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The Measurement of the Critical Size of a Homogeneous Mixture of Plutonium and Natural Uranium Oxides with Polythene

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SUMMARY

This report describes the measurement of the critical size of a plutonium oxide/natural uranium oxide/polythene mixture in rectangular geometry using homogeneous blocks of the material.

The plutonium density was 0.950 gm/cc with a H/Pu atomic ratio of 18.6 and a Pu/U atomic ratio of 0.335. The plutonium contained 5.9% of Pu-240.

The side of a polythene-reflected critical cube, estimated from the results of six assemblies, is 27.7 cm, containing 20.2 ± 0.2 kgm of plutonium. Details of the measured critical parameters corrected to 45°C are given in Table 1.

TABLE 1

Base Side, cm	Height, cm	Height / Base	Volume, litres	Critical Mass, kgm		
				Oxide	Pu	Pu-239
25.7	32.6	1.268	21.5	92.1	20.4	19.1
25.7	32.8	1.276	21.6	92.7	20.5	19.2
30.0	24.2	0.807	21.9	94.0	20.8	19.5
30.0	24.4	0.811	22.0	94.4	20.9	19.6
34.3	20.7	0.604	24.4	104.9	23.2	21.7
30.0 x 21.5	37.5	-	24.2	104.1	23.0	21.6

The experimental errors on these masses and volumes are estimated to have a standard deviation of ± 0.6%.

The effect of reflector thickness on critical mass was measured, and indicated that thin hydrogenous reflectors are relatively inefficient as compared with their effect on other plutonium or uranium assemblies, and that cadmium sheet between core and reflector is equivalent to reducing the reflector thickness from 20 cm to less than 2 cm.

1. INTRODUCTION

The critical parameters of mixtures of plutonium and natural uranium oxides and hydrogen containing compounds at a Pu/Unat atomic ratio of $\sim$ 0.3 are required for the criticality safety assessment of plants for the production of fast reactor fuel. The technique used at Aldermaston from 1961 to 1966 for the safety clearance of a pilot plant to produce fast reactor fuel was of necessity based on very conservative assumptions, and this technique would be restrictive if applied to larger plants [1,2].

In order to obtain reliable and realistic safety limits for larger plants, some basic critical size measurements are being made and it is intended to produce complete critical size data curves by using theory to interpolate between the experimental points.

The work is divided into three parts:-

(a) Estimation of the critical parameter of polythene-reflected compacts of PuO_2/Unat O_2 and polythene at a H/Pu atomic ratio of about 20.

(b) Measurement of the spectrum and the prompt neutron decay constant in a natural-uranium reflected assembly of the same compacts.

(c) Measurement of the critical size of mixed plutonium and natural uranium nitrate solutions with H/Pu atomic ratio in the range 200 to 1000.

This report describes the work on the first of these projects. An An account of the spectrum measurements is given by Paterson et al. [3].

2. PRODUCTION OF THE COMPACTS

For this work 30 kgm of plutonium as PuO_2 were made available. It was mixed with natural UO_2 and with powdered polythene and was fabricated by Production Group, Windscale, into 764 compacts. At room temperature most of the compacts were 2.15 cm high but a few were made with heights of 2.69 cm or 3.25 cm to aid the extrapolation to critical. All the compacts were 4.28 cm square. They were made by pressing weighed quantities of powdered polythene and sintered mixed oxide granules, heating, pressing at 105°C and cooling under pressure.

The spread of contamination was minimised by surrounding each compact with a 0.02 cm thick polythene skin. This skin, which represented about 5% of the total polythene in the compact, was made by loading the press with a polythene bag holding the mixed oxide granules and 75% of the polythene in the form of powder.

That part of the bag which did not form the skin (20% of the total polythene) was folded into the mix by the action of the press, thus becoming distributed throughout the compact.

This is illustrated in Figure 1 which shows a macrograph of a section of a UO_2/polythene compact produced by the same technique. (This test compact differed from the mixed oxide compacts in having chamfered edges at the top and bottom.)

The polythene film was insufficient to provide adequate containment of the plutonium, largely because of the presence of "flashings" on the edges, which, on removal, exposed traces of the compact material. The compacts were therefore coated additionally with a layer of lacquer containing aluminium. This had adequate adhesive properties and limited the spread of plutonium contamination to a workable level.

The plutonium and uranium oxides were mixed uniformly and neither the mixed oxides or polythene particles were larger than 0.1 cm in diameter. The homogeneity of the compact material may be seen from Figures 1 and 2. Figure 2 shows an autoradiograph of the sectioned compact illustrated in Figure 1.

3. DETAILED DESCRIPTION OF COMPACTS

3.1 Mass and composition

The average mass of oxide per block is given in Table 2. The oxide masses of individual blocks are within 0.3% of the values quoted in the table, except that 13 of the 2.69 cm high blocks were 3% below the average and 85 of the 2.15 cm high blocks were 1% below the average.

TABLE 2

Average Masses of Pu/U/CH_2 Compacts

Height at 20°C, cm	Number of Compacts	Oxide Mass, gm	Oxide Concentration, gm/cc	$\frac{\text{Oxide Mass}}{\text{Polythene Mass}}$
2.15	599	170.5	4.33	8.266 ± 0.003
2.69	105	212.8	4.32	8.219 ± 0.008
3.23	60	256.2	4.33	8.265 ± 0.01

The average Pu/U atomic ratio, determined by analysis is 0.3350, ie, 25.09% of the metal was plutonium.

Chemical analysis showed that the oxygen to metal ratio was 2.00 and the isotopic composition of the plutonium was as follows:-

Pu-239	93.56%
Pu-240	5.90%
Pu-241	0.52%

The average ratio of oxide mass to polythene mass was 8.27, almost all compacts having a ratio within 3% of this. The average values for the three types of compact are given in Table 2.

The average composition by weight of the lacquer is as follows:-

Hydrogen	5%
Carbon	40%
Aluminium	20%
Nitrogen	0
Chlorine	15%
Other elements	20%

Each of the smallest size blocks had an average 0.14 gm of lacquer, increasing the hydrogen content of the smallest block by 0.2%.

Each of the smallest size compacts therefore contained on average

	170.5 ± 0.1 gm of oxide
or	150.3 ± 0.1 gm of metal
or	37.7 ± 0.1 gm of plutonium
or	35.3 ± 0.1 gm of Pu-239
and	20.6 ± 0.1 gm of polythene
and	0.14 ± 0.02 gm of lacquer

The hydrogen to plutonium atomic ratio was 18.6 ± 0.1.

Impurities were measured by spectroscopic analysis at Windscale, the results being given below in parts per million by weight of the total compact:-

Li	< 15	P	4
B	< 0.1	Ca	30
C	80	Mn	< 4
F	1	Ni	3
Mg	< 8	Cu	< 7
Al	< 4	Ca	< 7
Si	∿ 20	Cd	< 5

Au < 1

3.2 Size and density

The size of the compacts quoted in Table 2 was measured using a vernier height gauge to measure stacks of compacts, so as to determine the average height when packed in the core. The measurements were made at room temperature (∿ 20°C). The volume of the smallest size compact is 39.4 ± 0.1 cc and the others $1\frac{1}{4}$ and $1\frac{1}{2}$ times this value to within the same accuracy.

The change of density with temperature was measured between 8°C and 55°C for one of the smallest size compacts. A plot of the results obtained is given in Figure 3. The criticality measurements were made at about 45°C and were normalised to this temperature. Converting the volume of the smallest size compact to this temperature gives its volume as 39.7 ± 0.1 cc, and hence the oxide density of the core was 4.29 ± 0.01 gm/cc, the plutonium density 0.950 ± 0.004 gm/cc and the Pu-239 density 0.889 ± 0.006 gm/cc.

4. EXPERIMENTAL TECHNIQUES

The measurements were made on the ARIES vertical assembly machine. This machine, formerly known as ATLAS, has been described in earlier papers [4,5]. In this experiment it was used in the subcritical operating mode, ie, the critical sizes were determined by extrapolation from subcritical assemblies.

The object of the experiment was to determine the size of a near cube of compacts reflected by 20 cm thick polythene*. The arrangement of core and reflector for doing this is shown in Figure 4. The core height was adjusted so that its top was level with the top of the side reflectors, which were adjusted to be in contact with the core sides. The experiment consisted of building up the core and reflector assembly on the lower platform of ARIES, as shown in Figure 4. This was then offered up to the top polythene reflector under remote control. The core was thus completely surrounded by effectively infinite polythene on all faces. A measure of the reactivity of this fully reflected core was obtained by counting the leakage neutrons. The experiment was then repeated with cores having the same "base" and a different "height". The reactivity of each of these cores as determined from count rate data was extrapolated to that at critical (ie, at infinite count rate) graphically.

BF_3 proportional counters were embedded in the lower polythene reflector, so that the neutrons to which they were exposed were effectively thermal. The compacts contained sufficient Pu-240 to provide adequate count rates without the addition of a chemical neutron source.

As a check on the accuracy of the experiment and of proposed calculations, parallelopipeds having four different sized bases were constructed, and two of these were repeated, following a period of work on a different core.

One core having a 30 x 30 cm core base was used for a series of experiments with polythene interleaved sheets to check the effect on the critical size of the polythene "skin" used for containment. This core was built up with the variable dimension horizontal, as shown in Figure 5. The core was assembled so that it was fully polythene reflected, as were the main series of experiments.

Some measurements were made of systems with one face reflected by "thin" polythene, or one face reflected by "thick" polythene with a layer of cadmium between core and reflector, or one face effectively unreflected. Again the variable dimension was horizontal. The experimental core was positioned at the edge of the upper and lower polythene reflectors as illustrated in Figure 6 which shows the effectively unreflected measurement. For this, 0.76 mm thick or 1.52 mm thick aluminium sheets were placed over the experimental core face for safety reasons.

5. CRITICAL SIZES OF POLYTHENE REFLECTED PARALLELOPIPEDS

Measurements were made on cores with base sizes of 25.7 x 25.7 cm, 30 x 30 cm and 34.3 x 34.3 cm. As a further check a 30 x 21.5 cm core was constructed and the 25.7 x 25.7 cm and 30 x 30 cm cores were rebuilt. Count rates were recorded for several stack heights near critical on each of these cores, after the core had been assembled long enough to reach equilibrium.

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*Polythene is $(CH_2)_n$ at a density of 0.92 gm/cc.

