in the present chamber. A factor of improvement of 25 is to be sought in the range.

[redacted]

IV. Proposed Design to Meet Job Specifications

As stated in Part I above, there are two lines of attack on the problem of increasing the range: (1) extend the top of the range by increasing the absolute sensitivity of the instrument, i.e., amperes ion current/neutron flux unit, and (2) extend the bottom by decreasing the magnitude of the induced activity in the chamber components.

The absolute sensitivity of the instrument has been measured several times by comparing the ion current read with it in the thermal column to the flux as measured at the same time with indium foils. The sensitivity is 1 to 3 x 10^{-14} amps/sec. The specific sensitivity (per unit boron-carbide coated area) deduced from this is approximately a factor of 10 poorer than that obtained by Broxon (CP-782) in his original model of the B_4C coated differential chamber. There is reason to believe that the sensitivity can be increased by improving the boron coat, either by making a better B_4C coat, or by employing one of the methods for depositing pure boron. Furthermore, there is always a factor of 5 to be gained by using boron enriched in B^{10}.

The induced activity in the chamber components can be reduced by proper choice of materials. The activity of the G.E. chamber was observed by removing a "hot" chamber from the pile and allowing the chamber to read its own activity continually for many hours. The composite activity could be said approximately to drop off with a 2.5 or 3 hour half-life. This decay is too slow to ignore when the chamber is expected to be reading pile power reliably for 1 to 2 hours after a shutdown. A rough estimate of the sources of the activity was made; approximately 6 parts due to 1.8 hour (half-life) Argon, 5 parts due to 2.6 hour Mn in the steel vessel, 1 part due to 5 year Cobalt in the three Kovar seals. This estimate was fairly well corroborated when the initial intensity

dropped by approximately 47% upon replacing Argon with Nitrogen and running the test again.

The proposed new chamber should have, perhaps, 2S aluminum to replace the Mn-bearing steel (the principal 2S Al activity (CP-1365) will decay with 2.4 minute half-life); it should have nitrogen or some suitable gas other than Argon; it should have insulating gas seals which are free of Cobalt; it should avoid the use of copper, silver, tungsten, vanadium, chromium, and nickel, among others, in addition to manganese and cobalt.

[redacted]

TABLE I.

Operating Level Before Shutdown = 30 MW
$F = 10^{18}$ fiss/sec; $F\nu = 2.3 \times 10^{18}$ neut/sec.

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Time After Shutdown	100 ϵ % Old Active Material Remaining	k_{eff} of Pile with Rods in $.92+\epsilon(\sigma k_{eff})_{Xe+Sm}$	P photo-n/sec	$P/1 - k_{eff}$	Range = $F\nu / \frac{P}{1 - k_{eff}}$
0.5 hr.	100	.79	2.33×10^{14}	11.1×10^{14}	$.021 \times 10^{5}$
	50	.86	1.16	8.3	.028
	2	.92	0.047*	0.59*	.39*
1.0 hr.	100	.74	1.59×10^{14}	6.1×10^{14}	$.038 \times 10^{5}$
	50	.83	0.80	4.7	.049
	2	.92	0.032*	0.40*	.58*
2.0 hr.	100	.65	0.97×10^{14}	2.8×10^{14}	$.082 \times 10^{5}$
	50	.78	0.48	2.2	.12
	2	.91	0.019*	0.21*	1.1*
48 hr.	100	.80	0.0364×10^{14}	0.18×10^{14}	1.3×10^{5}
	50	.86	0.0182	0.13	1.8
	2	.92	0.00073*	0.0091*	26.*
72 hr.	100	.87	0.0267×10^{14}	0.20×10^{14}	1.2×10^{5}
	50	.90	0.0134	0.13	1.8
	2	.92	0.00053*	0.0066*	35.*

* Note: Values in Columns 4 and 5 would actually be greater than shown, and values in Column 6 correspondingly smaller since there is considerable γ emission from Na^{24} produced by (n, α) reaction in aluminum, and this γ flux has not been taken into account in the table.

