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FURTHER STUDIES OF EXTERNAL ENVIRONMENTAL RADIATION

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March 1966

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ABSTRACT

The spectrometric techniques developed by the authors for measuring total and individual component gamma dose rates from naturally-occurring and fallout emitters are elaborated upon and extended to new applications. The calibration of high resolution 4" x 4" NaI(Tl) detectors for such measurements is described. Field studies utilizing these techniques during 1965, including measurements of gamma dose rates at approximately 50 ground sites scattered around the United States as well as on high altitude lakes and in deep mines, are summarized and the data presented in full. These results provide useful information relevant to continuing studies of the application of field spectrometry to the rapid assessment of fallout deposition, particularly ^{137}Cs, the variations of natural gamma dose rate with time, and the contributions of soil beta activity and cosmic radiation to free air ionization near the air-ground interface. A detailed description of the argon-filled high pressure ionization chamber used for total dose rate measurements is presented.

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I. INTRODUCTION

For the past several years the Health and Safety Laboratory has been conducting a detailed investigation of the properties of the external radiation environment. Previous reports have described the development of field gamma spectrometric techniques utilizing high pressure ionization chambers and a 5" x 3" NaI(Tl) detector.[1,2,3] These techniques allow reasonably precise and accurate estimates to be made of total open field gamma dose rates from each of the important individual components of the natural and fallout gamma radiation field. The results of a number of field studies utilizing these techniques have also been reported.[4]

The development of these techniques has made possible more detailed investigations of various aspects of the external radiation environment such as the variation of natural dose rates with time, geographical differences in fallout distribution, cosmic ray ionization variation with altitude, and β-ray ionization effects. In attempting to investigate these problems we have found it necessary to improve our instrumentation by acquiring new more sensitive NaI(Tl) detectors with much better resolution and stability than the 5" x 3" detector which our initial system utilized. Section II of this report describes these new detectors and discusses the laboratory calibration and calculations undertaken to allow total and component dose rates to be inferred from their response.

This improved instrumentation was used to study the external radiation field in more detail under a wide range of geographical conditions and radiation levels during an extended survey trip undertaken in August and September of 1965. Section III of this report describes the many different investigations carried out during the course of this trip. Using our spectrometric techniques in conjunction with high pressure ionization chamber readings over both land and on lakes at various altitudes, we were able to infer the variation of cosmic ray ionization intensity with altitude. Our spectrometric techniques were extended to the determination of ^{137}Cs concentrations in soil at a number of sites throughout the United States. These data

are being compared with radiochemical analysis of soil sample from these sites. Measurements were made at selected sites exhibiting unusually high or low radioactivity levels in order to study the response of our instrumentation under such conditions as well as to compare with simultaneous measurements by other investigators using different types of instrumentation. The influence of beta radiation on various instruments was studied by comparing the dose rate inferred from our high pressure ionization chamber and spectrometer to the dose rates measured simultaneously with thin-walled plastic chambers. Measurements were also made at particular sites where the natural and fallout gamma dose rates were of interest for related studies such as measurements in western Nebraska for correlation with neo-natal death rate and birth weight.

In addition to these particular studies, a number of sites visited on past trips were resurveyed to determine the changes if any in the natural and fallout gamma dose rates. The complete dose rate results inferred for all measurement sites are tabulated. The consistency of the various measurements was used to indicate the accuracy and precision of our techniques. The comparison of simultaneous data obtained from the new 4" x 4" NaI(Tl) detector and from the old 5" x 3" detector was used to verify the laboratory calibration of the 4" x 4" detector.

Most of the studies undertaken on this survey trip are part of our continuing investigation of external radiation problems. More detailed investigations of the β-ray ionization at various levels above the ground and the variation of natural γ dose rates with time are discussed in Section IV of this report along with our plans for the future. Also discussed in Section IV is the present state of our continuing program of high pressure ionization chamber development. Our newest ionization chamber is described and the theoretical and experimental determination of its response to gamma rays and cosmic rays is discussed in detail. Although most of the studies described in this report are yet to be completed the discussions and data presented indicate the scope of our investigations as well as the value of gamma-spectrometric and ionization chamber techniques for studying the external radiation environment.

II. CALIBRATION OF NEW 4" x 4" NaI(Tl) DETECTORS

In May of 1965, two new 4" x 4" cylindrical NaI(Tl) detectors for our field gamma spectrometric system were obtained from Harshaw Chemical Co. These detectors are coupled to specially selected 3" photomultiplier tubes. Each has a resolution better than 8.2% for the 0.66 MeV ^{137}Cs total absorption peak. Since the crystals are covered with only thin (.032") aluminum windows, cylindrical bakelite shields 1/4" thick were fabricated to fit over the detectors in the field. These shields provide necessary β-ray discrimination and also serve to thermally insulate the crystals minimizing temperature gradient effects on the crystal response during a measurement.

The method of calibration of photopeak areas, energy bands, and total spectrum "energy" to obtain total and individual component dose rates is described in HASL-150 (ref. 3). We shall thus only summarize the results of the present calibration using the same notation as in HASL-150. All the calibration results discussed here are for these 4" x 4" detectors with shields. The calibration of the two detectors differed by only about 2%, and thus only one set of results is given.

Photopeak Area Method

In determining the dose rates from particular natural or fallout gamma emitters in the soil the assumption is made that the estimated areas of the total absorption peaks shown in Figure 1 are proportional to the true peak areas and therefore to the incoming primary flux at the detector. The final calibration factor (N_F/I), which relates the estimated peak counts in the field spectrum to the total dose rate for a particular isotope, is the product of the ratios (N_O/Φ), the ratio of estimated absorption peak counts to primary flux for axial incidence; (N_F/N_O), the angular correction factor; and (Φ/I), the ratio of primary flux to total dose rate.

(N_O/Φ), the ratio of estimated absorption peak counts to primary flux for axial incidence, was determined in the laboratory for several energies using standard ^{137}Cs, ^{24}Na, ^{113}Sn, and ^{226}Ra sources and for other energies by comparison with our previously well calibrated 5" x 3" detector using ^{40}K, ^{85}Sr and ^{232}Th sources of unknown intensity. These results are given in Table I.

(N_F/N_O), the angular correction factor for 0.61 MeV and for 1.76 MeV γ-rays was obtained by numerical integration over the measured angular response of the detector for these energies and the calculated angular primary flux distribution from a uniformly distributed source. The measured angular response of the 4" x 4" detector to γ-rays of these energies was much flatter than for the 5" x 3" detector and thus the corresponding angular correction factors were much smaller. The angular corrections for other energies and other source distributions were estimated on the basis of these two calculations. Due to the flatness of the angular response the errors involved in these estimates are negligible.

(Φ/I), the ratio of primary flux to total dose rate, is the same as given in HASL-150 except for the case of the 1.76 MeV ^{214}Bi photopeak used for the dose rate estimate of the ^{238}U series. This particular ratio was revised slightly based on further analysis of existing ^{214}Bi decay schemes and γ-ray intensity measurements.

The final field spectra conversion factors (N_F/I), absorption peak counts per μr/hr, are given in Tables II and III. These values were verified by direct field comparison with the 5" x 3" detector at a large number of locations. The values of (N_F/I) for the three natural emitters, ^{40}K, the ^{238}U series, and the ^{232}Th series, are significantly higher than the corresponding values for the 5" x 3" NaI(Tl) detector. Thus, estimates of peak areas should be affected less by errors in estimating the continuum resulting in more precise dose rate estimates. The (N_F/I) for the various fallout emitters are also slightly higher. This increase in response is due primarily to the improved geometrical configuration, which results in a larger intrinsic peak efficiency for higher energy γ-rays and an improved angular response at all energies. In addition, the improved resolution allows a better estimate of the 1.76 MeV ^{214}Bi absorption peak, even in the presence of a large 1.46 MeV ^{40}K peak.

The new detectors are able to resolve the 0.66 MeV ^{137}Cs and 0.61 MeV ^{214}Bi peaks. At present however, the 0.66 MeV peak is often much larger than and overlaps the 0.61 MeV peak, and we cannot separately determine the areas of these two peaks or the 0.58 MeV ^{208}Tl peak. In order to estimate the ^{137}Cs dose rate, therefore, it is necessary to estimate the area of the entire smeared-out peak and subtract a contribution based on the ^{238}U and ^{232}Th dose rates determined from higher energy peaks. From the decay scheme data for these isotopes and the response data given in Tables I, II, and III these correction factors were determined to be 3000 counts/(μr/hr - ^{238}U) and 1300 counts/(μr/hr - ^{232}Th). A similar correction of 350 counts/(μr/hr - ^{232}Th) must be made to the 0.51 MeV peak before estimating the ^{106}Rh dose rate.

Energy Band Method

In determining natural emitter dose rates, the total "energy" (counts per channel multiplied by mean γ-ray energy corresponding to that channel) in the spectrum between energy values that bracket significant peaks is related to the total dose rate contribution from the emitter or series of emitters characterized by these peaks. The three bands used are centered about the 1.46 MeV peak (^{40}K), the 1.76 MeV peak (^{214}Bi-^{238}U series), and the 2.62 MeV peak (^{208}Tl-^{232}Th series).

As in the 5" x 3" detector calibration, three simultaneous equations relating the "energy" in the bands E_1, 1.32 - 1.60 MeV; E_2, 1.62 - 1.90 MeV; and E_3, 2.48 - 2.75 MeV to natural emitter open field dose rates were derived by applying a multiple regression analysis to the peak area estimate of the dose rates and E_1, E_2, and E_3 for a large number of field locations. The cosmic ray contribution to each energy band was first subtracted out using crystal response data from spectra taken over large lakes at different altitudes. (See Section III and Figure 3.)

The resulting equations for the 4" x 4" detectors with bakelite shields are

$$K = .078E_1' - .055E_2' - .022E_3'$$
$$U = .337E_2' - .179E_3'$$
$$T = .297E_3'$$

where K, U, and T are the dose rates in μr/hr for ^{40}K, the ^{238}U series, and the ^{232}Th series, respectively, and E_1', E_2', and E_3' are the total "energies" in BeV with cosmic ray contribution subtracted. The first constant in each of these equations was independently checked by calculation and/or laboratory calibration in a manner identical to that discussed in HASL-150 for the 5" x 3" detector.

The regression analysis to determine the equation for U resulted in a much better correlation in the case of the 4" x 4" detector ($r^2 = .98$) than was obtained for the 5" x 3" detector due most likely to the improved resolution enabling more precise 1.76 MeV peak area estimates. The correlation coefficients for the K and T equations were both $r^2>0.98$.

Total Spectrum "Energy" Method

In HASL-150 the total spectrum "energy" from 0.15 MeV to 3.4 MeV for the 5" x 3" detector was shown to be proportiona to the total dose rate from gamma radiation in the field. It was shown that in general the thicker the detector the less the dependence on incident γ-ray energy when using total spectrum "energy" as a measure of dose rate. The 4" x 4" detectors should thus enjoy a flatter energy response than the 5" x 3" detector. In addition, its improved angular response compared to the 5" x 3" detector allows a better estimate of the conversion of field spectrum total "energy" to dose rate to be made from laboratory calibration results.

