

THE LOS ALAMOS HUMAN COUNTER

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To appreciate the need for radiation detectors of greatly increased sensitivity, one has only to note the sharp rise in public concern over the effects of low intensity radiation on man over the past few years. Permissible levels of exposure have been reduced to the point where they are now comparable with the natural background irradiation level. On the basis of these trends, one might predict that not only will the fallout of fission products from nuclear weapons testing and the disposal of reactor waste products be subject to intense scrutiny, but also that there might be a legal prohibition of some of our most popular materials of construction, notably concrete and brick, on the basis of their high content of natural radioactivities such as radium and potassium. (That these materials can produce radiation doses up to several times the average background has been shown by HULTQVIST.¹)

Clearly, this trend necessitates the existence of instruments capable of making measurements at or below the natural levels of radioactivity. The maximum permissible levels are ineffective unless measurements can be readily made to determine the actual exposure levels.

Low-level counters are equally important from another viewpoint: namely, the measurement of the natural radiation levels themselves. If detectable biological effects can indeed result from radiation doses comparable to natural background, then studies of populations exposed to different natural background irradiation may be a fruitful and indeed perhaps the only possible way of determining quantitatively the relation between dose and effect. Remembering that it is common to speak of possible damage with a frequency of incidence as low as 1 per 100,000, it becomes obvious that only by the study of populations of several millions can one hope to obtain significant results without large extrapolations.

Present interest in unnatural radioactivities has concentrated on the fallout from nuclear weapons testing, since the question of the degree of hazard represented is already with us. This interest can be expected to shift in the future to the disposal of reactor wastes. As has been pointed out, a 100 MW (heat) reactor will produce in the course of one year of operation a total quantity of fission products equal to that produced by the detonation of a one-megaton fission bomb. If the United States produces 20,000 MW from reactors in 1965,² the fission products requiring disposal would be equivalent

to those produced by 200 megatons of fission bombs, which is some twenty times the annual average testing rate over the past five years. This power level is still small compared with possible eventual use.

Clearly, reactor-produced activity poses a very different sort of problem than that resulting from weapons tests, since the former is produced in a sealed system and becomes a hazard only when released. Considering the present concern over 50 megatons of fission products, it would appear doubtful that reactor wastes can ever be dispersed in natural systems by simple burial on either land or sea. However, in addition to the possibilities of accidental leakage, economic pressures will dictate the use of the simplest disposal systems. Research on the behavior of important fission products in nature is, therefore, of the utmost importance in establishing the limits of what can be permitted. These measurements must of necessity be made far below natural radioactivity levels and perhaps some good can be extracted from the evils of fallout by using this opportunity to gather information which may be of great economic value in a few decades.

Sr^{90} , Cs^{137} , I^{131} , Zr^{95} , Ru^{106} , Ce^{144} and Ba^{140} are among the fission products already reported in nature and some of these have been studied in detail with respect to their behavior in ecological chains. A continuation and intensification of these studies are certainly a necessity.

Since the ultimate concern is with the entry of these radioactivities into the human body via the food cycle, principal objects of study are man and his foodstuffs. The requirements of the counting system are, therefore, those given by LANGHAM in his review of biological applications.³ We may briefly reenumerate them:

1. Many samples must be measured because of biological variability. (A similar variability is, of course, encountered in the studies of other complex systems, e.g. ocean and atmospheric circulation.) Since 'many' may mean tens of thousands per year, counting time per sample must be short, say less than 10 min per determination.