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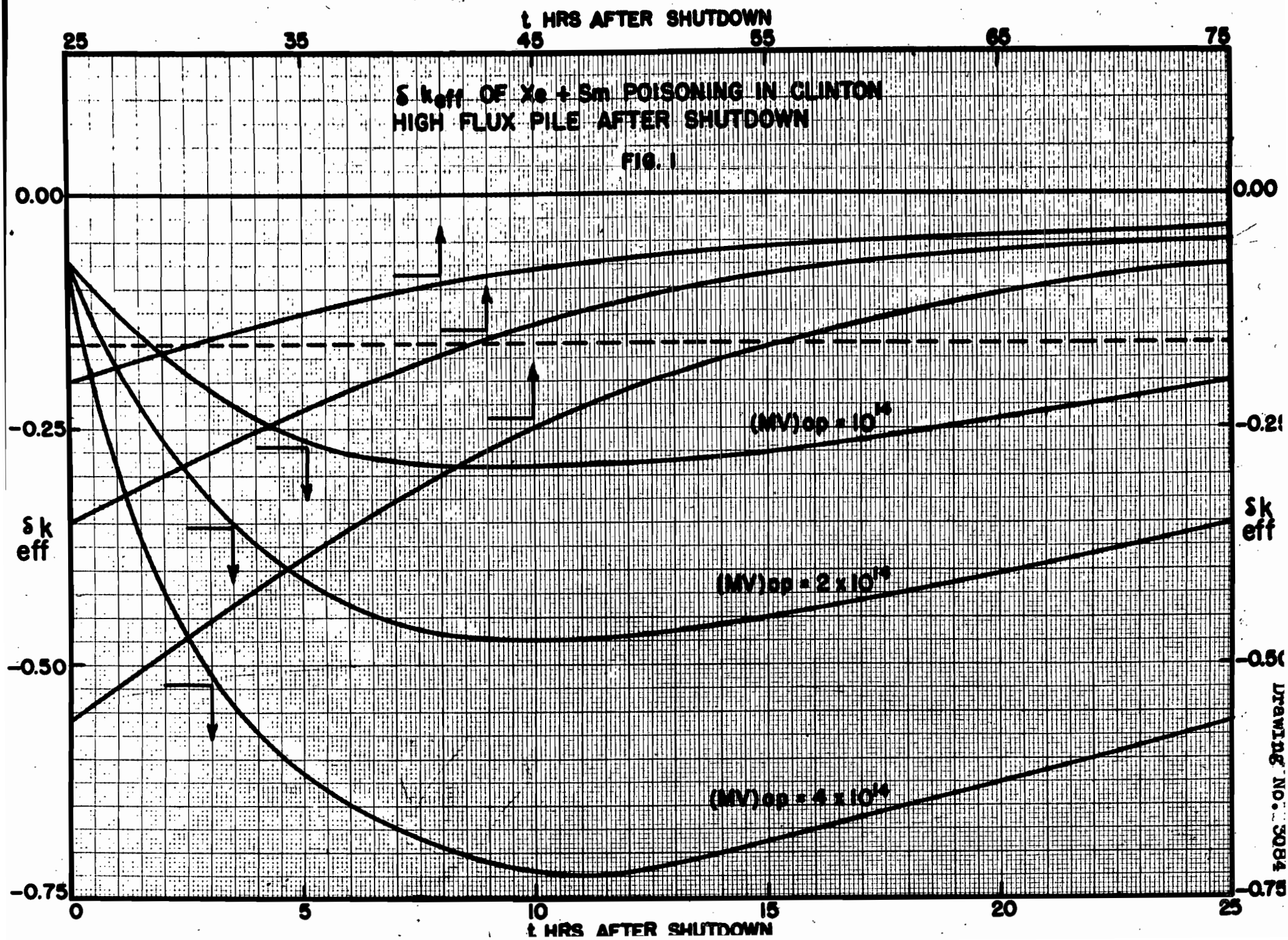

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APPENDIX

ION CHAMBER FOR DERIVATIVE CONTROL

I. Terminology

Pd	Dangerous power not to be exceeded.
Pa	Power at which level-control alarms.
P_{op}	Power of operating pile.
$P_o + A/k_1$	Total apparent power = Real power + apparent power due to $\beta\gamma$ activity.
P_o.....	Power at bottom of control range.

Note: "neutron current" means ion current flowing as a result of neutrons acting on ion chamber; likewise "β-γ" current means ion current flowing as result of β's and γ's.

I = Ion current in chamber.

A = $\beta\gamma$ current in ion chamber due to both pile and chamber activation as result of operation at P_{op}.

k_1 = neutron current/power of pile.

T = Period of motion of pile.

k = Period circuit proportionality constant, $\dfrac{\text{output volts}}{\dfrac{d \ln I}{dt}}$.

θ = Apparent period of pile.

