

These differences in mean background radioactivity might be reflected in significant differences in mean radiation exposure between the populations of these areas.

Entirely unrelated approaches were utilized by the Health and Safety Laboratory and Harvard groups in

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we have defined 'population exposure' as the free air dose 'experienced' by typical individuals in their usual rounds of activity. We consider only the air dose from the more penetrating components of the environmental radiation field, that is, the terrestrial γ - and ionizing cosmic radiation. This definition can be justified by the fact that the mean γ -doses to the skin and at various depths in the body are fairly well-known fractions of the free air γ -dose^{9,10}, and only the more penetrating components of the external radiation field significantly contribute to the dose at the depths of greatest interest, that is, those of the gonads and bone. It should be noted that the possibly important tissue dose contribution from cosmic ray neutrons is not determined by the techniques used in these investigations.

The Health and Safety Laboratory radiation survey was carried out in July and August 1962, and subsequent check measurements were made in May and September 1963 and May 1964. The instrumentation included high-pressure argon ionization chambers for total dose-rate measurements, a γ -spectrometer system for determination of component dose rates (particularly necessary for discrimination between the natural and fall-out γ -radiation), and portable scintillation detectors for surveys of the areas surrounding each outdoor measurement location as well as for the indoor measurements. The survey techniques, described in detail elsewhere¹¹⁻¹³, provide an overall accuracy of ± 5 per cent (*S.D.*) for the measured total dose-rate values and approximately ± 10 per cent for each of the various components of the total radiation field. The outdoor readings were taken in large, flat open spaces situated in populated areas (for example, parks, fields, lawns, vacant lots) with the instruments placed 3 ft. above the ground. The number of measurements in each area was determined by its population and size, the availability of proper sites, and the observed range and pattern of the previous readings. A sufficient number was taken to ensure that a reasonable radiation profile could be constructed for each area. The quite limited

illuminated areas (for example, parks, lots) with the instruments placed. The number of measurements in each area was determined by its population and size, the number of sites, and the observed range and standard deviation of the readings. A sufficient number of measurements were made to obtain a reasonable radiation profile for each area. The quite limited

spectrometer readings summarized in Table 1. In the region, except for 16 at Conway), separate ionization-chamber readings were made at many other sites along with a number of independent portable scintillometer surveys. The uniformity of the outdoor radiation levels in each area was remarkable. In general, streets and sidewalks did not significantly alter the observed profile.

Any attempt to estimate population exposure to environmental radiation must take into account the

2.14 874
 5.2 109
 1152
 3884
 812

Table 1. MEAN OUTDOOR γ -RADIATION LEVELS

Region	Bedrock	eU* (p.p.m.)	K		U		Th		Natural γ		Fall-out μ /h
			μ /h	%	μ /h	p.p.m.	μ /h	p.p.m.	μ /h	eU (p.p.m.)	
New Hampshire											
1. Manchester	Fitchburg Granite	23	2.5	1.5	1.1	1.5	3.4	9.4	7.0	9.2	2.2
2. Concord	Binary Granite	26	2.0	1.7	1.2	1.6	4.3	11.0	8.4	11.1	2.2
3. Franklin	Littleton Formation	23	2.4	1.4	1.2	1.6	3.5	10.7	7.1	9.4	1.8
4. Conway	Conway Granite	45	3.0	2.1	1.7	2.2	5.8	15.6	10.9	14.3	2.7
Vermont											
1. Rutland	Dunham Dolomite	5	2.6	1.5	1.0	1.3	2.0	5.6	5.6	7.4	2.3
2. Middlebury	Beldens Formation	5	3.2	1.9	0.8	1.1	2.6	7.2	6.6	8.7	2.0
3. Bennington	Glacial Drift	9	3.3	1.9	1.0	1.3	2.2	6.1	6.5	8.6	2.0
4. Burlington	Monkton Formation	11	2.4	1.4	1.0	1.3	1.8	5.0	5.2	6.8	2.4

* Mean bedrock radioactivity as estimated by Billings.

