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National Radiological Protection Board

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THE RADIOLOGICAL IMPLICATIONS OF USING BY-PRODUCT GYPSUM AS A BUILDING MATERIAL

by

M. C. O'RIORDAN, M. J. DUGGAN, W. B. ROSE, and G. F. BRADFORD

ABSTRACT

By-product gypsum, produced as a waste in the phosphate industry, could be used in bulk as a building material, but it has a higher radium content than other building materials and thus raises the question whether or not the resulting radiation doses to individuals and to the population of the country as a whole are acceptable.

The typical radium content is 25 pCi/g, and the corresponding dose rate from gamma rays to the gonads and bone-marrow of the occupants of a house would be 30 mrad/y, if by-product gypsum were a substantial constituent. This is comparable with the regional variations in the dose rate due to natural background radiation in Great Britain and less than the local variations. If as many as 10% of all new houses were eventually so constructed, the resulting gonad dose rate averaged over the population would ultimately reach 3 mrad/y, or about 3% of that from the natural background.

The report also deals with exposures to beta radiation and to radon; these exposures are less than the regional variations in natural exposures.

All the annual doses are at least a factor of 10 below the dose limits recommended by the International Commission on Radiological Protection for exposure of members of the public; these dose limits relate to the total exposure from all sources of radiation except natural background and exposures for medical purposes.

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INTRODUCTION

1. The building industry in Great Britain uses large amounts of waste products from other industries. For example, an appreciable proportion of concrete blocks is made from the foamed slag produced at ironworks and from the pulverized-fuel ash produced at power stations[1]. This practice is considered economically and socially beneficial, since over-all costs are reduced and less of the country is spoiled by the dumping of these wastes.

2. Natural gypsum has been used as a building material for centuries in this country, and there has recently been renewed interest in supplementing supplies of this material with gypsum obtained as a by-product in the manufacture of phosphoric acid from phosphate rock. At present, most of the by-product gypsum, sometimes called phosphogypsum, is pumped into estuaries or coastal waters, but it could be used to make blocks and plasterboard, partition systems and other building components[2,3,4], and also cement[5]. By-product gypsum contains somewhat more radioactivity than other building materials, however, and its use would increase the radiation doses to the public. We indicate in this report what the increases are likely to be, and we assess their significance in the light of the recommendations of the International Commission on Radiological Protection, which are accepted by the Medical Research Council in this country; we also compare them with the doses from natural background radiation.

BUILDINGS AND MATERIALS

3. In Great Britain, there is a large consumption of phosphate rock for the manufacture of fertilizers, detergents, and a variety of other phosphate chemicals. Annual imports of phosphate rock are about 1.6 million tonnes[6], most of it coming from North and West Africa, as shown in Table 1.

Table 1

Details of Phosphate Imports

Origin	Percentage
Morocco	67
Senegal	10
U.S.S.R.	8
Israel	7
Tunisia	4
U.S.A.	2
British Commonwealth	1
Europe	1

Phosphoric acid is produced as an intermediate, the overall reaction being summarized by Gutt[5] as follows:

$$Ca_5F(PO_4)_3 + 5H_2SO_4 + 10H_2O \rightarrow 5CaSO_4.2H_2O + 3H_3PO_4 + HF$$

The current output of phosphoric acid is such that some 2 million tonnes of by-product gypsum have to be disposed of annually. By comparison, about 3 million tonnes of natural gypsum were mined in Great Britain in 1971[7].

4. The average concentration of uranium in the earth's crust is about two parts per million[8], but almost all sedimentary phosphates are uraniferous, and concentrations in them tend to be one or two orders of magnitude higher[9,10]. Uranium and its daughter radium are close to radioactive equilibrium in phosphates. The ores also contain thorium and potassium. Typical activity concentrations of the principal radionuclides in imported phosphates, expressed in picocuries per gramme, are given in Table 2, which also shows measured concentrations in by-product gypsums[10] and the possible concentrations if the nuclides were completely carried over into the by-product.

Table 2

Activity Concentrations (pCi/g) of some Nuclides in Phosphates and By-Product Gypsums

Nuclide	Measured in phosphates	Measured in by-product gypsums	Possible in by-product gypsums*
^{238}U	40	4	29
^{226}Ra	42	21	31
^{232}Th	1	0.5	0.9
^{40}K	7	2	5

*If completely carried over

5. Although these by-product samples were not obtained from the measured phosphates, some conclusions may be drawn from the results. The bulk of the uranium is retained in the phosphoric acid; indeed this was the basis of the extraction of uranium from phosphates[11]. As one would expect, a considerable fraction of the radium is carried into the calcium sulphate. The effect of the reaction on the thorium and potassium is not important from the radiological point of view because of the much lower activity concentrations of these two nuclides. We took 25 pCi/g as the representative value of radium concentration in the by-product gypsum made in Great Britain, since it is roughly midway between the measured and possible values.

6. The radiation dose to the occupants of a building will depend on the amount of by-product gypsum used, the layout of the building, the dimensions of components and structural elements, the amount of time the building is occupied, and the positions of occupants. It is virtually impossible to take account of all these variables; so we predicted the radiological consequences of using a high, yet realistic, amount of by-product gypsum, instead of established materials, in a representative residential building conforming to Department of the Environment standards[12].

7. Specifically, we considered a two-storey, three-bedroom, centre terrace house with a square floor plan, a net floor area of 98 m^2, and a storey height of 2.6 m. Details of the house, derived from a Department of the Environment publication[13], are given in Fig. 1. In traditionally constructed houses of this type, concrete blocks are used extensively for internal walls and natural gypsum plasterboard for ceilings. We assumed:

(i) that all the ceilings were made of by-product gypsum plasterboard;

(ii) that all the concrete blocks in the internal walls were replaced by by-product gypsum blocks, except in the floor-supporting wall;

(iii) that the internal walls quadrisected the house, this assumption giving a slight underestimate of the actual amount of partitioning;

(iv) that no changes were made in any other components or structural elements.

We also assumed that the established and replacement components had identical thicknesses and densities, namely:

plasterboard 12.7 mm and 880 kg/m^3; blocks 76 mm and 820 kg/m^3.