2. A non-destructive measurement is highly desirable. This needs no elaboration for the case of monitoring people.

3. Because of the many types of samples to be measured, versatility in this respect is very important.

4. Obviously, high sensitivity is the *sine qua non*.

Since the measurement of natural radiocarbon is commonly regarded as a typical 'low-level' counting problem, it may be profitable to compare the natural K^{40} specific activity of man with the specific activity of C^{14} in elemental carbon samples to obtain some perspective of the magnitude of the problem. The average adult male weighs about 70 kg, of which some 133 g are potassium.⁴ Since the specific activity of potassium is three gamma-rays/sec g (due to the naturally radioactive isotope K^{40} , half-life 1.3×10^9 years), the natural gamma emission of the body due to this source is 400/sec. This is a specific

activity of 0.34 gamma-rays/min g. Contemporary carbon has a specific activity some forty times this due to natural C^{14} , namely 14/min g. In radiocarbon dating, a sample with a specific activity of 0.34 min/g would have an age of 30,000 years, and its activity could be measured to a precision of 10% only by counting for about 48 hr. The first of our criteria, however, requires a counting time of only a few minutes.

Experience with natural radiocarbon indicates the nature of the solution to this problem. Remember that *p*-cymene must be rejected as a scintillation solvent, since its natural C^{14} content gives a counting rate of eight times background for a 90 ml volume, a rate such that the C^{14} content can be measured to a precision of 1% in 20 min.⁵ This extremely short counting time, compared with conventional methods, results basically from the large sample used, in this case about 70 g.

The reason for the efficacy of large samples in improving sensitivity is that the figure of merit for the comparison of counting methods is S^2/B , the ratio of the square of the net sample rate to the background rate.⁶ Thus, if methods A and B give the same sample-to-background ratio, but these rates are both 100 times higher for A, then the counting time to obtain a given statistical precision is 100 times smaller for A. If, therefore, one measures a sample of 70 kg instead of a sample of 70 mg, the counting time required to detect a given specific activity will be reduced by a factor of one million. (In actuality, the gain is often greater than this, since sample capacity can rise as the volume of the detector or the cube of its linear dimensions, whereas background may rise only as the cross sectional area or the square of the linear dimensions.)

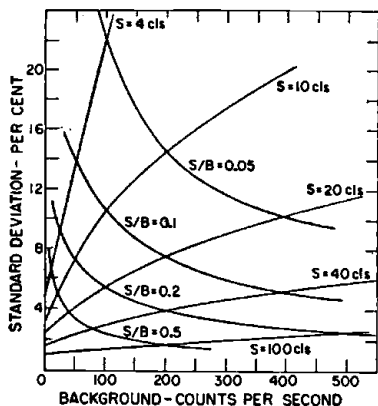


Fig. 1. Counting statistical error as a function of sample and background rates.

Figure 1 (modified after BURCH⁷), summarized graphically the relations between counting statistical error and sample and background rates. The numbers chosen are those appropriate to a large 4π liquid scintillation

counter measuring the natural gamma activity of people. The ordinate is the standard deviation in per cent of net sample count obtainable in 100 sec of counting time for various values of S/B or S as a function of background. In the Los Alamos Human Counter, the average person will give a net K^{40} count of about 80 counts/sec above a background of about 300. In addition to the increased precision with increasing rates, (S/B curves) the limited dependence of error for a given sample rate (S curves) on background should be noted. In the measurement of people and foodstuffs, it makes no difference whether background is 200 counts/sec or 400 counts/sec. In either case, the statistical error is 2% or better (about $0.0002 \mu c$) and the limits of the method are set by minute amounts of air-borne activity (radium-radon daughter activity) and surface contamination. The result is that, in sharp contrast to the situation in small sample counting, the actual background count is of little importance and no effort at background reduction (beyond ordinary lead shielding) is necessary.

A corollary advantage associated with large sample counting is that the very short counting time per sample greatly reduces the stability requirements and the hazards of electrical interference. With a counting time of only 2 min, the entire sequence of calibration-background-sample-background-calibration can be completed in ten minutes.

With the net sample count being weighted as the square in the figure of merit, it is clear that every effort to increase it will be very rewarding. We have discussed the value of increasing sample size and a similar premium must be placed on counting efficiency. The principal loss in efficiency in the counting of large samples is usually a geometrical one due to the difficulty of completely surrounding the sample with the detector. In practice, the liquid scintillation counter appears to be the only detector capable of combining 4π geometry with high inherent efficiency, although the possibility of using plastics should not be discounted.⁸

The Los Alamos Human Counter has been described in the literature several times,^{9, 10} so only a brief description will be given here. The counter itself is a cylindrical steel tank 6 ft long and 30 in. in diameter (Fig. 2). An axial well 18 in. in diameter accommodates the subject or sample which is surrounded by a layer of liquid scintillation solution (terphenyl and POPOP in toluene) 6 in. thick. The counter is shielded by 5 in. of lead.

