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DEPARTMENT OF HEALTH

NEW ZEALAND

THE NATURAL RADIOACTIVITY OF
BUILDING MATERIALS USED IN THE
CHRISTCHURCH URBAN AREA

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1. INTRODUCTION

Information on the natural radioactivity from the gamma emitters of the uranium-238 and thorium-232 series and from potassium-40 in common building materials is limited. Increasing interest in the terrestrial radiation dose to populations from the radioactive content of building materials is apparent, as a number of studies have been reported recently (UNSCEAR 1982). Other recent work has given results from the United States of America (Kahn 1979) and from West Malaysia (Chong and Ahmed 1982). Knowledge of the radioactivity levels in building materials is important in the assessment of population dose and possible radiological hazards. It is also of value for the development of standards or guidelines for the use of such materials in the building industry.

No measurements of the concentrations of the naturally occurring radionuclides have been reported for commonly used building materials in New Zealand, and there is no New Zealand standard prescribing acceptable levels of radioactivity of these materials.

The radioactivity of New Zealand soils has been previously investigated in terms of total emitted alpha and gamma radiations at various locations throughout the North and South Islands (Marsden and Watson-Monroe 1944) and total emitted gamma and beta radiations in the central and southern North Island areas (Gibbs and McCallum 1955). Dobbs and Matthews (1976) measured the concentrations of the naturally occurring radionuclides in 320 soil samples from throughout New Zealand.

In this work, samples of the most commonly used building materials in Christchurch were obtained from manufacturers or building sites, and analysed for the radionuclide concentration of the U-238, Th-232 series and for K-40, by gamma ray spectroscopy.

From the resultant radioactivity measurement, a dose rate "index" was calculated.

Hultqvist (1956), O'Brien (1958), and Dickson, Kerr, Perdue and Abdullah (1976) have calculated dose rates in air one metre above ground level from uniformly distributed quantities of the gamma ray emitting natural radionuclides. The calculated dose rate conversion factors taken from these references after averaging and conversion to SI units were as follows: for radium-226 and its daughters, 4.59×10^{-3} gray per year per becquerel per gram of sample (Gy y^{-1} Bq $^{226}Ra^{-1}$ g) or per Bq uranium-238 if secular equilibrium is assumed between uranium-238 and radium-226. Similarly the dose rate due to the thorium-232 series was calculated as 6.75×10^{-3} Gy y^{-1} Bq $^{232}Th^{-1}$ g and for potassium-40, 1.3×10^{-5} Gy y^{-1} g K^{-1} kg.

Koblinger (1978) and Karpov and Krisiuk (1980) have calculated indoor exposure rates from the known radionuclide concentrations in building materials. Both authors used mathematical models and hence made a number of assumptions. However, Koblinger's theoretical calculations agree well with his geiger-muller measurements. Karpov has devised equations for 2π and 4π geometry situations to give dose rates indoors and outdoors, given the concentrations of radionuclides in the materials present.

2. EXPERIMENTAL METHOD

Materials gathered for analysis included whole building material and samples of the basic constituents. For example, whole concrete block was analysed, as was river and dune sand, cement and various grades of aggregate, the latter being the constituents of the block. Samples of building materials were crushed, sieved, the material up to 1 mm diameter collected and sealed in 50 ml aluminium cans. Wood samples were carefully ashed in a muffle furnace and the ash sealed in the aluminium counting can. All samples were held for one month before analysis so that radioactive equilibrium was re-established between radium-226 and its daughter products, due to partial escape of radon during sample preparation.

The gamma radioactivity in the building materials was measured in the well of a 100 mm x 100 mm NaI(Tl) crystal detector coupled to a 120 mm diameter photomultiplier tube. The whole of this assembly was housed in a massive lead shield to reduce the cosmic and terrestrial radiation contributions. The output from the photomultiplier was fed through an amplification stage and then into 1024 channels of a Nuclear Data ND60 multi-channel analyser. A typical x-ray spectrum is shown in Figure 1. This figure also shows the regions of interest chosen for use in calculation of the radionuclide concentration.

The linearity of the detection system was established by measuring the peak positions of the known gamma energies (E_γ) of a range of radionuclides, and plotting E_γ against the channel numbers in which the peak position occurred. The equation of this line was

$$E_{(keV)} = 1.817 \times (\text{channel number}) - 3.535$$

The background count rate due to cosmic and terrestrial gamma radiation was determined at various atmospheric pressures, as the cosmic radiation intensity is influenced by atmospheric pressure. Icing sugar was used for these determinations and showed no detectable radioactivity above the normal instrument background.

The activity concentrations of the three species were determined by the solution of a set of simultaneous equations involving the net count rates in the following regions of interest in the gamma ray spectrum.

Radium-226: 270-316 keV covering the Pb-214 gamma ray line at 259.2 keV
and 323-400 keV covering the Pb-214 gamma ray line at 352.0 keV

Thorium-232: 190-250 keV covering the Pb-212 gamma ray line at 238.6 keV
and 850-1001 keV covering the Tl-208 gamma ray line at 860.1 keV
Ac-228 gamma ray line at 911.1 keV
Ac-228 gamma ray line at 968.9 keV

Potassium-40: 1370-1528 keV covering the K-40 gamma ray line at 1460.1 keV.