Since by-product gypsum blocks will have finished surfaces, we ignored the <u>in situ</u> plaster on concrete blocks and compared 76 mm concrete with 76 mm by-product gypsum. <u>In situ</u> plaster thicknesses range up to about 25 mm[14].

8. This representative house contains 4.2 tonnes of by-product gypsum.

9. Typical activity concentrations of the same nuclides in natural gypsum[10] and in lightweight and aerated concrete blocks, as used in Great Britain, are given in Table 3.

Table 3

Activity Concentrations (pCi/g) of some Nuclides in Established Building Materials

Nuclide	Natural gypsum	Lightweight and aerated concretes
^{238}U	0.4	4
^{226}Ra	0.6	1.6
^{232}Th	0.2	0.6
^{40}K	4	11

10. It is clear, from Table 3, that the radium concentration in established materials is very low; we therefore took 25 pCi/g as the increase in radium concentration both in the by-product gypsum blocks and in the plasterboard. The other nuclides are relatively unimportant; moreover, their concentrations in by-product gypsum are approximately the same as those in established materials.

RADIATION EXPOSURE FROM BY-PRODUCT GYPSUM

11. There are three types of radiation exposure associated with radium: exposure to beta rays, exposure to gamma rays, inhalation of radon.

Beta radiation

12. The beta-ray dose rate in air near the surface of a building component made of by-product gypsum containing 25 pCi/g of ^{226}Ra is some 20 μrad/h (180 mrad/y), determined both by calculation and measurement. We found, by measurement, that the beta radiation has an apparent absorption coefficient of about 8 cm^2/g [Appendix 1]. The tissues of most concern in this instance are the lens of the eye and the skin. The critical region for the lens of the eye is located at a depth of 3 mm, so the dose is reduced by a factor of about 10 by the overlying tissue. In the case of the skin, the epidermis, nominally 70 μm thick, does not absorb the beta rays appreciably. However, the absorption provided by wall finishes, clothing and furnishings, and the fall-off in dose rate with distance from the component readily reduce the dose by an order of magnitude. The increase in annual dose to the eye lens and the skin would therefore be less than 20 mrad.

Gamma radiation

13. We calculated the gamma-ray dose rate within the representative house due to the by-product gypsum using standard methods(15), supporting crucial aspects of the calculation

by experiment; this dose rate is typically 7 μrad/h in air [Appendix 2]. This single figure masks a complicated dose rate distribution within the house, even though we have considered a simplified structure; the dose rates actually vary by a factor of 2 or so about the typical value.

14. The resulting dose rate to the gonads and red bone-marrow is about 5.3 μrad/h when allowance is made for absorption in the overlying tissues(16,17). We also took into account the effective fraction of time that dwellings are occupied and derived a value of 0.7 from data on economic activity and leisure in a Government Statistical Service publication(18) and some crude estimates of our own. In choosing this factor, we discounted as insignificant coincident exposure to by-product gypsum in houses, places of work, and schools. This may sometimes occur, but it is not likely to be widespread and in any case, cannot greatly influence the result. Thus, the annual increment in the gonad and bone-marrow dose is about 30 mrad.

15. Because of variations in buildings and in the behaviour of people, there will be a spread of dose about this typical figure. The spread will extend upwards by a factor of only 2 or 3: it extends downwards to zero.

16. Since by-product gypsum may be widely used, it may make an appreciable contribution to the genetic dose to the whole population. It is necessary, therefore, to determine the average gonad dose as well as the individual dose, but to do this, it is essential to know the rate at which the housing stock is replaced and the fraction of the new stock that incorporates by-product gypsum. A period of 110 years has been suggested before all the present housing stock in Great Britain is gone(19), but no firm estimate can be made of the extent to which by-product gypsum may be used. If it were assumed that every new dwelling would be like the representative house, then in 110 years time, the average gonad dose rate to the population from by-product gypsum would be about 30 mrad/y. On the more reasonable assumption that about one dwelling in ten were to be so constructed, the figure would be about 3 mrad/y a century from now.

<u>Radon</u>

17. The first daughter product of radium is the noble gas radon, which itself decays to radioactive daughters. Radon and its daughters are constituents of the atmosphere, and their concentrations tend to be higher in buildings than in the open air. The air within a building contains radon which enters from outside, together with radon from the ground beneath and from the structure. The additional radon concentration which arises from the

replacement of established building materials by one containing a higher concentration of radium can be estimated. It is necessary to know the radium content of the new material, the fraction of the radon formed which escapes from the material, and the rate at which the building is ventilated.

18. We measured the fractional radon escape from by-product gypsum panels of various thicknesses and with various finishes [Appendix 3]; a summary of our conclusions is given in Table 4. Panel thickness did not have a marked effect on radon escape over the range of thicknesses we examined, that is up to 76 mm.

Table 4

Fractional Escape of Radon from Components

Untreated panels	0.1
Papered or painted panels	0.07
Untreated plasterboard	0.04

19. From the very few data available[20,21,22], we judged that the ventilation rate in houses is rarely less than one air change per hour averaged throughout the year. Ventilation rates can differ by more than two orders of magnitude depending on atmospheric conditions and personal preference. Allowing for fractional escape and assuming one air change per hour, we calculated the increase in radon concentration within the representative house, due to the use of by-product gypsum, to be about 0.2 picocuries per litre (pCi/l), averaged throughout the year. When we took occupancy into account, as for the gamma radiation, we found the effective increase to be about 0.15 pCi/l, which gives rise to an annual exposure of 0.04 working level months (WLM) [Appendix 3].

DISCUSSION

20. The radiation exposures resulting from the use of by-product gypsum, to the extent that we have postulated, are summarized in Table 5.

Table 5

Radiation Exposures from By-Product Gypsum

Type of exposure	Organ	Magnitude
Beta-ray	Skin and lens of the eye	Less than 20 mrad/y
Gamma-ray	Gonads and bone-marrow	30 mrad/y to the individual 3 mrad/y averaged over the population*
Radon	Lungs	0.15 pCi/l or 0.04 WLM/y

*A century from now

21. It is convenient to discuss each type of exposure in turn.

22. The tissues of most concern, in the case of exposure to beta rays, are the skin and the lens of the eye; the ICRP recommends[23] that the annual dose to these tissues be limited to 3 rem and 1.5 rem respectively for a member of the public. Since the beta-ray dose due to the use of by-product gypsum is at least two orders of magnitude below the ICRP dose limits, this source of exposure can be dismissed.