Scintillations are detected by 108 photomultipliers (2 in. diameter cathodes), which observe the solution through ports in the outer wall. The photomultipliers are connected in two banks of fifty-four tubes each, which are operated in coincidence in the usual manner. The energy resolution of the system is not good, but is adequate to separate gamma-rays whose energies differ by a factor of 2 or more. Thus, the machine is usually operated for simultaneous counting in two energy channels: 1-2 MeV, giving ordinarily only the natural K^{40} (1.45 MeV gamma) activity, and 0.5-0.8 MeV, giving

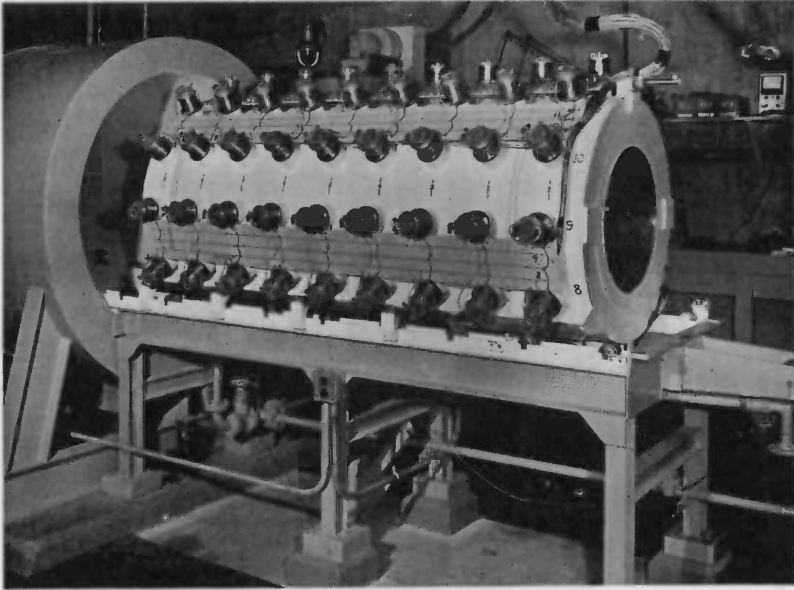


Fig. 2. Human counter outside its shield.