The results of these measurements are listed in Table 3.

The standard deviation of each individual measurement of the critical mass is a combination of the following:-

Arrangement and packing of blocks (from measurements of packing piles of blocks)	0.15%*
Placing reflector around core (from measurement of gaps and assuming a density exponent of unity)	0.34%*
Counting errors and errors of extrapolation	0.20%

*Not completely independent.

Apart from errors due to analysis and non-homogeneity, it is therefore expected that the measurement should be accurate within about 0.4% on mass.

TABLE 3

Measured Count Rates For Rectangular Cores Reflected by 20 cm Thick Polythene

Run No.	Core Size, cm at 45°C	Counts per Second			Counting Time, s	Core Temperature, °C
		C_1	C_2	C_3		
9	25.7 x 25.7 x 28.0	175	233	142	300	46
10	25.7 x 25.7 x 29.1	230	311	189	300	46
11	25.7 x 25.7 x 31.2	642	856	512	300	43
12	25.7 x 25.7 x 32.3	3117	3996	2402	200	45
32	25.7 x 25.7 x 31.2	695	850	424	200	49
31	25.7 x 25.7 x 32.3	2043	2478	1231	200	49
18	30.0 x 30.0 x 21.6	136	281	194	300	45
20	30.0 x 30.0 x 22.6	243	565	390	300	45
19	30.0 x 30.0 x 23.7	845	1901	1294	300	45
34	30.0 x 30.0 x 22.6	445	407	157	200	43
33	30.0 x 30.0 x 23.7	1219	1168	453	200	43
17	34.3 x 34.3 x 19.4	345	466	298	300	44
15	34.3 x 34.3 x 19.9	671	898	587	100	43
16	34.3 x 34.3 x 20.5	2206	2967	1903	100	43
54	30.0 x 21.5 x 36.6	2098	2095	1246	200	49
55	30.0 x 21.5 x 37.2	3980	4165	2313	200	49

6. DEPENDENCE OF CRITICAL MASS ON CORE TEMPERATURE

Since these measurements were made at different temperatures, the variation of critical mass with core temperature was measured.

A core built with a base of 6 x 6 compacts was precooled to ~ 0°C with solid CO_2. The compacts were loaded, taking care to avoid visible condensation, and were assembled to a separation of 0.2 cm, by which time the core temperature was 15°C. A completed assembly at this temperature would have been supercritical and the approach was stopped. The core was allowed to warm up naturally to 23°C, and the assembly procedure was then completed. By the end of the day the temperature had reached 30°C and the lower platform including the core and all but the top reflector was lowered.

The following day the stack, which had not been altered in any way, was reassembled. The measured temperature was 49°C.

After 2 hours the temperature had risen by only 0.5°C, but during this time a slight re-arrangement of the core material had caused a 0.007 cm reduction in its apparent height. The relevant count rates are quoted in Table 4.

TABLE 4

Temperature Coefficient Measurements
Run 31 (ie, 6 x 6 Compacts on Base, 15 Compacts High)

Date	Time	Separation, cm	Temperature, °C	Counts per Second		
				C_1	C_2	C_3
24.5.66	1207	0.21	14.0	6829	8434	4102
	1258	0.20	19.5	4937	6126	2979
	1353	0.20	23.0	3949	4900	2366
	1437	0.00	26.0	6675	8316	4040
	1656	- 0.0008	32.0	4597	5813	2796
25.5.66	1039	- 0.010	49.0	2043	2479	1231
	1242	- 0.003	49.5	2156	2566	1277

The change in the reciprocal count rate per compact (Δp) is seen to be proportional to the rise in temperature of the core, ie, for a 540 compact core,

$$\Delta p = \frac{540}{T_H - T_C} \left(\frac{1}{C_H} - \frac{1}{C_C} \right),$$

where C_H and C_C are the count rates when the core temperatures are T_H and T_C.

The temperature coefficient defined in this way is quoted in Table 5 on the basis of the data given in Table 4.

TABLE 5

Temperature Coefficient of Reactivity per Compact

T_H	T_C	τ = Change of Reciprocal Count Rate per Compact per °C × 10^4		
		C_1	C_2	C_3
19.5	14.0	54.8	44.0	90.0
23.0	19.5	78.4	63.4	134.0
32.0	26.0	61.2	46.8	98.6
49.0	32.0	86.4	73.4	144.8

7. CRITICAL SIZE MEASUREMENTS CORRECTED FOR TEMPERATURE EFFECTS

The last row of figures in Table 5 may be used directly to correct the data to a standard temperature for the cores with 6 × 6 compact base. Table 6 gives the data for these cores corrected to values of reciprocal count rate per unit cube at 45°C. The factor N, the number of compacts in the core, is introduced to remove the contribution to count rate change due to spontaneous fission. The errors quoted are determined by the statistics of counting and take no account of errors due to analysis or geometry.

TABLE 6

25.7 × 25.7 cm Base Core - Reciprocal Count Rate per Compact at 45°C

Run No.	Core Height at 45°C, cm	Mass of Oxide, kgm	N/C_1	N/C_2	N/C_3
9	28.0	79.79	2.670 ± 0.005	1.998 ± 0.004	3.284 ± 0.007
10	29.0	82.86	2.100 ± 0.007	1.552 ± 0.005	2.564 ± 0.008
11	31.2	89.00	0.832 ± 0.001	0.625 ± 0.0006	1.050 ± 0.001
12	32.3	92.07	1.732 ± 0.0001	0.1351 ± 0.000007	0.2248 ± 0.0001
32	31.2	89.00	0.716 ± 0.001	0.584 ± 0.001	0.1174 ± 0.001
31	32.3	92.07	0.2296 ± 0.0002	0.1884 ± 0.00001	0.3804 ± 0.0002

These data are graphed in Figure 7. They extrapolate to assemblies having critical masses of 92.90 and 93.55 kgm of oxide, corresponding to 32.5 and 32.7 cm sides.

The effect of change of temperature on critical size cannot be calculated in this manner for cores of other shapes as the efficiencies of the counters were markedly different for each assembly. However, the temperature of the remaining assemblies in the same series never differed by more than 1°C and consequently the error introduced by extrapolating the raw data is less than that due to a change of 1°C in the core temperature, ie, about 0.03 - 0.06% on mass, according to shape. Reciprocal count rates per unit cube are given in Table 7.

TABLE 7

Measured Reciprocal Count Rates per Compact
30 x 30 cm, 34.3 x 34.3 cm and 30 x 21.5 cm Base Cores

Core Size, cm at 45°C	Oxide Mass, kgm	N/C_1	N/C_2	N/C_3	Temperature, °C
30 x 30 x 21.6	83.54	3.596 ± 0.007	1.742 ± 0.002	2.528 ± 0.005	45
30 x 30 x 22.6	87.88	2.134 ± 0.004	0.910 ± 0.001	1.326 ± 0.003	45
30 x 30 x 23.7	92.06	0.6382 ± 0.0007	0.2852 ± 0.0002	0.4184 ± 0.0004	45
30 x 30 x 22.6	87.88	1.156 ± 0.006	1.264 ± 0.002	3.274 ± 0.004	43
30 x 30 x 23.7	92.06	0.442 ± 0.001	0.4614 ± 0.0003	1.191 ± 0.0006	43
34.3 x 34.3 x 19.4	98.21	1.670 ± 0.002	1.238 ± 0.002	1.934 ± 0.003	44
34.3 x 34.3 x 19.9	100.94	0.882 ± 0.001	0.6570 ± 0.0006	1.008 ± 0.001	43
34.3 x 34.3 x 20.5	103.66	0.2756 ± 0.0002	0.2048 ± 0.0002	3.196 ± 0.0002	43
30 x 21.5 x 36.6	101.45	0.2836 ± 0.0002	0.2710 ± 0.0003	0.4776 ± 0.0003	49
30 x 21.5 x 37.2	102.94	0.1517 ± 0.0001	0.1450 ± 0.0002	0.2610 ± 0.0002	49

Extrapolation of these data using the curves illustrated in Figures 8 and 9 gave the values of critical parameter set out in Table 8.

TABLE 8

Extrapolated Critical Mass

Base x Height, cm at 45°C	Height / Base	Critical Mass, kgm of Oxide	Temperature, °C
30 x 30 x 24.5	0.80	94.0	45
30 x 30 x 24.35	0.81	94.4	43
34.3 x 34.3 x 20.71	0.60	104.9	43
30 x 21.5 x 37.686	-	104.4	49

A 1°C rise in temperature increases the variable side of a 6 x 6 compact base core by 0.0194 ± 0.0004 cm. Buckling conversion shows that this would increase the cube side by 0.0039 ± 0.0002 cm, ie, by 0.014%, and of the other cores studied by the amount shown in Table 9.

TABLE 9

Critical Mass of Rectangular Parallelopipeds at 45°C

Base x Height, cm at 45°C	Temperature Corrected Critical Mass, kgm of Oxide	Temperature Correction, cm of Height
30.0 x 30.0 x 24.2	94.0	+ 0.000
30.0 x 30.0 x 24.4	94.4	+ 0.00862
34.3 x 34.3 x 20.7	104.9	+ 0.00862
30.0 x 21.5 x 37.5	104.1	- 0.076

This shows that the temperature effect is very small over the range of temperatures encountered during the experiment.

Table 10 quotes the complete set of results for 20 cm thick polythene reflectors after temperature correction.

TABLE 10

Critical Parameters of Rectangular Parallelopipeds Reflected by 20 cm Thick Polythene at 45°C

Base Side, cm	Height, cm	Height / Base	Volume, litres	Critical Mass, kgm		
				Oxide	Pu	Pu-239
25.7	32.6	1.268	21.5	92.1	20.4	19.1
25.7	32.8	1.276	21.6	92.7	20.5	19.2
30.0	24.2	0.807	21.9	94.0	20.8	19.5
30.0	24.4	0.811	22.0	94.4	20.9	19.6
34.3	20.7	0.604	24.4	104.9	23.2	21.7
30.0 x 21.5	37.5	-	24.2	104.1	23.0	21.6

8. DERIVATION OF THE CRITICAL CUBE PARAMETERS

The results of similar experiments with UO_2/wax and enriched U metal had been successfully analysed by simple 1 group theory [4,5] to obtain the critical cube sizes. The results of a similar analysis of the present experiment are given in Figure 10. The critical cube size is determined as 27.69 ± 0.06 cm corresponding to a volume of 21.23 litres and a mass of 91.1 kgm of oxide or 20.2 kgm of Pu.