23. The ICRP recommends a dose limit of 0.5 rem in a year for the irradiation of the gonads and bone-marrow of an individual member of the public. This figure, like other ICRP dose limits, relates to the dose from all sources except natural background and the exposure of patients for medical purposes. The dose due to gamma rays from the use of by-product gypsum is a small fraction, about 6%, of this limit. This dose may also be compared with variations in natural background radiation[24]. Persons are irradiated all the time by natural sources, that is cosmic radiation and both internal and terrestrial radioactivity; the result is that the normal dose rate to the gonads and bone-marrow is about 100 mrad/y, half of which is contributed by the terrestrial radioactivity[25]. In Great Britain, there is a difference of about 25 mrad/y between the average dose rates to the gonads and bone-marrow of the inhabitants of areas of sedimentary and igneous rock[24], with local variations considerably in excess of this.* The increase in annual dose caused by the use of by-product gypsum is about the same magnitude as the regional variations.

24. The increase in the average gonad dose rate to the population will become about 3 mrad/y a century from now if one dwelling in ten is like the representative house. This increase corresponds to 3% of the normal background dose rate. It is about 2% of the figure of 5 rem per generation which, according to the ICRP recommendations, should certainly not be exceeded from all sources additional to the natural background and the exposure of patients.

25. There is little information on radon concentrations in houses in Great Britain, but a value of 0.3 pCi/l is probably appropriate for areas of sedimentary rock, and 1.5 pCi/l for areas of igneous rock[26,27,28]. An average concentration of 1 pCi/l was found in an extensive survey of brick buildings in Sweden[29], an area of complex rock structure. Temporal variations of an order of magnitude can be experienced at the same location due

*In the original work on the estimation of these dose rates[24], a gonad and bone-marrow screening factor of 0.64 was applied to the dose rates in air, which resulted in a difference of 20 mrad/y between different areas. More recent depth dose estimations[16,17] show that the screening factor is about 0.75; consequently, the difference between the tissue doses will increase to 25 mrad/y.

to environmental factors[26,29,30]. In this context, the increase in radon concentration in the house, which is well within the range of natural concentrations, is less significant than the increase in gamma radiation. The ICRP is at present reviewing its recommendations about radon, but in the United States, 4 WLM per year was recently adopted as the appropriate maximum permissible exposure for exposed workers[31]. This figure also has some acceptance outside the United States. It implies an exposure limit of 0.4 WLM per year for a member of the public; our estimate of the exposure due to the use of by-product gypsum is an order of magnitude below this limit.

26. In summary, the radiation exposures due to the use of by-product gypsum are lower than the recommended limits, referred to above, by at least an order of magnitude; they are also comparable with the regional variations in natural sources of exposure and less than local variations. The economic and social benefits of utilizing by-product gypsum are that an additional supply of gypsum becomes available, and waste material, which would otherwise have to be dumped, is put to constructive use.

27. The National Radiological Protection Board considered this matter recently and issued a statement [Appendix 4] signifying agreement to the use of by-product gypsum for building purposes, provided that the radium concentration in finished components was limited to about 25 pCi/g and production and utilization were monitored so that the population dose could be assessed periodically.

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APPENDIX 1

THE DOSE RATE FROM BETA RADIATION

29. There are 8 important beta transitions in the ^{226}Ra decay scheme[32] with maximum energies ranging from 0.4 to 3.26 MeV.

30. We measured the beta transmission through Perspex (Lucite) with a thin-window anthracene scintillator and obtained an apparent absorption coefficient of 8 cm^2/g, which corresponds to an apparent maximum energy of about 2 MeV[33]. We then applied a dose rate calibration factor, derived from measurements with an extrapolation chamber, to the scintillator measurements and obtained the surface dose rate in air; the result was 18 μrad/h.

31. The dose rate in air at the surface of a semi-infinite volume source is given by:

$$\dot{D} = 1.07 \times 10^6 \, C_m \, E_{av} \frac{\text{stopping power of air}}{\text{stopping power of source}} \text{ rad/h} \qquad \ldots (1)$$

where C_m is the number of curies per g, assuming one beta particle per disintegration, and E_{av} is the average energy of the beta particles in MeV. We used the stopping power of aluminium in place of gypsum and did the calculation for the 8 beta energies; the result was 33 μrad/h. We then applied a factor of 1.3 for the absence of backscatter and obtained a value of 25 μrad/h for the surface dose rate in air.

APPENDIX 2

THE DOSE RATE FROM GAMMA RADIATION

32. There are 20 major gamma transitions associated with the decay of ^{226}Ra(32). We consolidated these as shown in Table 6.

Table 6

Energies and Intensities used in Dose Calculations

Gamma energy, MeV	Number per disintegration
0.295	0.26
0.352	0.36
0.609	0.53
1.120	0.37
1.764	0.24
2.204	0.08

33. The task was to estimate the dose rates at various locations in the house from the quadrisecting internal walls and the plasterboard ceilings, with due allowance for scatter and shielding. The properties of the structural elements are presented in Table 7 for convenience.

Table 7

Properties of By-Product Gypsum Elements in House

Properties	Internal Walls	Ceilings
Area	$3.5 \times 2.35\ m^2$	$3.5 \times 3.5\ m^2$
Thickness	76 mm	12.7 mm
Density	820 kg/m^3	880 kg/m^3
^{226}Ra concentration	25 pCi/g	25 pCi/g
Number upstairs	4, cruciform	4
Number downstairs	2, coplanar	4

34. We treated each by-product gypsum element as a plane disc source of equal area and total activity shielded by an inactive slab half as thick as the element. Fig. 2 shows the geometry. The expression for the energy fluence rate of uncollided photons at position P_1, on the axis of the disc, is given by the following equation.

$$\Psi_{axial} = 2.96 \times 10^9 \, C_a \, E \, (2\pi) \, [E_1 (b) - E_1 (b \, Sec \, \theta_1)] \, MeV/cm^2.s \qquad \ldots (2)$$

C_a = surface activity of the disc in Ci/cm^2, assuming 1 photon per disintegration.