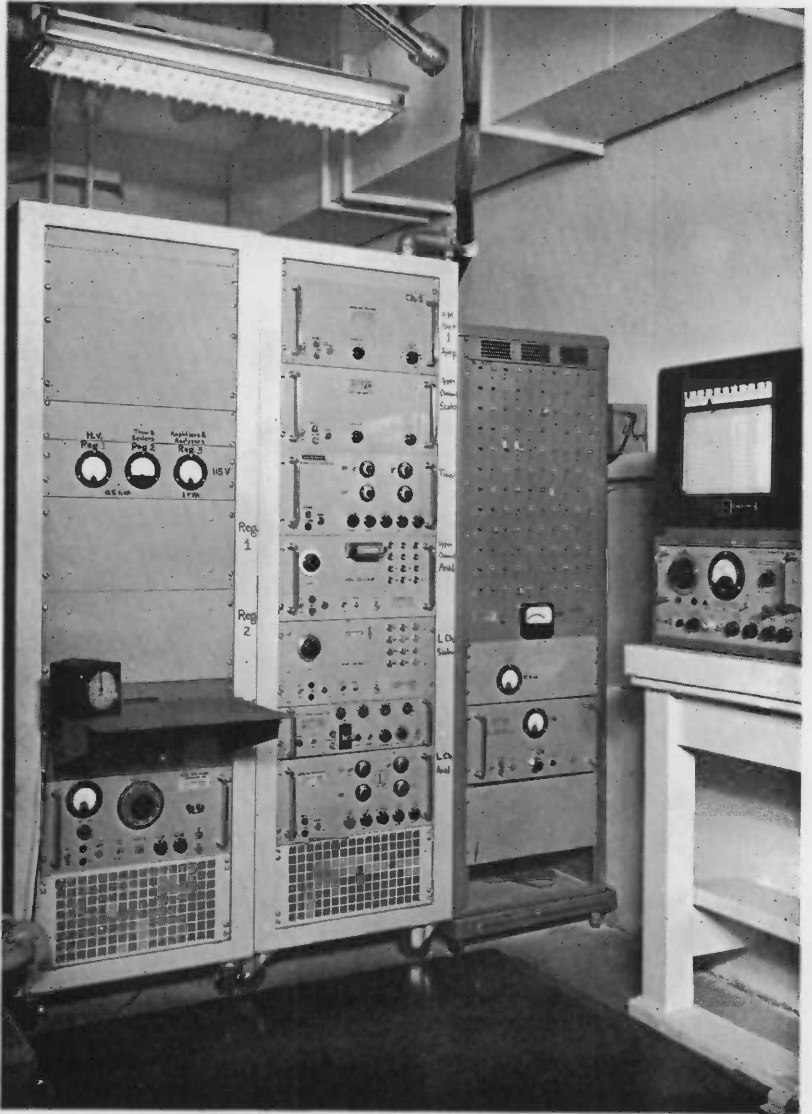


Fig. 3. Electronics.

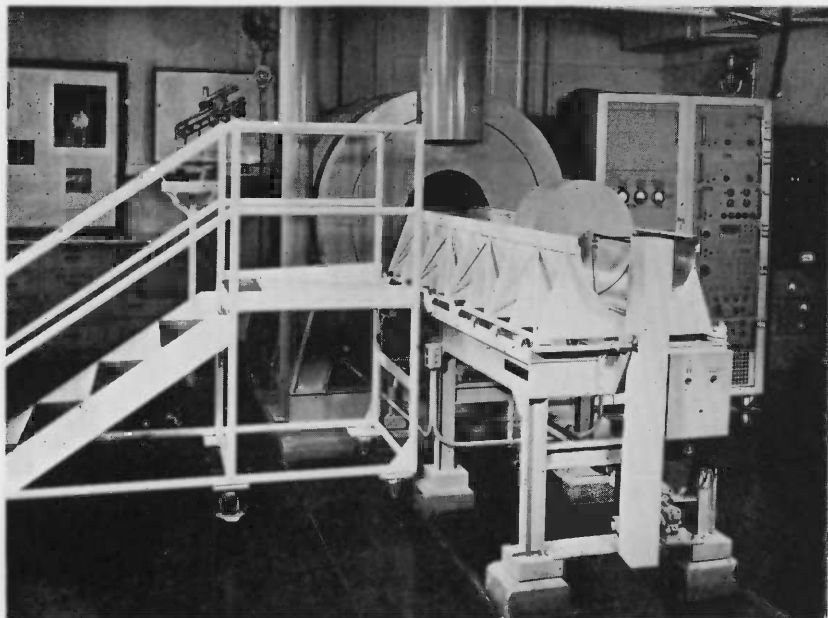


Fig. 4. General view of counter.