Table 2. MEAN WEEKLY DOSES IN MR./WEEK

Geological category	eU (p.p.m.)	Outdoor Natural γ	Outdoor Total γ *	Cosmic	Mean population exposure	
					1962†	Natural Dosimeters
Dunham Dolomite	5	0.94	1.34	0.62	1.69	1.37
Beldens Formation	5	1.11	1.43	0.62	1.74	1.49
Glacial Drift	9	1.09	1.43	0.62	1.76	1.49
Monkton Formation	11	0.87	1.27	0.50	1.61	1.29
Fitchburg Granite	23	1.18	1.52	0.60	1.82	1.54
Littleton Formation	23	1.19	1.63	0.61	1.91	1.56
Binary Granite	26	1.41	1.78	0.60	2.05	1.73
Conway Granite	45	1.83	2.27	0.61	2.43	2.07

* Includes fall-out, averaged over all locations within an area.
 † Obtained as indicated in the text; in units of air dose rate.

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					1962†	Natural	Dosimeters
Dunham Dolomite	5	0.94	1.34	0.62	1.69	1.37	2.07
Beidens Formation	9	1.11	1.43	0.69	1.74	1.49	2.86
Glacial Drift	11	1.09	1.43	0.62	1.70	1.49	3.01
Moakton Formation	23	0.87	1.27	0.59	1.41	1.29	2.70
Fitchburg Granite	23	1.18	1.52	0.60	1.82	1.54	3.13
Widdowson Formation	26	1.19	1.63	0.61	1.91	1.56	2.97
Binary Granite	45	1.41	1.78	0.60	2.05	1.73	3.21
Conway Granite	45	1.83	2.27	0.61	2.43	2.07	3.67

* Includes fall-out, averaged over all locations within an area.
 † Obtained as indicated in the text; in units of air dose rate.

effect of man-made structures on ambient radiation fields, since most individuals spend a large fraction of their time indoors. Portable scintillation detector readings were made in 160 private homes and apartments in the main towns to ascertain whether any consistent relationship existed between indoor and outdoor radiation levels. Several rooms in each dwelling were surveyed, including the living-room and at least one bedroom. Again, a strong uniformity exhibited itself in that the mean indoor levels were close to 70 per cent of the corresponding outdoor levels in each area⁴. This may be related to the fact that the vast majority of the dwellings were of wood-frame construction, with the building materials appearing to act generally as γ -ray shields with relatively little activity of their own.

With such data at hand, an estimate of mean population exposure to environmental radiation can be obtained by calculating a suitably weighted average of the indoor and outdoor readings of the survey instruments. Taking into consideration the greater occupancy time indoors of the average individual, the mean exposure levels have been estimated to be 80 per cent of the mean outdoor terrestrial γ -dose rates given in Table 1, plus the contribution from the ionizing components of the cosmic radiation at the ground altitudes of the various areas¹⁵. No correction of the cosmic-ray figures for typical structural shielding has been made, since this would be a reduction of the order of 10 per cent or less, which is comparable to the present uncertainty in the absolute cosmic-ray ionization intensity.

Table 2 shows the population exposure data arranged by geological region. The mean weekly outdoor doses in air are given for both natural and total (natural plus fall-out) γ -radiation and for cosmic rays, and the Health and Safety Laboratory population exposure estimates for the time of the survey (August 1962, including fall-out) and for the natural emitters only (that is, the mean life-time levels neglecting fall-out) are also given. The importance of the spectrometric technique is emphasized by the fact that estimates of the integrated natural γ -dose were obtainable even under conditions of near-maximum fall-out contamination. In many population investigations, it is just this quantity that is desired.

The Harvard investigation involved the use of a set of 200 Victoreen model 362 condenser ionization-chamber pencils, along with a stable pulse height readout system^{16,17} which is designed to allow readings of 1.0 ± 0.2 mr. at the 95 per cent confidence level with a single pencil. Mechanical and thermal stability was tested, and corrections made for average leakage rates observed in the laboratory.