The detectors were calibrated in the laboratory with our NBS standardized ^{226}Ra source and shown to be proportional to dose rate for dose rates exceeding 50 μr/hr with a conversion factor of 38.8 BeV/(μr/hr). The measured angular response when integrated over the calculated incoming angular distribution of primary flux from a uniformly distributed source predicts a field angular correction factor of 1.11. The use of the angular distribution of primary flux (which is very insensitive to gamma-ray energy in the range 0.5 - 3.0 MeV, see Reference 3, Figure 7) rather than the unknown angular distribution of total energy flux should be adequate since the angular response of the crystals is quite flat over the solid angle from which most γ-rays are probably entering the detectors.

The final field conversion factor is thus approximately 38.8 BeV/(μr/hr) x 1.11 = 43.1 BeV/(μr/hr). This value can be compared to a value of 43.0 BeV(μr/hr) obtained by plotting spectrum "energy" (corrected for cosmic ray response) versus ionization chamber dose rate for about 50 field measurements. Total dose rates at these 50 field sites ranged from 0.3 to 130 μr/hr. There were no systematic deviations observed in the proportionality of spectrum "energy" and ionization chamber dose rate.

III. MAJOR FIELD INVESTIGATIONS-1965

Preface

An extended cross country field trip was undertaken during August and September of 1965. The purpose of this trip was to carry out a number of interrelated studies of environmental radioactivity at a wide variety of geographical locations and with several different types of equipment. In addition, the trip offered an opportunity for a number of groups engaged in the study of environmental radiation problems to discuss their methods, problems, and future plans as well as to intercompare equipment responses at the same locations. During much of this trip we were accompanied by a team from the New York University (NYU) Cosmic Ray Laboratory. Several other research groups joined us for particular segments of the trip.

The major experiments completed by us were a resurvey of a number of our 1962 and 1963 field sites to compare present natural and fallout gamma dose rates with our previous measurements; a determination of cosmic ray ionization as a function of altitude using data obtained at land sites at altitudes up to 12,000 feet and over large lakes at altitudes up to 10,000 feet; a study of NaI(Tl) detector response to cosmic rays as a function of altitude; a series of simultaneous measurements with the NYU team over several lakes; field spectrometric estimates of ^{137}Cs soil activity at or near a number of U. S. Department of Agriculture - HASL Worldwide ^{90}Sr soil sampling sites for comparison with radiochemically determined ^{137}Cs concentrations; an intercalibration with teams from the Lawrence Radiation Laboratory (LRL), Rice University, and NYU over two solid rock outcrops of widely differing γ-ray activity; simultaneous measurements with the NYU team at several land sites to estimate β-ray activity; measurements at sites having very low gamma and cosmic ray activity such as deep mines or serpentine outcrops; and gamma dose rate measurements in western Nebraska for correlatio with birth defect data, in New Mexico near Alamagordo, for intercomparison with an aerial radiation survey and in Dallas, Texas, for comparison with a continuous monitoring experiment.

In carrying out the experiments listed above measurements e made at approximately 60 different sites around the country. e total data from all these locations allowed an intercalibration our new NaI(Tl) detectors with our well calibrated 5" x 3" tector over a wide range of component and total dose rates. e results of these measurements along with a few other surements made in the Northeast before or after the trip e presented in Tables IV and V. The total γ dose rate ven in these tables is in most cases a composite of up to r separate determinations, since at most locations two ization chambers and two NaI(Tl) detectors were used. nilarly the component dose rates given are the best values ed on the data from both the 5" x 3" and 4" x 4" detectors. e column labeled F.O. (2) is the difference between the tal natural gamma dose rate and the total gamma dose rate. e cosmic ray dose rates are based on our determination of smic ray ionization vs. atmospheric pressure.[5] As in our evious reports K, U, and T represent the dose rates from K, daughters of ^{238}U and daughters of ^{232}Th, respectively.

The accuracy of these dose rates is estimated to be ± 20% r U, ± 3% for total gamma, ± 0.3 μr/hr for fallout dose rate. ese estimates are substantiated by the excellent agreement tained between F.O. (2) and total fallout values over a wide nge of component and total dose rates. The precision of single measurement of K, U, or T is about 5%, of fallout se rate about 10% and of the total dose rate about 2%.

The major field investigations listed above will now be scussed in some detail.

survey of 1962 and 1963 Sites

Measurements were made at a number of the sites visited ring the 1962 and/or 1963 field trips. The results of the 62 and 1963 measurements as well as the 1965 measurements e shown in Table IV. These data indicate that fallout vels, as expected, are down from highs of around 5 μr/hr in 62 and 1963 to less than 1 μr/hr in most areas in mid 1965. is is consonant with a more detailed study of fallout levels the New York area.[6]

At many locations, especially in the central and Rocky ntain states, the natural gamma levels appear to be nificantly lower than in 1962 and 1963. We believe this

is indicative of greater soil water content during the 1965 measurement period compared to that of 1962 and 1963. These areas experienced greatly increased rainfall during the previous year or so while the Northeast experienced drought conditions. During the 1962 and 1963 surveys extremely dry and dusty conditions were prevalent over much of this area. The Denver area, in particular, experienced widespread flooding during the spring of 1965. This increased moisture is reflected in the Denver data (Table IV). The effect of moisture in the soil on dose rates and spectrometric dose rate measurements is being studied in some detail. (See Section IV.)

While the major fallout contributors to the gamma dose rate in 1962 and 1963 were ^{95}Zr - ^{95}Nb and ^{106}Rh, the major contributors during 1965 were ^{137}Cs, ^{106}Rh and ^{54}Mn with traces of ^{125}Sb and ^{144}Ce - ^{144}Pr detectable at almost all soil locations.

Studies of Cosmic Ray Ionization

In order to study cosmic ray ionization as a function of altitude spectra were obtained over a number of large lakes at various altitudes up to 10,000 feet. These results are given in Table V. The measurements at Red Mountain and at an open pit asbestos mine near Copperopolis, California shown in Table V are considered as cosmic ray measurements and treated with the lake measurements since the serpentine rock at both these locations exhibited very little gamma activit The 4" x 4" detector was placed in its stand as used in the field facing downward[3] at one end of a small aluminum or fiberglass boat. In all cases measurements were made more than 1/2 mile from shore to minimize interference from gamma emitters in the soil.

All of the spectra indicated the presence of some gamma activity. Two representative cosmic ray ionization spectra are shown in Figure 2. The only significant gamma contributors were radon daughters in the air. As shown in Table V our estimates of the gamma dose rate from the spectra range between 0.1 μr/hr and 0.5 μr/hr. Using these gamma dose rates we have estimated for each lake spectrum the total "energy" in the band 0.15 MeV to 3.4 MeV due to cosmic ray secondaries. The cosmic ray response for each of the three

energy bands used in determining natural component dose rates was also estimated. This detector response to cosmic ray secondaries as a function of altitude is shown in Figure 3. Figure 3 along with our gamma dose rate calibration of spectrum "energy" in the band 0.15 MeV to 3.4 MeV (43.0 BeV/(μr/hr)) indicates that the response from cosmic rays is less than 0.5 μr/hr gamma equivalent up to 6,000 feet. The crystal response appears to increase more rapidly with increasing altitude than does the cosmic ray ionization intensity, especially at higher altitudes.[5] This may be due to a transition effect. The electrons and photons are passing from a medium of low Z (air) to one of much greater Z (NaI) resulting in a rapid buildup of electrons and photons of lower energy in the crystal.[7] The crystal response in the energy region 0.15 MeV to 3.4 MeV is probably due more to photon interactions while the total ionization intensity is more dependent on charged particle interactions. Since in the lower atmosphere the flux of photons increases more rapidly with altitude than does the flux of charged particles, we would expect the crystal response to increase more rapidly with altitude than the cosmic ray ionization intensity.

Direct total dose rate measurements were also made over these lakes with our high pressure ionization chambers. These results are also given in Table V.

Since the total spectrum "energy" has been shown to be relatively independent of cosmic ray intensity up to fairly high altitudes, the gamma dose rate derived from this quantity at a land site can be multiplied by our well known ionization chamber gamma calibration factor and subtracted from the total ionization chamber reading to provide additional data of ionization chamber cosmic ray response versus altitude.

The spectrometric and ionization chamber results given in Figure 3 and Table V along with some independent calculations of cosmic ray intensity at certain pressure-altitudes, calculations of the cosmic ray response per unit dose rate of the ionization chambers, and data of other investigators have allowed us to infer the variation of cosmic ray ionization intensity versus altitude from which the HASL inferred cosmic ray dose rates of Table IV and V were obtained. This variation with altitude of cosmic ray ionization is discussed in detail in a separate paper.[5]

Our ionization chamber measurements at several of the lake sites were quite consistent with simultaneous measurements by the NYU group although they do appear to be slightly lower at the higher altitudes.[8] This may be due to the effect on our thicker-walled chambers of a slight change in the cosmic ray secondary energy spectrum with altitude.

Spectrometric Determination of ^{137}Cs Concentrations in Soils

Spectrometric measurements were made at or near a number of U. S. Department of Agriculture - HASL soil sampling sites. Estimates of the total activity of ^{137}Cs present in the soil at these locations were made from the ^{137}Cs dose rates determined by our spectrometric techniques.[3] These estimates will be compared with radiochemical determinations of ^{137}Cs and ^{90}Sr in recent soil samples taken at these sites in order to determine the validity of applying our field spectrometric techniques to study fallout deposition.

We assume fallout to be distributed with depth in the soil according to the relationship $S = S_o\, e^{-z/\alpha}$ where S (mc/cm is the activity at depth z (cm) below the surface and S_o is the activity at the surface.[3,6] We routinely use a relaxation length α = 3 cm and an *in situ* density of 1.6 gm/cm^3 (average over top 6" of soil) to represent a typical situation. The flux and total dose rate from such an exponential distribution depend on the quantity $\alpha\rho$, where ρ is the density.[3] For a given α and ρ the dose rate at one meter above the ground per 100 mc/mi^2 of activity can be calculated as can the expected number of 0.66 MeV ^{137}Cs absorption peak counts for our detector per unit dose rate and the expected number of counts per 100 mc/mi^2 total soil activity.

In order to illustrate the magnitude of the error involved in determining the ^{137}Cs dose rate and soil activity from a spectrum for a particular site the values of the above quantities are given below for 4 different products of α and ρ

$\alpha\rho$		Dose Rate (100 mc/mi^2)	Peak Counts (μr/hr)	Peak Counts (100 mc/mi^2)
4.8	(assumed typical model)	0.17	27500	4700
6.4	(denser soil or deeper penetration)	0.15	26000	3900
3.2	(less dense soil or shallower penetration)	0.20	29000	5800
0	(ideal plane source)	0.41	36500	15000

Thus a 33% change from our assumed typical model in relaxation length or density results in only about a 5% change in peak area per unit dose rate, about a 15% change in the actual dose rate, and about a 20% change in the peak area per 100 mc/mi^2 activity. Since soil density and isotope penetration probably vary significantly from site to site, the soil concentration of ^{137}Cs inferred from a spectrum taken at a single location could be considerably in error; however, to the extent that our depth distribution model represents an average situation, our estimates of ^{137}Cs activity for a large number of locations should reasonably reflect the variation in activity from area to area. Indeed preliminary comparison with the few radiochemical results available at present indicate that this is indeed the case and that field spectrometric estimates of ^{137}Cs soil activity can play an important role in studying fallout deposition.