The coefficients required in the concentration equations were determined by counting calibrated samples of known activity. Sodium hydrogen phosphate (analytical grade) spiked to a known activity with radium-226 or thorium-232 was used as a calibrated sample for these two determinations respectively. Analytical grade potassium carbonate was used for the potassium-40 calibration, as the natural abundance of K-40 is well known (Rankama, 1956).

The concentration of the radionuclides from the ^{238}U and the ^{232}Th series were calculated in units of becquerels gram^{-1} (Bq g^{-1}), that of potassium-40 was calculated in terms of grams of potassium per kilogram of sample (g K kg^{-1}).

The counting time of each sample was fixed at 50 000 seconds and the error in the method of determination of the radionuclide concentrations was estimated to be not greater than 15%.

The gain stability of the multi-channel analyser amplifier was checked prior to each sample's measurement and readjusted if necessary. A standard cobalt-60 gamma source was counted and the instrument gain adjusted such that the position of the 1332.5 keV gamma peak always appeared in a known fixed channel position.

3. RESULTS AND DISCUSSION

The radionuclide concentrations of the two naturally occurring series, uranium-238 and thorium-232 and that of potassium-40 in commonly used building materials in Christchurch, as determined by gamma ray spectroscopy are given in Table 1. Dose rates in air due to the three gamma emitting species have been calculated using the conversion factors given in Section 1. These individual air dose rates were summed to give a dose rate "index" for each building material.

$$\text{i.e. } D_{\gamma} = D_{\gamma}(U) + D_{\gamma}(Th) + D_{\gamma}(K)$$

These index dose rates are also presented in Table 1.

Each calculated dose rate is a relative figure rather than absolute, hence comparison between building materials can be made. An estimate of the precise dose that would be received inside a building cannot be made from these dose rate indexes.

Since about 98.5% of the radiological effects of the uranium-238 series are produced by radium and its daughter products, the contribution from ^{238}U and other ^{226}Ra precursors are normally ignored. Because of the probable disequilibrium between ^{238}U and ^{226}Ra in some building materials, in this report where the ^{238}U series is referred to, ^{226}Ra and daughters are more strictly implied.

As was expected, the highest radioactivity concentrations were measured in samples whose base material is a rock or soil derivative (i.e., concrete and brick products). The measured concentrations are highest in brick followed by concrete products and split limestone. This trend is similar to that of published overseas measurements given in the referenced articles. In the Christchurch products, a typical brick is made from a clay mud-stone material and concrete products are made from graded greywacke removed from pits in the Canterbury plains. The split compressed stone has a limestone base which was obtained from deposits in North Canterbury. Interior materials (e.g., timber and linings), glass and iron roofing materials, show typically low radionuclide concentrations and hence give a low dose rate index.

Knowledge of the radiation levels in buildings is important in the assessment of population radiation dose, as the "average" western population spend greater than 80% of their time indoors (Yeates and King 1973, Cardinale et al. 1971, Chapman 1983). The number of country-wide indoor surveys is

small compared to those taken outdoors, the average indoor exposure has thus been calculated from the outdoor value using an indoor - outdoor ratio. In a recent survey carried out in the urban Christchurch area using a high pressure ionization chamber, measurements were made both indoors and outdoors and from these an estimate was made of the mean annual population gonad dose (Chapman 1983).

In the calculation of indoor dose rates from the indoor - outdoor ratio, account must be taken of the distribution of the radioactive materials in the building materials and outdoors. The building materials act as both attenuator and emitter of radiation. Beck (1972) in discussing the physics of environmental gamma radiation fields, plots the fraction of the total dose rate above ground against soil depth. UNSCEAP (1977) suggest that by inference, a wall thickness of 50 g cm^{-2} would absorb practically all terrestrial radiation and that a thickness of 10 g cm^{-2} is sufficient to absorb half of it. In wooden houses, the source effect is small and the walls are an inefficient shield against terrestrial radiation exposure. However in homes made of stone, concrete or brick, the terrestrial gamma radiation is effectively shielded, hence the indoor dose rate is mainly dependent upon the concentration of the radioactive materials in these building products. If the building materials are of local origin then the assumption can be made that the concentration of the natural radionuclides in building materials will approximate their concentrations in the soil.

3.1 Relationships Between Radionuclide Concentrations and Dose Rate Index

It has been shown by other authors that various relationships exist between the component radionuclide content and the dose rate index e.g. for soils (Dobbs and Matthews 1976). These relationships also exist with the building materials analysed for this report. The total dose rate index (ΣD_γ) has been plotted against the concentrations of the three contributing species in Figures 2-4. The line for the uranium-238 series shows a linear relationship

with a Pearson correlation coefficient (r) of 0.90. The thorium-232 line shows a linear relationship with an r value of 0.97. Both lines show the relationship to be approximately independent of the particular material under consideration. As other authors have shown, there is a linear relationship between thorium and uranium concentrations, the ratio here being (Th : U); (1 : 1.1). Dobbs and Matthews (1976) showed that for various New Zealand soils, the ratio was approximately 1 : 1.2, these two figures agreeing to within statistical counting errors.

