BOOK22R 10131 on bottom edge

Notes:
-"Green Cubes" taped to spine
-"6" taped to side

Blank pages: 4,6,8,10,12,14,16,18,20,22,24,26,28,30-40,42,44,46,48,50,52,54,56,58,60,62-152, inside back cover sheets.

-pages 1 & 2 are missing
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Experimental Construction Material

Green Cubes

These cubes were formed by cold pressing a co-micropulverized mixture of TF_4 and Poly-tetra-fluoro ethylene. The pressure applied was about 45 tons per square inch. 1108 cubes were formed.

Constants of cubes, Green
Based on 1013 best cubes:
Average density 4.73 g/cc
Average height 1.003 inches
" length 1.0045
" width 1.0045
Average weight 78.442 grams.
Average $\frac{X}{T}$ = 95.3 %

Average wt. T per cube = 78.442 x 0.65218 = 51.158 grams.

Average wt X per cube = 51.158 x 95.3 = 48.754 grams.

Average volume = $\frac{78.442}{4.73}$ = 16.584 or $\frac{16.584}{16.387}$ = 1.0120 in^3

Average dimension considered as cube = 1.004"

Blocks prepared by mixing Greensalt and Poly TFE.

Weight percent of Poly TFE in cube = 13.697 %
" " " TF_4 in cube = 86.303 %
Percent of Green salt composed of T = 75.568 %
(Arrived at from average of Y-12 figures for conversion).

Range of densities and heights used in 1108 cubes.
0.994 – 1.013 density 4.64 – 4.81

Constants of Cubes - White.
Cubes prepared by milling down Polythene from 1½" dia extruded cylinder obtained from Plax Corp.

Average Volume 1.015 in^3 = 16.63 cu cm.
" weight 15.114 grams.
Average density 0.909
Average dimention 1.005"

From Oak Ridge report - Composition $CH_{1.87}$

Ratio $\frac{N_H}{N_T}$ = 9.36 for 1:1 cubes.

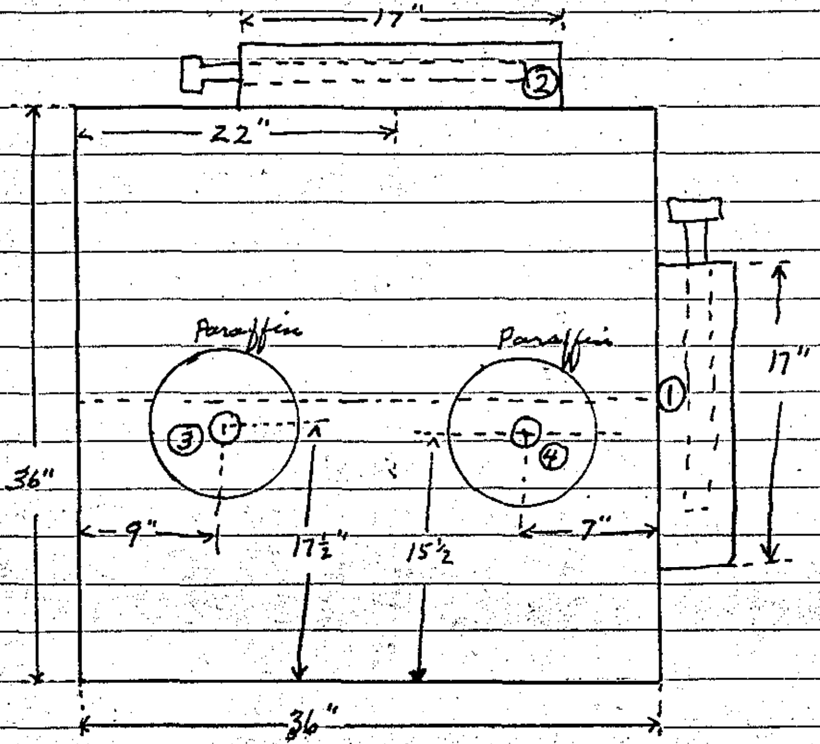
Cadmium sheet used for Shielding
16.5 mils. thick
0.356 grams per cm^2.