The extrapolation length, including the reflector saving, for 20 cm thick polythene is 2.1 cm or 8% of the cube side. The corresponding extrapolation lengths determined for polythene reflected UO_2/wax compacts and for polythene reflected enriched U metal were 38% and 31% of the core side respectively.

It is emphasised that these discrepancies are much too large to be explained by the experimental errors as quoted and this simple approach is therefore not valid for this core material. Nevertheless, the correction to the cube from four of the assemblies is very small, and this enables us to quote the cube side with an accuracy of ± 0.6% on mass or volu].

9. EXPLANATION OF TEMPERATURE COEFFICIENT OF REACTIVITY

Returning to the temperature coefficient measurements, the data of Table 6 may be quoted in terms of the fractional decrease of critical mass per unit temperature rise and these data may then be compared with the data given in Figure 3 for the thermal expansion of the compacts to check whether the temperature coefficient of reactivity can be adequately explained by thermal expansion.

These temperature coefficients are listed in Table 11. The final column quotes a core density exponent (Y) derived from the data in the previous two columns. The density exponent may be defined by the relation

$$\frac{M_1}{M_2} = \left(\frac{\rho_1}{\rho_2}\right)^{-Y},$$

where M_1 and M_2 are the critical masses of two cores of identical composition, having densities of ρ_1 and ρ_2 respectively, The values obtained, while not very precise due to errors of measurement of temperature (± 0.5°C) and variations of the temperature distribution within the core (unknown), are not inconsistent with an expected value of 1.5; and point to the fact that the thermal expansion of the compacts is sufficient to explain the temperature coefficient measurements.

TABLE 11

Temperature Coefficient of Reactivity

T_H, °C	T_C, °C	$\frac{\Delta M}{M}$ per °C x 10^4, Average for 3 Counters	$\frac{\Delta \rho}{\rho}$ per °C x 10^4	Derived Density Exponent
23	14	4.34 ± 0.4	2.24 ± 0.1	1.9 ± 0.3
32	26	4.04 ± 0.6	7.86 ± 0.1	2.1 ± 0.6
49	32	5.90 ± 0.3	4.12 ± 0.2	1.4 ± 0.2

10. REFLECTOR REPLACEMENT AND CORE INTERLEAVED MEASUREMENTS

For the reflector replacements a core with a 30 x 30 cm base was rearranged on the 20 cm thick polythene slab so that one side face was in line with the edge of the polythene. This face was then reflected by a layer of polythene up to 5.7 cm thick or by a very thin aluminium sheet for support only (Figure 6). The assembly procedure consisted of

reflecting the top surface of the core by 20 cm thick polythene. The siting of the core on ARIES was arranged to minimise reflection from structural supports etc.

To estimate the effect of adding polythene heterogeneously to the core, single or double sheets of the material were added every $\frac{1}{2}$ or 1 unit on a 30 x 30 cm core in the manner shown in Figure 5. A single polythene sheet had a thickness of 0.075 cm, a mass of 61.9 gm, and changed the average H/Pu atomic ratio of the core from 18.6 to 19.7 if interleaved every $\frac{1}{2}$ compact layer.

Extrapolation to the critical length of each of these assemblies was achieved by normalising the reflected count rate with the count rate when the assembly was unreflected at the top face, ie, at the start of the assembly procedure. This yielded a number which was effectively independent of the efficiency of the counters used, or on changes in source strength at the core so that a comparison could be made between different types of assembly.

This number is the function

$$R = \frac{\text{count rate with top face unreflected}}{\text{count rate with top face reflected}}.$$

The function R was found to vary almost exponentially with stack length and the critical length was determined by a plot of this function against length on logarithmic graph paper.

The function R must extrapolate to zero at delayed critical, as does N/C. The form of the graph of R plotted against the difference between the critical length and the core length was found to be independent of the amount of reflector added to the end face and this fact helped to provide a check of individual measurements.

Tables 12 and 13 give the results of individual measurements of critical length for the replacement and the interleaved cores respectively.

Figure 11 is a plot of log (1 - R) against the difference between the actual core and critical core lengths. The abscissa is quoted in terms of numbers of compacts so that, in the case of the interleaved cores, the abscissa is proportional to the length of the compact or the core rather than total core length. The effect of the thin aluminium support plate was shown to be negligible by re-measuring the most reactive assembly with a double thickness of aluminium in position.

TABLE 12

Measurements on 7 × 7 Base, Including Replacement Series

Run No.	Core Temperature, °C	Details of Reflector on Experimental Face	Core Length L† (Units)	Count Rate Ratio (R)	$L_c - L$ (Units)	Critical Core Length L_c (At Core Temperature) (Units)†	Critical Core Length* at 45°C (Units)†	Critical Core Length at 45°C, cm
		Polythene						
18	45	20 cm	5.000	0.583	0.626	5.626	5.626	24.248
19	45	20 cm	5.500	0.170	0.126	5.626	5.626	24.248
20	45	20 cm	5.250	0.418	0.376	5.626	5.626	24.248
33	43	20 cm	5.500	0.214	0.150	5.650	5.653	24.364
34	43	20 cm	5.250	0.444	0.400	5.650	5.653	24.364
		Polythene						
35	53	5.71 cm	5.875	0.051	0.044	5.919	5.906	25.455
35a	53	5.71 cm	5.625	0.366	0.294	5.919	5.906	25.455
36	53	2.54 cm	6.000	0.397	0.337	6.337	6.323	27.252
37	49	2.54 cm	6.125	0.255	0.210	6.330	6.323	27.252
39	49	2.54 cm	6.250	0.113	0.080	6.330	6.323	27.252
46	53	3.58 cm	6.000	0.215	0.160	6.160	6.147	26.493
		Aluminium						
42	47	0.076 cm	6.625	0.140	0.100	6.725	6.722	28.972
43	47	0.152 cm	6.625	0.140	0.100	6.725	6.722	28.972
44	46	0.076 cm	6.500	0.296	0.225	6.725	6.722	28.972
20 cm Polythene + 0.05 Cm								
49	50	20 cm	6.000	0.445	0.519	6.519	6.513	28.071
50	49	20 cm	6.500	0.029	0.020	6.520	6.513	28.071

*The temperature correction applied was 0.0017 units per °C, based on buckling conversion for the cube.
†At 45°C 1 unit is 4.29 cm, ie, the width of one compact. In terms of height or length, one unit is 4.31 cm, ie, the height of two compacts.

TABLE 13

Polythene Interleaved Measurements on 7 x 7 Base

Run No.	Core Temperature, °C	Polythene		Core Length L (Units)	Count Rate Ratio (R)	$L_c - L$ (Units)	Critical Core Length L_c (At Core Temperature) (Units)	Critical Core Length L_c at 45°C*	
		Width, mm	Separation, mm					Units	cm
28	51	0.75	21.5	5.00	0.520	0.546	5.546	5.535	23.856
29	51	0.75	21.5	4.50	0.719	1.046	5.546	5.535	23.856
30	56	0.75	21.5	5.50	0.074	0.054	5.554	5.535	23.856
57	46	1.50	21.5	5.00	0.318	0.275	5.275	5.273	22.727

*The temperature correction applied was - 0.0017 units per °C based on a buckling conversion from the cube.

11. INTERPRETATION OF REFLECTOR REPLACEMENT MEASUREMENTS

The effect of thin polythene reflectors is illustrated in Table 14, which shows the reflector saving relative to that for a 20 cm thick reflector, and by Figure 12 which is based on a graph in reference [4] and compares the difference in relative reflector saving with that for other experimental assemblies.

TABLE 14

Reflector Savings for Thin Polythene Reflectors

Reflector Thickness, cm	Reflector Saving, cm	Relative Reflector Saving
0.00	0.00	0.00
2.54	1.72	0.37
3.58	2.45	0.53
5.71	3.48	0.75
20.00	4.64	1.00

Figure 12 shows that thin hydrogenous reflectors are relatively less efficient than with the U or Pu assemblies studied previously, and this is of interest from the point of view of criticality assessment. No attempt has been made to estimate the bare critical mass from these measurements as was done for the uranium assemblies [4] since this involves the use of simple diffusion theory, which appears not to be valid for these experiments (see above).

A sheet of cadmium is frequently used as a means of reducing the effectiveness of a reflector, especially in storage or transport. The effect of a cadmium sheet as shown by its effect on one face, would increase the critical size of a core of mixed oxide at H/Pu = 18.6 reflected by 20 cm of polythene to that of a core reflected by only 1.5 cm of polythene. To compare the effect of a cadmium sheet, with different cores and/or reflectors, a figure of merit (c) was defined in reference [4] as

$$C = \frac{r\ (\text{no cadmium}) - r\ (\text{cadmium})}{r\ (\text{no cadmium})} ,$$

the terms r (cadmium) and r (no cadmium) being the reflector savings of the cadmium covered core and the core not covered by cadmium respectively. For the mixed oxide core used in the present work, C = 0.80, which is greater than the value for the 30% enriched uranium core described in reference [4], even for H/U 235 = 80.

12. INTERPRETATION OF INTERLEAVED MEASUREMENTS

The effect of adding polythene sheets to the core may be illustrated as in Figure 13 by equating the mass of a cube containing the sheets to that of a homogeneous cube. (Strictly, the extrapolation of a heterogeneous assembly to critical is not meaningful, unless it happens to be an exact number of layers. For this exercise, the real core is regarded as being replaced by a uniform one having the same reactivity "worth" and Figure 13 enables a comparison to be made between heterogeneous and homogeneous cores.) The straight lines are based on data by Chalmers [6]. Figure 13 shows that the error introduced by heterogeneity in the compacts is likely to be small, since the thickness of the polythene skin surrounding each compact is only $\sim$ 0.02 cm.

