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RADIATION MONITORING

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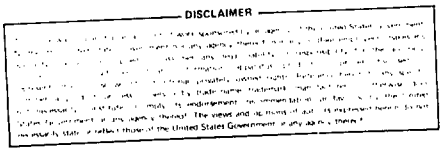
INTRODUCTION

In the strict sense, this paper will not discuss any real "advances" in radiation monitoring. What is presented here has been known and applied at high-energy accelerator laboratories for several years. However, the increasing application of a variety of high-LET radiations, produced by accelerators, to radiodiagnosis and radiotherapy which have been described in this course has led to the need to more widely disseminate this knowledge.

At the present time the number of people exposed to man-made high-LET radiations is rather small,[1] but it may well be that the increasing application of accelerators to the problems of medicine will substantially increase the fraction of the general exposure resulting from high-LET radiations. This is perhaps particular interest because of the recently voiced concerns over the incidence of leukemia induced by fission neutrons.[2]

The radiation phenomena at high energy accelerators have been rather thoroughly investigated because it was necessary to be able to construct these instruments so that their radiation environments were safe for human occupation and that their use for research was not inhibited by high radiation backgrounds. This latter consideration was in many instances the over-riding factor.[3]



Most of our basic knowledge of accelerator health physics has been obtained at high-energy laboratories because these institutions have available the resources needed for the required fundamental investigations.[4] Experience has shown that the radiation environments of high-energy accelerators are in many respects similar to those produced by lower-energy accelerators. Many of the techniques of radiation monitoring developed at high-energy laboratories may be applied equally to low or high-energy accelerators. Unfortunately there is some evidence that the available information is not widely known.[5]

TYPES OF MONITORING

A Comprehensive radiation monitoring program has three components:

(1) Area monitoring
(2) Environmental monitoring
(3) Personal monitoring

There is a strong argument for performing all three types of monitoring at accelerator installations. Each component may be subject to occasional difficulties in interpretation, but all components are mutually supportive.

Two examples will suffice. In the first, if a member of the staff inadvertantly contaminated his personal dosimeter (film badge, thermoluminescent dosimeter) with radioactive material, the individual's dosimeter reading would then be suspect. Investigation of the accelerator operations log, personal dosimeter readings of colleagues, area monitoring records--and even environmental monitoring records--then shows no unusual exposure to radiation had occurred. These facts would warrant entering the normally expected radiation exposure into the individual's record.

The second example actually occurred at the research laboratories of a well-known electrical engineering company. Physicists working with an electron accelerator were puzzled when they noted that their area radiation monitors continued to indicate radiation for some minutes after the accelerator had been turned off. Investigation revealed that increasing the electron beam energy had led to significant photo-neutron production, with the consequent induction of radioactivity in beam collimators and the accelerator structure. This rediscovery of neutron induced activity, some forty years after the original work of Fermi and his colleagues in Rome,[6] led to a reevaluation of the personal dosimetry and area monitoring program. The inadvertent neutron production would, however, have gone

unnoticed if only a β-γ personal dosimetry program had been pursued.

Little will be said in this lecture on personal dosimetry because the techniques of personal dosimetry are well understood, and because few advances have occurred in the past five years and, finally, because of the constraints of space and time.

Area Monitoring

> "The most important parts of a program of monitoring for external radiation in workplaces is the conduct of a comprehensive survey when any new installation is put into service or when any substantial changes have been made, or may have been made, in an existing installation. An example of this type of monitoring is the surveying of the area round a research reactor immediately on restarting after a shutdown".[7]

The terms "area monitoring" and "environmental monitoring" are often used equivalently. For our purposes here area monitoring is taken to mean radiation measurements made in the work place by either fixed or portable radiation detectors, not worn by individual members of the staff. "It is largely of a confirmatory nature but may include the use of fixed detectors to identify the onset of abnormal or emergency conditions, such as criticality accidents."[8]

The ICRP has suggested that routine area monitoring, referred to as "environmental monitoring", is only necessary under certain conditions:

> "If the radiation situation in the workplace is not liable to change, except as a result of substantial alterations to the protective equipment or the processes carried out in the workplace (which should be followed by comprehensive surveys), then routine environmental monitoring is not needed. If, however, the radiation fields in the workplace are liable to change, but the changes are not likely to be rapid or severe, then occasional checks, mainly at fixed points, will usually give sufficient warning of deteriorating conditions. Alternatively, the results of individual monitoring for external radiation may be used for this purpose.
>
> "If the radiation fields are liable to increase rapidly to serious levels, then a system of warning

instruments will be required, either in the environment or worn individually by the workers.[10] It is particularly important to identify situations calling for this type of warning monitoring because, if carried out effectively, a program of warning monitoring may prevent the receipt of high doses at high dose-rate and thus eliminate a genuinely dangerous situation. Other types of monitoring, while contributing to the overall safety of the operation, rarely fulfil such a positive function."[9]

The interpretation of environmental monitoring data has been discussed in paragraphs 45-47 of ICRP Publication 12:[11]

"(45) The general problem of interpreting radiation dose-rate measurements in the workplace in terms of the dose to organs and tissues of the workers is extremely complex. The dose rate and the quality of the radiation will vary in space and with time, while the workers move through their environment in a way which is neither predictable nor accurately known or recorded. It is therefore essential to introduce major simplifying assumptions. One simplification is to assume that measured γ and neutron dose rates at a point accurately reflect the dose rates in the gonads and red bone marrow of a man at the same point, while the total dose rate due to β- and γ-radiation and neutrons reflects the dose rate to skin. The errors caused by ignoring (or, in the case of neutrons, standardizing) back-scatter and depth-dose effects are trivial compared with the difficulty of relating the dose rate at a number of points in space and time to the integrated dose to a worker.