Graphical plots of the potassium-40 content against ^{238}U and ^{232}Th content showed no correlation. A plot of the potassium-40 content against the dose rate index also showed a linear correlation, but the spread of values was much greater than those of the uranium or thorium plots.

By taking into account the relationship between the uranium and thorium series concentrations the total gamma ray dose rate index can be expressed as

$$\begin{aligned} \Sigma D_\gamma &= k_1 C_{Ra} + k_2 C_{Th} + k_3 C_K \\ &= k_1 C_{Ra} + 0.91\, k_2 C_{Ra} + k_3 C_K \\ &= (k_1 + 0.91\, k_2)\, C_{Ra} + k_3 K \end{aligned}$$

where k_1, k_2 and k_3 are dose rate indices for unit concentration and C_{Ra}, C_{Th}, C_K are the concentrations of radium, thorium, potassium respectively. This essentially makes the equation a two compartment system and suggests that by analysing samples for uranium, or thorium content only, along with the potassium content, a measure of the total dose rate index can be estimated with reasonable accuracy.

3.2 Suggested Activity Limits in Materials Used in Building

To limit the radiation dose the population would annually receive from building materials, a number of proposed standards have been suggested. One

developed by Krisiuk in the Soviet Union is now endorsed in Norway and is proposed as a standard in the Federal Republic of Germany. A recent National Radiological Protection Board Bulletin (NRPB 1982) refers to an article from the USSR on Basic Radiation Standards (BRS-76), which is based on Krisiuk's model and specifies limits on radioactivity allowable in building materials. In essence it is as follows:

> "The specific activity of natural radionuclides in building materials must not be higher than 1×10^{-8} Ci kg^{-1} for ^{226}Ra, 7×10^{-9} Ci kg^{-1} for ^{232}Th or 1.3×10^{-7} Ci kg^{-1} for ^{40}K. For a mixture of these radionuclides the relationship
>
> $$\frac{C_{Ra}}{1 \times 10^{-8}} + \frac{C_{Th}}{7 \times 10^{-9}} + \frac{C_{K}}{1.3 \times 10^{-7}} \leqslant 1$$ must be satisfied."

C is expressed as Ci kg^{-1} of radionuclide.

This criterion however only considers the external hazard from γ radiation. To make allowance for the radiation hazard to internal respiratory organs due to the daughter product of radium (radon-222) and its short lived secondary products, it has been suggested that the acceptable maximum concentration of radium should be reduced to half the level in the above equation. Measurements of the activity concentrations in building materials in the Soviet Union however showed that only a few materials would not satisfy the above expression. In the Federal Republic of Germany, sample analysis showed that 12% of materials tested exceeded that limit (UNSCEAR 1982).

The substitution of measured concentration values of the naturally occurring radionuclides in Christchurch brick samples in the above expression, give it a value approaching 0.5.

Kahn (1979) in the United States of America, derived a similar equation which contained suggested limiting values for the concentrations of the various radionuclide species. Other than BRS-76 limits from the USSR, it is unknown

if other countries have specific building codes covering radionuclide concentrations.

In the USA two extreme examples of high levels of radionuclide concentrations in building practice are reported. In Colorado during the period 1952-1966, tailings from uranium mills were used as back fill material under houses and also as building materials. Action was taken because of the elevated radon concentrations rather than the external radiation dose. The other case was in Idaho and Montana where the use of phosphate slag has been prohibited in the making of interior wall board linings.

3.3 Dose Rate Calculations from Radionuclide Concentrations in Building Materials

Formuale for the calculation of dose rates inside buildings from the known concentrations of the gamma emitting radionuclides in building materials have been reported by O'Brien (1958), Beck (1972) and Eichholz, Clark and Kahn (1980). These equations are all similar in format.

Karpov and Krisiuk (1980) have dervied 2π and 4π geometry equations and suggested that as well as the dose rate being dependent upon the radionuclide concentration, wall thickness, room shape and window and door dimensions must also be considered. The real values of the dose rates are therefore less than the 4π equation would suggest. They also give a more general equation for the calculation of the dose rate above a slab of finite dimensions. Koblinger (1978) derived a Monte Carlo computer program for equating the dose rate to other parameters. From this was calculated the total dose rate at a room centre which was compared to measurements made with direction and energy independent geiger-muller counting equipment. Satisfactory agreement between the two was found.

Substitution of the measured radionuclide concentrations of samples from parks around Christchurch into the 2π geometry dose rate equations show agreement with measurements taken with a high pressure ionization chamber

1 metre above these surfaces, to within experimental accuracy. Some comparisons are given in Table 2.

4. CONCLUSION

The natural gamma radioactivity of a variety of common building materials in Christchurch, has been measured by gamma spectroscopy. Using conversion factors from the literature, relative dose rate indices for the various building materials were calculated and compared. An increasing order of radioactivity concentration was found from timber to compressed limestone to brick products. These levels are however less than the acceptable limits of radioactivity based on some overseas criteria suggested as building standards.