$\alpha = A/k_1P_o = \dfrac{\beta\text{-}\gamma \text{ current at } P_{op}}{\text{neutron current at } P_o}$

θ_c = Cut-off apparent period, i.e., the value of θ at which the period circuit starts to shut down the pile.

t_c = Time to reach θ_c after pile starts moving.

t_d = Delay time (after t_c) before pile is actually shut down by safeties; includes delay between actually reaching θ_c and the period circuit showing it, as well as delay in mechanism to throw rods in.

k_2 = β-γ current/power of pile.

S_R = Relative sensitivity, $= \dfrac{k_1}{k_2} = \dfrac{\text{neutron current}}{\beta\gamma \text{ current}}$, both measured at same power.

[redacted]

APPENDIX

II. Equations

Current in ion chamber for pile at P_o starting up on period T:

$$I = A + k_1 P_o \, e^{t/T} \, . \tag{1}$$

Derivative control instrument will give an output

$$k \frac{d \ln I}{dt} = k \frac{1}{I} \frac{dI}{dt} = k \frac{k_1 P_o \, e^{t/T}}{T(A + k_1 P_o \, e^{t/T})} = \frac{k}{T\left(\frac{A}{k_1 P_o} e^{-t/T} + 1\right)} = \frac{k}{\theta} \tag{2}$$

where θ is the apparent period and will vary with time.

$$\theta = (1 + \alpha e^{-t/T}) \, T \tag{3}$$

where $\alpha = \frac{A}{k_1 P_o}$.

Also for the special case

$$\theta_c = (1 + \alpha e^{-t_c/T}) \, T \, . \tag{3a}$$

If we set the derivative control equipment so that it will alarm when $\theta = \theta_c$ and the pile is shut down t_d seconds later, the power at shut-off is

$$P_s = P_o \, e^{\frac{t_c + t_d}{T}} \tag{4}$$

$$t_c = T \ln \frac{\alpha T}{\theta_c - T} \quad \text{from (3a).} \tag{5}$$

[redacted]

APPENDIX

III. Discussion

Now to examine equations (3), (4), and (5), consider the plot of equation (3):

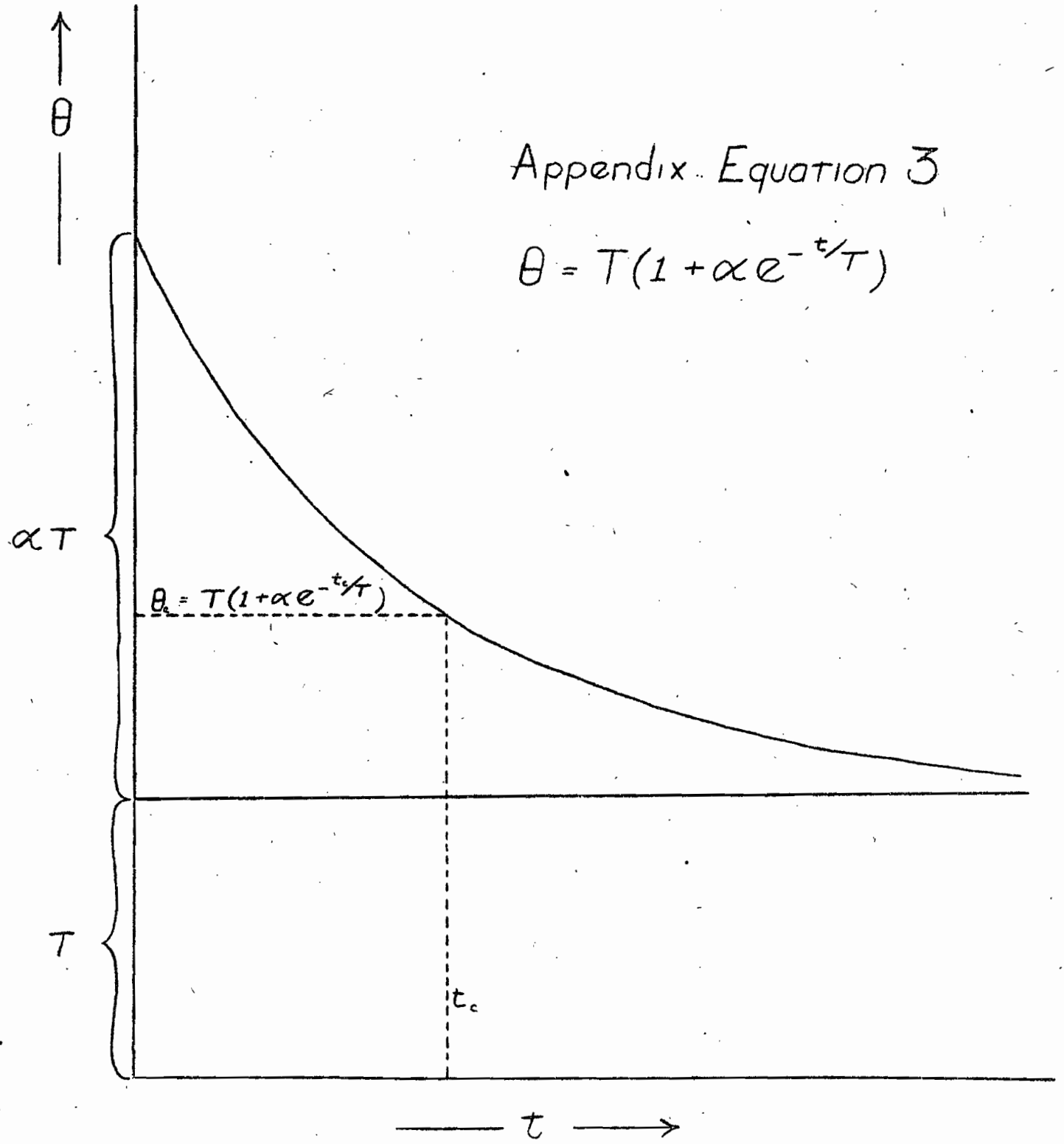
It is seen that the apparent period θ starts out high at $(1 + \alpha)$ T and drops asymptotically toward the real period T. The time, t_c, at which the apparent period becomes as small as the cut-off apparent period, θ_c, is determined solely by the α, T, and θ_c as seen from the graph as well as from equation (5).