"(46) For some applications, it is convenient to assume that someone will be present for the whole of his working time at the point of highest dose rate in the workplace. This method, which establishes an upper limit to the dose which can be received, has the advantage of needing no restriction of movement within the workplace. In practice, actual doses received in such an environment are likely to be well below this maximum and, if the design of protection of the workplace and process has been adequate, well below the Maximum Permissible Doses recommended by the Commission.

"(47) If it is not practicable to keep dose rates in the workplace low enough for this simple system of interpretation to be of value, it becomes necessary to

assess, and sometimes restrict, the access time in areas of high dose rate. This is achieved qualitatively by the use of warning signs or by the planning of operations. Any quantitative interpretation is provided by individual monitoring."

The techniques that may be used for area monitoring have been discussed in preceding lectures of this course[12,13] and a further description is not necessary here. Rather an example of area monitoring at particle accelerators used in radiotherapy will be given.

Comprehensive Radiation Survey made at the LBL 184" Synchrocyclotron Medical Facility

The 184 inch synchocyclotron can accelerate helium ions (alpha particles) to an energy of 920 MeV. Pilot studies are underway using the helium-ion beam for the treatment of brain-, eye-, pancreas- and other tumours.[14] The production of the large uniform irradiation fields necessary for this application utilizes beam scatterers, collimators and energy-degraders to obtain the desired depth-dose characteristics. These beam line elements are sources of secondary particles which produced an unwanted radiation field which is a source of patient exposure outside the area of treatment and might also result in exposure to the medical and ancilliary staff. It was therefore necessary to determine the characteristics of this secondary radiation field and determine potential patient and/or staff exposure.

Schimmerling and his colleagues[15-17] have described the radiation surveys made at this facility in some detail. Figure 1 shows a plan view of the accelerator facility and the path of the transported 920 MeV alpha-particle into the medical treatment area. The medical treatment area is shown in more detail in Fig. 2. Secondary particles are produced in the first and second scatterers, at the edge of the iron pipe collimators, in the water column and, finally, in the patient collimater. The radiation field inside the medical treatment area is entirely due to beam interactions with the beam transport system, there being no significant leakage through the cyclotron shielding wall. Neutrons are the dominant component of the radiation field at the patient table.

Measurements were made to:

1. Identify the major sources of secondary particles in the beam transport system.
2. Measure the source strengths of these components.

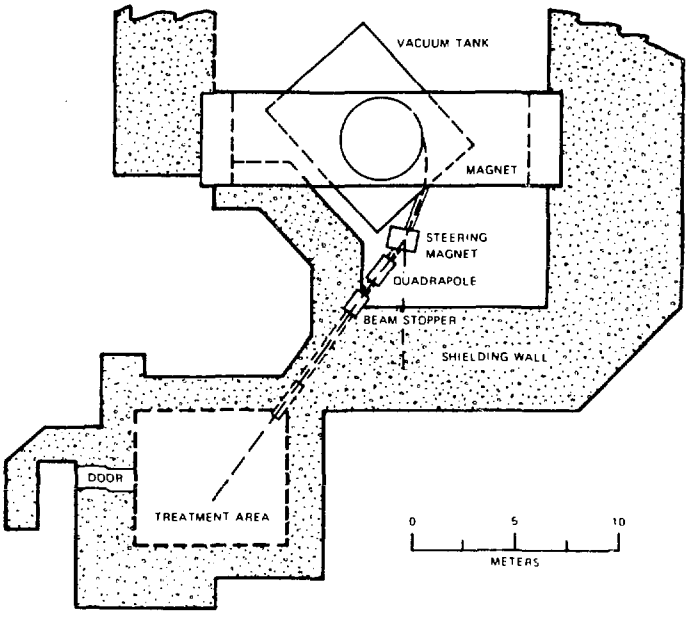


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Fig. 1. Plan view of the 184-in. synchrocyclotron.

3. Determine the neutron intensity and spectrum at locations on the patient table.
4. Calculate the absorbed dose to the patient resulting from the secondary particle.

The neutron detectors selected for this series of measurements included moderated BF_3 counters, thorium and bismuth fission chambers, and aluminum, carbon and indium activation detectors. Figure 3 shows the neutron fluence profiles measured along the line parallel to and 20 cm. distance from the beam line. The curves correspond to different beam line configuration listed in Table 1. Curve B approximately corresponds to the configuation used in patient therapy with a phantom placed in the beam to simulate the patient. The measured profiles are consistent with the hypothesis that each secondary source is dominated by an isotropic component but with a smaller forward, directed contribution. Figure 4 shows an analysis based upon this assumption while Table 2 gives the estimated source strengths.

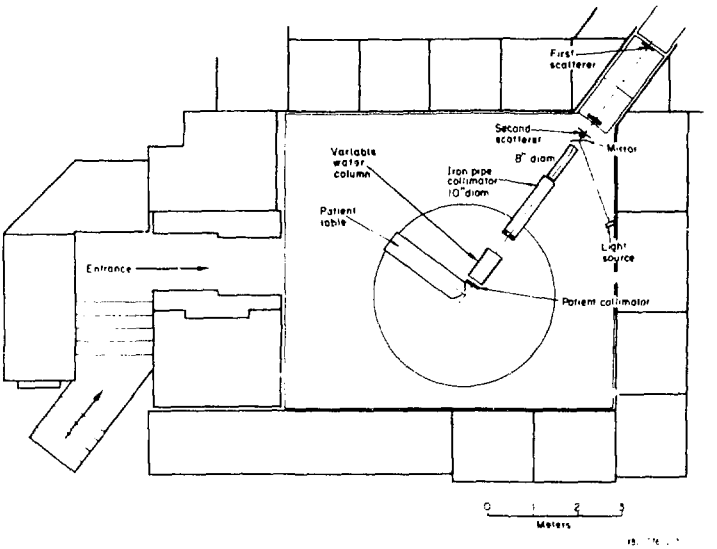

Fig. 2. Plan view of the biomedical cave of the 184-in. synchrocyclotron.