5. ACKNOWLEDGEMENTS

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TABLE 1: Radionuclide Concentrations and Dose Rate Indexes (in air) from Building Materials.

	^{226}Ra Bq/g	^{232}Th Bq/g	^{40}K gK/kg	D_γ Ra	D_γ Th	D_γ K	Dose Rate Index, ΣD_γ $\mu Gy\ y^{-1}$
CONCRETE	x 10^{-2}	x 10^{-2}					
Mixed Concrete	4.58	3.23	15.05	210	218	196	624
Canterbury Pit A	3.50	3.60	17.64	161	243	229	633
Canterbury Pit B	3.89	4.02	17.78	179	272	231	682
River Sand	3.24	3.71	20.52	149	250	267	666
Dune Sand	3.17	3.39	13.34	146	229	173	548
Concrete Block A	2.76	2.62	12.74	127	177	166	470
Concrete Block B	3.76	3.57	14.47	173	241	188	602
Roof Tile A	4.26	2.97	14.65	196	200	191	587
Roof Tile B	1.86	1.85	9.54	86	125	124	335
BRICK	x 10^{-2}	x 10^{-2}					
Brick Type A	6.16	5.64	23.12	283	381	301	965
Brick Type B	6.38	6.18	13.86	293	417	180	890
Brick Type C	5.44	4.85	13.42	250	328	175	753
Brick Type D	5.06	4.36	13.80	232	294	179	705
Clay Tile A	4.39	4.36	7.36	202	294	96	592
Clay Tile B	4.22	4.12	25.38	194	278	329	801
SPLIT COMPRESSED STONE	x 10^{-3}	x 10^{-3}					
Base Material A	5.58	5.51	1.74	26	24	23	73
Base Material B	2.93	0.46	0.31	13	3	4	20
Base Material C	9.42	2.26	0.79	43	15	10	68
Block Type A	5.09	3.18	0.46	23	21	6	50
Block Type B	10.18	2.11	0.62	47	14	8	69
Block Type C	7.96	4.03	0.83	37	27	11	75
Block Type D	2.15	1.84	0.21	10	12	3	25

	^{226}Ra Bq/g	^{232}Th Bq/g	^{40}K gK/kg	D_γ Ra	D_γ Th	D_γ K	Dose Rate Index, ΣD_γ $\mu Gy\ y^{-1}$
TIMBER	x 10^{-4}	x 10^{-4}					
Timber A	1.07	0.23	0.07	0.49	0.16	0.88	1.5
Timber B	1.29	0.67	0.24	0.59	0.46	3.2	4.3
Timber C	1.70	0.61	0.06	0.78	0.41	0.76	2.0
Timber D	0.54	-	2.1	0.25	-	27.4	27.6
OTHER MATERIALS	x 10^{-2}	x 10^{-2}					
Cement	6.59	0.13	-	302	9	-	311
Slate	2.97	3.46	24.0	136	234	312	682
Galvanized Iron	0.01	-	-	3.1	-	-	3.1
Glass	0.42	0.10	2.86	19	7	37	63
Interior Lining A	0.26	-	0.34	12	-	4	16
Interior Lining B	2.59	2.32	11.95	119	157	155	431
Interior Lining C	0.88	0.47	0.59	40	32	8	80

TABLE 2: Comparison of Dose Rates (nGray hr^{-1}) Found by Two Separate Methods

Site	High Pressure Ionization Chamber	Karpov's 2π Equation
A	38.4	49.0
B	40.0	52.4
C	35.4	48.0
D	40.0	62.6
E	48.0	57.0

TABLE 3: Equations for Radioactivity Concentration Calculation.

$$Ra\ (Bq) = 0.1106X - 0.0913Y - 0.0164Z + 0.0048Q$$

$$Th\ (Bq) = -0.0295X + 0.1884Y + 0.0044Z - 0.0489Q$$

$$K\ (g\ K) = -0.0067X - 0.0023Y + 0.0010Z + 0.0446Q$$

Here X is net counts per minute in counting region of interest bounded by channel number 180 - 222 inclusive.

Y = Net cpm in ROI channel numbers 470 - 553.

Z = Net cpm in ROI channel numbers 342 - 392.

Q = Net cpm in ROI channel numbers 756 - 843.