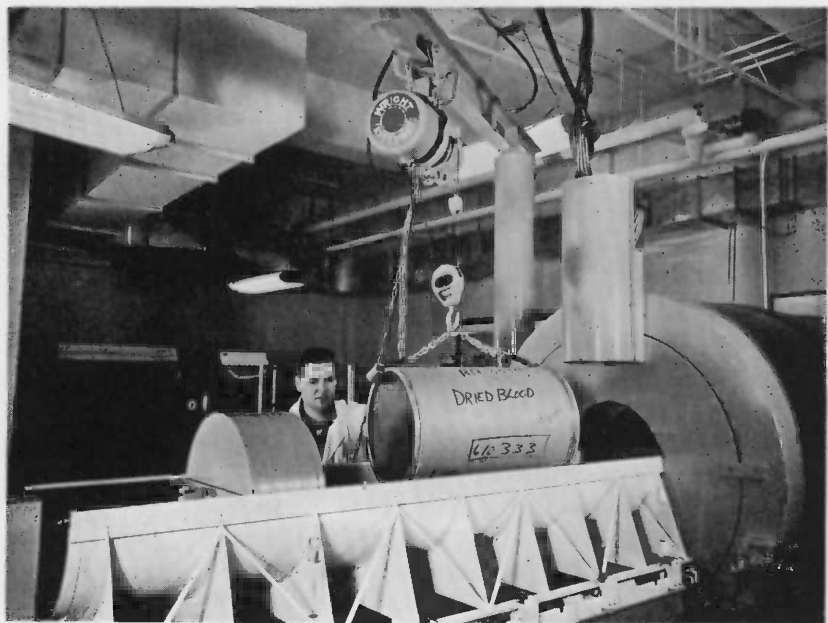


Fig. 5. Loading food sample into counter sling.

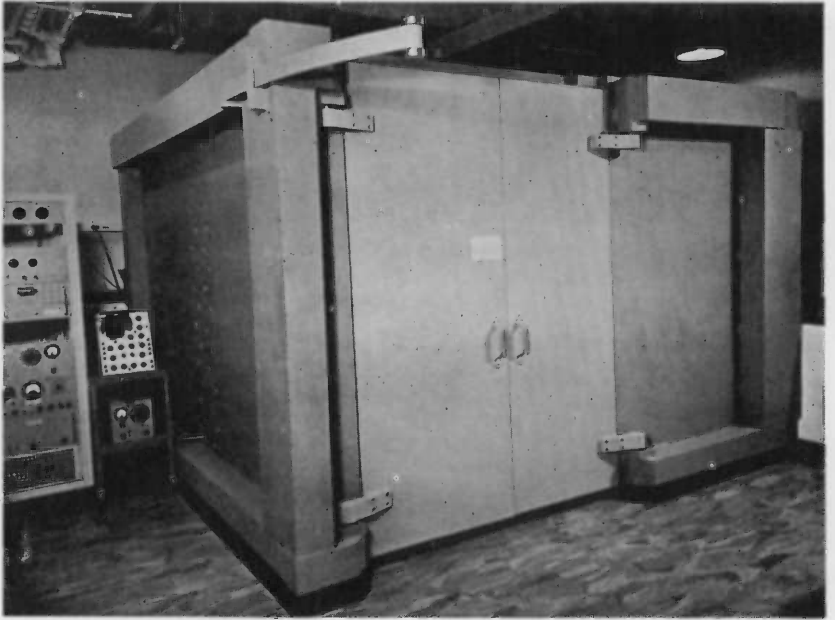


Fig. 6. Exterior of steel room shield for crystal counter.

some K^{40} activity (easily calculable from the upper channel count and also any Cs^{137} activity (0.66 MeV gamma) present in the sample.

The electronics are shown in Fig. 3 and include two linear, overloadable amplifiers, one for each bank of tubes. Both amplifiers feed the pair of coincidence pulse height analyzers, one for each energy channel. A scaler for each channel and an electronic timing circuit permitting preset times of 1–1000 sec complete the central rack. The right-hand relay rack contains the high voltage supply and the control and distribution system. The supply is conventional except for the 30 MA capacity required to operate so many tubes in parallel. The control panel permits the adjustment of the gain of each photomultiplier individually without removing the counter from the shield. Individual switches permit the tubes to be examined singly, and the gain is controlled by a variable resistance in series with the tube's bleeder string.