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3. W.J. Paterson et al.: "Neutron Spectrum Measurements in the Fast Reactor Assembly VERA 19A, and Tests of the Time of Flight Spectrometry Methods in VERA 5A and VIPER." SM101/40, IAEA (1967)

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6. J.H. Chalmers: SM70/9. "Criticality Parameters for Mixtures of Plutonium Oxide, Uranium Oxide and Water". Criticality Control of Fissile Materials - Proceedings at the Stockholm Symposium, 1-5 November 1965, pp. 3-9, IAEA (1966)

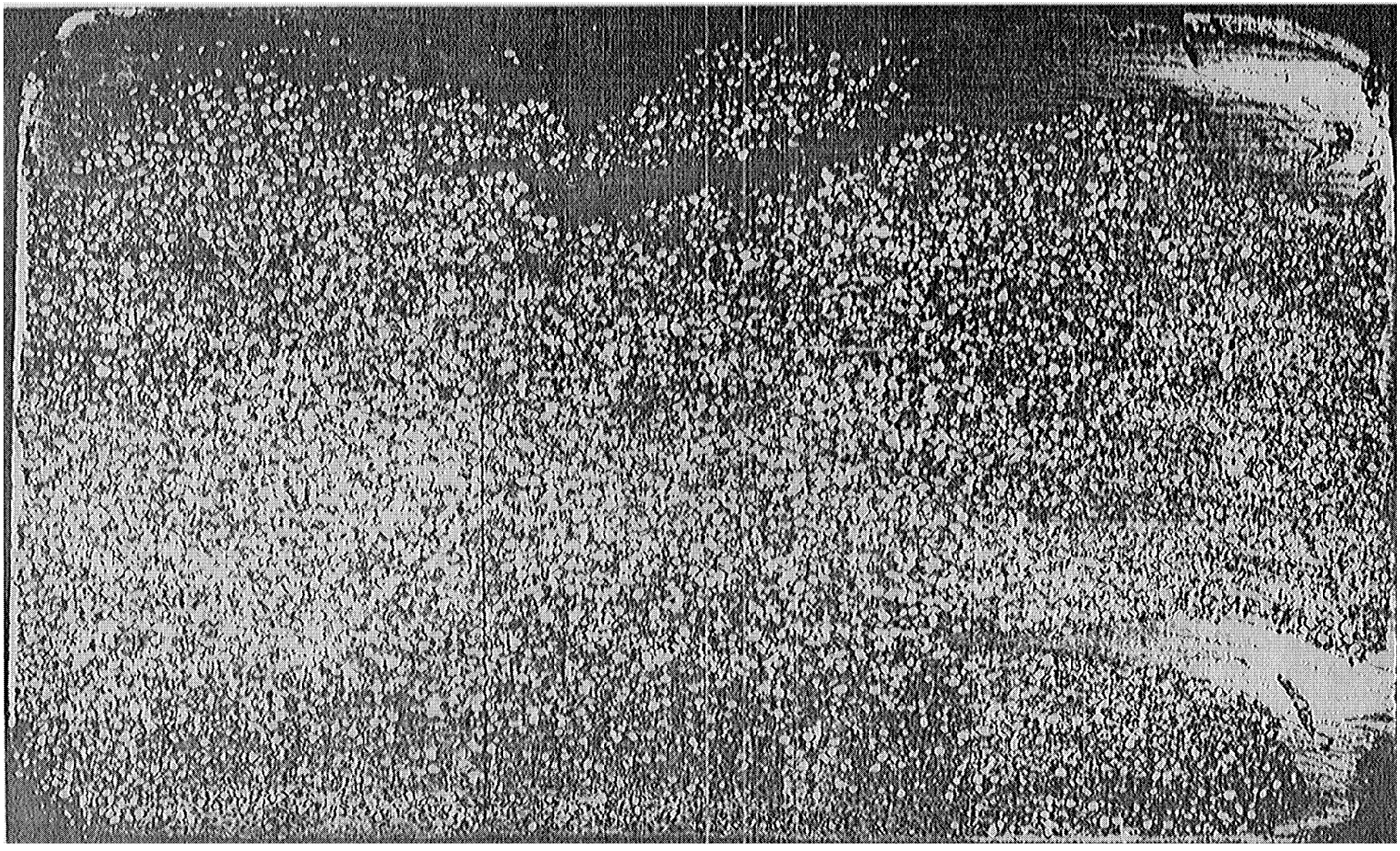

FIGURE 1. MACROGRAPH OF UO_2/POLYTHENE COMPACT

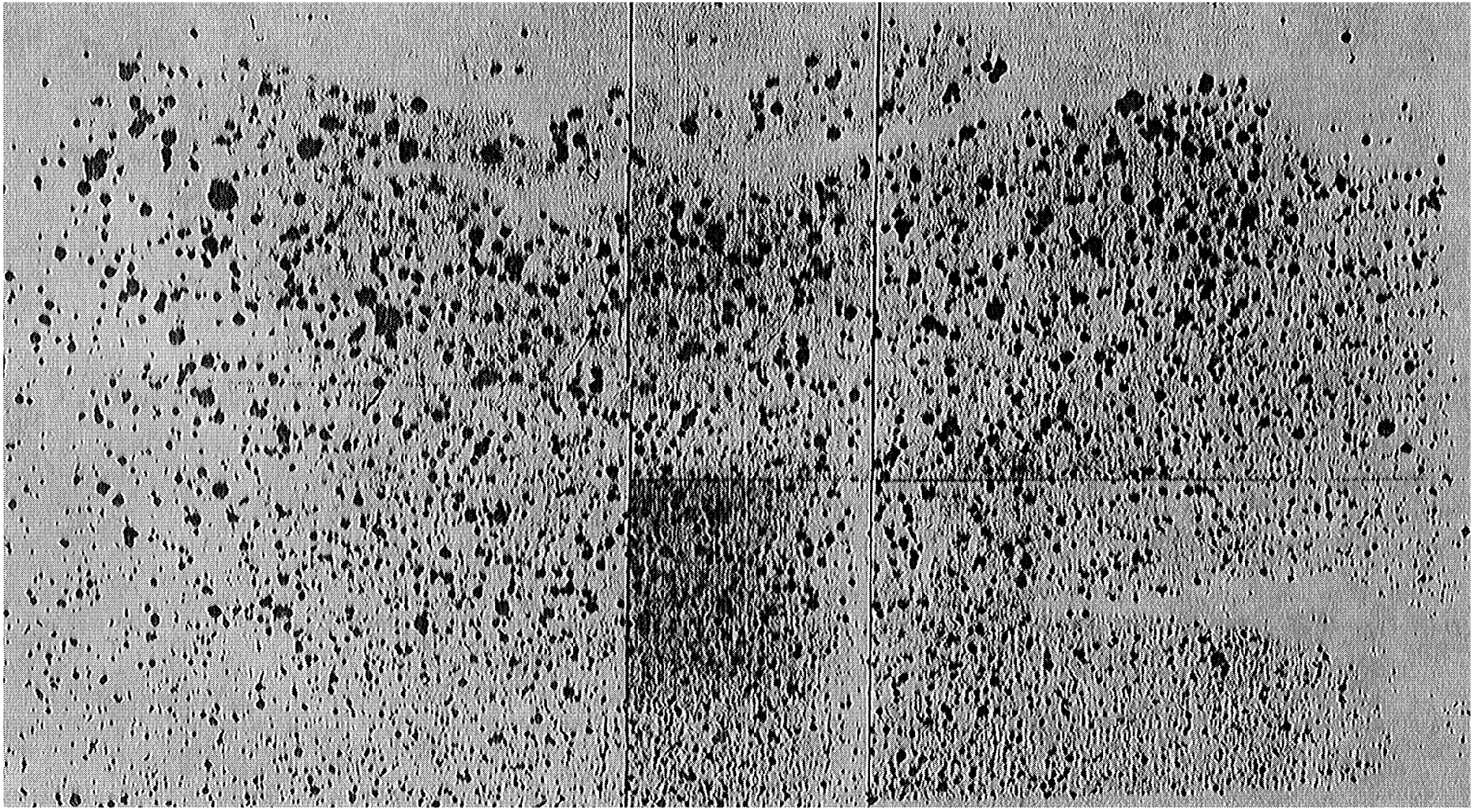

FIGURE 2. RADIOGRAPH OF UO_2/POLYTHENE COMPACT

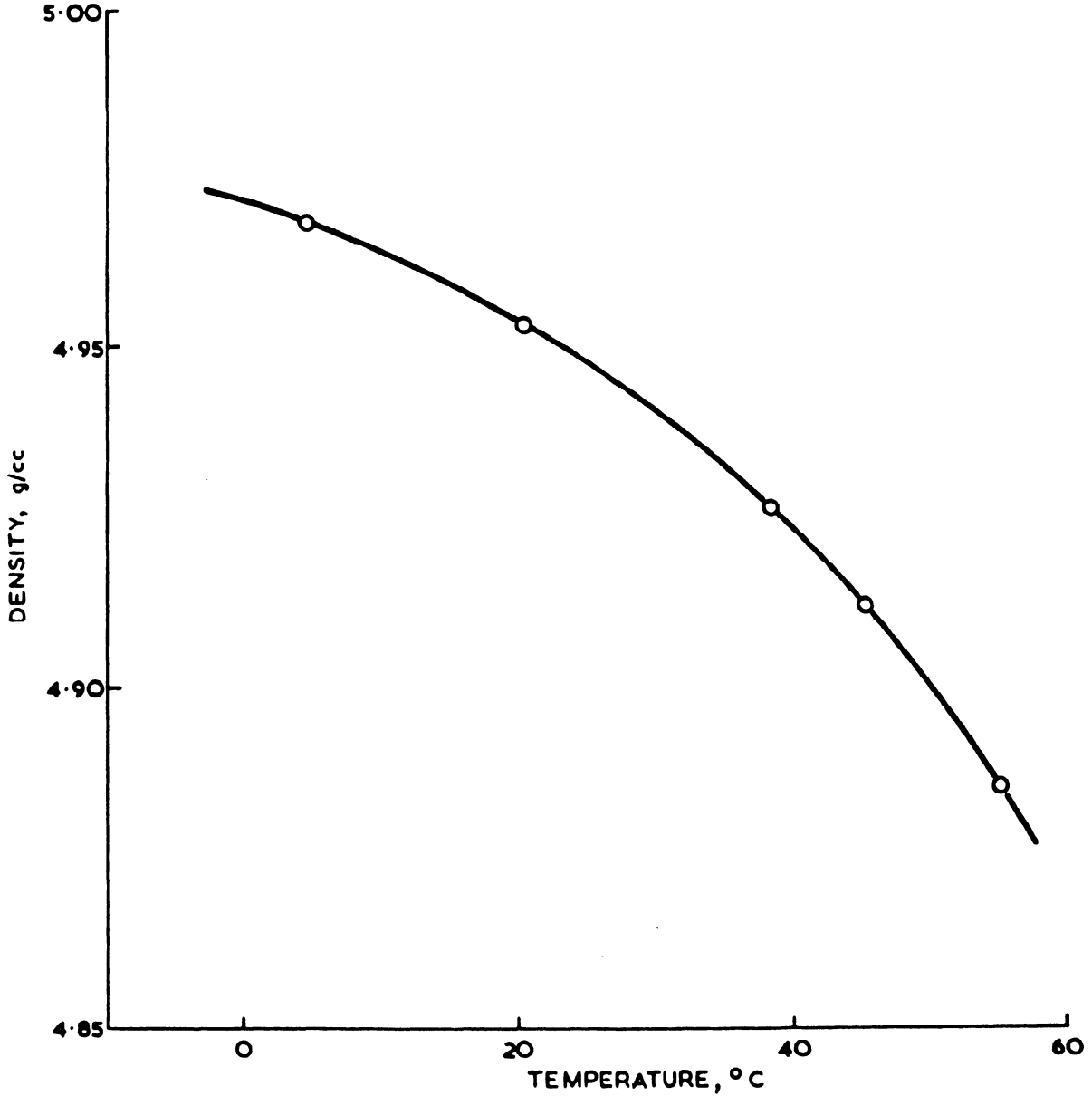

FIGURE 3. CHANGE OF DENSITY WITH TEMPERATURE FOR A PARTICULAR COMPACT