RADIOACTIVE DECAY PROPERTIES OF THE ^{238}U SERIES

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities		
			α	β	γ
$^{238}_{92}U$	Uranium I	4.51×10^9 y	4.15 (25%) 4.20 (75%)	–	–
$^{234}_{90}Th$	Uranium X_1	24.1 d	–	0.103 (21%) 0.193 (79%)	0.063 (3.5%) 0.093 (4%)
$^{234}_{91}Pa$ (99.87%)	Uranium X_2	1.17 min	–	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
$^{234}_{91}Pa$ (0.13%)	Uranium Z	6.75 h	–	0.53 (66%) 1.13 (13%)	0.100 (50%) 0.70 (24%) 0.90 (71%)
$^{234}_{92}U$	Uranium II	2.47×10^5 y	4.72 (28%) 4.77 (72%)	–	0.053 (0.2%)
$^{230}_{90}Th$	Ionium	8.0×10^4 y	4.62 (24%) 4.68 (76%)	–	0.068 (0.6%) 0.142 (0.07%)
$^{226}_{88}Ra$	Radium	1602 y	4.60 (6%) 4.78 (95%)	–	0.186 (4%)
$^{222}_{86}Rn$	Emanation Radon (Rn)	3.823 d	5.49 (100%)	–	0.510 (0.07%)
$^{218}_{84}Po$ (99.98%)	Radium A	3.05 min	6.00 (~100%)	0.33 (~0.019%)	–
$^{214}_{82}Pb$ (99.98%)	Radium B	26.8 min	–	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{218}_{85}At$ (0.02%)	Astatine	~2 s	6.65 (6%) 6.70 (94%)	? (~0.1%)	–
$^{214}_{83}Bi$ (99.98%)	Radium C	19.7 min	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
$^{214}_{84}Po$ (0.02%)	Radium C′	164 μs	7.69 (100%)	–	0.799 (0.014%)
$^{210}_{81}Tl$ (99.98%)	Radium C″	1.3 min	–	1.3 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
$^{210}_{82}Pb$	Radium D	21 y	3.72 (.000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)
$^{210}_{83}Bi$ (~100%)	Radium E	5.01 d	4.65 (.00007%) 4.69 (.00005%)	1.161 (~100%)	–
$^{210}_{84}Po$ (.00013%)	Radium F	138.4 d	5.305 (100%)	–	0.803 (0.0011%)
$^{206}_{81}Tl$	Radium E″	4.19 min	–	1.571 (100%)	–
$^{206}_{82}Pb$	Radium G	Stable	–	–	–

RADIOACTIVE DECAY PROPERTIES OF THE ^{40}K AND THE ^{232}Th SERIES

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities		
			α	β	γ
$^{40}_{19}K$		1.26×10^9 y	–	1.32 (89%)	1.46 (11%)
10.7% ↓ 89.3%					
$^{40}_{18}Ar$	$^{40}_{20}Ca$	Stable	–		
$^{232}_{90}Th$	Thorium	1.41×10^{10} y	3.95 (24%) 4.01 (76%)	–	–
$^{228}_{88}Ra$	Mesothorium I	5.8 y	–	0.055 (100%)	–
$^{228}_{89}Ac$	Mesothorium II	6.13 h	–	1.18 (35%) 1.75 (12%) 2.09 (12%)	0.34 (15%) 0.908 (25%) 0.96 (20%)
$^{228}_{90}Th$	Radiothorium	1.910 y	5.34 (28%) 5.43 (71%)	–	0.084 (1.6%) 0.214 (0.3%)
$^{224}_{88}Ra$	Thorium X	3.64 d	5.45 (6%) 5.68 (94%)	–	0.241 (3.7%)
$^{220}_{86}Rn$	Emanation Thoron (Tn)	55 s	6.29 (100%)	–	0.55 (0.07%)
$^{216}_{84}Po$	Thorium A	0.15 s	6.78 (100%)	–	–
$^{212}_{82}Pb$	Thorium B	10.64 h	–	0.346 (81%) 0.586 (14%)	0.239 (47%) 0.300 (3.2%)
$^{212}_{83}Bi$	Thorium C	60.6 min	6.05 (25%) 6.09 (10%)	1.55 (5%) 2.26 (55%)	0.040 (2%) 0.727 (7%) 1.620 (1.8%)
64.0% ↓ 36.0%					
$^{212}_{84}Po$	Thorium C'	304 ns	8.78 (100%)	–	–
$^{208}_{81}Tl$	Thorium C''	3.10 min	–	1.28 (25%) 1.52 (21%) 1.80 (50%)	0.511 (23%) 0.583 (86%) 0.860 (12%) 2.614 (100%)
$^{208}_{82}Pb$	Thorium D	Stable	–	–	–

LIST OF FIGURES

Figure 1. Typical x-ray spectrum with regions of interest shown for radionuclide concentration calculation.

Figure 2. Radium-226 concentration plotted against the dose rate index.

Figure 3. Thorium-232 concentration plotted against the dose rate index.

Figure 4. Potassium-40 concentration plotted against the dose rate index.