Boron Plastic
¾ inch thick
0.124 grams /cm^2 Boron

Percent Boron 4.3 % by weight

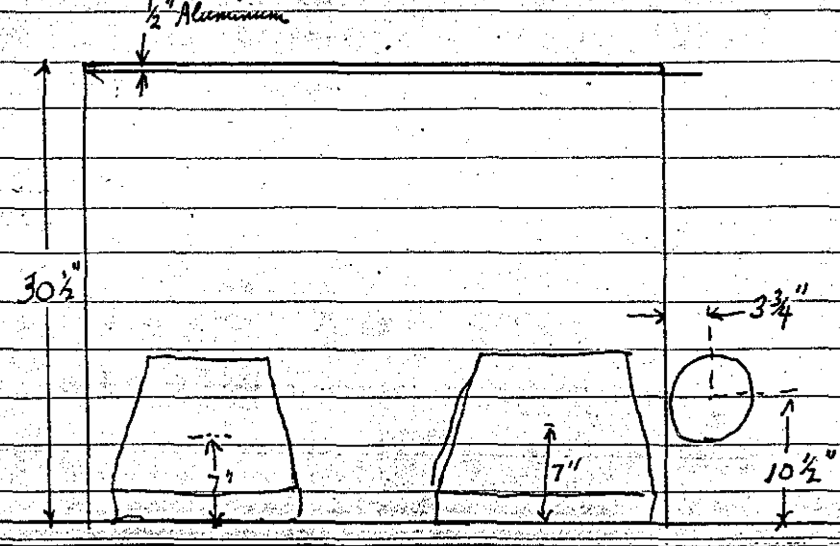
Density of Plastic 1.6 grams/cc.

Experimental Arrangement



①② Two independent BF_3 filled ion chambers in paraffin cylinders connected to DC. amplifiers. Amplifiers Register on recording Easterline-Angus 0-1 MA Meters

③④ Two independent Boron lined proportional counters in center of paraffin cylinders. These counters fed to amplifiers and scale of 64 circuits to registers



neutron Source of about 20 curies of Po+Be was used near assemblies at all times.

Experiment #1 April 4, 1946

Object of Experiment: To determine critical mass of untamped - unmoderated Green cubes. If not critical, to estimate critical mass by simple multiplication experiment.

(a) Cube 10×10×10 was stacked on aluminum table top. Considerable distance from critical. Quite safe.
78.4 Kg. Mix - 51.15 Kg. T.

(b) Multiplication experiment performed by keeping 20 ~~cu.~~ Source near center of cubes and taking counts on 8"×8"×8" cube, 9"×9"×9" cube and 10"×10"×10" cube.

Counter number 3 proved unreliable.
" " 4 data given.

10"×10"×10" cube. 10 min count - #4 counter.
clicks 3437 end.
2655 begin
Counts 64×782 = 50,048
Counts per Min $\boxed{5004}$

9"×9"×9" cubes. 10 min count.
clicks 4571 begin
3879 end.
Counts 64×692 = 44,288
C/m = $\boxed{4,429}$

8"×8"×8" cubes 10 min count
clicks 5356
4744
counts = 64×612 = 39168
C/m = $\boxed{3,917}$

Support source only in same position as center of cubes.
clicks 6051 - 5665
Counts = 64×386 = 24704 C/m = $\boxed{2,470}$

Multiplication

		10^{2}/Multiplication
10"x10x10"	2.03	4.93
9x9"x9"	~~1.58~~ 1.79	5.58
8"x8"x8"	1.58	6.32