E = photon energy, in MeV, per disintegration.

$E_1(b)$ = exponential integral.

b = sum of the number of mean-free-paths in half-slab and air.

θ = half-angle subtended by disc at position of interest.

35. We evaluated this expression for each photon energy, applied the conversion factors needed to give absorbed dose rate in air[34], and summed the results to obtain the dose rate in air on the axis, $\dot{D}_{axial}$.

36. The dose rate off the axis, at position P_2, is given by equation (3).

$$\dot{D}_{non-axial} = \dot{D}_{axial} \, K(^d/Ro, \, ^h/Ro, \, \bar{\mu}Ro) \qquad \ldots (3)$$

$\bar{\mu}$ is the sum of the number of mean-free-paths in the half-slab and in air divided by the distance of the disc from the parallel plane through P_2. The function $K(^d/Ro, \, ^h/Ro, \, \bar{\mu}Ro)$ may be obtained from Ref. 35.

37. We checked the validity of equation (2) by treating the elements as right-circular cylinders with uniform activity distribution and calculating the energy fluence rate at an exterior point P on the axis. The geometry is shown in Fig. 3. This model, unlike the disc model above, deals with self-absorption rigorously[15]. We assumed that the actual energy fluence rate is the mean of the limiting energy fluence rates Ψ_1 and Ψ_2 which are defined in equations (4) and (5).

$$\Psi_1 = 2.96 \times 10^9 \, C_V E \left(\frac{2\pi}{\mu_s}\right)\left[E_2(b) - E_2(b_3) + \frac{E_2(b_3 \, Sec \, \theta_1)}{Sec \, \theta_1} - \frac{E_2(b \, Sec \, \theta_1)}{Sec \, \theta_1}\right] MeV/cm^2.s \ldots (4)$$

$$\Psi_2 = \text{as equation (4), but } \theta_2 \text{ used for } \theta_1 \qquad \ldots (5)$$

C_V = activity per unit volume in Ci/cm^3, assuming 1 photon per disintegration.

E = photon energy, in MeV, per disintegration.

μ_s = linear attenuation coefficient of cylinder.

$E_2(\;)$ = exponential integral.

b = number of mean-free-paths in air.

b_3 = $b + \mu_s h$.

h = cylinder height.

θ = half-angle subtended at P by front or back of cylinder.

38. We then calculated the dose rate in air from the uncollided photons as in the case of the disc; the results were virtually identical. It should also be noted that Ψ_1 and Ψ_2 are almost identical because of the very small heights of the cylinders.

39. The energy fluence rate from uncollided photons at the surface of an element, and hence the dose rate in air, may be obtained from the expression for a semi-infinite slab with uniform activity distribution(36), as given in equation (6).

$$\Psi = 2.96 \times 10^9 \, C_v E \left(\frac{2\pi}{\mu_s}\right) [1 - E_2 (\mu_s t)] \text{ MeV/cm}^2\text{.s} \qquad \ldots (6)$$

C_v, E, and E_2 have the same meaning as in equation (5).

μ_s = linear attenuation coefficient of element.

t = thickness of element, in cm.

40. As noted, all these expressions give the dose rate due to uncollided photons. There will, however, be some dose build-up due to Compton interactions in the element itself and in the intervening air. As part of a general experiment to confirm the validity of the foregoing expressions, we determined the value of the build-up factor in the following manner.

41. We constructed two panels of dense by-product gypsum, described in Table 8, and measured the dose rate 1.07 m along the axis.

Table 8

Properties of Dense By-Product Gypsum Panels

Properties	Thin panel	Thick panel
Area	2.13×2.13 m^2	2.13×2.13 m^2
Thickness	11.5 mm	98.8 mm
Density	1850 kg/m^3	1540 kg/m^3

42. We then substituted equivalent, and relatively inactive, panels of natural gypsum plasterboard and flint lime bricks, allowed for ground scatter, and obtained the net dose rate at the same position due to the excess ^{226}Ra activity in the dense by-product gypsum.

The dose rates were measured by digitizing and scaling the output current of a large tissue-equivalent scintillation detector. Say that the ratio of the measured dose rates from the thick and thin panels is x and the calculated ratio, using the cylinder model, is y. If it is assumed that the build-up factor for the thin panel is unity, the build-up factor for the thick panel is x/y = B. We found B = 1.1 approximately. The result of a spectrometric comparison supported this value. The internal walls of the house have much lower surface density than the thick panels considered above however; the build-up factor for the walls is therefore virtually unity. The same is true for the ceilings.

43. The variation of dose rate with distance along the axis of an internal wall and along the axis of a ceiling in the representative house is shown in Fig. 4. Also, a few off-axis dose rates are tabulated on the chart.

44. The dose rate at a position in a room is due, not only to the photons coming from the walls and ceiling of the room itself, but also to photons coming from elements in other rooms and to photons scattered within the house.

45. We calculated the contribution of photons from other rooms in the manner described above, but applied a correction factor for attenuation in the intervening elements. In doing so, we assumed that all the radioactivity was concentrated at the centre of the contributing element. The correction factors were small, being no more than 25%.

46. We estimated the contribution of scattered photons experimentally. On a cuboid frame with a 2.13 m edge, we erected a 100 mm thick wall of by-product gypsum to act as a source of radiation. Back and side walls of inactive flint lime bricks, 100 mm thick, acted as scatterers; as far as reflection of ^{226}Ra gamma rays is concerned, this is virtually infinite thickness(37). When allowance was made for ground scatter of the gamma rays from the by-product gypsum and the effect of the walls on terrestrial radiation, we found that the dose rate at the centre was increased by about 10% by each scattering element. This increase is higher than albedo theory indicates(37). The discrepancy may be due, in part, to differences in the irradiation geometries considered and, in part, to statistical errors in the measurements, but since scatter is a second order effect, any further effort to reconcile the estimates would have been disproportionate.

47. In the representative house, the situation is complicated by the fact that some of the elements are not thick enough to act as full reflectors and some contain windows. We made allowance for these factors, however, and for the solid angles subtended by the reflectors,

and estimated the dose rates at the centres of the rooms due to both primary and scattered photons. The total dose rates are about 8 μrad/h in air at the centres of upstairs rooms and 6.5 μrad/h in air at the centres of downstairs rooms. It seems reasonable to average these values, so we concluded that the net dose rate within the house, due to the use of by-product gypsum, is typically 7 μrad/h in air.