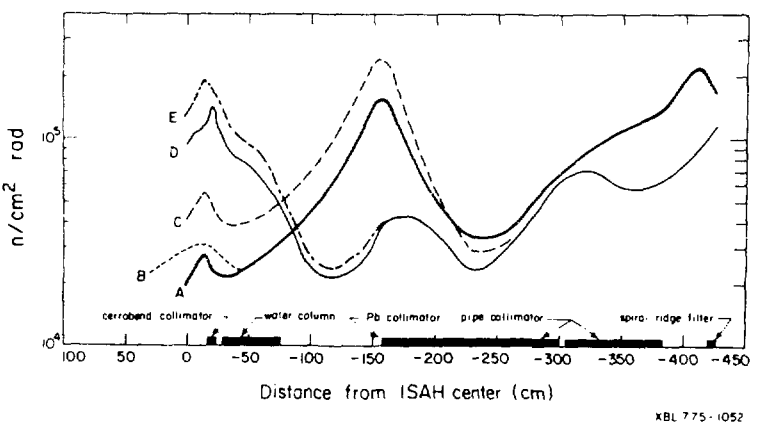

Fig. 3. Neutron fluence profiles along the beam line measured by the $^{27}Al \rightarrow {}^{24}Na$ reaction, for the beam line configurations given in Table 1. The equivalent 14-MeV flux density is shown.

Table 1. Beam Line Configurations

Exposure (See Fig. 3)	Brass Collimator	Spiral Ridge Filter	Lead Collimator	Water Column (cm, water)	Cerrobend Collimator	Head Phantom
A	In	In	In	0.0	In	Out
B	In	In	In	16.0	In	In
B'	In	In	In	16.0	In	Out
C	In	Out	Out	0.0	In	Out
D	In	Out	Out	0.0	In	Out
E	In	Out	Out	0.0	Out	Out

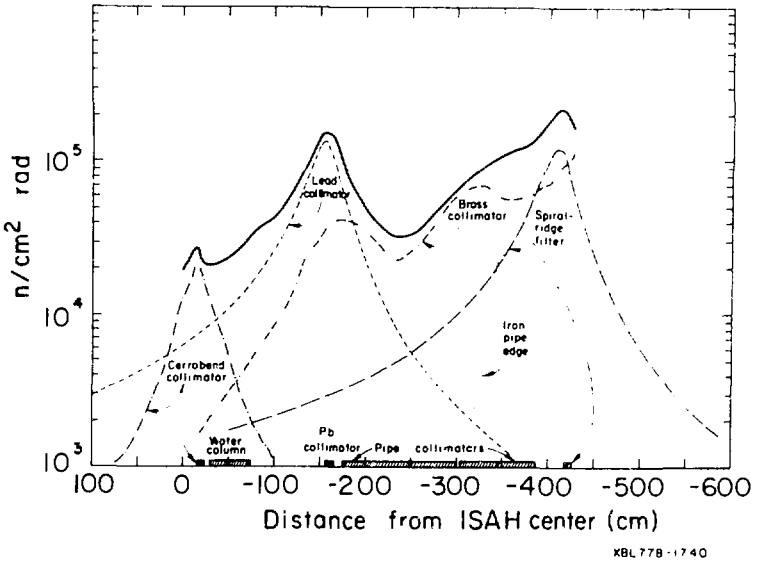

Fig. 4. Analysis of neutron fluence profiles. The heavy solid curve shows the experimentally determined profile, and the dashed curves show the profiles for the three major sources of neutrons.

Table 2. Point Source Strengths

Z Location Along Beam Line (cm)	Beam Element	Source Strength per Incident Rad (n/sec)
-25	Water column/Corrobend collimator	1.5×10^8
-165	Lead collimator	7.0×10^8
-350	Iron pipe	1.7×10^8
-420	Spiral ridge filter	6.0×10^8

From the data of Table 2 the relative contributions to the neutron fluence along the patient table from the sources of secondary radiations may be calculated (Table 3).

At distances out to 50 cm. from the beam axis, the water column and patient collimator are the dominate sources of neutron exposure to the patient outside the treatment region. At larger distances from the beam axis, the lead collimator dominates.

Table 3. Relative Fluence Contribution

X Location on Patient Table (cm)	Percent Fluence Contribution From:			
	Water Column and Cerrobend Collimator	Lead Collimator	Iron Pipe	Spiral Ridge Filter
0	89	9.2	0.5	1.2
50	64	30	1.7	4.3
100	39	49	3.4	8.6
150	27	56	4.6	12
200	21	57	5.7	15

Figures 5 and 6 show neutron fluence measurements along the patient table, both with and without a phantom in the primary beam. From these measurements the neutron spectrum may be estimated by solving the set of Fredholm equations obtained.[18] When the neutron spectrum is known the absorbed dose in soft tissue, D, may be calculated from:

$$D = \int_{E_{min}}^{E_{max}} f(E)\, \phi(E) dE$$

where f(E) are fluence to absorbed dose conversion factors. Values of f(E) given by Rindi[19] were used in the work reported here. The absorbed dose is not a sensitive function of the neutron spectrum and consequently, although the spectrum is not well determined from the solutions of the degenerate Fredholm equations of the first kind,[18] the absorbed dose can be quite well determined. Figure 7 shows the distribution of absorbed dose along the patient table.