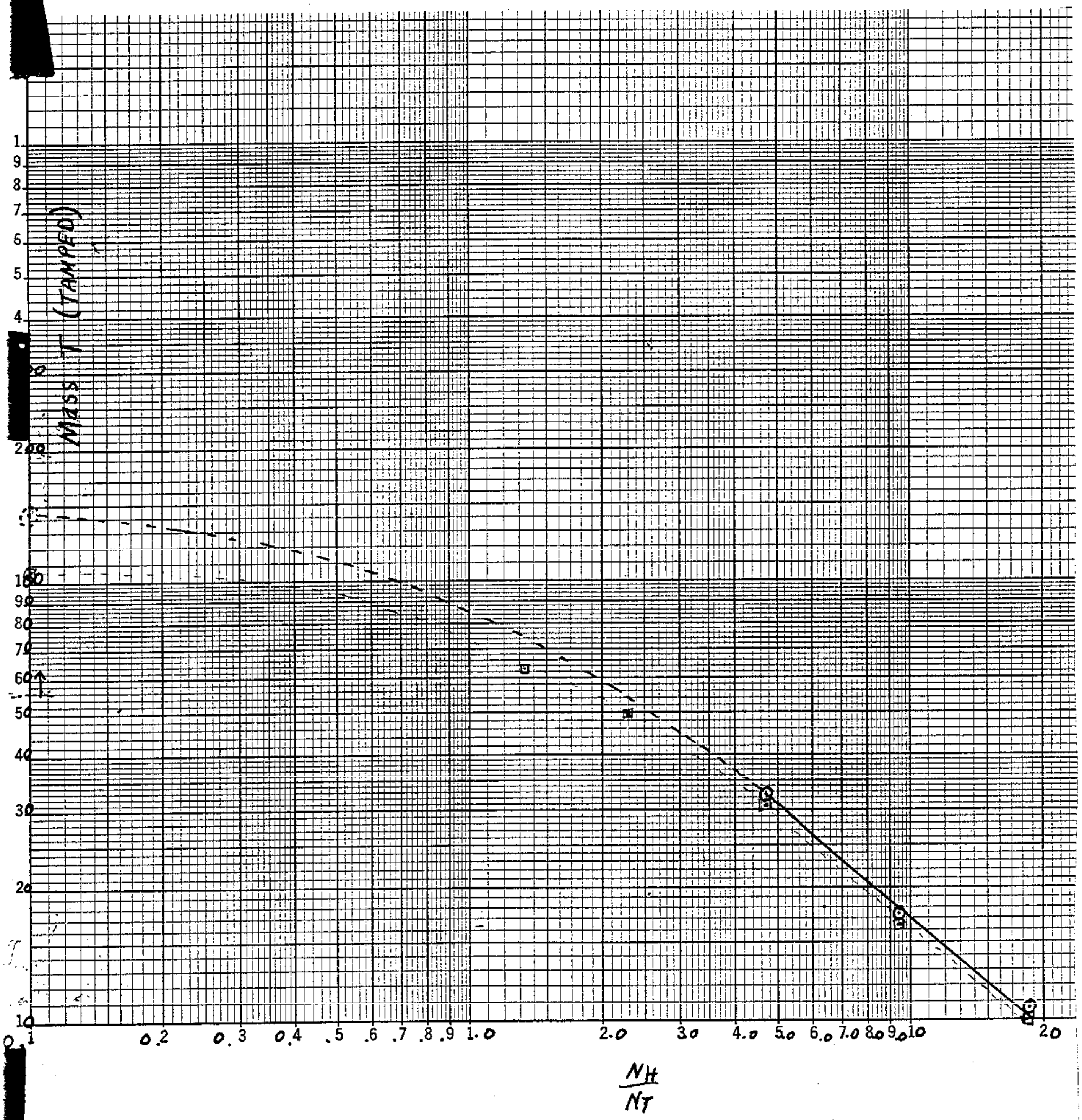
When 1/multiplication is plotted against cube size - Extrapolation is 17" cube for critical untamped Green cubes.

$17^3 = 4913$

$4913 \times 78.44 = 385$ Kg of Mix.

$4913 \times 51.15 = 251$ Kg of T.

$4913 \times 48.76 = 239$ Kg. X


MASS T (TAMPED)
1
9
8
7
6
5
4
200
100
90
80
70
60
50
40
30
20
10
0.1
0.2
0.3
0.4
.5
.6
.7
.8
.9
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10
20
NH/NT

Experiment 2 April 5, 1946

(a) Will Green cubes completely surrounded by paraffin become critical?

(b) If not, from multiplication experiments, what number will?

(a) 10"x10"x11" completely surrounded by more than 6" of paraffin did not go critical

86.28 Kg. Mix

56.26 Kg T.

(b) Multiplication experiment was performed by placing 20 c. Source in center of 8x8x8", 9x9x9", 10x10x10" cubes surrounded by paraffin. The counts were taken on these three size cubes and compared with counts obtained when 8x8x8" and 10x10x10" cavities were substituted for the cubes. Counter #4