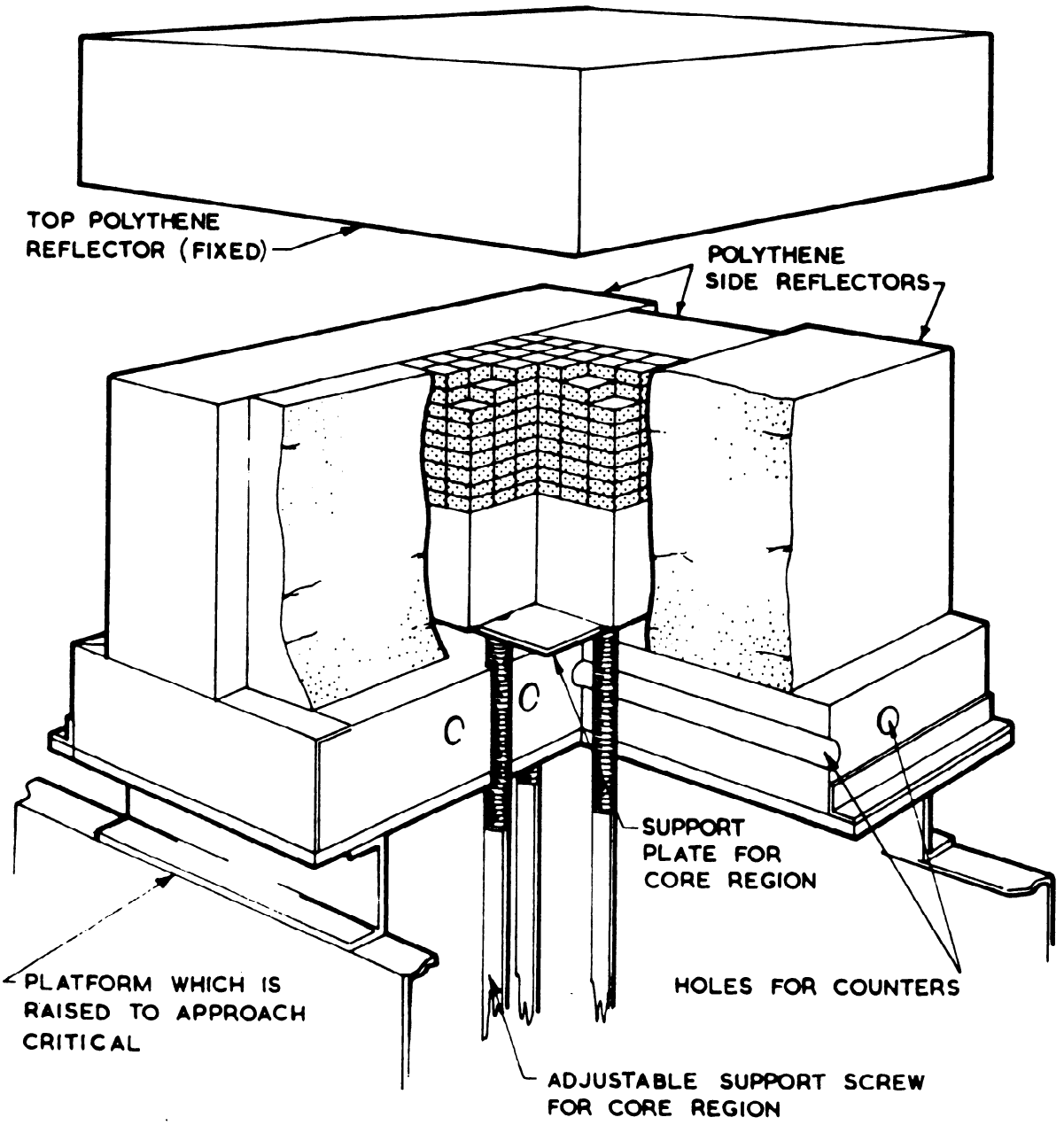

FIGURE 4. CORE AND REFLECTOR ARRANGEMENT FOR FULL POLYTHENE REFLECTION

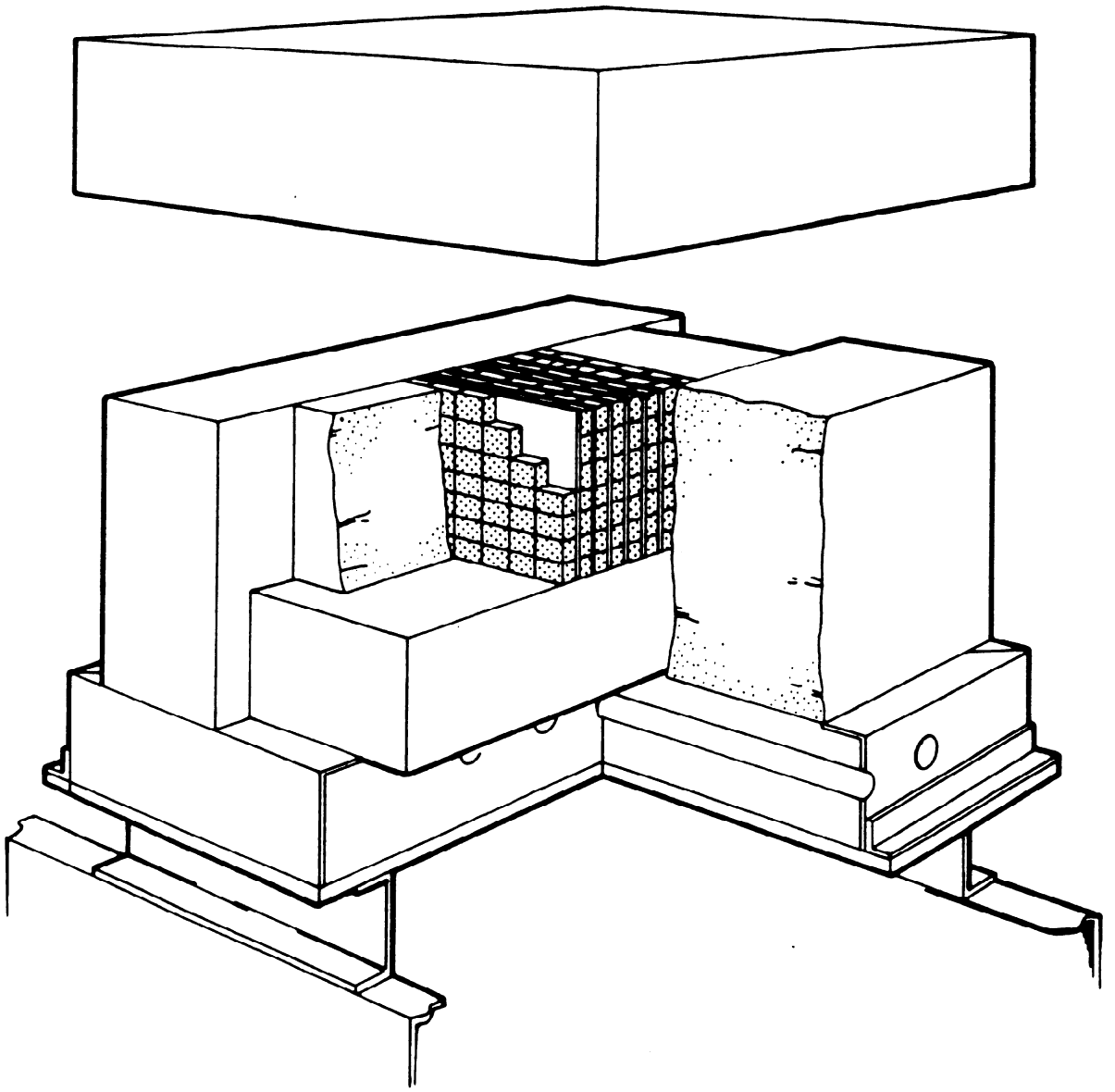

FIGURE 5. CORE AND REFLECTOR ARRANGEMENT FOR POLYTHENE INTERLEAVED ASSEMBLY

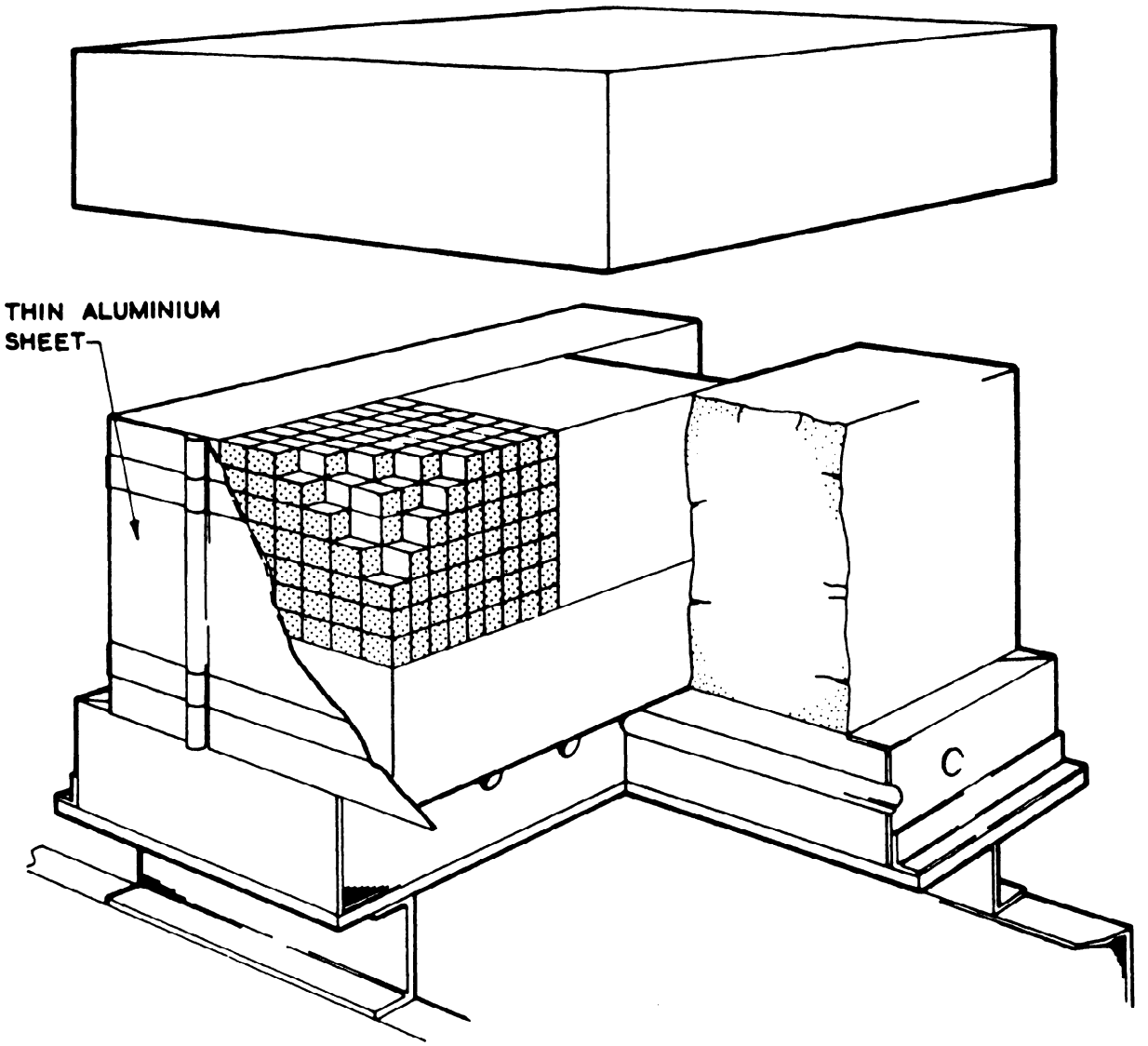

FIGURE 6. CORE AND REFLECTOR ARRANGEMENT FOR REPLACEMENT ASSEMBLY

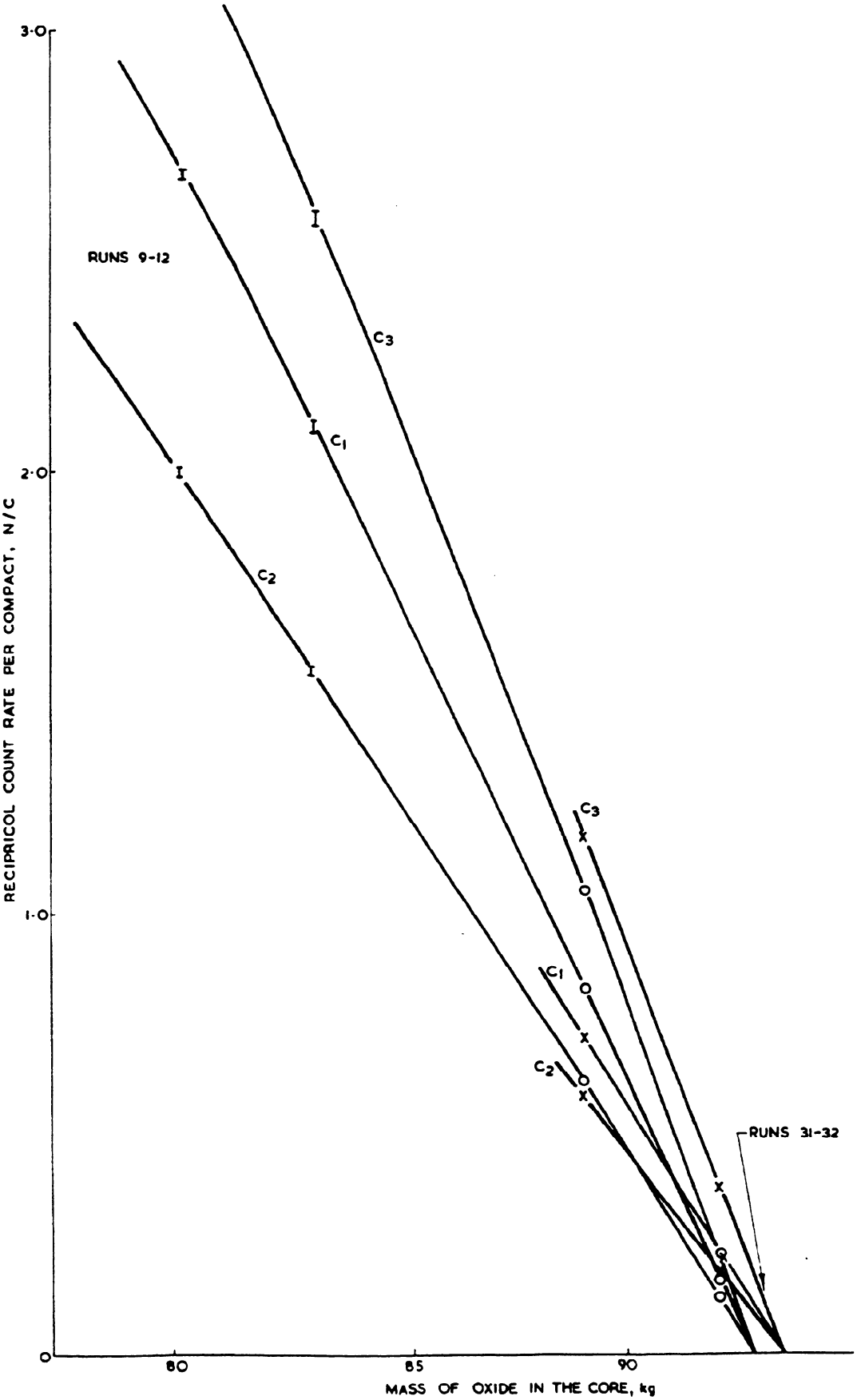