An over-all view of the counter is shown in Fig. 4. The loading ramp permits the subject to climb into the canvas sling in the loading trough. The sling is then drawn into the counter by an electric motor. The entrance port is closed by a loosely fitting lead plug riding at the head of the sling. No ventilation is used since there is enough active deposit from air-borne radon to increase background significantly. The usual counting time of 200 sec is so short that there is no need for forced ventilation. The subject carries with him a 'panic switch' controlling the sling drive, so that he can leave the counter at any time. This effectively alleviates almost all cases of claustrophobia.

For the measurement of foodstuffs, a sample of 50–300 lb is used, and the electric hoist shown in Fig. 5 serves to introduce the sample into the sling. In the past two years, 1500 measurements of K^{40} and Cs^{137} in foodstuffs and over 2000 determinations on human subjects have been made, in addition to the uses of the machine on related projects such as the determination of biological retention of important nuclides by dogs, monkeys and humans.

The problem of data processing becomes a serious one with short counting times, and it has been necessary to use electronic computing. The raw counting data are entered onto punched cards and all calculations are performed by machine. Answers are returned both in tabular form and on punched cards. The latter are extremely useful for the analysis of population distributions, correlations, etc. which can also be carried out by machines.

The NaI crystal, while offering several advantages, is not competitive in terms of geometrical efficiency. Crystals as large as 8 in. in diameter give only about 1% efficiency for human whole-body assay, and therefore require counting times of 15–60 min even after the most strenuous efforts have been made to reduce background. The question of the relative importance of counting time and energy resolutions must be decided on the basis of the particular application involved. In most monitoring operations, a basic problem is the expeditious handling of the large number of negative results.

If neither type of detector sees any extraneous activity, the identity of the activity they didn't see is not determined by increased energy resolution. Furthermore, the excellent discriminatory powers of biological systems against unwanted elements means that in general very few of the fission products will be found in foodstuffs or in man. It has been our experience that in the monitoring of people and foodstuffs, the presence of gamma-emitting fission products other than Cs^{137} is indicated by anomalous potassium results. Ba^{140} is one of the most abundant fission products at moderate times after fission (1–100 days) and is readily absorbed by plants and animals because of its similarity to calcium. The 1.60 MeV barium-lanthanum gamma-ray is counted in the K^{40} channel and amounts as small as $0.001 \mu\text{C}$ can be easily recognized by the increase in the expected K^{40} assay. In the case of foodstuffs, the barium is readily identified with the liquid scintillator by its characteristic 12.8 day half-time. We first identified its presence in venison during 1956 and have observed it in milk during the 1957 tests. These results will be submitted for publication. The levels observed are far below the maximum permissible concentrations.

In spite of the fact that most low-level contamination problems can be handled without the need of superior energy resolution, it is extremely valuable to have detailed gamma-ray spectra run on unusual samples and on selected routine samples as a confirmation of the identity of the activities present. In addition, the NaI crystal spectrometer offers other unique advantages which supplement the speed of the 4π liquid system. Among these may be mentioned the ability of the crystal to localize the activity either within the body (useful in distinguishing inhalation from ingestion) or externally (useful in distinguishing contamination of the hair or hands from internally-deposited activity). This ability is also of value in medical tracer studies, e.g. Cr^{51} -tagged blood cells which may localize in the spleen instead of remaining in the circulating blood. An additional advantage of the crystal is its ability to detect gamma-rays of very low energy. The large liquid scintillators so far constructed begin to show a serious decrease in gamma efficiency at several hundred keV energy. This is not inherent in the liquid (after all, the tritium beta of 6 keV average energy can be efficiently counted under optimum conditions), but is a result of the difficulty of getting the light out of a large volume. Use of the new 15 in. diameter photomultipliers promises to improve this situation, and one can expect large liquid scintillators to count gamma-rays efficiently down to at least 100 keV energy.