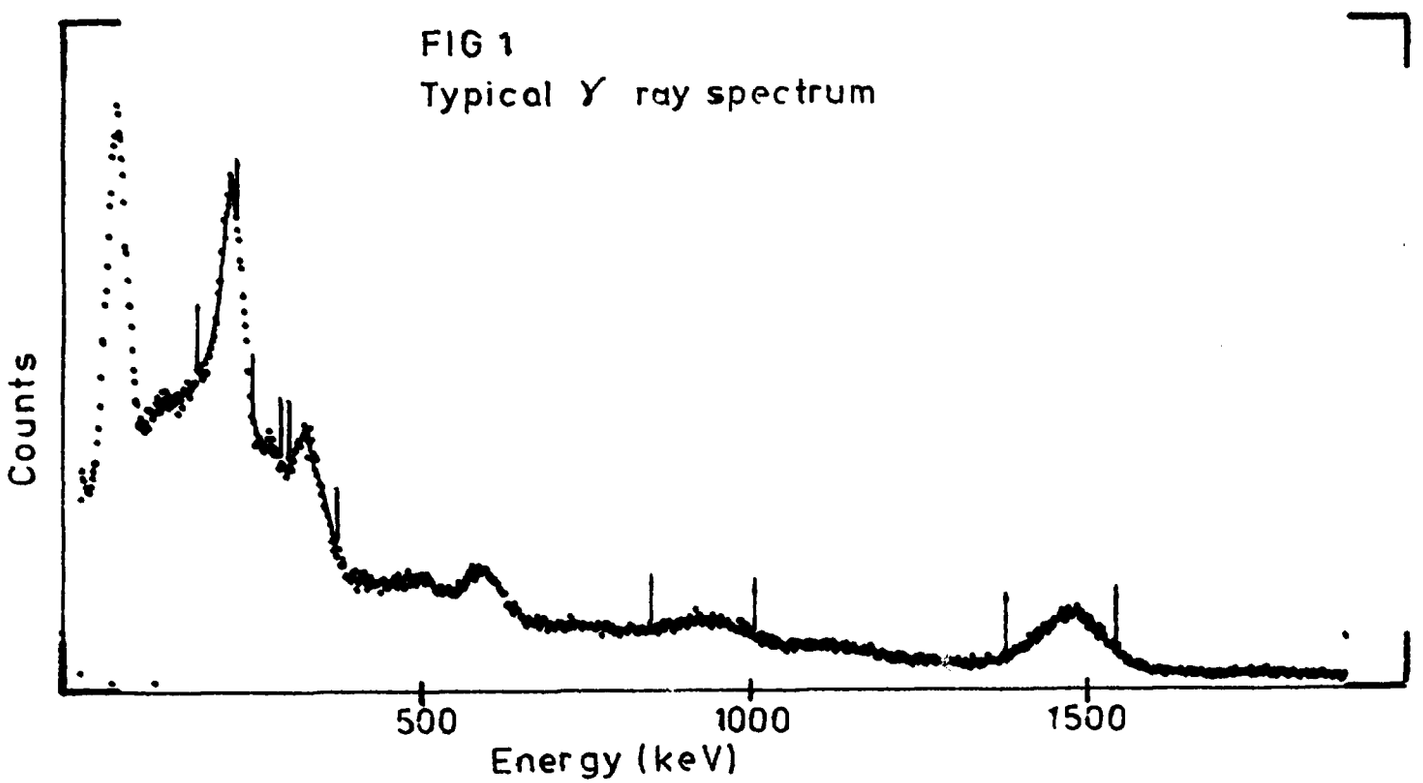


FIG 1
Typical γ ray spectrum