The table above also indicates the fortuitous relative insensitivity of our spectrometric dose rate estimates to differences in density and relaxation length. This results since the dose rate estimates are based on the ratio of primary flux to total dose rate and both these quantities change in the same direction for a given change in $\alpha\rho$.

At the Largo, Md. Site listed in Table IV, a depth profile soil sample was taken directly after our measurement by Alexander of the U. S. Department of Agriculture. The soil density and moisture content were also measured. The radiochemical determination of the ^{137}Cs activity at this site and its distribution in depth should be valuable in testing our model. These results together with the radiochemistry results for the other sites measured will be compared with our spectrometric estimates of ^{137}Cs soil concentrations as soon as the radiochemistry is completed.

Measurements over Solid Rock

Since solid rock is usually more homogeneous than soil, samples of the rock when analyzed γ spectrometrically in the laboratory for potassium, ^{238}U, and ^{232}Th should allow a reasonable comparison with our field spectrometric estimates of the activity present. Two of the sites for which data are given in Table IV, at Shaver Lake, Cal. and Courtright Reservoir, Cal., were on solid rock outcrops. Laboratory analyses of the rock were done by Smith and Wollenberg of the Lawrence Radiation Laboratory (LRL).[9]

Adams of Rice University obtained data at these sites with his field spectrometer system[10] and the NYU group made measurements of the total ionization intensity in air using their thin-walled ionization chambers.

Although all the results of the other groups have not yet been received, it appears that our values for potassium and ^{232}Th concentration agree reasonably well with the analysis by LRL considering the fact that the sites geometrically were not very good half spaces, thus affecting our conversion from dose rate to concentration.

Our inferred ^{238}U concentrations disagree considerably, however, this may be due to a substantial radon migration from the rock in the field situation. It is also possible the laboratory samples may not have been representitive due to lack of homogeneity.

Measurements of Low Level Radiation

Measurements were made at three locations where gamma and/or cosmic ray dose rates were unusually low in order to study our instrument response as well as for general interest. The results of these measurements are also given in Table V.

The first location was an abandoned magnesite mine on Red Mountain in Santa Clara County, Calif. The serpentine wall material exhibited almost no detectable gamma activity. Since the overhead cover was 430 feet of rock the dose rate from μ mesons was reduced to a negligible amount. A two hour spectrum showed the only detectable activity from outside of the detector itself to be from radon daughters in the air, resulting in a dose rate of less than 0.1 μr/hr. No inherent radioactivity sufficient to affect any of our field measurements was apparent in any of our instruments.

Directly outside the mine the serpentine material was also very low in natural gamma activity with the only significant gamma activity coming from deposited fission products. Thus this set of measurements was a useful addition to our lake data for our cosmic ray ionization study.

The second location was at the open pit asbestos mine near Copperopolis, Calif., where measurements had been taken previously.[3,4] The site where measurements were made during the trip was only recently excavated and thus was completely clear of fission product activity. The natural activity of the serpentine rock itself was almost negligible and again the only significant terrestrial gamma activity was from radon daughters in the air. (See Figure 2.) The total terrestrial gamma activity was estimated from the spectrum to be less than 0.2 μr/hr and thus these data provided an excellent near sea level measurement for use in our cosmic ray ionization study.

The third location was in a deep salt mine near Houston, Texas. The major sources of activity in this mine were from ^{40}K in the salt and radon daughters in the air. The total dose rate measured was about 0.2 μr/hr.

In order to further compare the results of our low level measurements to those of other investigators using different types of instruments, a number of measurements were made in low level counting rooms at the Lawrence Radiation Laboratory, Rice University, and HASL. These measurements substantiated our confidence in the response of our instruments under such conditions.

Study of β-ray Ionization Intensity

The high activity of beta-emitting fallout isotopes such as ^{90}Sr, ^{144}Ce, and ^{106}Rh present in the soil during recent years has stimulated our interest in examining the free air dose rate and skin and gonadal doses due to β-rays. We had not considered this aspect of environmental radiation to be important in past studies and our equipment is designed not to respond to β-rays. Since ionization intensity measurements made by the NYU group with their relatively thin plastic-walled (1/4" plexiglass) chambers[11] include a contribution from β-rays, the difference between their measurement and a measurement made with our instruments when corrected for the wall thickness of their chamber should roughly indicate the free air β-ray ionization. Such measure ments can also be compared with theoretical estimates of the free air dose rate from β-ray emitters in the soil. Thus a series of experiments and theoretical studies in conjunction with the NYU group were initiated. In conjunction with these studies the NYU group made simultaneous ionization chamber measurements at several of our field locations during this cross country trip and also at several sites in the New York City area. These β-ray studies are discussed further in Section IV.

Special Studies

Correlation with Neonatal Death Rate and Birth Weight - Several measurements were made at sites in Western Nebraska to provide Grahn of Argonne National Laboratory with additional information on natural gamma dose rate levels for use in his studies of the relation between ionizing

radiation and neonatal death rate and birth weight.[12] This particular area was used as a control area for his studies. As shown in Table IV the few sites surveyed varied very little in total natural emitter dose rate.

Correlation with Aerial Survey Data - Measurements were made in the Alamagordo, N.M., area with a group from the ARMS[13] program to enable these investigators to correlate their aerial spectral measurements with our ground data. In addition simultaneous ground measurements by the ARMS group with an air-filled plastic-walled ionization chamber were made to calibrate its response against our instruments.

Comparison with Continuous Monitoring Experiment - Measurements were also made at the Texas Instrument continuous monitoring gamma spectrometer site[14] at Dallas, Texas. The total natural emitter dose rate at this site was quite low. The individual natural gamma and fallout gamma emitter concentrations at this location inferred from our measurements agreed very well with the values estimated by Foote of Texas Instruments.

Measurement in High Uranium Area - In order to verify our ^{238}U series dose rate calibration, measurements were made at the Lucky Mick uranium mine near Carlile, Wyo. The site was a flat cleared area previously used for storage of ore. The soil was thoroughly permeated with uranium ore and thus approximated a very thin slab source distribution of very high activity. The consistency of the various dose rates determined spectrometrically and by ionization chamber measurement substantiated our ^{238}U series calibration.

Intercalibration of Detectors

Our 1965 field measurements, besides giving us the opportunity to carry out a number of major investigations under varying geological and radiological conditions, also allowed us to substantiate our limited laboratory calibrations of our new 4" x 4" detectors by comparing their response in the field against our well calibrated 5" x 3" detector. In particular the wide range of potassium, uranium and thorium dose rates encountered allowed us to obtain good energy band equations for the new detectors.

IV. CONTINUING ENVIRONMENTAL RADIATION STUDIES

Beta Radiation

We are actively engaged in studying the free air ionization due to β-rays from both natural and fallout emitters in the soil not only because of its possible significance to population exposure but also because of its effect on various types of instrumentation used to measure gamma dose rates and the possible subsequent misinterpretation of the readings of these instruments. The significance of the latter was impressed upon us when readings with various NYU thin plastic-walled ionization chambers at field sites in the New York area were reduced by 30% or more when the chambers were raised from 40 cm to 130 cm off the ground. β-ray sensitive instruments such as thin-walled ionization chambers, geiger counters, and unshielded NaI detectors are frequently used to measure gamma ray dose rates in air. As mentioned before our instrumentation is designed not to respond to β-rays.

Our first relatively detailed experiment was carried out over soil at a site at Greenwood Lake, N.Y. The gamma ray and cosmic ray free air ionization were determined by our spectrometric and high pressure ionization chamber techniques. Measurements of ionization intensity with an NYU spherical thin-walled plexiglass chamber (minimum wall thickness $\doteq$ 250 mg/cm^2) were made at a succession of heights above the ground from 40 cm up to 180 cm.[11] The gamma plus cosmic ionization total which was essentially constant over these heights was subtracted from these readings and the remaining values of ionization were plotted on semilog paper as a function of mean detector height. The resulting points were well fit by a straight line corresponding to a half-thickness of 150 mg/cm^2 in air. Since plexiglass has about the same mass stopping power for electrons as air, the chamber wall should roughly be equivalent to 1.6 half-thicknesses and the free air ionization about three times the measured values ($2^{1.6} \doteq 3$). However, the large size and varying thickness of this chamber makes this approximatio somewhat tenuous. The resulting estimates of free air

ionization at one meter above the ground were 7I(ion pairs/ cm^3/sec at 760 mm. and 0^oC) due to gamma rays and cosmic rays and about 13I due to beta rays.

We have attempted to calculate, using the theoretical approach of O'Brien et al[15] the free air β-ray ionization expected from the major beta emitters in the soil. Their results suggest that one group transport theory can be successfully applied to environmental beta ray dosimetry. Using estimates from deposition data of ^{90}Sr, ^{144}Ce and ^{106}Rh present in the soil at the time of the Greenwood Lake measurements and our spectrometric estimates of ^{40}K, ^{238}U, and ^{232}Th concentrations at the site, we calculated the total β-ray ionization expected at various heights. The calculation, however, is extremely sensitive to the depth distribution of beta emitters in the soil, much more so than for gamma emitters. The theory does predict an approximately exponential decrease with height; however the calculated absolute ionization intensities are significantly less than the values inferred from the chamber measurements. If we consider only fallout emitters the calculation of half thickness in air is less dependent on depth distribution or source intensity. A half thickness of ~150 mg/cm^2 is then verified by the theory. The discrepancy in absolute ionization intensity could well be due to errors in assumed source intensity and/or distribution or to an incorrect ionization chamber wall correction. Measurements at other sites with other instruments are clearly necessary before any final conclusions can be made as to the agreement of experiment and theory.

Further experimental studies using new ultra thin-walled ionization chambers constructed of different materials as well as sets of filters which can be placed over the chambers are planned in conjunction with the NYU group. A more intense theoretical study, combined with the results of these planned experiments, should provide a reasonable picture of the contribution of β-rays to the external environmental radiation field.

In any case, these weakly penetrating β-rays contribute only a very small fraction of the total dose received by the gonads or bone marrow.