Because of the complementary nature of the two instruments, we have constructed at Los Alamos a low-level crystal installation duplicating the excellent design of Marinelli and co-workers at the Argonne National Laboratory.^{11, 12} This installation uses an 8 in. diameter by 4 in. thick NaI crystal in a special copper-quartz can inside a $10 \times 10 \times 7$ ft (inside dimensions) steel room with walls of 7 in. thick pre-war armour plate, as

shown in Fig. 6. Using this apparatus we have verified the assignment of the short-lived, hard gamma activity observed in foods to Ba-La¹⁴⁰. The ultimate sensitivity of the two systems seems to be rather similar, the principal difference being the counting time required. For the determination of the natural potassium activity of the average person (about 0.013 μc) to a precision of 3% requires about 3 min in the 4π liquid scintillator and 15-60 min with the crystal spectrometer.

Much of the data obtained with the Human Counter have already been published. A brief summary of some of it may serve to indicate the sort of

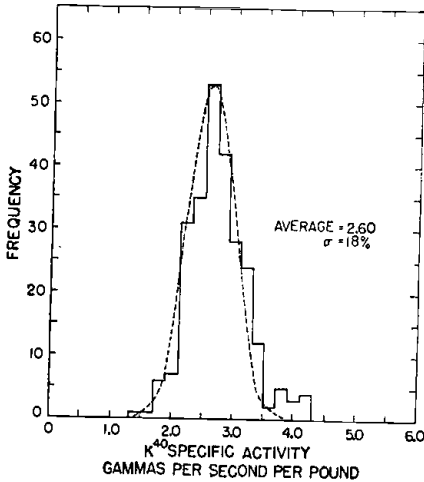


Fig. 7. Potassium specific activity of general population.

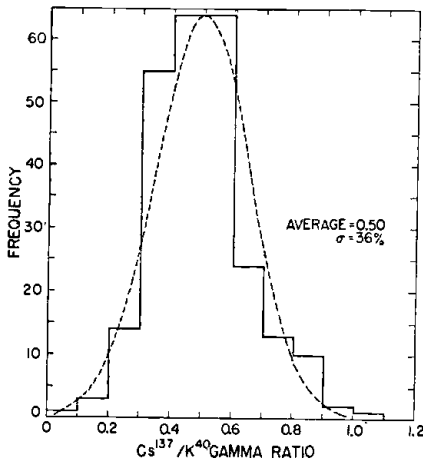


Fig. 8. Cs¹³⁷/K⁴⁰ gamma ratio for general population.

information which can be gathered with an instrument of this type. Figures 7 and 8⁴ show the population distribution curves for K^{40} and Cs^{137} , respectively. With the exception of the small tail on the high side of the K^{40} curve (due to small amounts of surface contamination probably), the curves are essentially Gaussian. The difference in the widths is quite noticeable; the distribution of homeostated K^{40} has a σ of 18%, while that of the trace element Cs^{137} , which is free to vary with the intake rate, is twice as wide.

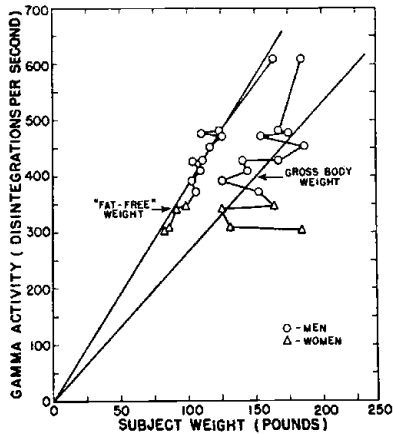


Fig. 9. Correlation of body potassium with weight.

Correlations of the human body K^{40} activity 'fat-free weight' estimated from body water (as determined by a tritium water dilution measurement, Fig. 9^{13, 14}), indicates that the measurement of K^{40} is an accurate index of fat : muscle ratio, a quantity of considerable interest to physiologists. Effects of nutritional variations on body composition can be accurately studied by this means. Measurements of body K^{40} may also be of clinical use since there are definite syndromes associated with potassium deficiencies.

The sensitivity of the large liquid scintillation detector is of the order of 10^{-10} c in samples as large as 100 kg, permitting determination of hard gamma-emitting nuclides at factors of 1000 or more below permissible levels. The implications of such a sensitivity for the problem of low-level environmental contamination by power reactors have already been pointed out.¹⁰

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