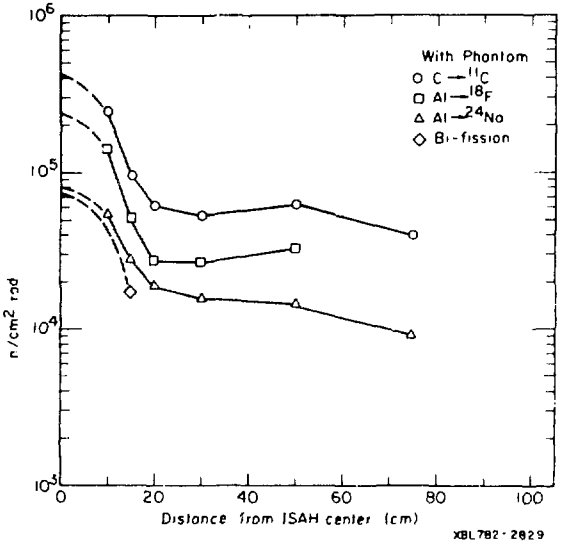

Fig. 5. Neutron fluence, as a function of distance from ISAH center, measured along the patient table with four detectors. (Head phantom in place; 16-cm water energy degrader) The equivalent 14-MeV flux density is given for the ^{27}Al → ^{24}Na reaction.

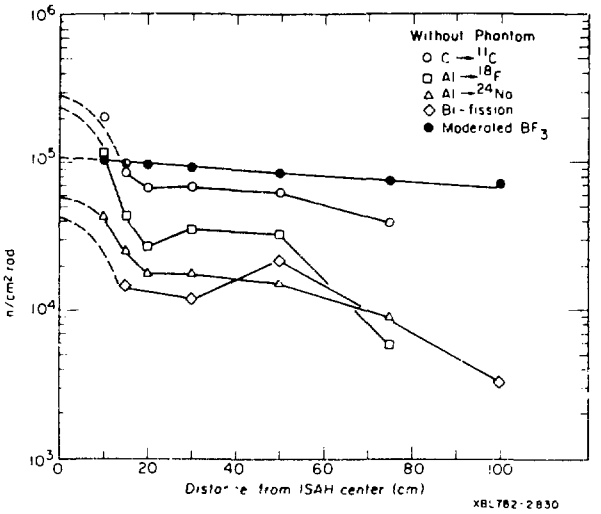

Fig. 6. Neutron fluence, as a function of distance from ISAH centr, measured along the patient table with five detectors. (No head phantom in place; 16-cm water energy degrader.) The equivalent 14-MeV flux density is given for the $^{27}Al \rightarrow {}^{24}Na$ reaction.

Table 4 summarizes the maximum absorbed dose to the patient at various locations along the patient expressed as a ratio to the primary beam dose in the plateau region. The dose to the irradiated tumor would be a factor of about 1.4 higher.

Environmental Monitoring

Function. The function of environmental monitoring may be defined as follows:

> "Environmental monitoring is intended to show that the working environment is satisfactory for continued operations and that no change has taken place calling for a reassessment of operating procedures. It is largely of a confirmatory nature but may include the use of fixed detectors to identify the onset of

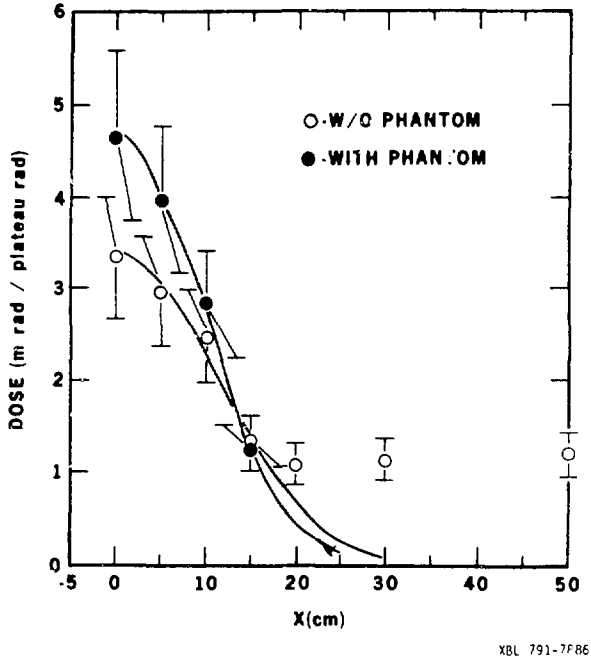

Fig. 7. Estimated absorbed dose distribution along patient table.

Table 4. Ratio of Absorbed Dose from Neutrons to that from Primary Beam

Distance from ISAH Center (cm)	No Phantom ($\times 10^{-3}$)	Phantom ($\times 10^{-3}$)
0	3.33	4.64
5	2.97	3.96
10	2.49	2.83
15	1.35	1.27
20	1.10	
30	1.15	
50	1.21	

abnormal or emergency conditions, such as criticality accidents. The term is also used for monitoring outside the boundaries of installations handling radioactive materials or radiation sources, but the context is usually sufficient to avoid confusion between the two meanings."[8]

Objectives: The objectives of a program of environmental monitoring are principally:

1. To estimate the actual and potential exposure of man (and in some cases other organisms) to radioactive materials and radiation. Insofar as possible individual exposures should be determined, and estimates made of probable upper limits.
2. To check the effectiveness of control measures within the facility.
3. To carry on scientific investigations which are related to the overall program.
4. To predict trends in radiation levels.
5. To identify sources of specific contaminants.
6. To ensure compliance with regulations.
7. To establish good public relations.

Techniques. About five years ago a significant change in attitude by government agencies towards man-made radiation became evident.

"The recent trend toward the quantitative definition of "as low as practicable" guidelines pertaining to the release of radionuclides to the environment from nuclear facilities and the resulting dose places a significantly increased burden on environment surveillance programs. It was previously believed that adherence to the admonitions of expert bodies such as the ICRP to limit unnecessary radiation exposure was recommended "maximum permissible" annual levels of 500 mrem to individuals or 170 mrem to a "suitable sample."[20] The U. S. Regulatory agencies are now preparing numerical limitations on environmental radiation dose to man from lightwater power reactors and the nuclear power fuel cycle.[21]

"The net effect of these limitations is to lower the "maximum permissible" dose to off-site individuals by two orders of magnitude. While the merits of such a reduction in terms of public health and realistic benefit-risk assessment are arguable, the rationale for this change has been that practical, though

costly, techniques for the treatment of nuclear facilities effluents will permit plant operations within the limits.