Variation of Natural Dose Rates with Time

Repeated measurements at sites at Pelham, N.Y., and Mamaroneck, N.Y., over the past several years indicate that the dose rate from the natural emitters varies significantl with time (see Table VI). Such variations have also been reported by other investigators.[16,17] The major causes for such variations are changes in soil water content which res in increased attenuation of gamma rays passing through the ground and changes in the dose rate from the uranium series

The effect of increased soil water content on dose rat from both a uniformly distributed source (natural emitters) and an exponentially distributed source (fallout emitters) was calculated using our equations for the dose rate from emitters in the soil.[3] For 1.46 MeV ^{40}K γ-rays the ratio o primary flux to total dose rate, which is the factor determ our field spectrometric dose rate estimates, changes by les than 5% when the soil water content increases from zero to 30% by weight. The corresponding actual dose rate decrease is about 30%. A soil water content of 30% by weight is not at all uncommon during wet periods. For ^{137}Cs 0.66 MeV γ-r the same change in water content results in a 5% reduction in the flux to total dose rate ratio while the total dose rate decreases by about 17%. Thus the effect on our spectrometric dose rate estimates is small in both cases while the significant effect on the total dose rate is greater for the uniformly distributed natural emitters than for the closer to the surface fallout emitters.

The dose rate from the uranium series is affected by soil water in two conflicting ways. The clogging of the pores in the soil impedes the escape of radon from the soil air into the atmosphere. If this condition persists for a few days, radon levels in the soil air will build up towards ^{226}Ra-^{222}Rn equilibrium resulting in an increased dose rate from the radon daughters. The additional soil water, however, also increases the γ-ray attenuation as in the case of the other natural emitters. It is thus not unusual to find decreases in ^{40}K and ^{232}Th dose rates accompanied by either a slight increase or no change at all in the ^{238}U series dose rate.

The dose rate from the ^{238}U series may also be increased due to "natural fallout". Under normal conditions most of the free radon in the top few inches of soil escapes into the atmosphere and is widely dispersed.[18] The resulting dose rate from gamma emitting daughters in the atmosphere usually amounts to only a few tenths of a μr/hr.[3] This was substantiated by our spectral measurements over large lakes where the radon daughter air concentrations would be expected to be fairly similar to those over nearby land areas. However, these particulate gamma emitting daughters are effectively washed out of the atmosphere during rainfall and thus the term "natural fallout". This washout results in a fairly high concentration of short-lived (T 1/2 ≐ 30 min.) gamma emitting radon daughters close to the soil surface and a corresponding sizeable temporary increase in the ^{238}U series dose rate.

To study the variation of natural gamma radiation with time experimentally, in May, 1965, HASL and NYU attempted to monitor the radiation background continuously for several days over a soil location at Greenwood Lake, N.Y. Measurements were made hourly of the total gamma dose rate with both our ionization chambers and an NYU plastic-walled chamber. The temperature, barometric pressure, relative humidity, and wind speed were also monitored. Pulse height spectra were accumulated every two hours and air samples of α activity at one meter above ground were taken every two hours.

During a four day period the soil moisture content did not change appreciably, and no significant changes were observed in the ^{40}K and ^{232}Th dose rates. The radon daughter concentrations at one meter above the ground inferred from the air samples increased markedly during the calm evening and early morning hours. The corresponding ^{238}U series dose rate, inferred from the spectra, did not show any significant changes, indicating the radon daughter distribution in the soil air was not building up significantly. The slight correlation in the variation of the ^{238}U series dose rate and radon daughter concentration in the air which was detected was probably due to a slight increase in the dose rate from the airborne daughters. Large variations in relative humidity often reaching into the high 90's resulted in a multi-channel analyzer failure early in the third day and thus the

correlation study between radon daughter levels and the ^{238}U series dose rate (specifically the counts in the 1.76 MeV ^{214}Bi peak) could not be completed.

The total gamma dose rates were relatively constant during this four day period with a variation of only a few tenths of a μr/hr except for the period immediately following a brief heavy shower on the third day. Measurements immediately after the shower with our high pressure ionization chambers were significantly higher indicating the presence of "natural fallout". (A similar effect was obtained at the Elko, Nev. site (see Table IV) on our recent field trip.) The NYU dose rate measurements fell, however, and remained depressed for several hours. This was probably due to the greatly enhanced attenuating effect a small increase in soil moisture had on the β-ray component which accounted for a large proportion of the total ionization in the NYU chamber. The dependence of free air β-ray ionization from emitters in the soil on isotope distribution and soil moisture suggest that spot measurements of environmental radiation with thin walled chambers would be very hard to interpret.

Fluctuations in natural dose rate with time necessitate that care be taken in interpreting the data obtained from a single set of measurements at a site. The greatly reduced natural levels encountered at many of our midwestern and central U.S. locations in 1965 compared to our 1962 and 1963 measurements indicate the danger of misinterpreting spot measurements. Such spot measurements are useful when a large number of them can be used to deduce a pattern over a large area.

We intend to continue to study the effect of the migration of radon on natural dose rates, and a more careful controlled monitoring experiment may be undertaken. If small differences in exposure to penetrating radiation prove to be biologically significant, then the fluctuations in the natural gamma dose rate level have to be considered in studies of population exposure.

High Pressure Ionization Chambers

The measurement of the very low ionization levels from natural and fallout γ-radiation requires very sensitive instrumentation capable of providing precise readings under all kinds of field conditions. The instruments we have developed for measuring these total gamma dose rates are several steel-walled cylindrical ionization chambers filled to high pressures with the purest commercially available argon. Our newest model is shown in Figure 4. This chamber* consists of a cylindrical tank 12" long and 6 1/2" in diameter with a .135" thick stainless steel wall.

Its sensitive volume of 5.58 liters was originally filled to a pressure of 1000 psi with argon. The ionization current is measured by a Victoreen Dynamic Capacitor Electrometer to an accuracy of about 1% (after careful calibration of electrometer output voltage reading with a potentiometer). A precision of 1-2% can also be obtained by averaging a large number of instantaneous readings taken in rapid succession. The chamber is equipped with a switch to allow the potential between the wall and guard ring to be reversed. Measurements are always made for both polarities to cancel any small unidirectional polarization currents which are sometimes induced in the insulators. The chamber has been found to be saturated for gamma fields in excess of 100 r/hr when used at an operating potential of 300 V. The 300 V battery is located in an aluminum can on top of the pressure vessel along with the head of the electrometer. The electrometer readout unit can be operated up to 150 ft. away through a cable connection, thus eliminating shielding of the chamber by the operator.

The energy response of this chamber was investigated down to 90 KeV using a filtered X-ray beam as well as ^{226}Ra, ^{60}Co, ^{137}Cs and ^{144}Ce gamma sources. Although the attenuating effect of the steel wall becomes very large for low energy gamma rays, these experiments substantiated our theoretical predictions that this effect would be significantly moderated by the increased absorption of low energy gamma rays in argon relative to air. The net reduction in dose

*RSG-42 Ionization Chamber manufactured to our specifications by Reuter-Stokes, Inc., Cleveland, Ohio.

rate was only about 50% for 70 keV X-rays and only about 18% for 134 keV ^{144}Ce gamma-rays. Since under normal conditions only a small fraction of the external gamma dose rate is from gamma-rays of energy less than 150 keV,[3] the error in the total field dose rate due to energy dependence is in most instances no more than 1 or 2%.

The angular response of the chamber was also determined experimentally and a correction factor +2% was adopted to account for the slightly greater response for gamma-rays entering perpendicular to the chamber axis.

In order to investigate recombination and wall effects, an experiment was carried out in a constant gamma radiation field of about 60 μr/hr. The chamber pressure was reduced in steps from 1000 psi down to less than 50 psi. The resultant linear plot of ionization current versus pressure indicated that essentially no current was being lost due to recombination. The extrapolated intercept for zero gas filling indicated a wall effect due to an excess of electrons from the wall causing ionization in the gas of less than 1% of the total current. These quantities must be known to theoretically predict the response of the chamber to gamma radiation.

Measurements in deep mines have substantiated calculati showing that the ionization produced by radioactive contamination of the chamber walls and electrodes is negligible compared to the ionization current obtained per unit dose rate at our operating pressure and volume.

The ionization current per μr/hr for gamma rays can be calculated from the known volume and pressure. This calcula tion also requires a prior determination of the ionization to be expected in argon relative to air, which requires an accurate knowledge of the W values for the two gases and the mass energy transfer coefficients for the energy gamma rays in question. Also, the effective attenuation of the wall (~.90), which was estimated experimentally by measuring the dose rate from a collimated source inside steel cylinders of varying thickness, enters into the calculation. Considering all the uncertainties involved in these quantities as well as an uncertainty of several percent in the filling pressure

the calculation cannot be relied upon other than as a check on a careful experimental calibration. The value of the ionization current per μr/hr for gamma rays obtained by calculation was 4.45×10^{-14} amperes. This calculation is given in detail in Appendix 1. The value obtained from a careful calibration using an NBS standardized radium source was $(4.60 \pm .10) \times 10^{-14}$ amperes/μr/hr. The latter value was also obtained (to within 2%) using less accurately standardized ^{60}Co and ^{137}Cs sources. The calibration procedure adequately accounts for the effect of scattered gamma-rays from the laboratory floors and ceiling by careful shadow shielding of the source. Both of the above calibration factors are for 59 atmospheres of gas and normal incidence of gamma rays to the chamber axis.

The calculation of ionization current per μr/hr for cosmic radiation again requires the determination of the relative ionization produced in a 1 atm. argon filling to that which would be produced in 1 atm. of air, but this time the incident particles are primarily high energy electrons and muons rather than gamma-rays. In the gamma ray case the ratio of ionization produced in argon relative to air depends primarily on the relative Compton cross sections for the two media while in the cosmic ray case this ratio depends on the relative values of the mass energy stopping powers for minimum ionizing electronic particles.[19] These ratios are not necessarily the same although they do turn out to be quite similar. The theoretical stopping power prediction for the number of ion pairs produced in argon to that in air per unit flux is about 1.51.[19,20] However, measurements of this quantity made by several investigators under thick shields sufficient to shield out all particles except muons predict a value of about 1.68.[21,22,23] If we use the latter value along with slight corrections for the attenuating and electron enhancement effects of the wall, we calculate a cosmic ray calibration factor of 5.01×10^{-14} amperes/(μr/hr). (See Appendix 1) From our independently derived cosmic ray ionization curve vs. pressure altitude and calculated values of the total ionization intensity at sea level[5] we deduce a value of 5.09×10^{-14} amperes/μr/hr. The latter value is used routinely.

The agreement of the two calibration factors given above suggests a significant discrepancy between the experimental

and theoretical ratios of ionization for fast charged particles in argon relative to air which may be partly responsible for the higher values of cosmic-ray ionization in the lower atmosphere measured by Neher using argon filled chambers.[5] In order to pursue this question further we are planning with the cooperation of the NYU group to expose two identical thin walled chambers filled with argon and air, respectively, to the predominantly cosmic ray field on a large lake. If both chambers are properly saturated the resultant ratio of ion currents per atmosphere should be helpful in investigating this discrepancy. If the experimental value of 1.65 - 1.70 is verified then further study will be necessary to explain why present stopping power theory fails to predict this value. Since the experimental value of 1.65 was obtained in all cases using thick walls it is possible that the discrepancy may be related to a fast particle wall effect, although Johnston[19] claims this is unlikely. It is clear, however, that the interaction of high energy particles with a thick-walled chamber is still not perfectly understood and is worthy of continued study since such chambers are still being used on balloon flights for high altitude cosmic ray studies.[19]

Theoretical Investigation of Gamma Ray Transport

Our present theoretical calculations of dose rates for various source distributions in the soil and air, based on the dose rate buildup theory of O'Brien et al,[24] is apparently adequate for the calculation of the total dose rate from distributed sources. However, it does not allow a calculation of the angular distribution or energy spectrum of the incident flux at the detector. The knowledge of these distributions would be valuable in interpreting the response of various types of instrumentation to different kinds of source distributions and source energies as well as for calculating the actual energy deposition in various organs of the body. At present these distributions can be calculated only by time consuming Monte Carlo methods. Because of the machine time required these methods have only been applied to a few particular problems and only for a few source energies. In particular Monte Carlo calculations have substantiated the experimental prediction of an interface effect for a point source near the boundary of two media of very different

densities. It has been assumed for the distributed source considered in our methods, however, that such an effect is not important. It would be interesting to theoretically verify this assumption.