These dosimeters were distributed in pairs to five individuals in standard occupational categories in each of 16 areal units, half urban and half rural. The dosimeters

were worn for one week, collected, read, and then re-distributed. The experiment was conducted for five weeks, resulting in a total sampling of 400 individuals, 25 in each areal unit (that is, 50 in each of the eight geological regions). The details of this study are discussed by Segall^{1,3}.

Estimates of population exposure from the mean values of the Harvard dosimeter data in the various areas are given in the last column of Table 2. These air dose values are derived from Segall's data^{1,3} by assuming that each of the dosimeters, worn on the body surface, read 100 per cent of the cosmic-ray ionization and 85 per cent of the γ -ray ionization in free air. The latter figure is based primarily on the recent measurements of body attenuation factors by Spiers and Overton⁶.

The Health and Safety Laboratory and Harvard population exposure results are plotted as a function of estimated mean bedrock radioactivity in Fig. 1, with the respective regression lines indicated. Plotted also in Fig. 1

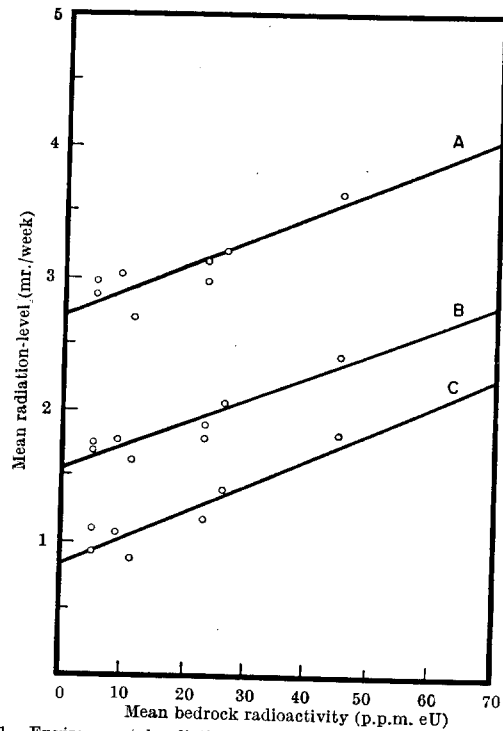
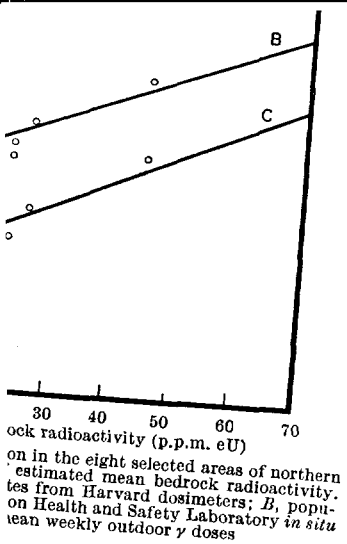


Fig. 1. Environmental radiation in the eight selected areas of northern New England as a function of estimated mean bedrock radioactivity. A, Population exposure estimates from Harvard dosimeters; B, population exposure estimates based on Health and Safety Laboratory *in situ* measurements; C, mean weekly outdoor γ doses



formations and their respective overburdens of soil in terms of natural radioactivity. The apparent near-linearity of the population exposure estimates as a function of bedrock radioactivity derives from the similar relationship between estimated mean soil and bedrock radioactivities, since the outdoor (and to some extent the indoor) radiation-levels to which the general population is exposed are closely related to the content of natural γ -emitting radioisotopes in the upper layers of the soil.

Fig. 2 shows the Harvard dosimeter data plotted directly as a function of the Health and Safety Laboratory 1962 total exposure results. The high degree of correlation ($r > 0.9$) between the Harvard and Health and Safety Laboratory estimates of population exposure is evident; a line of unit slope fits the data quite well. The 1.2 mr./week value for the Y-axis intercept of this line is a measure of the apparently systematic deviation between these two sets of data. While not enough information is at present available to explore this problem fully, one obvious possibility is that the pocket dosimeters consistently exhibited enhanced leakage under field conditions as compared with that measured in the laboratory and corrected for in the data interpretation.