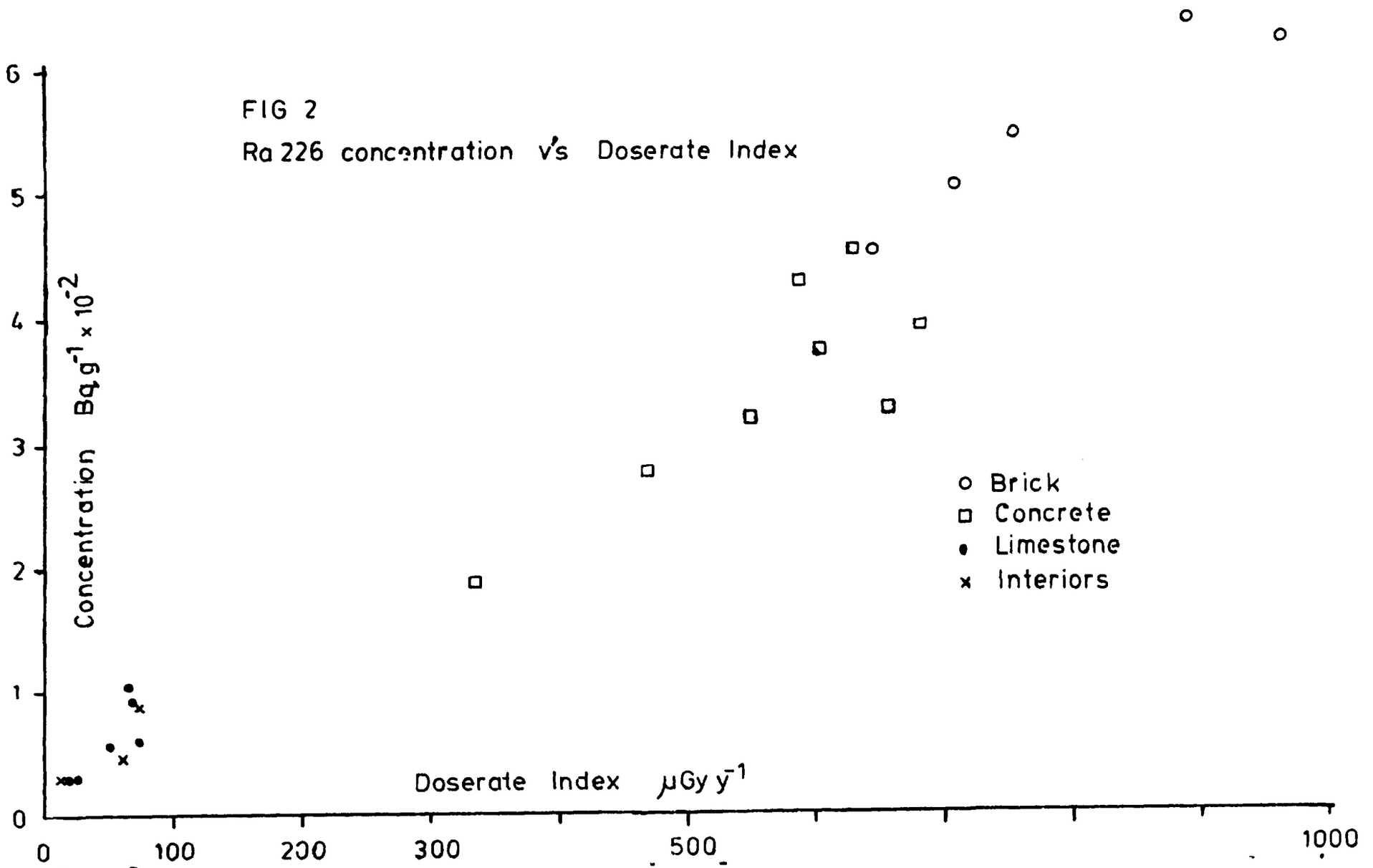
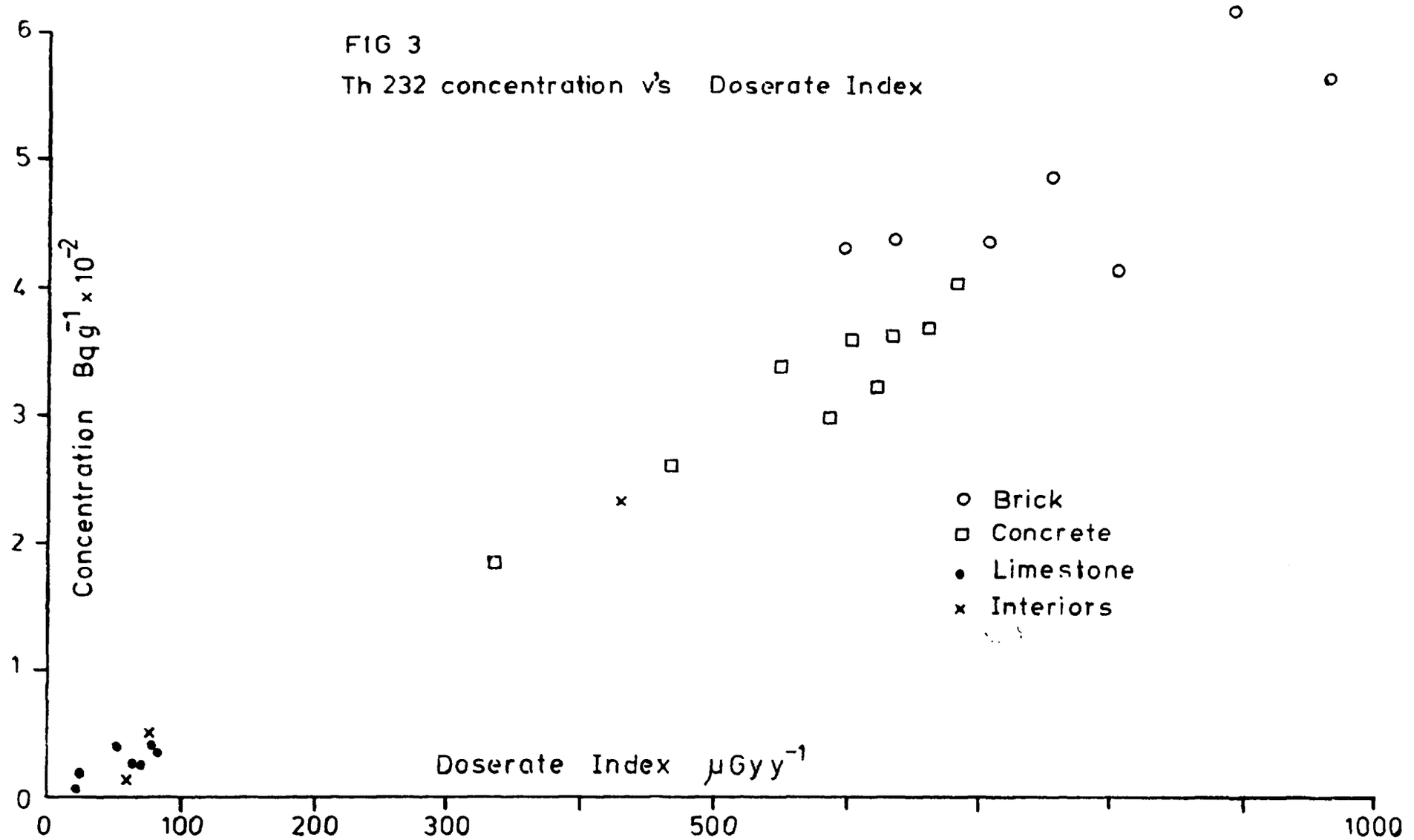