When $\alpha = 0$ this means that there is no β-γ activity in the pile or chamber after a shutdown; the apparent period will be the same as the real period, and θ will reach or be less than θ_c either immediately ($\theta_c \geq T$) or never ($\theta_c < T$).

TABLE I.

Conclusion: For $\alpha = 0$	t_c	P_s
$\theta_c \geq T$	0	$P_o\, e^{td/T}$
$\theta_c < T$	∞	In this case the level-control would shut off the pile.

When $\alpha > 0$ the apparent period will start off high and drop asymptotically towards T; θ_c may be set at such a large value that θ will always be below it, and the alarm is given immediately, $t_c = 0$; θ_c may be set at an intermediate value such that the apparent period takes a finite time, t_c, to drop to it; or θ_c may be lower than the real period, and the alarm is never given, $t_c = \infty$.


θ
Appendix. Equation 3
$\theta = T(1 + \alpha e^{-t/T})$
αT
$\theta_c = T(1 + \alpha e^{-t_c/T})$
T
t_c
t

[redacted]

APPENDIX

TABLE II.

Conclusion: For $\alpha > 0$	t_c	P_s
$\theta_c \geq (1+\alpha)T$	0	$P_o e^{td/T}$
$T < \theta_c < (1+\alpha)T$	$T \ln \frac{\alpha T}{\theta_c - T}$	$P_o \alpha \frac{T}{\theta_c - T} e^{td/T}$
$\theta_c \leq T$	∞	In this case the level-control device would shut off the pile.

In the special and most generally applicable case of $\alpha > 0$

and $T < \theta_c < (1+\alpha)T$

we have

$$P_s = P_o \alpha \frac{T}{\theta_c - T} e^{td/T} = \frac{A}{k_1} \frac{T}{\theta_c - T} e^{td/T} \tag{6}$$

which shows that the power at shutdown is not a function of the initial power but rather of the spurious power due to β and γ activity.

It will be found useful to introduce the proportionality constant, k_2, $\beta + \gamma$ current per power unit. Now define the dimensionless "Relative Sensitivity" of the chamber:

$$S_R = \frac{k_1}{k_2} = \frac{A/\alpha P_o}{A/P_{op}} = \frac{P_{op}}{P_o} \frac{1}{\alpha} \tag{7}$$

From (6) we find

$$\frac{1}{\alpha} = \frac{P_o}{P_s} \frac{T}{\theta_c - T} e^{td/T} = \frac{P_o}{P_d} \frac{T}{\theta_c - T} e^{td/T} \tag{8}$$

if we wish to shut the pile down at P_d, and

$$\boxed{S_R = \frac{P_{op}}{P_d} \frac{T}{\theta_c - T} e^{td/T}}. \tag{9}$$

[redacted]