48. Selecting a typical value simplifies further analysis, but masks the underlying complexity even in this simple structure. An idea of the gradients of the dose rates due to by-product gypsum may be obtained from Fig. 5, which shows the loci of points of equal dose rates in upstairs and downstairs rooms.

APPENDIX 3

EXPOSURE TO RADON

49. We measured the fractional escape of radon in the following way. Several samples of the building components were placed in a steel tank of volume about 12,500 litres and the tank sealed. A number of 3 litre air samples were withdrawn from the tank during the following 2 to 3 weeks and their radon contents measured by a standard method[38]; the method involves counting the alpha particles from the radon daughters deposited on a negatively charged zinc sulphide screen. We inferred the radon content of the air in the tank at radioactive equilibrium and compared this with the radium content of the samples under test. We repeated this procedure for various building components with various surface finishes.

50. The representative house contains 3.1 tonnes of by-product gypsum in the walls and 1.1 tonnes in the ceilings; these imply additional radium contents of about 75 and 27 μCi respectively for a radium concentration in by-product gypsum of 25 pCi/g. The rate of production of radon from radium is about 2.1 pCi of radon per second per μCi of radium, but only a fraction of the radon formed will escape into the atmosphere. If the fractions escaping from the walls and ceilings are taken to be 0.07 and 0.04 respectively (Table 4), it follows that the rate of escape of radon into the rooms of the house will be 13.2 pCi/s.

51. The volume, V, of the air space in the house is about 2.3×10^5 litres. We assumed the ventilation rate to be 1 air change per hour, so that the number of air changes per second, n, is 1/3600. If the radon concentration in the house due to by-product gypsum is C pCi/l, the rate of loss of radon, as a result of ventilation, is nCV pCi/s. In the steady state, this loss must equal the rate of entry of radon into the house atmosphere from the by-product gypsum, the rate of loss by radioactive decay being negligible, so that nCV = 13.2 pCi/s, giving C = 0.21 pCi/l. Taking an occupancy factor of 0.7, we see that the effective radon concentration is about 0.15 pCi/l.

52. The concentration of the daughters may be expressed in terms of the working level (WL). A working level is defined as any combination of radon daughters (RaA to RaC') in one litre of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy from the decay of these daughters to RaD. If the daughters are in radioactive equilibrium with radon, 1 WL corresponds to 100 pCi/l of radon. At a ventilation rate of 1 air change per hour, it can be shown, from the laws of radioactive decay, that the proportions of the radon and daughter concentrations are given approximately by equation (7).

$$\text{Radon} : \text{RaA} : \text{RaB} : \text{RaC} = 100 : 95 : 60 : 40 \quad \ldots (7)$$

53. For a radon concentration of 100 pCi/l and these proportions of daughters, the concentration of daughters was calculated to be 0.53 WL. The radon concentration in the house of 0.21 pCi/l will therefore give rise to a daughter concentration of 0.0011 WL. A working level month (WLM) is the product of the length of exposure in "working months" (170 h) and the concentration of radon daughters in working levels. An occupancy factor of 0.7 for the house corresponds to 118 hours per week, or 511 hours per calendar month. Therefore, the number of working level months in a year is $0.0011 \times \frac{511}{170} \times 12 = 0.04$ WLM.

APPENDIX 4

THE BOARD'S STATEMENT ON THE USE OF BY-PRODUCT GYPSUM IN BUILDING MATERIALS

54. The Board has considered the proposals from the building industry for the use of by-product gypsum in certain building materials. This note is a statement of the Board's conclusions; a full account of the scientific aspects of the studies which have been undertaken is in preparation.

55. By-product gypsum contains more natural radioactivity, principally in the form of radium, than do most other building materials but offers significant technical and economic advantages. There are also some benefits from utilising a substance which otherwise has to be disposed of as a waste.

56. Measurements have been made on samples in various forms to enable the Board to assess the likely radiation dose to the inhabitants of industrial and domestic buildings incorporating materials which contain this substance. Most of the by-product gypsum in its finished form at present has a concentration of radium of no more than 25 picocuries per gram, although the figure is somewhat higher in a few cases.

57. The additional dose to individuals living in houses incorporating such materials would be less than the additional dose resulting from a move from a region of low to a region of high natural background radiation within the United Kingdom. This situation should not therefore be a matter of concern.

58. However, the total dose as averaged throughout the population must also be considered, and this will depend on the extent of the utilisation of the material as well as on its radioactivity. Any estimate of the future extent of utilisation is necessarily speculative. If, after a few decades, this material has been used in say 10% of all buildings, the increase in the average population dose would be about 2% of the background dose observed over most of the United Kingdom. The variation observed in background dose in different parts of the country is about ten times as great as this.

59. The Board considers that such an increase would be justified by the benefits of using by-product gypsum in building materials. The Board wishes to be assured, however, that the extent of utilisation would be recorded so that the situation could be reviewed periodically. Such reviews would take account of the degree of utilisation, the average activity concentration of the material and the latest radiobiological knowledge. If one of these reviews led to the conclusion that the use and/or the activity concentration of the material should be restricted, this could be done on a reasonable time scale.

60. The Board emphasises that a decision to apply limits arises from the need to restrict the total dose from this source to a small proportion of the total population dose from all sources of radiation. It therefore decided that by-product gypsum may safely be used as a building material subject to the following provisos:-

(1) Sources of the raw material giving rise to concentrations of radium in the finished product significantly in excess of 25 picocuries per gram should be avoided so that the average over the whole country shall not exceed 25 picocuries per gram.

(2) Arrangements should be made for recording the production and utilisation of the material and measuring its radioactivity. The information thus obtained should be reported to the Board annually to enable it to carry out periodic assessments of the population exposure.