We are therefore attempting to develop new approximate methods or modify existing methods to predict the angular distributions and energy spectra for various source distributions for a two media geometry such as the earth-air situation. Such methods would be useful not only for environmental gamma radiation problems but also for solving general shielding problems.

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APPENDIX 1

CALCULATION OF IONIZATION CHAMBER RESPONSE

Gamma Ray Response

$$k_t = \left(\frac{(\mu e/\rho)_a}{(\mu e/\rho)_{air}}\right)\left(\frac{\rho_a}{\rho_{air}}\right)\left(\frac{W_{air}}{W_a}\right) VP \frac{.576}{(\mu r/hr)} \text{ ion pairs}$$

$$\left(1.6 \times 10^{-19} \frac{\text{amperes}}{\text{ion pair}}\right) (F \times G) \frac{\text{amperes}}{(\mu r/hr)}$$

where

V = active volume of chamber (5.58×10^3 cm^3),
P = filling pressure (59.2 atmospheres at stp.),
F = effective attenuation due to wall (.90, see pg. 24 of text),
G = enhancement due to steel-argon boundary (1.01),

$\frac{e/\rho)_a}{e/\rho)_{air}}$ = the average ratio of mass energy absorption coefficients over the range 0.3 - 2.5 MeV (.91), and

$a/\rho_{air})$ = the ratio of gas densities (1.38), (W_{air} = 33.8 and W_a = 26.4).

Then

$$k_t = (.91)(1.38)\left(\frac{33.8}{26.4}\right)(5.58\times10^3)(59.2)(.576)(1.6\times10^{-19})$$
$$(.90)(1.01)$$

$$= 4.45 \times 10^{-14} \text{ amperes}/(\mu r/hr).$$

The estimated uncertainty in this calculated value is 5-10%.

Cosmic Ray Response

$$k_c = RVP \frac{.576(\text{ion pairs}/cm^3\text{-sec})}{\mu r/hr} \frac{1.6 \times 10^{-19} \text{ amperes}}{\text{ion pairs}} (F \times G)$$

where

R = ratio of ionization in 1 atm. of argon to ionizatior
in 1 atm. of air for the same flux (1.68),
F = attenuation due to walls (.96), and
G = enhancement due to steel wall-argon filling (1.02).

Then

$$k_c = (1.68)(5.58\times10^{3})(59.2)(1.6\times10^{-19})(.96)(1.02)(.576)$$

$$= 5.01 \times 10^{-14} \text{ amperes}/(\mu r/hr).$$

to ionization
8),

ling (1.02).

2) (.576)

TABLE I

CALIBRATION OF 4" x 4" NaI(Tl) DETECTOR

Energy (MeV)	Isotope	(N_O/Φ)* (4 x 4")**	(N_O/Φ)* (3 x 5")
.393	^{113}Sn	68000	88000
.514	^{85}Sr	65000	81000
.662	^{137}Cs	55000	69000
1.37	^{24}Na	38000	35000
1.46	^{40}K	37500	34500
1.76	^{214}Bi	23000	18500
2.62	^{208}Tl	22800	16800
2.73	^{24}Na	22000	-

*counts/unit flux/20 min.
**with 1/4" bakelite shield

TABLE II

DOSE RATE CALIBRATION OF 4" x 4" DETECTOR - NATURAL EMITTE

	K	U	Th
Isotope	^{40}K	^{214}Bi	^{208}Tl
Gamma Energy (MeV)	1.46	1.76	2.62
Dose Rate Contribution (μr/hr)	1.71/%	0.76/p.p.m.	0.36/p.p
(N_O/Φ)*	37500	23000	22800
(N_F/N_O)	1.08	1.05	1.03
(Φ/I)	0.192	0.037	0.049
(N_F/I) $\frac{\text{Peak Counts}}{(\mu r/hr)}$ (20 min.)	7800	900	1150

*Calibrated with 1/4" Bakelite shield.

TABLE III

DOSE RATE CALIBRATION OF 4" x 4" DETECTOR - FALLOUT

Isotope	^{140}Ba-^{140}La	^{103}Ru-^{103}Rh	^{106}Ru-^{106}Rh	^{137}Cs	^{95}Zr-^{95}Nb	^{54}Mn
Gamma Energy (MeV)	0.49	0.50	0.52	0.66	0.75	0.84
(N_O/Φ)	65000	65000	65000	55000	51000	48000
(N_F/N_O)	1.14	1.14	1.14	1.11	1.10	1.07
(Φ/I)						
half space	0.06	0.34	0.18	0.29	0.26	0.23
exponential*	0.10	0.55	0.29	0.45	0.41	0.36
plane	0.14	0.77	0.40	0.60	0.54	0.48
(N_F/I)** $\frac{\text{Peak Counts}}{(\mu r/hr)}$						
half space	4450	25000	13000	17500	14500	12000
exponential*	7400	41000	21500	27500	23000	18500
plane	10400	57000	30000	36500	30000	25000

*Assuming 3 cm. relaxation length.
**Twenty minute spectrum.

TABLE IV

TERRESTRIAL GAMMA MEASUREMENTS (μr/hr)

Town & Location	Date	Total Gamma	Natural Gamma K	U	Th	Total	Fallout Gamma Cs^{137}	Mn^{54}	Zr^{95}-Nb^{95}	Rh^{106}	Other	Total	F.O. (2)*	HASL Inferred Cosmic
Pelham, N.Y.	4-30-65	6.9	2.1	1.4	2.8	6.3	0.6	0.1	-	0.1	-	0.8	0.6	3.6
(Park)	5-21-65	7.9	2.2	1.3	3.1	6.6	0.8	0.2	-	0.2	0.2	1.4	1.3	3.6
	7-29-65	7.7	2.2	1.3	3.0	6.5	0.8	0.1	-	0.1	0.2	1.2	1.2	3.6
Mamaroneck, N.Y.	4-30-65	6.8	2.0	1.3	2.8	6.1	0.6	0.1	-	0.1	-	0.8	0.7	3.6
(Open Field)	5-21-65	7.8	2.2	1.3	3.4	6.9	0.7	0.2	-	0.2	0.1	1.2	0.9	3.6
	7-29-65	8.0	2.2	1.3	3.3	6.8	0.8	0.2	-	0.2	0.2	1.4	1.2	3.6
Greenwood Lake,	4-28-65	8.7	2.0	1.4	4.3	7.7	0.6	0.1	-	0.2	0.1	1.0	1.0	3.7
N.Y. (Lot)	5-18-65	9.1	2.1	1.9	4.1	8.1	0.7	0.1	-	0.2	0.1	1.1	1.0	3.8
	5-24-65	8.6	2.1	1.7	4.0	7.8	0.6	0.2	-	0.2	0.1	1.1	0.8	3.7
New York City (Fordham Univ.)	7-28-65	8.6	2.2	1.4	4.2	7.8	0.9	0.1	-	0.1	0.1	1.2	0.8	3.6
Carlisle, Pa.	8-3-65	7.7	2.4	1.5	3.0	6.9	0.5	0.1	-	0.2	0.1	0.9	0.8	3.7
(Lawn of Army	10-1-63	9.5	3.0	1.5	3.1	7.6	-	-	1.6	0.3	-	1.9	1.9	3.5
War College)	4-5-63	11.2	3.3	1.5	3.6	8.4	-	-	3.4	1.0	-	4.4	2.8	3.5
Argonne, Ill.	8-5-65	8.9	2.0	2.2	2.4	6.6	0.5	0.1	-	0.3	1.2(A^{41})**	2.1	2.3	3.8
(Field, ANL)	10-3-63	10.8	2.8	1.7	3.0	7.5	-	-	2.5	0.3	-	2.8	3.3	3.7
	10-15-62	9.5	2.4	1.7	3.0	7.1	-	-	1.9	0.6	-	2.5	2.4	3.7

* The difference between the value of the total gamma dose rate and that of the total natural gamma dose rate.

**During the measurement an apparent escape of A^{41} from a nearby reactor resulted in an additional gamma dose rate of about 1 μr/hr

10-19-62	9.9	2.4	1.7	3.0	7.1	-	-	1.9	0.8	-	2.7	-	-		

* The difference between the value of the total gamma dose rate and that of the total natural gamma dose rate.

**During the measurement an apparent escape of A^{41} from a nearby reactor resulted in an additional gamma dose rate of about 1 μr/hr.

			Natural Gamma				Fallout Gamma							HASL Inferred
Town & Location	Date	Total Gamma	K	U	Th	Total	Cs^{137}	Mn^{54}	Zr^{95}-Nb^{95}	Rh^{106}	Other	Total	F.O. (2)	Cosmic
Spring Valley,	8-6-65	5.6	1.4	1.2	2.0	4.6	0.4	0.1	-	0.1	0.1	0.7	1.0	4.0
Minn. (Field	10-5-63	8.7	2.0	1.4	2.4	5.8	-	-	2.1	0.3	-	2.4	2.9	3.8
off U.S. 16)	9-22-62	8.6	2.0	1.6	2.5	6.1	-	-	2.2	0.4	-	2.6	2.5	3.8
Sioux Falls,	8-7-65	8.0	2.1	1.8	3.0	6.9	0.6	0.1	-	0.2	0.1	1.0	1.1	4.1
S.D. (School	10-5-63	11.0	2.3	2.1	3.3	7.7	-	-	3.3	0.3	-	3.6	3.3	3.9
Lawn)	9-23-62	12.7	2.7	2.2	3.7	8.6	-		3.2	0.8	-	4.0	4.1	3.9
Murdo, S.D. (Field)	8-7-65	8.1	2.6	0.9	2.9	6.4	0.		-	0.1	0.2	1.1	1.7	4.3
Rapid City, S.D.	8-8-65	5.3	1.1	1.5	1.7	4.3	0.6		-	0.2	0.1	1.0	1.0	4.7
(Lot, N. Side)	10-7-63	7.9	1.6	2.0	2.4	6.0	-		2.3	0.5	-	2.8	1.9	4.7
	9-24-62	10.6	1.9	1.7	2.9	6.5	-	-	3.1	0.8	-	3.9	4.1	4.7
Spearfish, S.D.	8-8-65	7.1	2.3	1.1	2.3	5.7	0.5	0.1	-	0.2	0.2	1.0	1.4	4.9
(Church Lawn)	10-7-63	10.2	-	-	-	-	-	-	-	-	-	-	-	4.9
	9-24-62	11.3	3.0	1.5	3.0	7.5	-	-	3.0	0.7	-	3.7	3.8	4.9
Sundance, Wyo.	8-8-65	8.0	2.2	1.9	2.4	6.5	0.8	0.2	-	0.2	0.2	1.4	1.5	5.6
(West Side Lot)	10-7-63	12.0	2.5	2.4	2.7	7.6	-	-	3.6	0.8	-	4.4	4.4	5.6
	9-25-62	11.9	2.6	2.0	2.5	7.1	-	-	4.6	0.5	-	5.1	4.8	5.6
Keyhole Res., Wyo. (Shore)	8-9-65	8.2	2.2	1.9	3.3	7.4	0.5	0.1	-	0.2	0.1	0.9	0.8	5.2
Carlile, Wyo. (Lucky Mick Uranium Mine Recent Ore Storage Site)	8-9-65	109.4	-	108.8	-	108.8	-	-	-	-	-	-	-	5.2