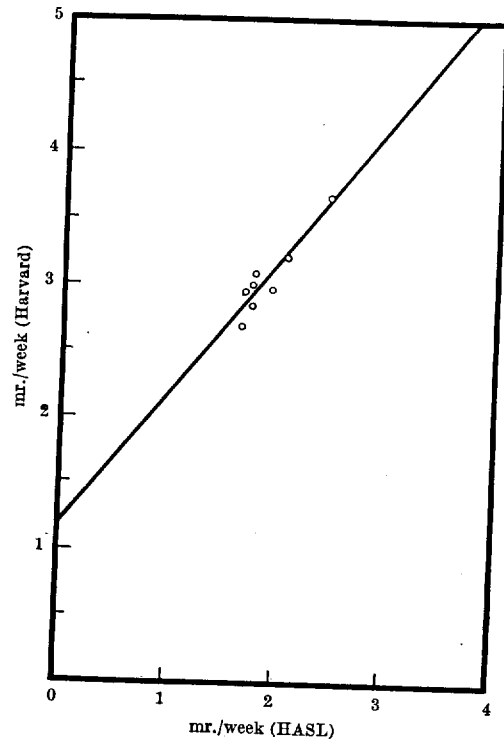
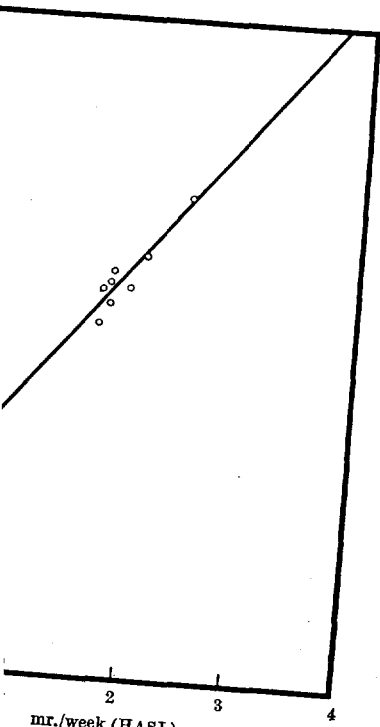


Fig. 2. Harvard population exposure estimates as a function of comparable Health and Safety Laboratory (HASL) estimates for the eight New England areas examined

In any event, there is little doubt that the dosimeter results are too high. This can be shown by carrying out a simple mathematical analysis of the various contributions to the population exposure-level, P , utilizing the accurate Health and Safety Laboratory measurements of outdoor environmental radiation dose rates. If I_c , I_n and I_f are the measured mean outdoor dose-rate contributions from cosmic, natural γ -, and fall-out γ -radiation, respectively, and I_h is the mean indoor γ -dose rate produced by sources in the building materials, we can write the following expression for P :

$$P = f_i (I_c + s_f I_f + s_n I_n + I_h) + f_o (I_c + I_f + I_n)$$

where f_i and f_o are occupancy time factors for indoor and outdoor locations, respectively, and s_f and s_n are mean transmission factors of the buildings and residences for outdoor fall-out and natural γ -radiation. Substituting



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 or γ -dose rate produced by sources
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$$s_n I_n + I_h) + f_o (I_c + I_f + I_n)$$

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 tural γ -radiation. Substituting

reasonable values for these factors and the various weekly
 doses into the formula, we get:

$$P = 0.8 [0.60 + (0.2) (0.37) + (0.3) (1.18) + I_h] + 0.2 [0.60 + 0.37 + 1.18] = 1.25 + 0.8 I_h \text{ mr./week}$$