N.R.P.B. Harwell
14th June 1972

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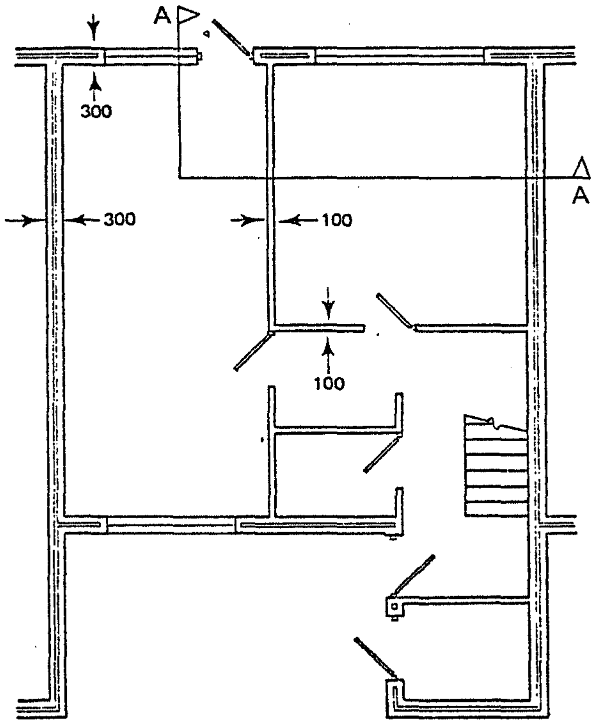
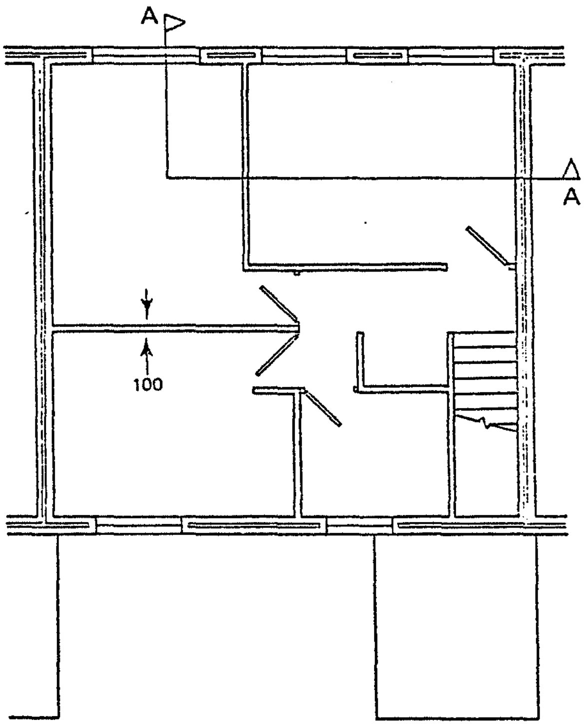
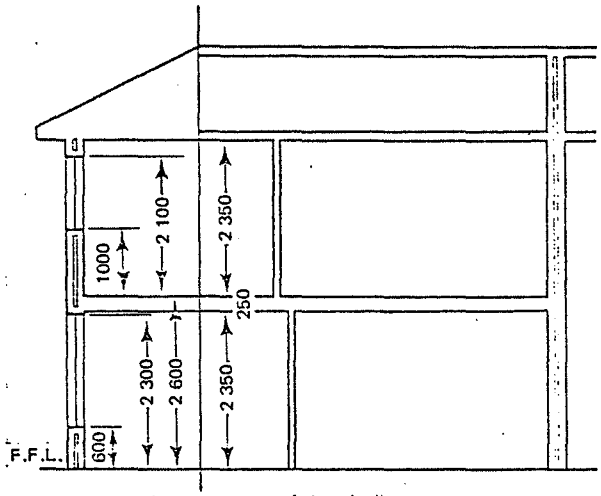


Ground floor plan



First floor plan

ELEMENT	ZONE
External wall:	
brick outer leaf concrete block inner leaf with *in situ* plaster.	300 mm
Separating wall:	
brick with *in situ* plaster.	300 mm
Floor-supporting internal wall:	
concrete block with *in situ* plaster.	100 mm
Other internal walls:	
concrete block with *in situ* plaster.	100 mm
Upper floor:	
softwood boards, joists and plasterboard ceiling.	250 mm
Roof:	
trussed rafters, battens and tiles, plasterboard ceiling.	—