Town & Location	Date	Total Gamma	Natural Gamma				Fallout Gamma							HASL Inferred Cosmic
			K	U	Th	Total	Cs^{137}	Mn^{54}	Zr^{95}-Nb^{95}	Rh^{106}	Other	Total	F.O. (2)	
Chadron, Neb.	8-10-65	8.5	2.3	1.7	3.3	7.3	0.4	0.1	-	0.2	0.1	0.8	1.2	4.8
Alliance, Neb.	8-10-65	8.3	3.3	1.6	2.6	7.5	0.3	0.1	-	0.2	0.1	0.7	0.8	5.1
Scottsbluff, Neb.	8-11-65	8.3	2.5	2.0	2.8	7.3	0.4	0.1	-	0.1	0.1	0.7	1.0	5.0
Fort Collins, Colo. (Colo. State Univ. Farm Pasture - Soil Sampling Site)	8-11-65	8.9	2.5	1.8	4.0	8.3	0.2	0.1	-	0.1	0.1	0.5	0.6	5.8
	10-10-62	10.3	2.7	1.7	4.2	8.6	-	-	1.7	0.4	-	2.1	1.7	6.1
Denver, Colo. (Lot, S.W. Side)	8-12-65	8.7	2.5	1.6	3.4	7.5	0.4	0.1	-	0.1	0.1	0.7	1.2	5.9
	10-18-63	10.2	2.7	2.2	4.2	9.1	-	-	1.3	0.3	-	1.6	1.1	6.3
Denver, Colo. (Park, E. Side)	8-12-65	10.8	3.1	1.8	5.1	10.0	0.4	0.1	-	0.1	0.1	0.7	0.8	5.9
	10-18-63	13.1	3.4	2.7	6.3	12.4	-	-	0.8	0.1	-	0.9	0.7	6.3
	10-10-62	12.5	3.4	1.2	6.2	10.8	-	-	1.5	0.3	-	1.8	1.7	6.3
Denver, Colo. (Lot, W. Side)	8-12-65	7.7	2.3	1.3	3.5	7.1	<0.1	<0.1	-	0.1	0.1	0.4	0.6	6.0
	10-18-63	10.7	3.1	1.5	4.0	8.6	-	-	1.2	0.2	-	1.4	2.1	6.3
Denver, Colo. (Field Near Airport)	8-13-65	12.3	3.9	1.9	5.5	11.3	0.3	0.1	-	0.1	0.1	0.6	1.0	6.0
	10-19-63	14.1	5.3	2.3	6.0	13.6	-	-	0.7	0.1	-	0.8	0.5	6.3
	10-10-62	14.5	5.2	2.1	6.9	14.2	-	-	1.3	0.2	-	1.5	0.3	6.3
Denver, Colo. (Lot, N. Side)	8-13-65	13.8	3.4	2.4	7.4	13.2	0.3	0.1	-	0.1	0.1	0.6	0.6	5.9
	10-18-63	15.8	4.0	2.5	8.7	15.2	-	-	0.4	0.2	-	0.6	0.6	6.3

Denver, Colo.	8-13-65	13.8	3.4	2.4	7.4	13.2	0.3	0.1	-	0.1	0.1	0.6	0.6	5.9
(Lot, N. Side)	10-18-63	15.8	4.0	2.5	8.7	15.2	-	-	0.4	0.2	-	0.6	0.6	6.3

Town & Location	Date	Total Gamma	Natural Gamma				Fallout Gamma							HASL Inferred Cosmic
			K	U	Th	Total	Cs^{137}	Mn^{54}	Zr^{95}-Nb^{95}	Rh^{106}	Other	Total	F.O. (2)	
Summit Lake, Colo. (Shore Area)	8-14-65	10.3	3.7	1.6	3.2	8.5	0.5	0.1	-	0.2	0.1	0.9	1.8	15.3
Leadville, Colo. (Lot)	8-15-65	9.3	2.7	1.8	4.1	8.6	0.3	0.1	-	0.1	0.1	0.6	0.7	10.8
Climax, Colo. (Lawn at High Altitude Obs.)	8-16-65	9.8	2.6	2.0	3.7	8.3	0.6	0.1	-	0.3	0.3	1.3	1.5	12.3
Twin Lakes, Colo. (Shore)	8-17-65	9.3	3.1	2.5	3.6	9.2	0.1	-	-	-	-	0.1	0.1	9.8
Craig, Colo. (Lot)	8-19-65	6.3	1.9	1.3	2.5	5.7	0.4	0.1	-	0.1	0.1	0.7	0.6	7.4
Salt Lake City (Lot, E. Side)	8-19-65	5.7	1.8	1.1	2.1	5.0	0.3	0.1	-	0.1	0.1	0.6	0.7	5.7
Elko, Nev.	8-20-65	9.8	2.7	3.0	3.5	9.2	0.6	0.1	-	0.1	0.1	0.9	0.6	5.8
(Field, S. Side)	10-8-63	11.1	2.8	2.0	3.3	8.1	-	-	2.2	0.3	-	2.5	3.0	6.0
	10-8-62	9.2	3.1	1.1	3.5	7.7	-	-	1.3	0.5	-	1.8	1.5	6.0
Reno, Nev.	8-21-65	5.1	1.3	1.0	1.8	4.1	0.4	0.1	-	0.1	0.1	0.7	1.0	5.5
(Idylwild Park)	10-7-63	5.5	1.5	1.2	2.2	4.9	-	-	0.8	0.2	-	1.0	0.6	5.7
Bonny Doon, Cal.	8-24-65	12.3	7.8	1.4	1.8	11.0	0.8	0.2	-	0.1	0.2	1.3	1.3	4.1
(Fern Patch Near	10-12-63	12.7	7.7	2.5	1.5	11.7	-	-	1.2	-	-	1.2	1.0	4.0
Town)	10-6-62	13.5	8.5	2.2	1.9	12.6	-	-	1.6	0.2	-	1.8	0.9	4.0

Town & Location	Date	Total Gamma	Natural Gamma				Fallout Gamma							HASL Inferred Cosmic
			K	U	Th	Total	Cs^{137}	Mn^{54}	Zr^{95}-Nb^{95}	Ru^{106}-Rh^{106}	Other	Total	F.O. (2)	
Shaver Lake, Cal. (Rock Outcrop)	8-26-65	8.7	2.3	2.2	3.8	8.3	0.4	-	-	0.1	-	0.5	0.4	6.2
Courtright Res., Cal. (Rock Outcrop)	8-27-65	22.9	4.7	5.8	12.7	23.2	<0.1	-	-	-	-	<0.1	-0.3	8.3
Goleta Beach, Cal. (Sand Beach)	8-31-65	5.9	2.6	1.5	1.7	5.8	<0.1	-	-	0.1	0.1	0.2	0.1	3.6
Linda Loma, Cal. (School Lawn)	8-31-65	6.2	2.3	0.8	2.6	5.7	0.2	-	-	0.1	0.1	0.4	0.5	3.8
Alamagordo, N.M. (South of Town)	9-2-65	8.3	2.8	2.1	3.3	8.2	0.1	-	-	0.1	-	0.2	0.1	5.0
Alamagordo, N.M. (South of Town)	9-3-65	7.5	2.4	2.0	2.9	7.3	0.1	-	-	0.1	-	0.2	0.2	5.0
Dallas, Texas (Texas Instr. Monitoring Site)	9-4-65	3.3	0.6	0.9	1.4	2.9	0.5	0.1	-	0.1	0.1	0.8	0.4	3.6
Houston, Texas (Rice Univ.)	9-5-65	4.4	0.8	0.9	2.6	4.3	0.1	-	-	0.1	-	0.2	0.1	3.4
	4-10-63	9.4	0.9	0.6	3.0	4.5	-	-	4.4	1.2	-	5.6	4.9	3.5
Lake Charles, La. (School Lawn)	9-8-65	4.6	-	-	-	-	-	-	-	-	-	-	-	3.5
	4-14-63	8.5	0.7	0.9	1.9	3.5	-	-	4.2	1.0	-	5.2	5.0	3.4
New Orleans, La. (Field Near Airport)	9-9-65	6.4	1.9	1.2	2.6	5.7	0.3	0.1	-	0.1	0.1	0.6	0.7	3.5

Lake Charles, La. (School Lawn)	9-8-65	4.6	-	-	-	-	-	-	-	-	-	-	-	3.5
	4-14-63	8.5	0.7	0.9	1.9	3.5	-	-	4.2	1.0	-	5.2	5.0	3.4
New Orleans, La. (Field Near Airport)	9-9-65	6.4	1.9	1.2	2.6	5.7	0.3	0.1	-	0.1	0.1	0.6	0.7	3.5

			Natural Gamma				Fallout Gamma							MASL Inferred
Town & Location	Date	Total Gamma	K	U	Th	Total	Cs^{137}	Mn^{54}	Zr^{95}-Nb^{95}	Rh^{106}	Other	Total	F.O. (2)	Cosmic
Aiken, S.C. (Lot Near Airport)	9-11-65	4.0	0.1	1.2	1.4	2.7	0.7	0.1	-	0.1	0.2	1.1	1.3	3.7
	4-17-63	8.3	0.2	1.0	1.8	3.0	-	-	5.2	1.4	-	6.6	5.3	3.5
Rolesville, N.C. (Lot off H.W. 401)	9-11-65	18.6	5.2	2.3	10.2	17.7	0.6	0.1	-	0.1	0.1	0.9	0.9	3.7
Largo, Md. (U.S. Dept. of Agr. Soil Sampling Site)	11-9-65	7.2	1.8	1.5	2.9	6.2	0.8	0.1	-	0.1	0.1	1.1	1.0	3.6

TABLE V

COSMIC RAY IONIZATION AND ULTRA LOW BACKGROUND FIELD MEASUREMENTS (μr/hr)