APPENDIX

IV. Conclusion

A pile normally operated at P_{op} drops to a low power level P_o and is to be started again. To combat the danger that it may start up with such a rapid period T that it will run away before control equipment can stop it, a derivative control device is adjusted to start shutting the pile off at an apparent period θ_c and to shut off t_d seconds later, so that the pile is off at the dangerous power level P_d. The derivative-control device is limited in its efficacy partly by an ion chamber which reads the power of the pile. The chamber will indicate a spurious power (due to β and γ activity of both pile and chamber) in addition to the real power. This spurious power causes the apparent period θ to be larger (slower) than the real period T; and the time, t_c, for θ to drop to θ_c is delayed by the spurious power. Thus the above mentioned characteristics of the pile and the control-equipment determine a maximum allowable Relative Sensitivity for the Ion Chamber. Equation (9) gives the minimum allowable S_R.

All else being equal, if S_R is greater than this the pile will shut down at some power less than P_d. Shutdown power may be calculated from Table II, using the substitution

$$\alpha = \frac{P_{op}}{P_o \, S_R}$$

Note: The minimum (fastest) period that can be stopped by the derivative control equipment even with $t_c = 0$ is : $T_{min_{DC}} = \dfrac{t_d}{\ln P_d - \ln P_o}$

[redacted]

APPENDIX

V. Numerical Examples

To make some calculations, assume:

$P_{op} = 3 \times 10^7$ watts

$P_a = 4.5 \times 10^7$ watts

$P_d = 6.75 \times 10^7$ watts

$P_o = 3 \times 10^2$ watts

t_d = 0.1 sec for both level-control and derivative control devices. This is considered a pessimistic figure; it is thought of as including the delay in moving the rods too.

θ_c = 1.0 sec. (This must be set small enough to avoid hampering the normal speed of bringing the pile up to power - say about a 10 sec period - and yet large enough to overlap with the range of large (slow) periods which the level-control device must take care of. The smallest period controllable by the level-control, on the basis of t_d = 0.1 sec., would be

$$T_{min_{LC}} = \frac{t_d}{\ln P_d - \ln P_a} = \frac{0.1 \text{ sec}}{0.41} = 0.25 \text{ sec.}$$

(probably a pessimistic figure, 10 times the fastest possible period, yet 1/10 the likely accidental periods.)

T = 0.01 sec. This is greater than

$$T_{min_{DC}} = \frac{t_d}{\ln P_d - \ln P_o} = \frac{0.1 \text{ sec}}{12.3} = 0.008 \text{ sec.}$$

"Relative Sensitivity" required is

$$S_R = \frac{P_{op}}{P_d} \quad \frac{T}{\theta_c - T} \quad e^{t_d/T}$$

$$= \frac{3 \times 10^7}{6.75 \times 10^7} \quad \frac{.01}{.99} \quad e^{10} = \frac{3 \times 2.2 \times 10^2}{6.75} \simeq 100.$$

For $S_R = 100$,

$$\alpha = \frac{P_{op}}{P_o \, S_R} = \frac{10^5}{10^2} = 10^3$$

and $\theta_c < (1 + \alpha)T$

since $1 < (1 + 10^3)\, 10^{-2}$.

[redacted]

From Table II

$$t_c = T \ln \frac{\alpha T}{\theta_c - T} = 10^{-2} \ln \frac{10^3 \times 10^{-2}}{1 - 10^{-2}} = 0.023 \text{ sec.}$$

$$\text{Power at } t_c = P_o\, e^{t_c/T} = 3 \times 10^2\ e^{0.023/0.01} = 3 \times 10^3 \text{ watts.}$$

That is, for an $S_R = 100$ the derivative control device would not give the alarm until the power had risen to 3×10^3 watts in .023 sec. and would not shut off the pile till exactly at the danger level of 6.75×10^7 watts, 0.1 sec later.

However the actual S_R of the present G. E. chamber is

$$S_R = \frac{4 \times 10^{-6} \text{ neutron amps}}{10^{-9}\ \beta\gamma \text{ amps}} = 4 \times 10^3.$$

In this case

$$\alpha = \frac{P_{op}}{P_o S_R} = \frac{10^5}{4 \times 10^3} = 25$$

and

$$\theta_c > (1 + \alpha)T$$

since

$$1 > (1 + 25)10^{-2}.$$

∴ From Table II,

$$t_c = 0$$

and

$$P_s = P_o\, e^{td/T} = 3 \times 10^2\ e^{0.1/0.01} = 6.6 \times 10^6 \text{ watts}$$

a factor of 10 under the danger level, P_d.

[redacted]

[redacted]