"Questions immediately arise relating to how well the actual doses can be assessed and documented, given the fact that most existing environmental surveillance programs were designed to assure that critical populations groups do not receive doses that are much higher than the proposed limits. If the public and regulatory agencies are to be assured that nuclear facilities are operating within their design specifications, both experimental and calculational methods are required to allow accurate dose assessment at the very low exposure levels that are expected to exist."[22]

The assessment of the population dose equivalent around nuclear facilities requires, first, the development of reliable techniques in determining the man-made contributions to radiation exposure. Population dose inference must then be based on the incorporation of these experimental data into suitable models which take into account population distribution, living habits, meteorological conditions, and other significant factors which influence population dose.

Radiation Measurements. We have seen that we may need to make measurements of man-made radiation of the order of 1 millirem/yr in a natural background of about 100 millirem/yr. Furthermore, the natural background may show seasonal fluctuations of as much as 20 millirem/yr.

At first sight such a task seems impossible! The separation of various components of an observed fluctuating radiation level and the derivation of the component due to the operation of a nuclear installation at levels of ~1 millirem year is indeed a formidable task. The normal strategy employed is to place fixed radiation monitors around the installation that can record either the integrated dose equivalent or dose equivalent rates as a function of time. The selection of detector locations will depend upon several factors, such as population density, wind direction and local rainfall patterns.[23]

In many cases the dominant component of the radiation field will be γ-rays. In such cases Geiger counters,[24,25] ionization chambers,[26,27] scintillation detectors,[28,29] or thermoluminescent dosimeters[30,31] have proved to be convenient detectors. Under some circumstances, for example around high energy accelerators, neutrons may be the dominant component of the radiation field.[32] Stephens[33] and his colleagues have

described environmental monitoring techniques used at the Lawrence Berkeley Laboratory under such conditions. Here moderated BF_3 counters are used to detect the neutrons while Geiger counters are used to measure the γ-rays.[34]

Ionization Chambers. Beck et al[35] have described the use of a pressurized ionization chamber that can detect changes in ambient radiation levels of about 0.1 μr/hr (~1 mr/yr). The chamber consists of an 8 liter stainless steel sphere filled with argon at a pressure of 25 atmospheres. Chamber current is measured with MOSFET electrometer. At exposure rates of 0.1 μr/hr the chamber current is $\sim 2 \times 10^{-5}$ amps. Sensitivity of the instrument is essentially limited by leakage current which could be lower than 10^{-16} amps but in field use may be several times higher.

In routine use the output of the chamber is sampled every ten seconds and the data recorded on magnetic tape. A commercial version of this instrument is produced by Reuter-Stokes, Cleveland, Ohio (see Fig. 8). The output may be recorded on strip-chart.

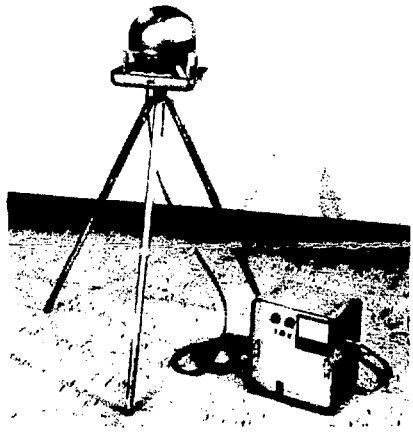

Fig. 8. Ionization chamber and electrometer. The chamber is filled with argon at a pressure of 40 atmospheres and is capable of measuring exposure rates of about 1 mr/yr. (Reuter-Stokes, Cleveland, Ohio).

Readings of the exposure rates as a function of time from instruments at several locations may be used to separate the various components of a radiation field. Several factors contribute to the variations in the reading of an instrument continuously monitoring background. Fluctuations in natural background occur over periods of a few hours to a few days.

Burke[36] has studied the temporal variations in natural background at several residential locations in New York and New Jersey. These locations were selected to assure that there were no radiation contributions from man-made sources (except for residual nuclear weapons in test global fallout). Radiation exposures were measured with LiF thermoluminescent dosimeters (Harshaw TLD-700), placed for monthly periods at the selected sites. Figure 9 shows typical results for the period of September 1972-September 1973. The accuracy of each measurement is estimated to be ±3.5 percent. These data clearly show a

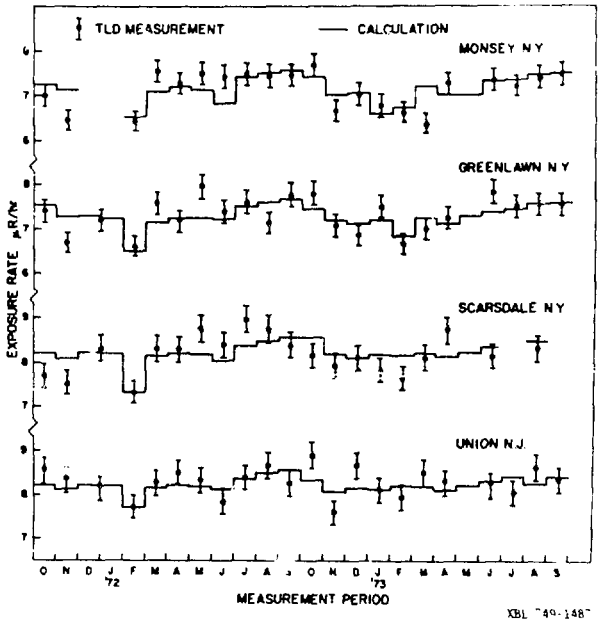

Fig. 9. Comparison of exposure rates measures at residences near New York City with calculated values using a climatic exposure model (from de Planque Burke, 1974).

significant variation in background level with time even when averaged over periods as long as a month. Such temporal variations in exposure rates can primarily be due to three causes:

1. Variations in climate conditions.
2. Variations in the rate of fallout deposition.
3. Variations in cosmic ray intensity.