10x10x10" Tamped - clicks 902.8

828.0

Counts = 64 x 74.8 = 4780

c/m = 478

ditto - 498. Average $\boxed{488}$ c/m

9"x9"x9" 176.0

114.0

Counts 64 x 62.0 = 3970

c/m = $\boxed{397}$

ditto $\boxed{400}$ Average $\boxed{406 \text{ c/m}}$

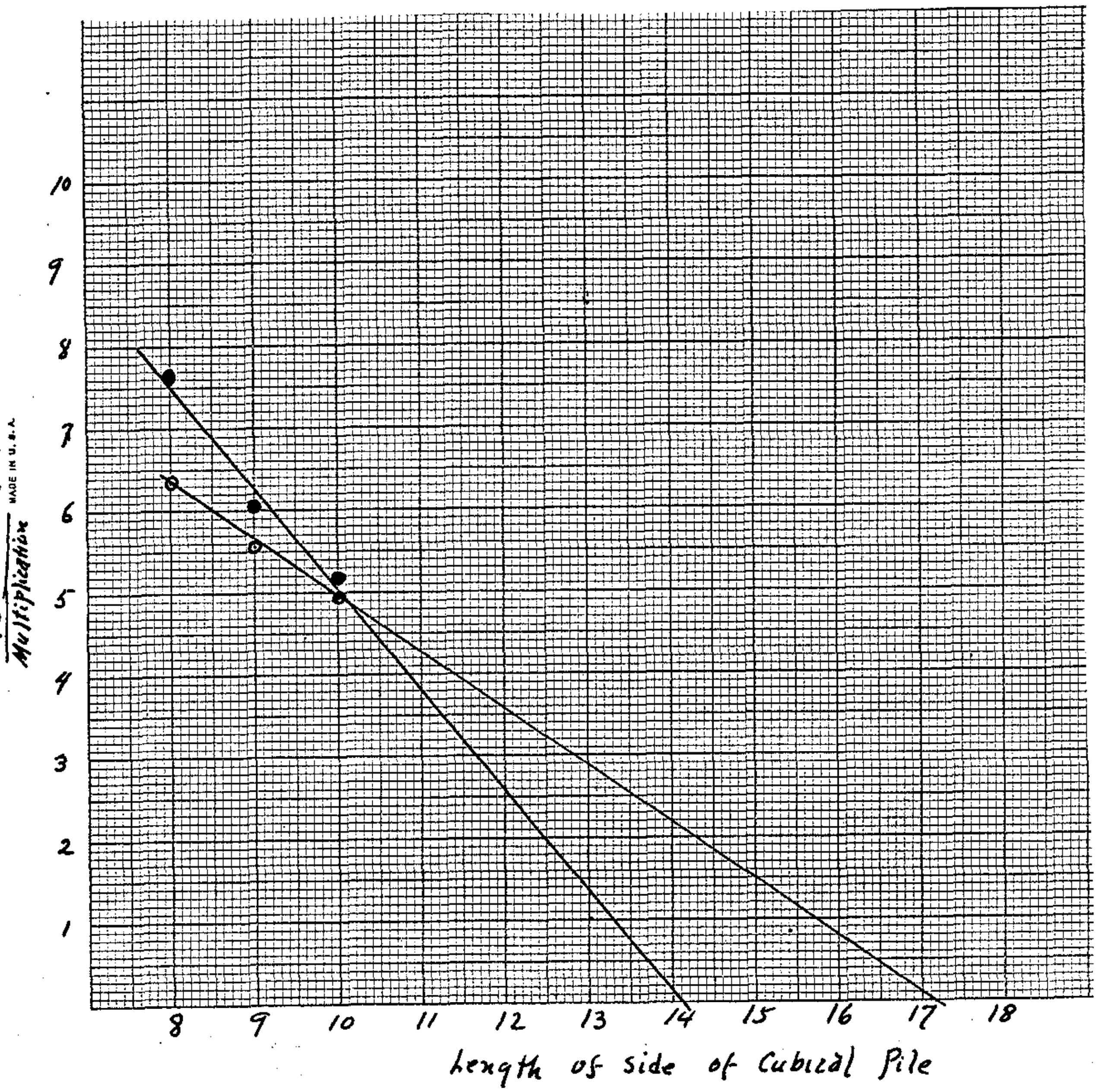
ditto $\boxed{420}$

8"x8"x8" clicks 508.0

459.0

Counts 64 x 49.0 = 3140 $\boxed{314 \text{ c/m}}$

ditto $\boxed{312.5}$ Average $\boxed{313.2 \text{ c/m}}$


10 / Multiplication
10
9
8
7
6
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1
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11
12
13
14
15
16
17
18
Length of side of Cubical Pile

Substitute 8"x8"x8" plywood box. Source in center.
Tiny with paraffin as before.
30 min count.
Δ clicks 111.5 (30 m)
Clicks/m. 3.72
Counts per Min $\boxed{238}$

Bg. no source negligible

10"x10"x10" box. 30 min count.
$\boxed{253\ c/m}$.

Assume, by interpolation, c/m for 9" box = $\boxed{245\ c/m}$

Multiplications

	c/m / c/m		Recip. x 10
10 x 10 x 10	$\frac{488}{253}$ =	1.93	5.18
9 x 9 x 9	$\frac{406}{245}$ =	1.66	6.02
8 x 8 x 8	$\frac{313}{238}$ =	1.31	7.62

When plotted, these values extrapolate to cube 14.1 inches on Side

$\overline{14.1}^3 = 2803$

2803 x 78.44 = 220 Kg. Mix.

2803 x 51.15 = 143. Kg T.

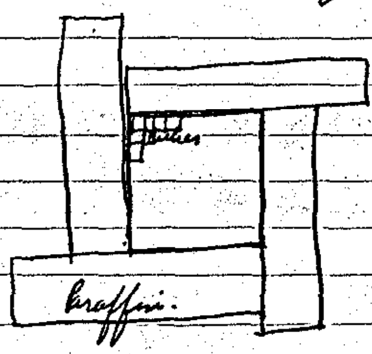
7-Criticals

Experiment 3 April 8, April 9

Object: How many cubes of 1:1 Green: Polyethylene mix in a cubical geometry, fully paraffin tamped, will go critical

Procedure

Plywood box 10" 8 i.d. cubical was placed on table with more than 6 inches of paraffin underneath. The box was filled with 1:1 cubes, with source on table next to box. With tamping only on bottom, did not go critical. Paraffin tamper in the form of slabs 6" x 18" were added until assembly went critical. Cubes removed, and smaller box substituted until assembly went critical (barely) with full paraffin tamping of 6" or more all round. This usually required several critical assembly set ups.