Section A-A

FIG.1 TRADITIONALLY CONSTRUCTED TERRACE HOUSE
SCALE 1:100

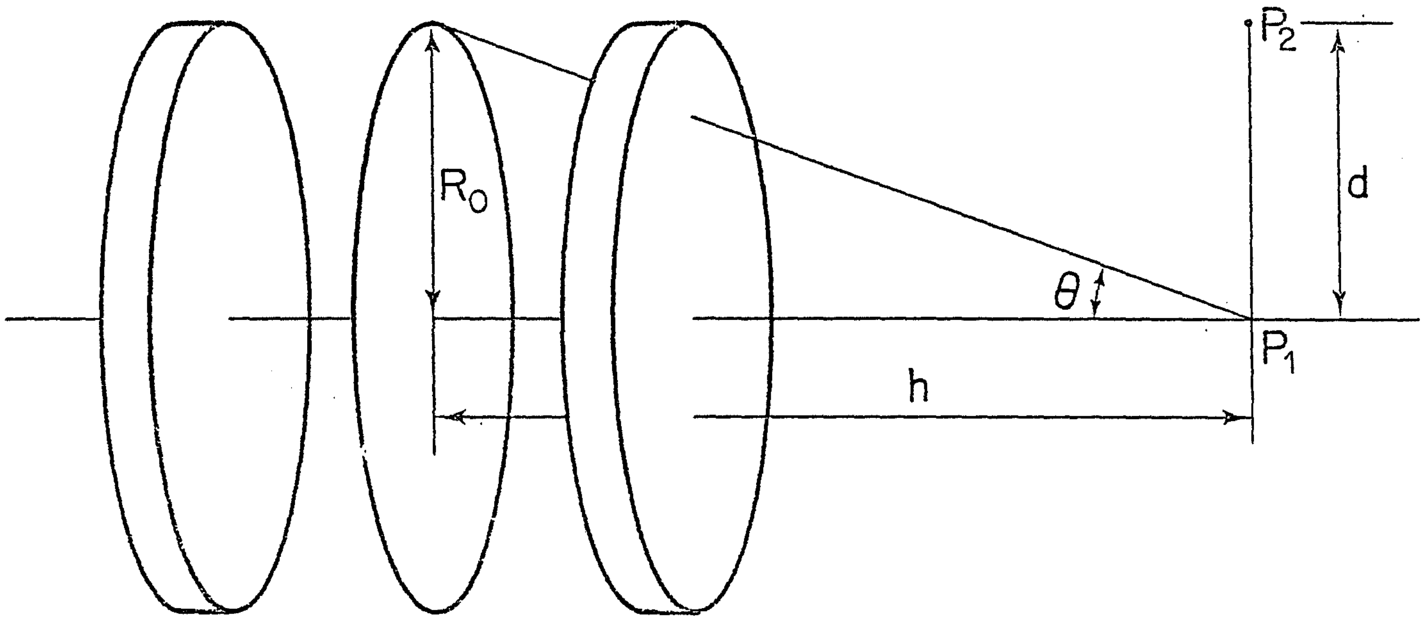


FIG. 2. DISC SOURCE GEOMETRY

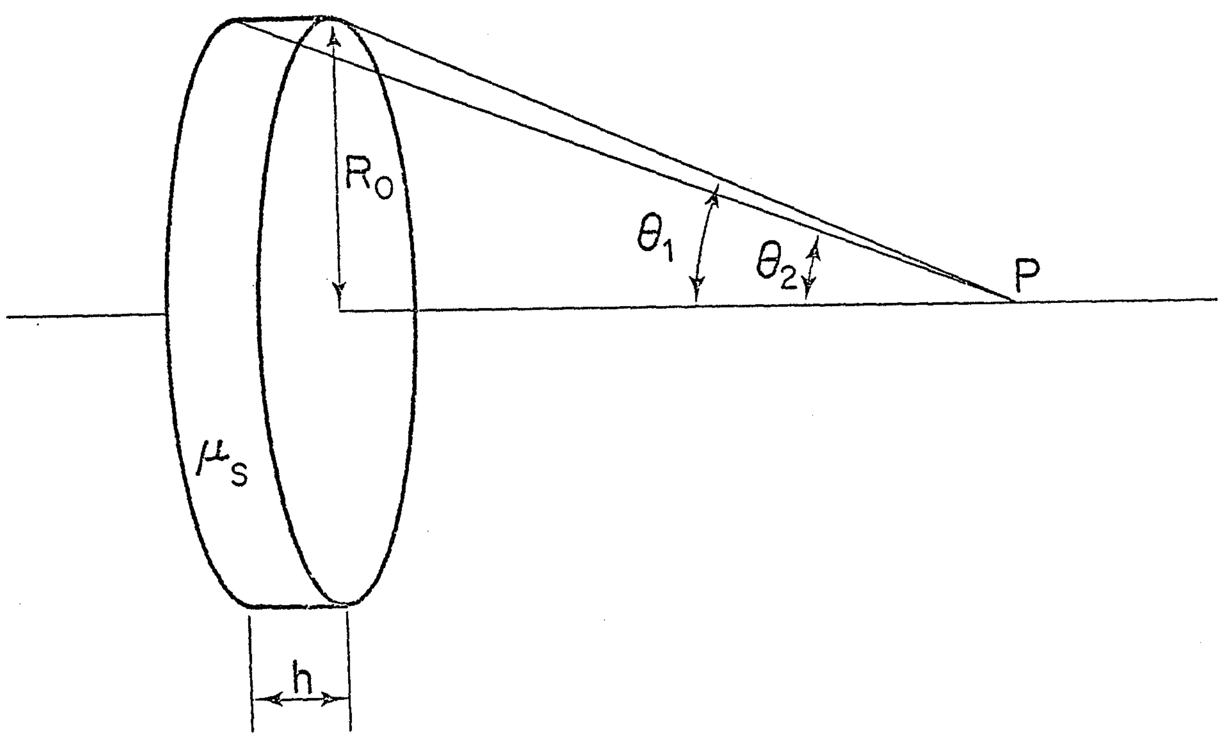
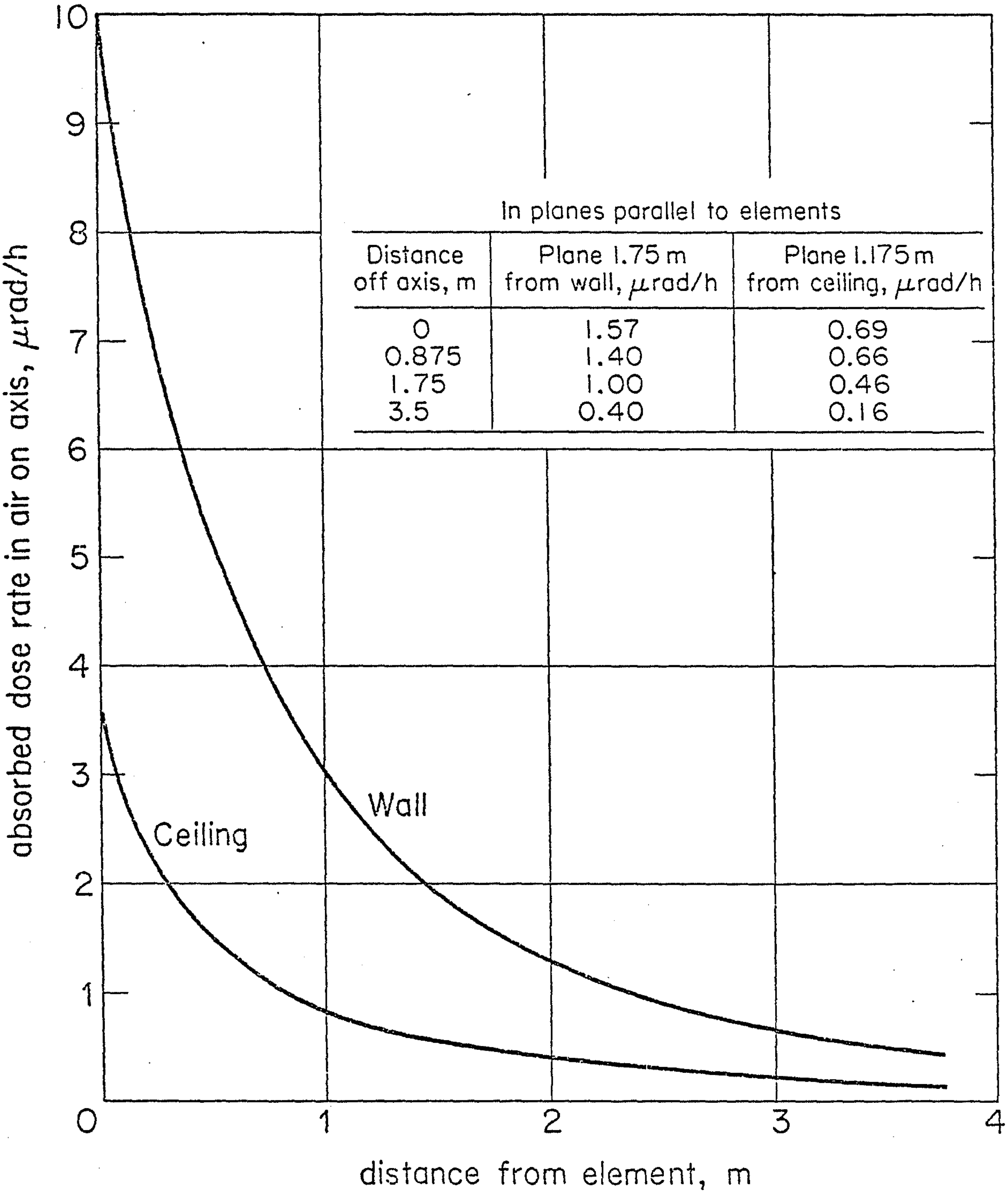