Burke and O'Brian[37] have shown the variations of the type shown in Fig. 9 exhibit a seasonal pattern. An analysis of fallout deposition pattern during the period of measurement and estimates of the possible fluctuations in cosmic ray intensity showed that these components could account for only a small fraction of the observed variations. Variations in climatic conditions therefore remain as the probable cause of the observed fluctuations in background exposure rate.

The moisture content of soil, or the presence of standing water or snow cover can influence ambient radiation levels in two ways. First, the increased soil density resulting from high moisture content (or the water or snow cover itself) leads to increased attenuation of radiation emitted in decay of the radionuclides contained in the soil. Secondly, the presence of water in the interstices of the soil may inhibit the diffusion of radon and thoron into the atmosphere.

^{226}Ra decays by α-emission to its daughter ^{222}Rn which has a half-life of 3.8 days. Similarly, ^{224}Ra (a descendant of 232 Th) decays to "thoron" (^{220}Rn) which has a half life of 54 sec. Both these gases diffuse with the atmosphere. Eisenbud[38] quotes Pearson and Jones as estimating the average diffusion of ^{222}Rn as 1.4 $pCi/m^2/sec$.

The atmospheric concentration of the noble gases, thoron and radon in the atmosphere, depend upon many geological and meteorological factors. The complex diffusion processes from the soil into the atmosphere and the subsequent dispersion in the air are still largely not understood. In general, radon concentrations are 50-100 times greater than those of thoron found at a given location, largely because of the difference in radioactive half lives [3.8 days for ^{222}Rn compared to 54 sec for ^{220}Rn (thoron)]. The concentrations of radon at a given location show great variation from day-to-day. For example, Lockhart measured variations of more than two orders of magnitude in Washington, D.C. during 1957.[38]

> "It is likely that these variations are dependent on meteorological factors that influence the rate of emanation of the gases from the earth. Thus, the rate of emanation from soil may increase during periods of

diminishing atmospheric pressure and decrease during periods of high soil moisture, owing to the solubility of radon. It is also likely that the history of an air mass for several days prior to observation influences its radon and thoron concentration".[39]

Figure 10 shows the correlation between radon daughter washout peaks and precipitation reported by the USAEC Health and Safety Laboratory, New York. Measurements were made near the site of the Harkness Park Nuclear Power Stations during reactor shutdown. Exposure rates recorded by an ionization chamber are shown on the upper graph. Rainfall (in cm) are indicated directly below. Rain washes down dust to which radon daughters have become attached and the radiation level rises. Following washout a significant reduction of ~ several tenths μr/h in the background level is observed. This is due to the addition of water to the soil. As the water evaporates the radiation level slowly increases back to the original level.

Although the daily variations in radon concentration may be quite large the variations in averaged monthly exposure attributable to these fluctuations is extremely small compared to

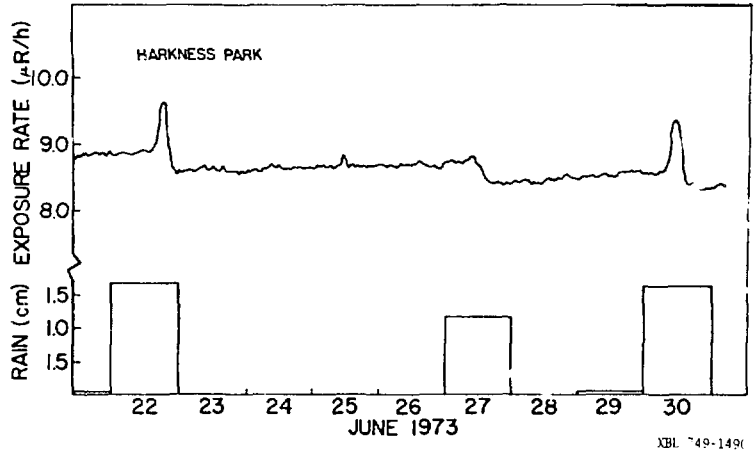

Fig. 10. Correlation between radon daughter washout peaks and precipitation data during reactor shutdown. Addition of rain water to soil lowers background levels but evaporation in the days that follow results in a slow rise. (From USAEC Health and Safety Laboratory.)

observed month-to-month variations. Burke[36] therefore suggests that the observed fluctuations in terrestrial gamma radiation is primarily due to changes in the density of the soil-water medium and in standing water or snow cover on the ground surface.[40-42]

By comparison with the time periods of variations in natural background variations due to instrument noise and random fluctuations occur in time intervals comparable to the instrument response time (~5 secs). Both the time characteristics and magnitude of fluctuations in exposure rates measured by an instrument such as the Reuter-Stokes ionization chamber may be used to discriminate between natural and man-made radiation. For example, substantial variations in the exposure rate due to plumes of gaseous effluents from stacks occur due to changes in wind speed, wind direction and atmospheric turbulence can occur over periods of a minute or less.