Location	Date	Total Gamma *	Natural Gamma K	Natural Gamma U	Natural Gamma Th	Natural Gamma Total	Fallout Gamma Total	Altitude (Ft.)	Total Ion Chamber Dose Rate	HASL Inferred Cosmic Ray Dose Rate**
Measurements for Determining Cosmic Ray Intensity										
Keyhole Res., Wyo.	8-9-65	-	-	-	-	-	-	3950	5.46	5.17
Turquoise Lake, Colo.	8-16-65	.10	.01	~.1	0	~.1	0	9245	10.86	10.30
Twin Lakes, Colo.	8-17-65	.19	.02	~.3	0	~.3	0	8745	9.92	9.60
Granby Res., Colo.	8-18-65	.48	<.1	~.5	0	~.5	0	7900	8.87	8.50
Lake Tahoe, Calif.	8-22-65	-	-	-	-	-	-	6000	6.79	6.78
Red Mountain, Calif.	8-25-65	.57	.06	~.1	<.1	~.2	.5	2910	5.04	4.61
Shaver Lake, Calif.	8-26-65	.33	.03	~.4	0	~.4	0	5180	6.25	5.96
Courtright Res., Calif	8-27-65	.13	.03	~.3	~.01	~.3	0	7710	8.60	8.28
Copperopolis, Calif. (Asbestos Mine)	8-28-65	.19	.01	~.2	~0	~.2	0	933	4.15	3.86
Parodox Lk., N.Y.	9-1-64	-	-	-	-	-	-	598	4.18	3.78
Saranac Lk., N.Y.	9-2-64	-	-	-	-	-	-	1407	4.48	4.02
Elk Lk., N.Y.	9-2-64	-	-	-	-	-	-	1825	4.68	4.19
Measurements at Low Background Locations										
Red Mt. Mine, Calif.	8-25-65	.06	<.01	<.06	-	~.06	0	Inside Deep Mine	<.1	0
Houston, Texas	9-6-65	.19	~.05	~.15	-	~.20	0	"	.19	0

Elk Lk., N.Y.	9-2-64	-	-	1825	-	4.68	Inside Deep Mine	< .1
							"	.19
Measurements at Low Background Locations								
Red Mt. Mine, Calif.	8-25-65	.06	<.01	<.06	-	-.06	0	0
Houston, Texas (Salt Mine)	9-6-65	.19	-.05	-.15	-	-.20	0	4.19

*From spectrum total "energy", corrected for cosmic response.

TABLE VI

VARIATION IN NATURAL GAMMA DOSE RATES (μr/hr) AT PELHAM, N.Y. AND MAMARONECK, N.Y., 1963 - 1965

	Pelham				Mamaroneck			
Date	K	U	T	Total	K	U	T	Total
5-3-63	2.8	1.5	3.6	7.9	2.4	1.2	3.4	7.0
5-13-63	3.0	1.0	3.3	7.3	2.6	1.2	3.4	7.2
5-27-63	2.9	1.2	3.4	7.5	2.4	1.2	3.3	6.9
6-24-63	2.5	1.2	3.4	7.1	2.6	1.0	3.6	7.2
8-6-63	2.5	1.6	2.9	7.0	2.5	1.3	3.3	7.1
8-26-63	2.3	1.7	3.6	7.6	2.7	1.4	3.7	7.8
9-12-63	-	-	-	-	2.8	1.8	3.7	8.3
9-27-63	-	-	-	-	2.4	1.8	3.6	7.8
10-29-63	2.3	1.2	3.4	6.9	2.8	1.1	3.3	7.2
11-20-63	2.4	1.2	3.0	6.6	2.3	1.3	3.4	7.0
4-17-64	2.1	1.3	2.6	6.0	1.9	1.4	2.7	6.0
5-8-64	2.4	1.7	3.1	7.2	-	-	-	-
7-21-64	2.1	1.4	2.6	6.1	-	-	-	-
8-12-64	2.7	1.2	3.2	7.1	-	-	-	-
9-25-64	3.1	1.7	3.4	8.2	2.5	1.4	3.5	7.4
10-21-64	2.1	1.4	2.8	6.3	1.9	1.7	3.2	6.8
11-2-64	2.3	1.7	3.0	7.0	2.3	1.8	3.3	7.4
11-27-64	2.1	1.4	2.8	6.3	2.2	1.3	2.9	6.4
4-30-65	2.1	1.4	2.8	6.3	2.0	1.3	2.8	6.1
5-21-65	2.2	1.3	3.1	6.6	2.2	1.3	3.4	6.9
7-29-65	2.2	1.3	3.0	6.5	2.2	1.3	3.3	6.8
Average	2.4	1.4	3.1	6.9	2.4	1.4	3.3	7.1

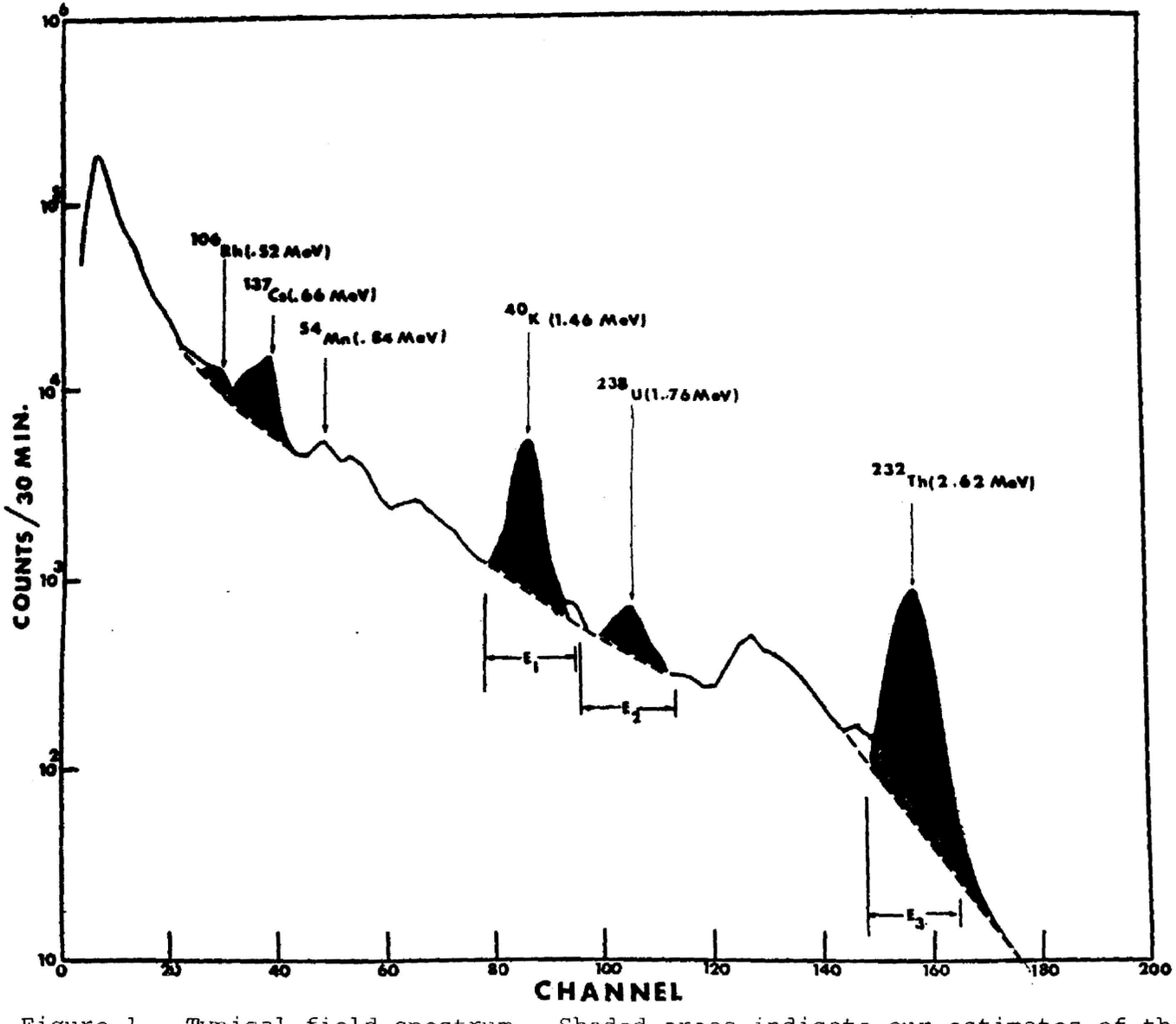


Figure 1. Typical field spectrum. Shaded areas indicate our estimates of the

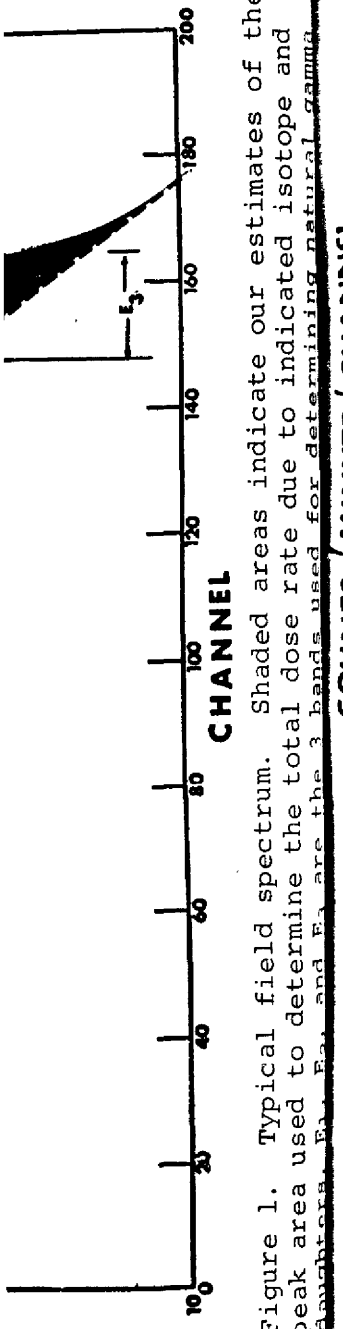


Figure 1. Typical field spectrum. Shaded areas indicate our estimates of the peak area used to determine the total dose rate due to indicated isotope and daughters. E_1, E_2, and E_3 are the 3 bands used for determining natural gamma