Since we have determined that the indoor total γ -levels
 average 0.7 of the outdoor levels in these areas, we find
 that:

$$I_h \approx 0.5 I_f + 0.4 I_n = 0.66 \text{ mr./week}$$

Substituting this in the above expression for P , we get:

$$P \approx 1.8 \text{ mr./week}$$

This result is not strongly dependent on the particular
 values assumed for the various factors in the above
 equation. It is quite consistent with the similarly
 calculated Health and Safety Laboratory population
 exposure estimates, and much lower than the dosimeter
 results. The mean contribution from building materials
 to population exposure would have to be close to 2 mr./
 week to validate the dosimeter data, which is considerably
 higher than the measured values for the total indoor
 γ -dose rate in most of the 160 residences where scintillation
 detector readings were made. Even without such evidence,
 it seems to be an unreasonably high value to assign to
 mean regional indoor radiation-levels produced by radio-
 activity in building materials. For it implies total indoor
 γ -doses averaging approximately 3 mr./week, whereas the
 scattered data given in the 1962 United Nations report¹⁸
 indicate that readings of 1 mr./week are typical of normal
 situations in wood or brick houses.

The results of both surveys indicate that the range of
 population exposure to environmental radiation is quite
 narrow throughout the regions studied. It follows that
 northern New England does not provide a good 'labora-
 tory' for the study of the effect on large human populations
 of differences in long-term environmental radiation
 exposure. Of much greater significance is the correlation
 between the two entirely independent and undoubtedly
 somewhat imprecise techniques for estimating these
 exposure-levels. This correlation can be at least partially
 understood as a consequence of the relatively high degree
 of uniformity in radiation-levels observed within each
 area. Under such fortunate conditions, the method of using
 a few hundred field measurements to infer the total radi-
 ation profile has yielded apparently realistic values for
 population exposure, for which the Harvard dosimeter
 data provide strong qualitative support. Spiers *et al.*⁷, in
 their discussion of the extensive population investigation
 in Scotland, have already indicated some of the difficulties
 involved in obtaining and interpreting data of this type.
 But it can be concluded from the work recorded here that

more direct—but not necessarily more accurate—methods of estimating mean population exposure-levels.

Another conclusion which is suggested by the New England results is that the basic limitation of the pocket ionization-chamber technique in terms of measuring normal human exposure to environmental radiation is now the difficulty in determining mean leakage rates under actual field conditions while being worn and handled. There appears to be no fundamental reason why this difficulty cannot be at least partially overcome by suitably controlled experimentation, and thus the pocket chamber technique can be considered as a potentially practical one for this kind of measurement. It should be remarked that the dosimeters admirably fulfilled their basic purpose in the Harvard investigation, namely, the determination of differences in population exposure-levels between areas.

There are, of course, a number of other possible methods for determining mean population exposure to environmental radiation. For example, photographic film dosimetry techniques have been applied to this general problem area with some success. O'Brien *et al.*¹⁹ described a film-scintillator (sodium iodide) system which Roser and Cullen²⁰ have utilized in the measurement of population exposure in Brazil on a limited scale. The approximately thousand-fold enhancement of the film response produced by the scintillator is almost too great for the high-background areas of Brazil; such a method would almost certainly be feasible in areas of more normal background levels for certain kinds of studies. The basic limitation here is the cost of the dosimeters, which precludes their widespread use. The problem of reciprocity law failure must also be taken into account in the calibration of the dosimeters.

A similar kind of dosimeter has been described by Henson²¹, using photographic film and a plastic scintillator (*N.E.* 102). While less sensitive than the sodium iodide system, it exhibits little energy dependence and good precision (± 10 per cent *S.D.* for two weeks' exposure at normal background). Reciprocity failure was observed but has not proved excessive. The main problem seems to be a strong dependence on temperature in its response, which varies with the dose rate. The error present in any particular reading is not known, so that the use of this dosimeter has not been recommended.

There has also been recent progress in increasing the sensitivity of normal radiographic film by means of post-exposure to visible light and improved development techniques that may render such film useful for environmental radiation studies without the necessity for external enhancement of its response. McLaughlin²² has reported

each is capable of yielding useful quantitative information in a reasonably uniform radiation environment, at least can be used as a basis for evaluating methods that are not necessarily more accurate—methods that determine mean population exposure-levels.