Looking from top.

Sides were usually added, one piece at a time. Then one or more sides removed and top tampers added. Then sides replaced one at a time.

Results

1:1 Green cubes: polythene Critical dimensions of cube: 9 x 9 x 8.44 (9" x 9" x 8 18/41)

342 Green cubes.

342 x 78.44 = $\boxed{26.8 \text{ Kg } TF_4 - PTFE \text{ Mix}}$

342 x 51.15 = $\boxed{17.5 \text{ Kg. } T}$

4 criticals

Experiment 4 April 9

object:

To find critical dimensions of tamped 2 Blythene: 1 T cubical array.

Results. 9"x8"x $8\frac{2}{3}$"

208 cubes of T mix.

$208 \times 78.44 =$ $\boxed{16.3 \text{ Kg. T- PTFE Mix}}$

$208 \times 51.15 =$ $\boxed{10.6 \text{ Kg. T.}}$

5 criticals

Experiment 5 April 10

Object: To find critical size of Paraffin tamped cube composed of 2 TF : 1 Polythene cube ratio.

Results.

$10'' \times 10'' \times 9\frac{23}{33}$

646 T-TFE cubes.

$646 \times 78.44 = \boxed{50.7 \text{ Kg. T-TFE Mix}}$

$646 \times 51.15 = \boxed{33.0 \text{ Kg. T}}$

3 criticals

Experiment 6   April 12, 1946

Object. To find critical dimensions of 1:1 T-PTFE mix: polythene cubes, fully paraffine tamped, with cadmium between cube and tamper.

Results: 11" x 11" x $10 \frac{14}{61}$"

619 cubes of T-PTFE Mix.

619 x 78.44 = $\boxed{48.6 \text{ Kg. T. PTFE Mix}}$

619 x 51.15 = $\boxed{31.7 \text{ Kg. T}}$

Ratio T, cadmium/no cadmium = $\frac{31.7}{17.5} = \boxed{1.81}$ = Ratio.

Cadmium sheet 16.5 mils thick
0.356 grams/cm²

Experiment 7 April 12, 1946

Object: To find critical dimensions of 1:1 array of cubes in a boron filled plastic box, outside of box completely tamped with paraffin.

Results dimensions
$11'' \times 11'' \times 9\frac{38}{61}''$ $(11 \times 11 \times 9\frac{38}{61})$

583 cubes of T-PTFE Mix.

$583 \times 78.44 =$ $\boxed{45.7 \text{ Kg. T-PTFE Mix}}$

$583 \times 51.15 =$ $\boxed{29.82 \text{ Kg. T}}$

Ratio $\frac{\text{shielded}}{\text{unshielded}} = \frac{29.82}{17.5} = \boxed{1.70}$ = Ratio.

Conclusion:
This boron filled plastic is a less effective shield than the cadmium.

Boron Shield 3/4" Thick
0.124 grams/cm² Boron.
Percent Boron by weight 4.3 %.
Density of Plastic 1.6 g/cc.

Made by Monsanto.

Experiment 8 April 15 Monday

Object: To find the critical mass of a fully paraffin tamped assembly of ratio 1 Green cube: 1 polythene cube: 0 empty space.

Assembly went critical (just) with cube (rectangular parallelopiped) 13 x 13 x 12 cubes. Actual dimensions 12⅛" x 13⅛" x 13¼. Assembly was stacked with aluminum sheet spacers 13 x 13 x .012½".

Total number green cubes 675

Notes on Lecture by Morrison April, 1946

Neutron Kinetics

Two types of neutrons are produced in fission, prompt and delayed. The latter are very advantageous in that the time scale for neutron multiplication is expanded by their existence to allow critical assembly work to be done with much less danger. Of a given number of fission neutrons from U-235, 0.78 percent are delayed. For elements 49 and 23, this percentage must be multiplied by 0.46 and 0.33 respectively.

The periods of the five groups of delayed neutrons range from 10 milliseconds to 83 seconds, the most important being of periods 6, 33, and 83 seconds. One may assume, roughly, that between 0.1 and 1.% of fission neutrons are delayed. The physical process giving rise to them is as follows: highly excited fission fragments give up β-rays followed by neutrons. In a succession of β-emissions, a nucleus may be produced in which a neutron is less tightly bound, favoring emission.

Neutron Multiplication

The neutron multiplication index K, is defined, for a particular energy range of neutrons, and for a particular assembly as:

$$K \equiv \frac{\text{Number of neutrons produced in one generation}}{\text{Number of neutrons initially present}}$$

In one generation, for one original neutron, K are produced; in two generations $K \cdot K$ or K^2 etc, so that the total number due to one generation is

$$1 + K + K^2 + K^3 \cdots = \frac{1}{1-K}$$

In the following discussion we shall be interested in the process of multiplication as a function of time, rather than space, and will be concerned with finding out the interval of time required, on the average, to go from 1 neutron to K-neutrons. Typical figures for metal assemblies are:

Energy 1 MEV.