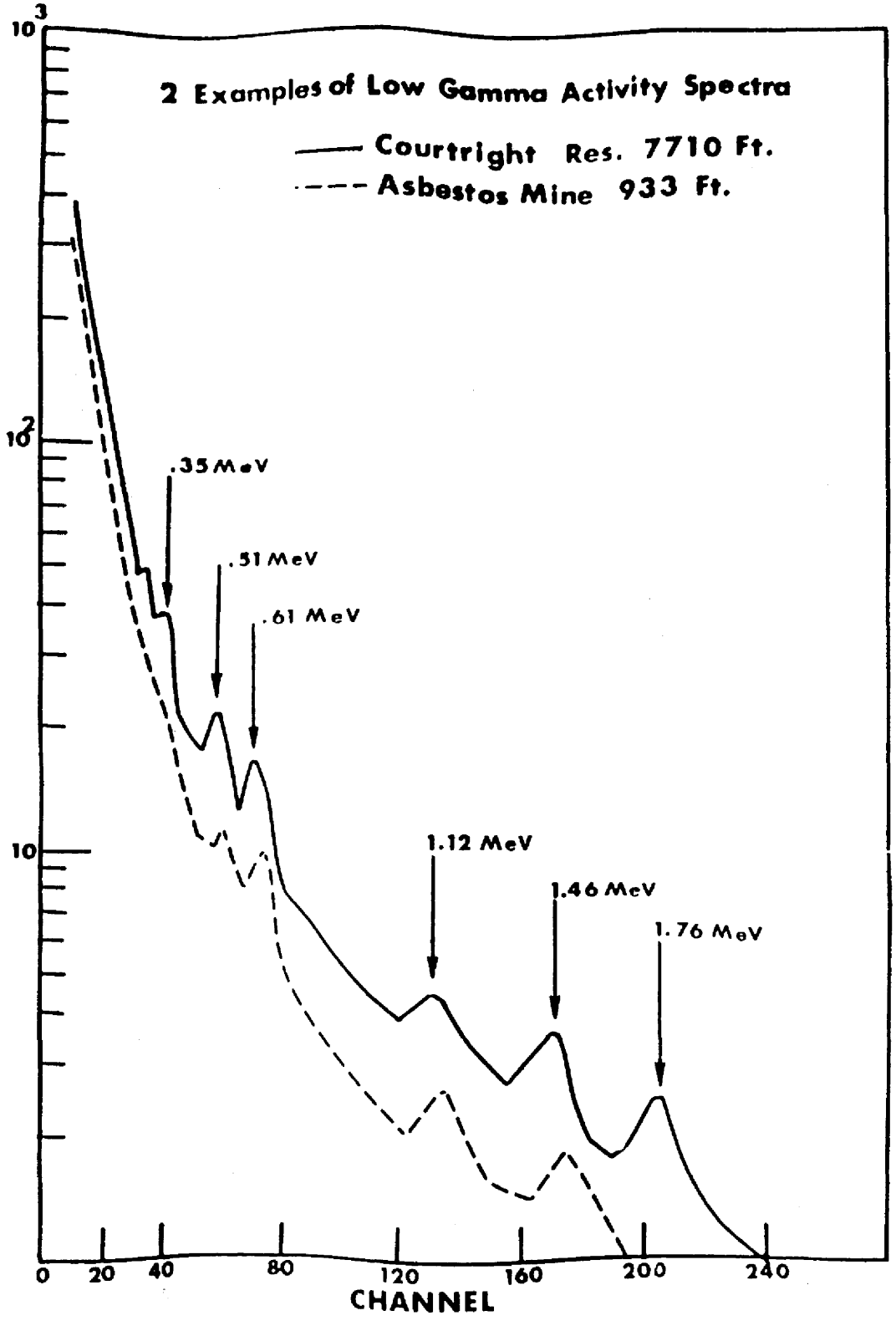
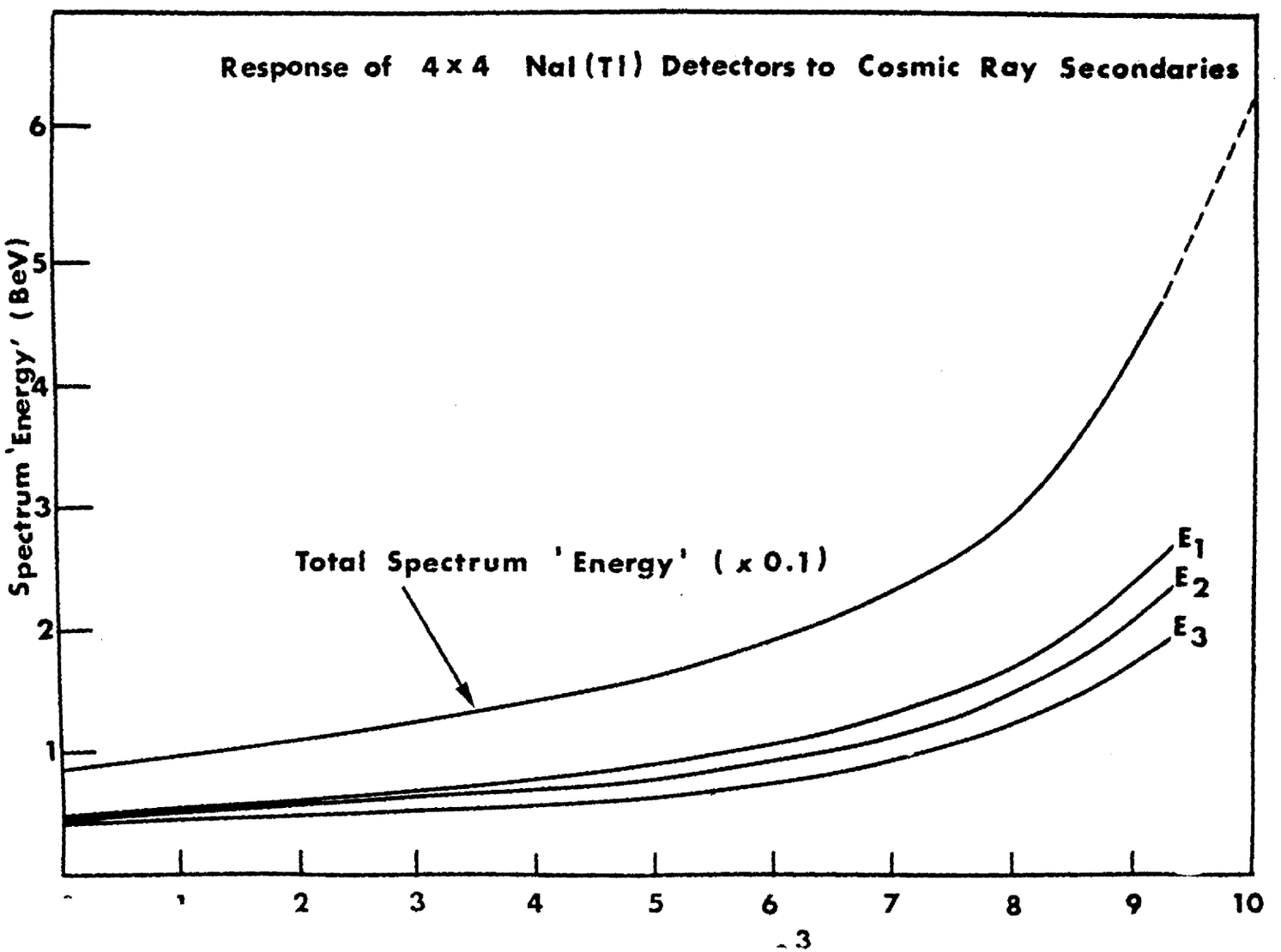
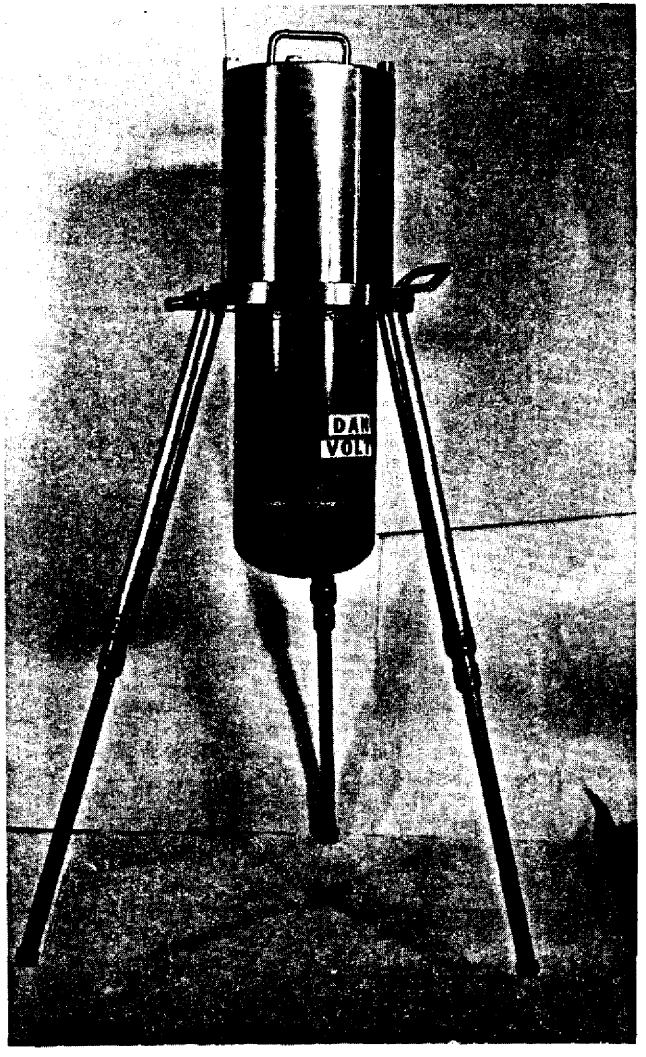


Figure 2. Examples of spectra taken at low gamma activity sites.


Response of 4 x 4 NaI(Tl) Detectors to Cosmic Ray Secondaries
Spectrum 'Energy' (BeV)
6
5
4
3
2
1
Total Spectrum 'Energy' (x 0.1)
E1
E2
E3
1
2
3
4
5
6
7
8
9
10
-3



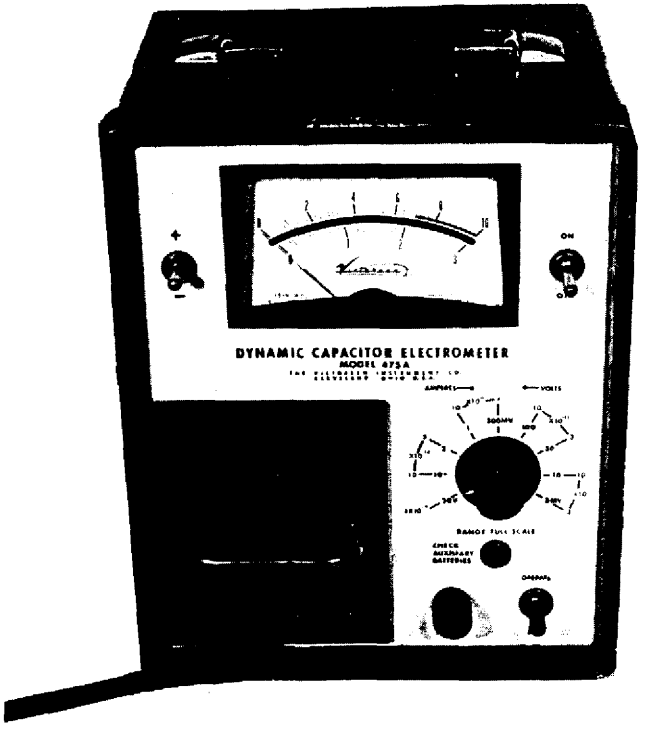


Figure 4. Pressurized argon-filled ionization chamber with electrometer readout unit.