FIGURE 7. EXTRAPOLATION TO CRITICAL FOR CORE HAVING 25·7cm X 25·7cm BASE

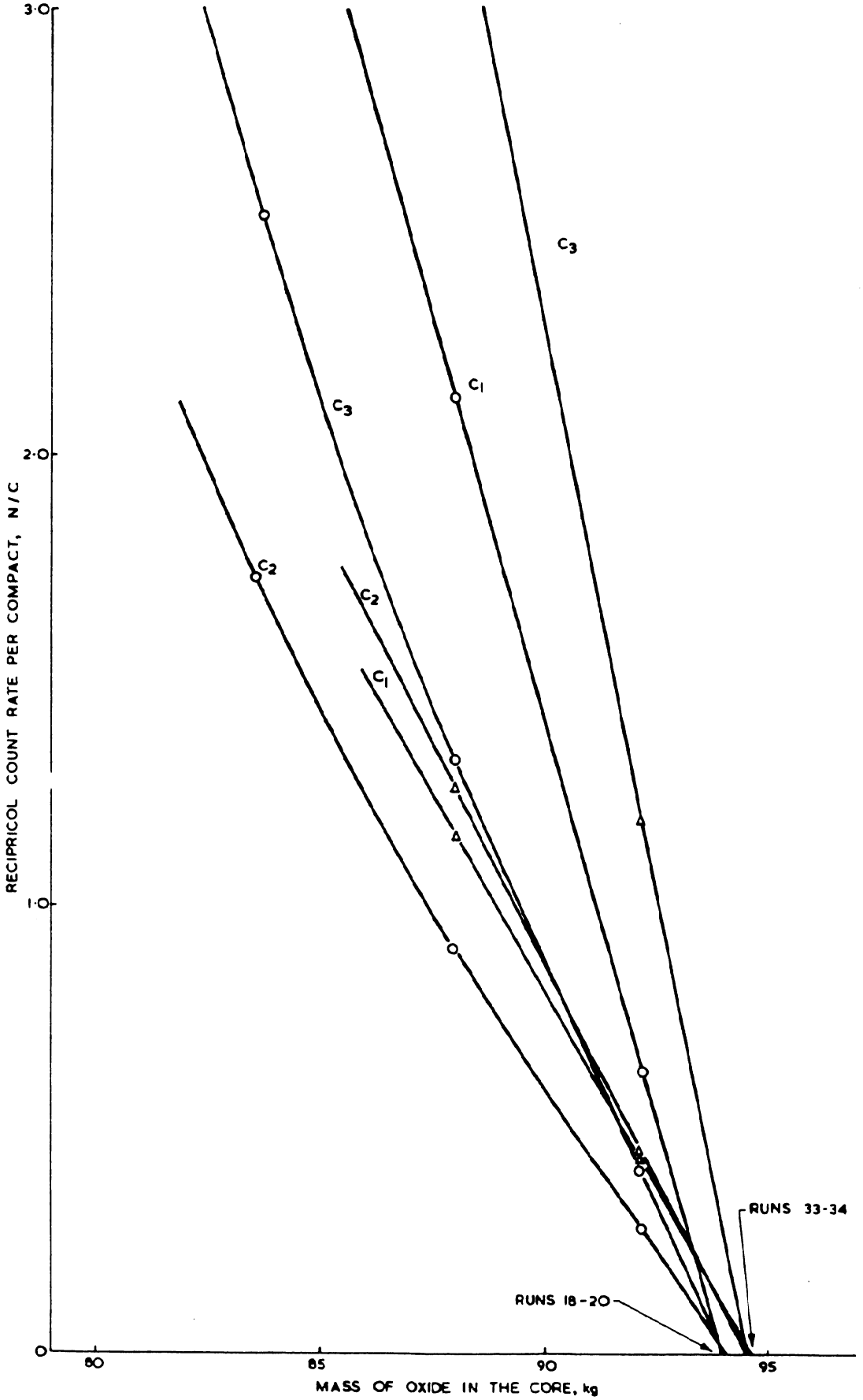

FIGURE 8. EXTRAPOLATION TO CRITICAL FOR CORE HAVING 30·0cm X 30·0cm BASE

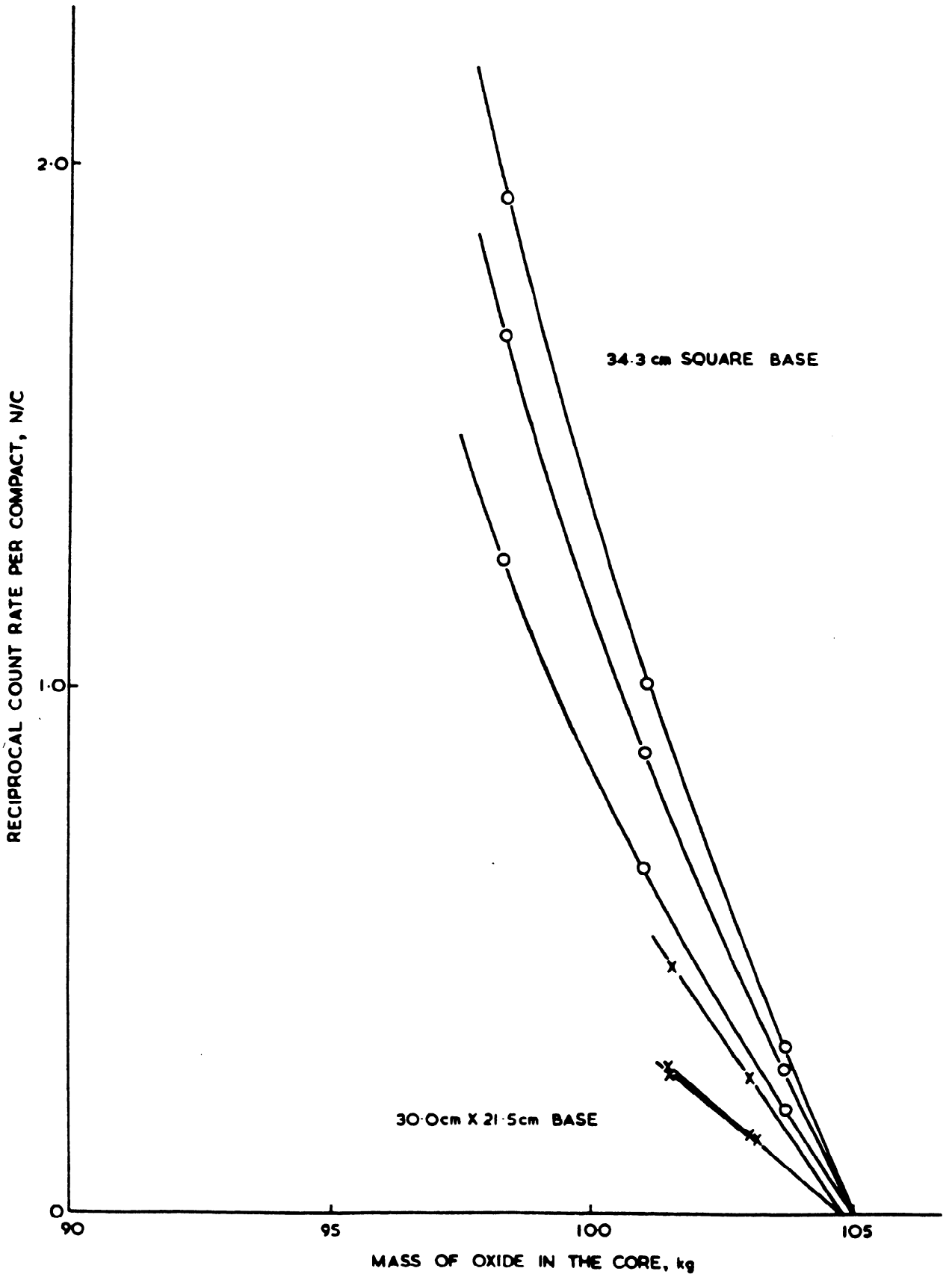

FIGURE 9. EXTRAPOLATION TO CRITICAL FOR CORE HAVING 30·0cm X 21·5cm & 34·3cm X 34·3cm BASE

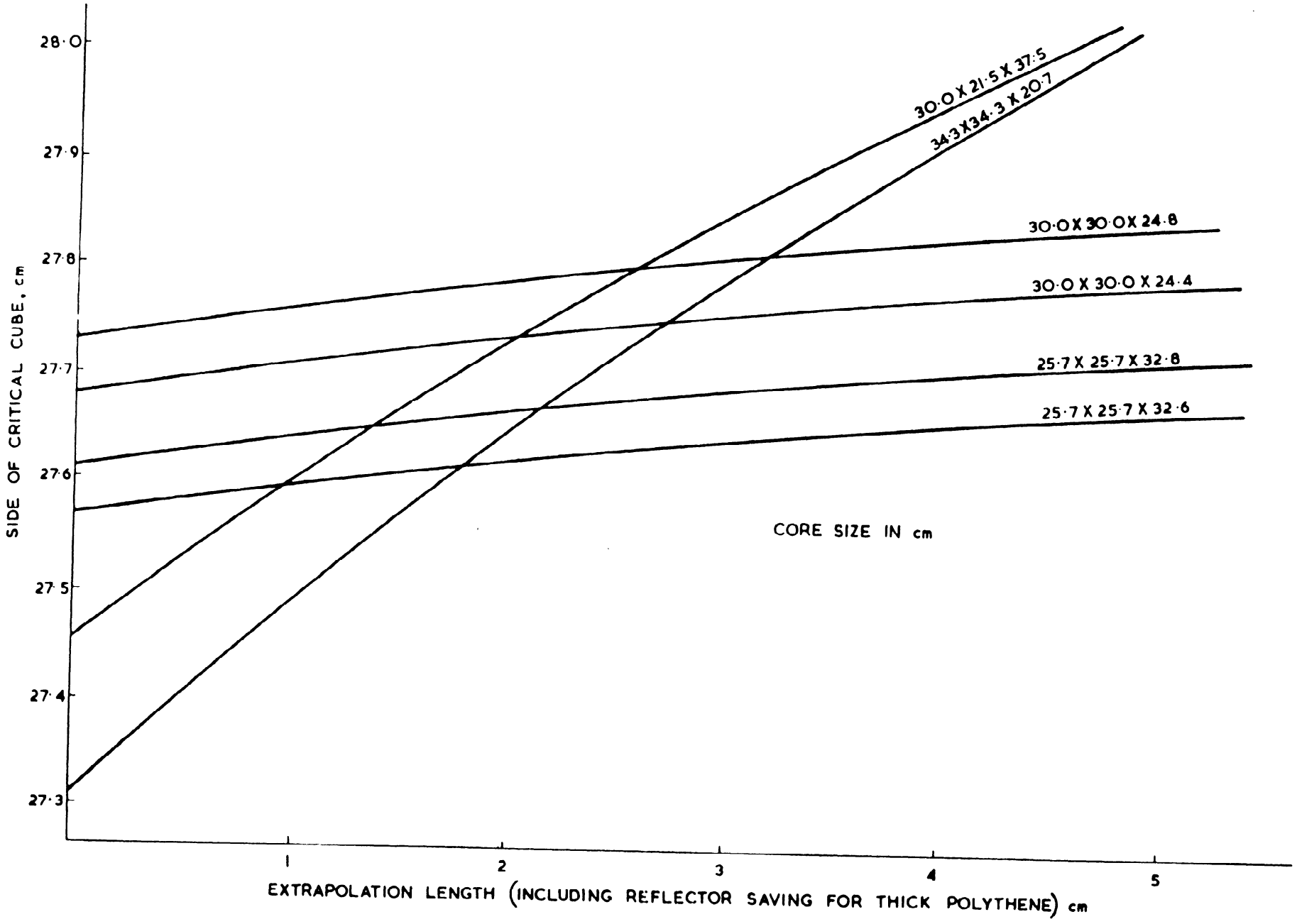