Velocity 5×10^8 cm/sec.

Cross Section, $\sigma = 2.6$ Barns.

mean free path $\lambda = 10$ to 12 cms.

These lead to a figure for time between generations of 2×10^{-8} seconds.

For a pile which contains hydrogeneous material this interval may be many thousands of times longer, but still remains far below time intervals of the order of seconds.

It is convenient to write the effective K as consisting of two components

$$K_{eff} = K_{prompt} + K_{delayed}.$$

In this discussion the effective K for an assembly is considered, not the K_∞ applicable to an infinite pile.

Energy of Delayed Neutrons

On the average, the energy of delayed neutrons is somewhat less than for prompt neutrons. Thus in most assemblies there will be less leakage of the delayed neutrons, and they may therefore be somewhat more effective than the prompt neutrons. The average energy of prompt neutrons is about 1 Mev., although some neutrons of this group have energies of 12 Mev or higher.

Space Dependence of Neutrons

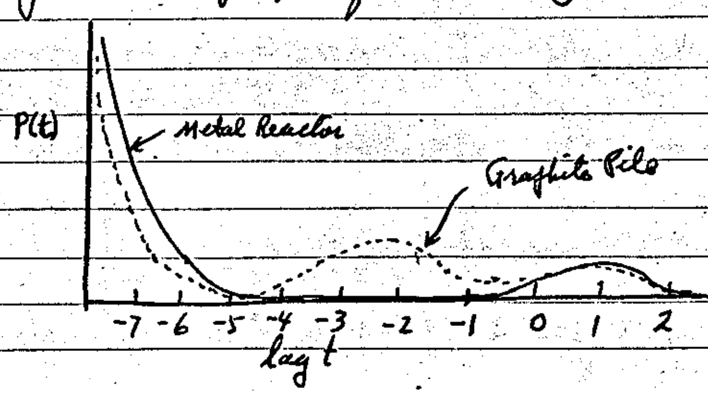
In this discussion of the kinetics of critical assemblies the space dependence of the neutrons will be neglected. It will be assumed that the general level of neutron density rises or falls in time in a uniform manner. This is equivalent to assuming that

$$n(t, \vec{r}) = n(t)\, g(\vec{r}),$$

and that the equations are separable and solvable. We will be concerned here with the time dependent equation.

Time Dependence of Neutron Density:

If one neutron is introduced into a pile, K total neutrons are produced after various time intervals. One can construct a graph of the average number of daughter neutrons resulting as a function of the time of appearance. For a metal pile the graph qualitatively is as follows.



Most of the neutrons in the metal reactor are prompt, and escape from the system after a period of about 10^{-6} sec. Later, a few delayed neutrons appear after, on the average, of 10's of seconds. A pile of the Hanford type is described by the dotted curve. In this type of reactor considerable time is required to slow down the prompt neutrons to thermal energies for capture.

The probability, P(t), is defined as the probability that a neutron will exist in a time dt after a time t from the injection of a neutron into an assembly. The probability curve is normalized so that

$$\int_0^\infty P(t)\,dt = 1$$

An assumption is made as to the form of $P(t)$. It is assumed to be a sum of exponential terms. This is a good ~~approximation~~ representation for the delayed neutron effects, which occur exponentially. It is also a good approximation for the fast prompt neutron effects. Thus

$$P(t)\,dt = \sum_{i=1}^{i=6} \delta_i e^{-\lambda_i t} \lambda_i\,dt.$$

The δ's are the portions of the total number of neutrons characteristic of the associated period. By definition

$$\sum_{i=1}^{i=6} \delta_i = 1$$

Fundamental Equation

An integral equation can now be written to describe the number of fissions per second in a pile, using the above symbols

$$n(t) = S(t) + \int_0^\infty n(t-\tau)\, P(\tau)\, d\tau \cdot K(t)$$

Where

$n(t)$ = total number of fissions per second.

$S(t)$ = fissions per second in the source.

The number of fissions present at a time t by the number of fissions per second at $t-\tau$, where τ is a variable encompassing all times previous to t.

[Number of neutrons per second, and Number of

fissions per second can be used interchangeably in an assembly with the application of a proportionality factor of about [2.5 for U-235.]
The factor K is usually considered a constant for a given assembly, independent of time.