FIG 2
Ra 226 concentration v's Doserate Index
Concentration Bq g^{-1} x 10^{-2}
Doserate Index µGy y^{-1}
0
1
2
3
4
5
6
0
100
200
300
500
1000
Brick
Concrete
Limestone
Interiors

FIG 3

Th 232 concentration v's Doserate Index



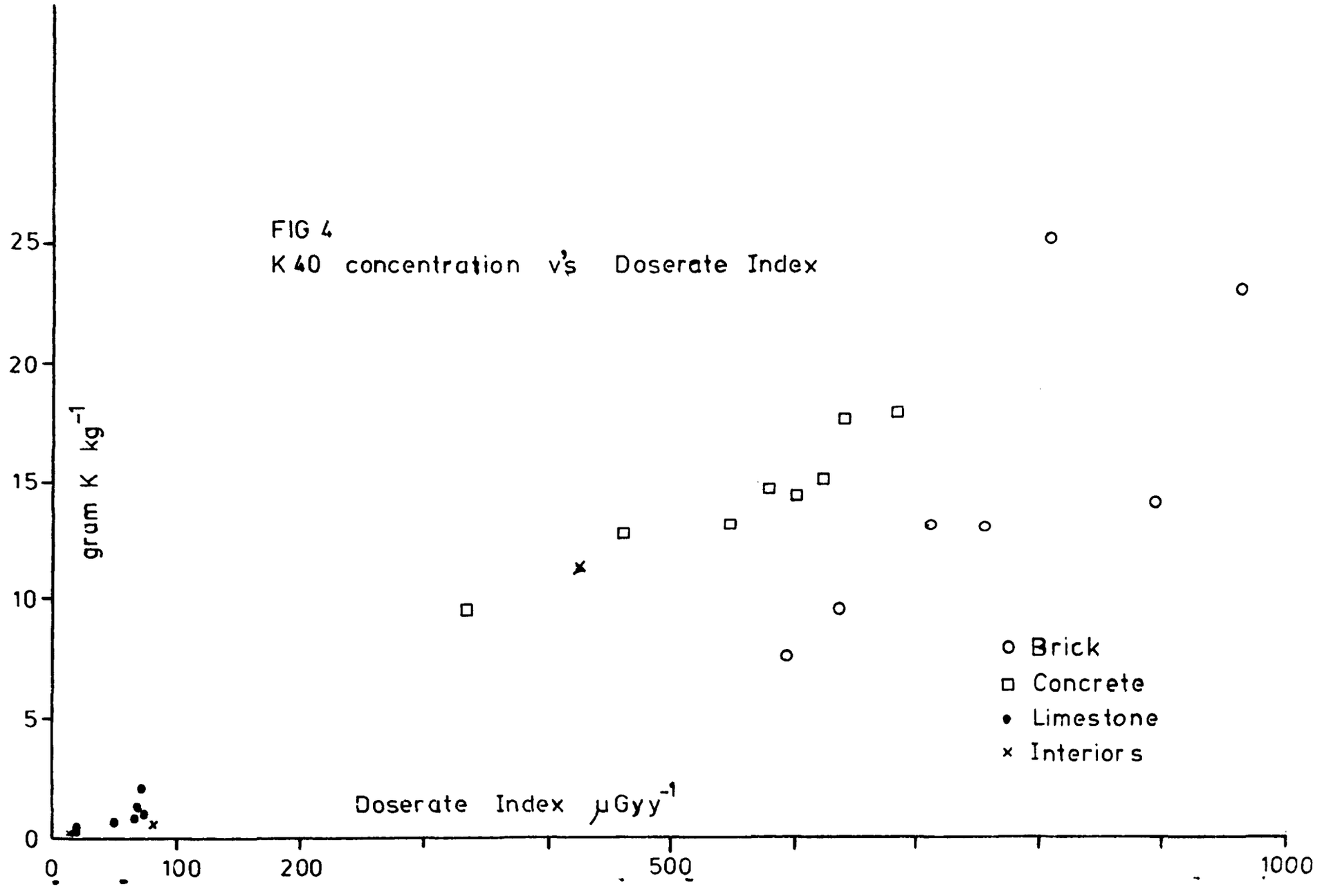


FIG 4
K 40 concentration v's Doserate Index
25
20
15
10
5
0
gram K kg^{-1}
0
100
200
500
1000
Doserate Index μGyy^{-1}
Brick
Concrete
Limestone
Interiors