FIGURE 10. BUCKLING CONVERSION OF THICK POLYTHENE REFLECTED CRITICAL PARALLELOPIPEDS TO CUBE GEOMETRY

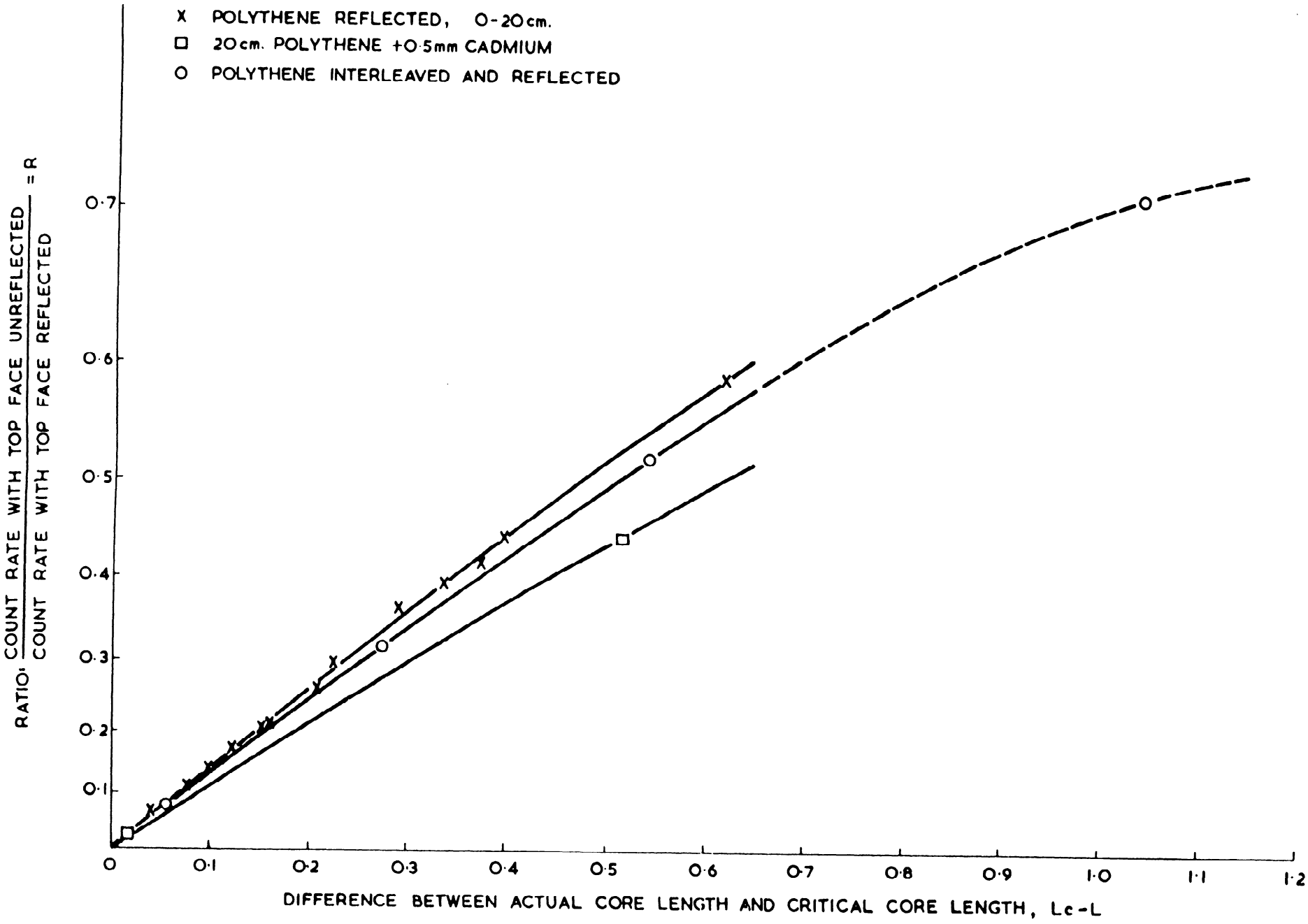

FIGURE 11. COUNT RATE RATIO (R) FOR 30·0cm X 30·0cm SQUARE BASED CORE

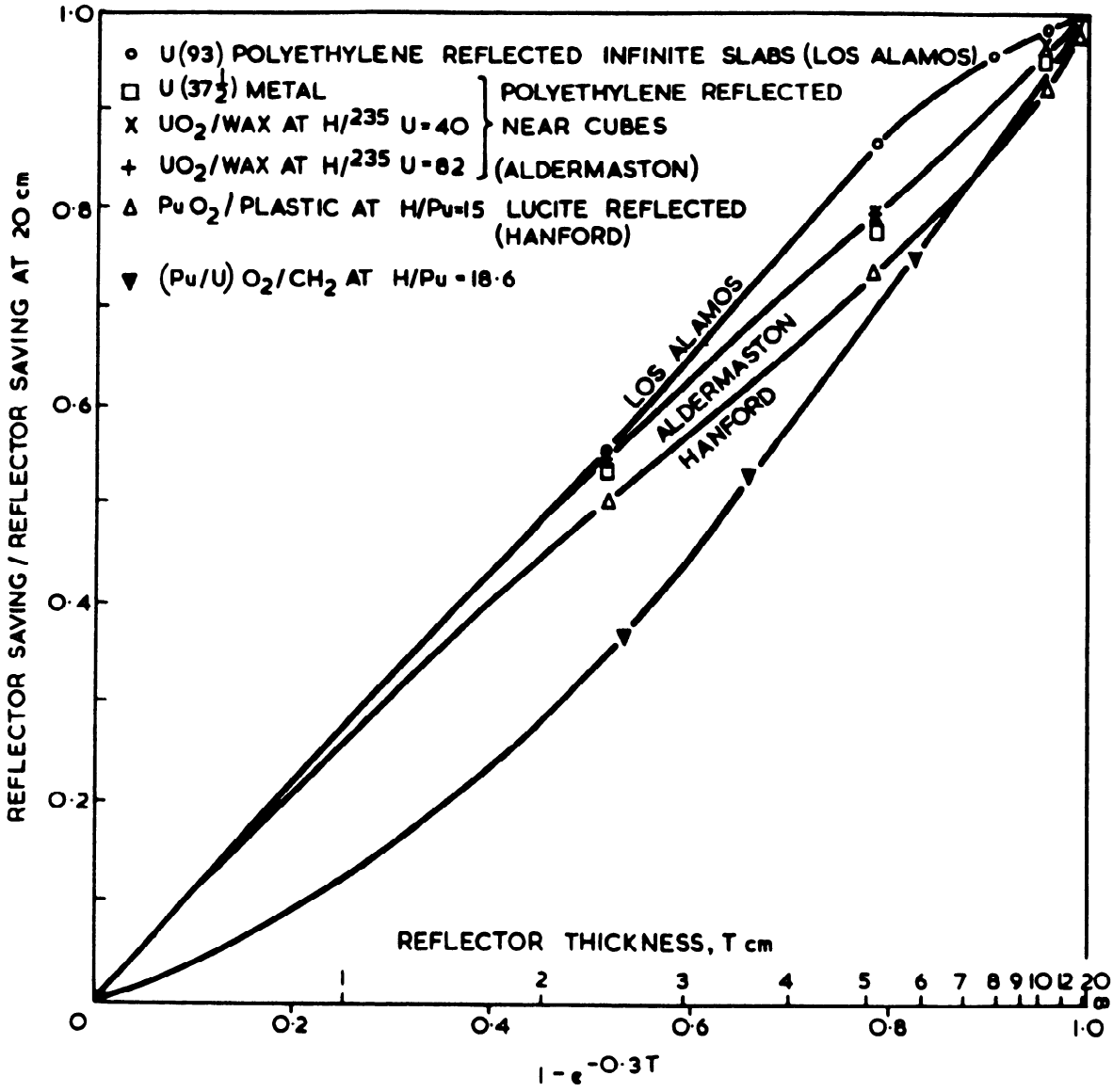

FIGURE 12. VARIATION OF REFLECTOR SAVING WITH THICKNESS

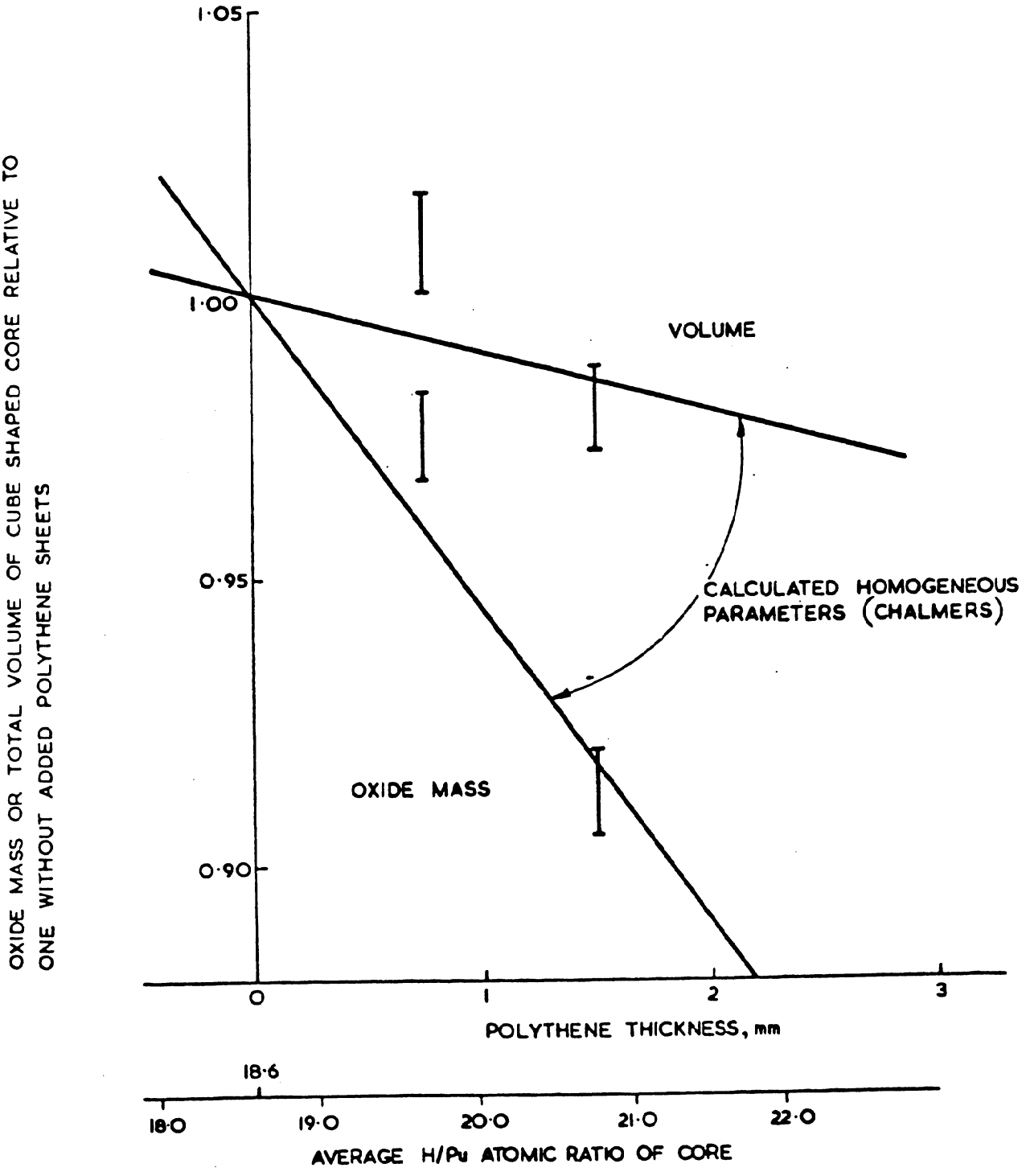

FIGURE 13. EFFECT OF ADDING POLYTHENE SHEETS TO A CORE ON ITS CRITICAL PARAMETERS