Special Solutions of Equation

Case 1 $K<1$, n constant

Try solution $n = n_0$, $S = S_0$

$$n_0 = S_0 + n_0 K \int_0^\infty \rho(\tau)\, d\tau$$

$$n_0 = S + n_0 K$$

$$n_0 = \frac{S}{1-K}$$

Case 2

$K=1$

Assume as solution $n = n_0 + \alpha t$

Substitute in equation

$$n_0 + \alpha t = S_0 + K \int \left[n_0 + \alpha(t-\tau) \right] \rho(\tau)\, d\tau$$

This reduces to

$$0 = S_0 - \alpha \int_0^\infty [\tau]\, \rho(\tau)\, d\tau$$

$$\alpha = \frac{S_0}{\int_0^\infty \tau\, \rho(\tau)\, d\tau}$$

The integral can be seen to have a form of an average time, interpreted as the mean time between fissions, $\bar{\tau}$.

Then $\alpha = \frac{S_0}{\bar{\tau}}$

$$n = n_0 + \frac{S_0}{\bar{\tau}} t$$

According to this equation, if $K=1$, and a source is placed in an assembly, n will increase linearly with time to infinity.

An estimate of $\bar{\tau}$ can be made as follows.

$$\bar{\tau} \sim 10^{-8} + 10 \text{ sec. } (0.5\% \text{ of processes}) \sim \frac{1}{20} \text{ sec.}$$

In the case of a fast reactor, the number of neutrons present in a pile at any instant is small, of the order of 2-3. This is because the life of the neutrons on the average is so short. This gives rise to fluctuations in the neutron leakage from such piles, as measured on instruments. In the case of hydrogen moderated piles the average life of the neutrons is longer and less fluctuations are observed at low power level.

<u>Case III</u>

$K > 1$

Try for solution $n = n_0 e^{\alpha t}$

The basic equation becomes:

$$n(t) = n_0 e^{\alpha t} = K \int_0^\infty n_0 e^{\alpha(t-\tau)} p(\tau)\, d\tau$$

$$\frac{1}{K} = \int_0^\infty \sum_i f_i \lambda_i e^{-(\lambda_i+\alpha)\tau} d\tau$$

Integrating:

$$\frac{1}{K} = \sum_i \frac{f_i \lambda_i}{\lambda_i + \alpha}$$

Subtracting 1 from each side

$$\frac{K-1}{K} - \frac{\sum f_i \lambda_i}{\lambda_i + \alpha} - \sum f_i = \sum \frac{f_i\, \alpha}{(\lambda_i + \alpha)}$$

Insert a new variable $\alpha = \frac{1}{T}$, where T is the time for n to change by a factor e.
Recalling that

$$n = n_0 e^{\alpha t}$$

and $\lambda_i = \frac{1}{\tau_i}$, where τ_i is a sort of mean life:

$$\text{Then } \frac{K-1}{K} = \frac{\delta K}{K} = \sum f_i \frac{\tau_i}{T+\tau_i}$$

$$\text{or } \delta K = K \sum f_i \frac{\tau_i}{T+\tau_i}$$

This can now be broken down into various delayed components, and prompt component.

$$\delta K = \frac{K_p \tau_p}{T+\tau_p} + \gamma f \sum a_i \frac{\tau_i}{T+\tau_i}$$

where subscript p refers to prompt.

The quantity γ refers to the relative effectiveness of the delayed neutrons in the pile as compared with the faster prompt neutrons. It depends upon the structure of the pile, but is usually about 1.2. The quantity f is sensitive only to the type of fissionable material used, and is ~~.~~ 0.0078 for 25. The coefficients a_i refer only to the characteristic of delayed neutron periods, and are about the same for 25, 23, and 49.

Consider the special case $K_{prompt} = 1$, and $\tau_p \doteq 10^{-8}$ sec. Neglect delayed neutrons to see the effect of multiplication. The first part of δk

becomes.

$$\delta K = \frac{10^{-8}}{T + 10^{-8}} \quad \text{or} \quad T \sim \frac{10^{-8}}{\delta K} \quad \left[\frac{10^{-8}}{\delta K} \right]$$

Thus the rise time of neutrons is almost instantaneous in terms of finite time intervals such as 0.1 sec., even if δK is 10^{-4} or 10^{-3}. Thus, without the existence of delayed neutrons, critical assemblies would be extremely difficult to control.

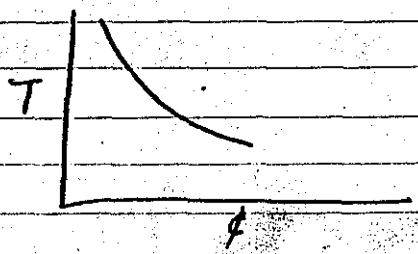
In actual practice the first term of δk is insignificant in comparison with that involving delayed neutrons, and is neglected.

$$\text{Thus} \quad \frac{\delta K}{\gamma f} = \sum a_i \frac{\tau_i}{T + \tau_i}$$

This important relation gives the excess in K in terms of the neutron rate of increase in an assembly and the characteristics of delayed neutrons.

$$1 = \frac{\delta K}{\gamma f} = 100 \text{ cents.}$$

Graphs may be constructed relating the doubling, or e-folding time of the neutron flux in a pile to the cents value.