FIG. 3. CYLINDER SOURCE GEOMETRY



In planes parallel to elements

Distance off axis, m	Plane 1.75 m from wall, μrad/h	Plane 1.175 m from ceiling, μrad/h
0	1.57	0.69
0.875	1.40	0.66
1.75	1.00	0.46
3.5	0.40	0.16

FIG. 4. DOSE RATES FROM ELEMENTS IN HOUSE

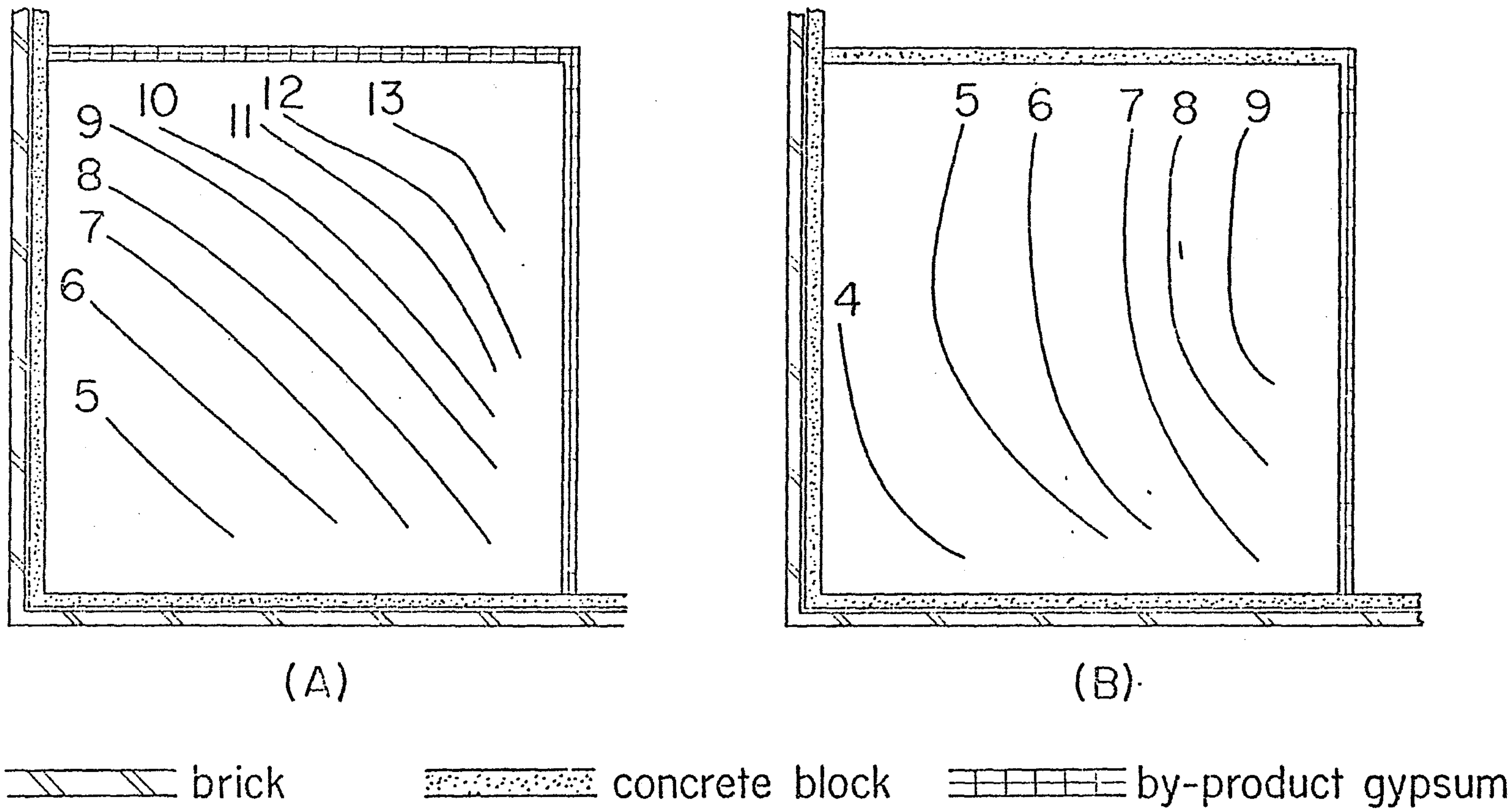


FIG. 5. LOCI OF POINTS OF EQUAL DOSE RATES, μrad/h, IN HORIZONTAL CENTRE PLANES UPSTAIRS (A) AND DOWNSTAIRS (B)

SCALE 1:50

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