An increased exposure rate from a man-made source, such as the plume from the stack of nuclear power reactor, may have strong directional properties. For example, we would expect to find elevations in exposure rates up wind of the stack of nuclear reactor but not down wind. On the other hand, if rainfall is widespread, radon daughter washout may produce an elevation in radiation level observable at all monitoring stations around the reactor. Such criteria may prove important in discriminating between natural and manmade radiation levels. Another important parameter to be considered is the magnitude of deviations from the average radiation level produced by man-made and natural radiation sources. Gogolok and Miller[43] have described how chambers that continuously read exposure rate may be used to estimate exposures resulting from gaseous effluents from nuclear installations. Figure 11 shows the exposure rates, averaged over an interval of one hour at two locations near a boiling water power reactor. The large fluctuations are due either to radon daughter washout or the presence of gaseous radioactive effluent. Figure 11 also shows the standard deviation of exposure rate averaged over a 5 min. period from the hourly average. The standard deviation of natural background is found to be less than 0.2 μr/hr. Analysis using calculation of "the standard deviation clearly shows that the peak occurring at the beginning of the 6th day of monitoring is due to radon daughter washout, while the peaks occurring on the 5th, 8th and 9th at location one and on the 3rd, 5th and 11th days at location two are due to the noble gas plume. On the 3rd day, radon daughter washout occurred at both locations, while the gaseous plume was detectable only at location two. The standard deviation variations distinguish these contributions even though they occurred simultaneously."[22]

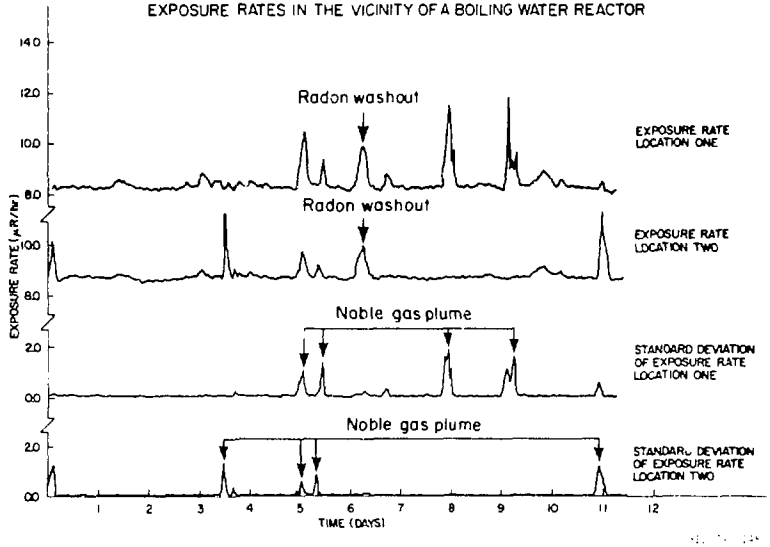

Fig. 11. Exposure rates measured at two monitoring stations in the vicinity of a boiling water reactor.

Scintillation Counters. A NaI scintillation counter has been found extremely valuable in environmental radiation studies carried out in the Bay Area by the Health Physics Department of the Lawrence Berkeley Laboratory.[28]

The detector is a thallium-activated sodium iodide crystal 3 in. in diameter and 3 in. thick. The crystal is optically coupled to a Dumont 6363 multiplier phototube, also 3 in. in diameter. The crystal and phototube assembly is shock-mounted in 1/2 in. foamed rubber, and is contained in a stainless steel canister 1/16 in. thick, 5 in. in diameter, and 12 in. high. (see Fig. 12) The casing excludes β-particles below about 3 MeV and this makes it possible to correlate field readings with laboratory pulse-height analysis of field samples, without being influenced by a changing β-γ ratio caused by changes in the field environment.

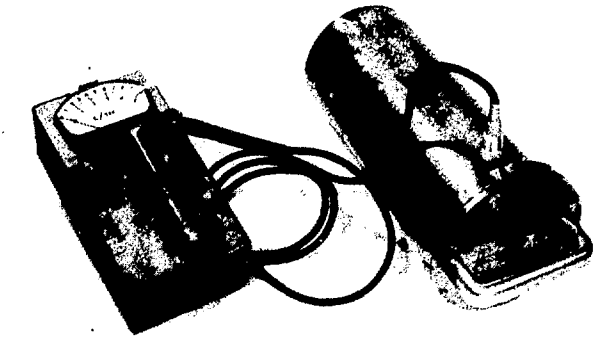

Fig. 12. Portable NaI scintillation counter used for radiation surveys at LBL.

The transistorized count-rate meter was designed by Goldsworthy.[44] His design has been slightly modified for our purpose but is basically the same. The instrument contains a Cockcroft-Walton high-voltage supply, a four-transistor linear pulse amplifier, an integral pulse-height selector circuit, and a rate-meter circuit. The electrical power for the instrument is supplied by a 10.8V mercury battery, which provides 300 hr or more of operation. The count-rate meter has four linear ranges spanning an interval from 0-50,000 counts/sec, or from 0-1.25 mr/hr. Experience at LBL has shown the instruments to be specific detectors of terrestrial gamma radiation and to be reliable and rugged in field service.[45-47] Figure 13 shows the instrument in use.

With the threshold set at about a photon energy of 100 keV the sensitivity of the instrument is such that 400 counts per sec corresponds to an exposure rate of 10 μr/hr. The instrument is calibrated using a radium source. Because the spectra produced by terrestrial gamma radiation and by fallout in a field environment are closely similar to that produced by our standard radium sources, this conversion factor can be used in any field situation.

Fig. 13. The portable NaI scintillation counter in use surveying exposure rates around a granite rock.

In the field measurements are made within areas roughly 30 by 30 ft. over which several readings are taken during a visit. Readings for a location are then averaged and the value entered into a log book. Readings are made with the detector ≈3 ft. above the ground surface. A simple geometric analysis shows that above a uniformly radioactive surface ≈90 percent of the detectable radiation comes from within a circle of ≈20 ft. radius. The effective area increases markedly as local relief increases.

One feature of the NaI scintillation counter that should be noted is its different response characteristics to environmental radiation compared to an ionization chamber. The ionization chamber measures ionization produced in a gas and, therefore, responds proportionally to the exposure rate produced by terrestrial radionuclides and cosmic radiation. For example at Berkeley where the environmental levels due to terrestrial radionuclides are ~30 millirem/yr, the relative response of an ionization chamber will be about 2/3 due to terrestial radionuclides and 1/3 due to cosmic radiation. A scintillation counter, on the other hand, responds to ionizing event rates (not exposure rate). Thus, for example, a 3" X 3" NaI has a

count rate of 400 cps in a γ-radiation field of 10 μr/hr while the corresponding counting rate due to μ mesons it is about 1 count per sec.