Other measures of reactivity used by various groups.

1 in-hour = 2.3×10^{-5} change in K.

1¢ = .01 % change in K (approximately)

1¢ = 100 microres

$\simeq$ 4 in-hours.

Calculation of T - t curve.

Delayed neutrons

a_i	τ_i
0.167	0.7 sec.
0.621	6.5 sec.
0.187	34 sec.
0.025	83 sec.
1.000	

$f = .0078$
$\gamma = 1.2$ (assumed)
$\gamma f \doteq 10^{-2}$

$$\frac{\delta K}{\gamma f} = \sum_i \frac{a_i \tau_i}{T + \tau_i}$$

Assume T_{sec} =	$\sum \frac{a_i \tau_i}{T+\tau_i}$	
0.1	0.969	= 97 cents.
1.0	0.815	= 81 "
10.0	0.423	= 42 "
100	0.096	= 9.6 "
1000	0.012	= 1.2 cents

$$\text{eg.} \left(\frac{\delta K}{\gamma f}\right)_{0.1} = \frac{(0.167)(0.7)}{0.1 + 0.7} + \frac{(0.621)(6.5)}{(0.1 + 6.5)} + \frac{(0.187)(34)}{(0.1 + 34)} + \frac{(0.025)(83)}{(0.1 + 83)}$$

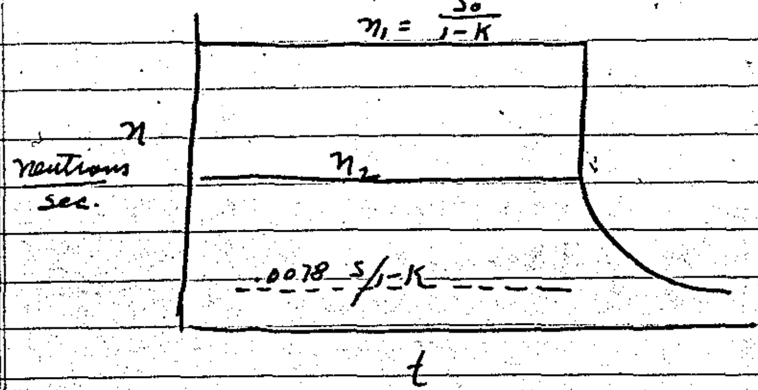
$$= 0.146 + 0.612 + 0.186 + 0.025$$

$$= 0.969 = 97 \text{ cents.}$$

End Morrison Lecture "Neutron Kinetics" Notes

"Source Jerk"

If a source is suddenly removed from an assembly which is near critical, the rate at which the neutron intensity falls off is a useful indication of the nearness to criticality. This may be seen as follows. Assume $K < 1$.



Assume source large compared with ~~the~~ spontaneous fission source in the material. This is easily acheived in 4-25. After source has been in the assembly a long time $n_1 = S_0/1-K$, (see case 1, solution). Because of this, a virtual delayed neutron source of strength $.0078\ S/1-K$ neutrons ~~fissions~~ per sec. This is because .0078 of the neutrons from fission are delayed. When the source is suddenly removed the neutron rate ~~density~~ suddenly drops to

$$n_2 = \frac{\frac{.0078S}{1-K}}{\frac{1-K_p}{1}}$$

In other words, the virtual source is amplified by $1-K_p$, since time is not available for it to come to equilibrium and be amplified by $1-K$.

$$\frac{n_1}{n_2} = \frac{1-K_p}{.0078}$$

$$(1-K_p) = .0078\ n_1/n_2$$

Case I $(1-K) = .0078$

$$(1-K_p) = .0078\,\frac{n_1}{n_2}$$

$$K_p = (1-.0078)K$$

$$\boxed{1-K+.0078K = .0078\,\frac{n_1}{n_2}}$$

$$K = 1-.0078$$

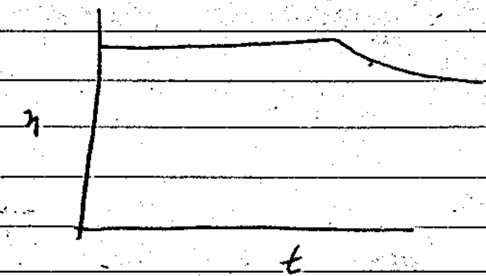
$$\boxed{\frac{n_1}{n_2} = 2}$$

Case II $1-K = 2(.0078)$

$$n_1 = 3n_2$$

etc.

when very near critical, removal of source results in a gradual decrease in neutrons per second from the equilibrium value



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Authority of EJM. Date 5/27/60

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