The conclusion which is suggested by the New England survey is that the basic limitation of the pocket chamber technique in terms of measuring exposure to environmental radiation is now determining mean leakage rates under field conditions while being worn and handled. There can be no fundamental reason why this can be at least partially overcome by suitable modification, and thus the pocket chamber can be considered as a potentially practical one for measurement. It should be remarked that the pocket chamber has admirably fulfilled their basic purpose in the investigation, namely, the determination of relative population exposure-levels between areas.

In addition, a number of other possible methods for determining mean population exposure to environmental radiation have been applied to this general problem with some success. O'Brien *et al.*¹⁹ described a sodium iodide system which was utilized in the measurement of population exposure to radiation in Brazil on a limited scale. The approximate enhancement of the film response by the use of a scintillator is almost too great for the use of such a method in areas of more normal background radiation. The basic principle of certain kinds of studies. The basic principle of the dosimeters, which present a serious cost of the dosimeters, which present a serious problem of reciprocity failure, so be taken into account in the use of dosimeters.

A plastic scintillator dosimeter has been described by O'Brien *et al.* using photographic film and a plastic scintillator. It is more sensitive than the sodium iodide system, has little energy dependence and good stability. The *S.D.* for two weeks' exposure at 100 rads was 10%. Reciprocity failure was observed in the field use. The main problem seems to be the dependence on temperature in its response, and the error rate. The error present in any field use is not known, so that the use of this method is not recommended.

Recent progress in increasing the sensitivity of photographic film by means of post-exposure and improved development techniques has made such film useful for environmental exposure measurement without the necessity for external calibration. McLaughlin²² has reported

a six-fold increase in the response of commercial radiographic film by use of these techniques that permits a determination of a 3-mr. γ -ray exposure with a precision of ± 0.2 mr.

A very promising approach to the problem of determining human exposure to low-level ionizing radiation has evolved out of the recent development of thermoluminescent materials for personnel dosimetry. Commercially available dosimeter systems using lithium fluoride²³ and calcium fluoride²⁴ are claimed to provide measurable responses at the 10-mr. and 5-mr. level of γ -ray exposure, respectively, with approximately ± 20 per cent accuracy (*S.D.*). These limits may eventually be somewhat lowered and the precision improved with refinements in read-out techniques. Cullen²⁵ has recently utilized 156 lithium fluoride dosimeters for a population exposure investigation in a high background area in Brazil, with 50 mg of the material placed in religious medals to be worn for a three-month period. This exposure time provided a total γ -dose of several hundred milliroentgens, well above the minimum now routinely detectable. In general, thermoluminescent dosimeters have the significant advantages of small size and relatively low unit cost, and may prove to be a useful tool for future population investigations. The Health and Safety Laboratory is at present engaged in evaluating the available thermoluminescent dosimeter systems for their applicability to the routine measurement of human exposure to environmental radiation, and field tests along the lines of the New England survey are planned when sufficiently promising dosimeter systems are developed.

These recent advances in direct personnel dosimetry, particularly in the extension of the sensitivity limits to ever lower γ -dose levels, render the detailed examination of human exposure to environmental radiation on a routine basis increasingly feasible, even in the extremely low-level radiation fields that are characteristic of the normal environment. But the reliability and reproducibility of the readings of the various types of dosimeter in terms of absolute dose under the stresses of actual field use remain to be thoroughly explored. The New England survey results seem to indicate the adequacy of *in situ* measurements in establishing a radiation profile over extensive areas, a profile that when sufficiently uncomplicated may be properly interpreted in terms of population exposure to environmental radiation. These results also emphasize some of the problems associated with adequately calibrating the response of personnel dosimeters under field conditions. It appears that the use of highly accurate ionization-chamber and spectrometric techniques for *in situ* measurements will be required in the near future for all population studies of the type described here, if only to provide a standard by which the adequacy of the new techniques for direct human exposure measurement

- ²¹ Blase, E. F., Legerquist, R. F., Palmer, R. C., and Rutland, D. F., *Health Phys.*, **9**, 888 (1963).
- ²² Cullen, T. L. (personal communication, 1964).

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