γ-Spectrometers. Although detectors which measure gross γ-ray exposure may provide a great deal of information, it is sometimes desirable that particular radionuclides be identified. Such an example might be in studies of the relative contribution to background due to terrestrial and fallout radionuclides.[28]

The portable scintillation counter described by Wollenberg et al.[28] measures the gross γ exposures rates. If soil samples are removed from the area in which gross measurements are made they may be assayed in the laboratory for uranium, thorium potassium as well as fallout radionuclides by γ-spectrometry.

Wollenberg et al. have described the use of a 4 in. dia., 2 in. thick NaI (Tl) γ-spectrometer located in low background facility.[48] Figure 14 shows a typical spectrum obtained from

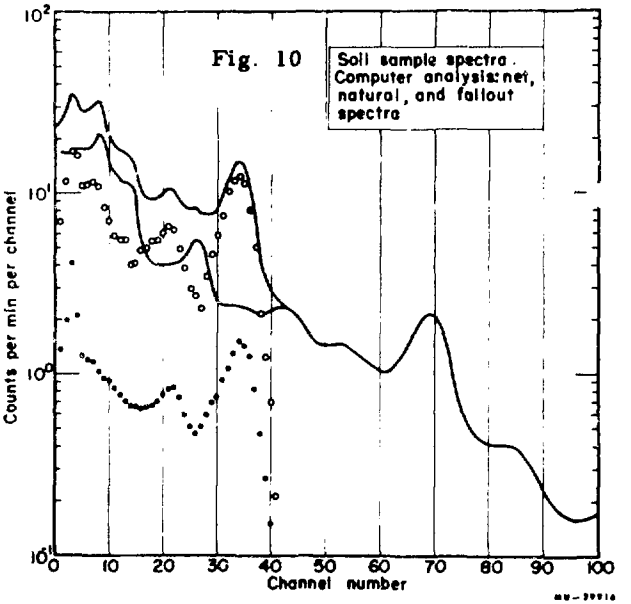

Fig. 14. Comparison of measured exposure rates.

a surface-soil sample taken in the San Francisco Bay Area. The upper curve shows the total spectrum resulting from natural and fallout radionuclides, after coorection for instrumental background. The lower curve shows the spectrum calculated from the uranium, thorium and potassium concentrations derived from the upper curve. (Prominent peaks in the natural spectrum are listed in Table 5.)

The two curves are seen to coincide at an energy of about 0.9 Mev. Subtraction of the two curves gives the spectrum due to fallout nuclides, shown as open circles in Fig. 14. Recognizable peaks are attributed to ^{144}Ce at 0.14 MeV, Rh and Ru isotopes at 0.45-0.52 MeV, and ^{95}Nb-^{95}Zr at ≈0.76 MeV. Recounting of this sample about 6 months later would show a ^{137}Cs peak at 0.66 MeV, presently masked by the Nb-Zr peak because of the shorter effective half-life (≈ 50 days) of ^{95}Nb-^{95}Zr compared with the 28 yr. half-life of ^{137}Cs.

An interesting comparison may be made between the calculated fission product spectrum derived from the soil sample with that obtained from dried weeds collected from a ditch in the Santa Cruz Mountains. (Black dots in Figure 14) The only activities in the weed sample are from fission products.

Studies such as this with a γ-spectrometer then make it possible to distinguish between fallout and natural sources of natural background. Thus, if it is assumed that fallout was evenly deposited in time Wollenberg et al.[28] show that in the years from 1958 to 1968 an integrated γ-ray dose of 282 mr was superimposed on a natural terrestrial of 482 mr and a cosmic-ray dose of 350 mr. Roughly three times as much γ-emitting radioactivity was deposited in the San Francisco Bay Area between March 1958 and the end of 1960 as has been deposited since 1960.

Table 5. Prominent Peaks in the Natural Spectrum

Energy (MeV)	Decay series	Nuclide
0.24	Th	^{224}Ra
≈0.60	U and Th	^{214}Bi and ^{208}Tl
0.90	Primarily Th	^{208}Tl
1.12	U	^{214}Bi
1.46	^{40}K	^{40}K
1.76	U	^{214}Bi

Intercomparison between estimates using these techniques and measurements made by the U.S. Health and Safety Laboratory using an ionization chamber and a portable γ-ray spectrometer showed good agreement. It is also of interest to note that Wallenberg et al.[28] have reported excellent agreement between exposure rates measured directly in the field and those calculated from the measured radionuclide composition of rock samples taken to the laboratory. If the composition of the soil or rock is known, the γ-ray level may be calculated quite accurately. Table 6 gives the exposure rate in μr/hr for measured contributions in ppm.

Figure 15 shows the agreement obtained. It is of interest also to note that Fig. 15 illustrates the influence of moisture content on the ambient radiation level for the San Francisco Bay Area, where the soil moisture measurements indicate an average of 30 percent difference in ambient radiation level between dry (summer) and wet (winter) conditions. When it is necessary to measure man-made radiation levels as low as 5 millirem/yr it is necessary that these fluctuations be well understood in the locality where observations are made.

Beck et al.[49] have discussed the relative merits of Ge(Li) and NaI detectors. Table 7 summarizes this comparison. For many applications the lower cost, greater sensitivity, and facility of a large NaI crystal make it very convenient.

Figure 16 shows a typical preoperational γ-ray spectrum measured at a reactor site. This spectrum together with a measurement of total exposure rate may be used to identify the five principal components of the background radiation exposure rate.

Table 6. Exposure Rate in μr/hr for Measured Contributions in ppm.

Element	Exposure rate in μr/hr per ppm of element. (detector 3 ft above ground surface)
U	0.76
Th	0.36
K	1.71×10^{-4}

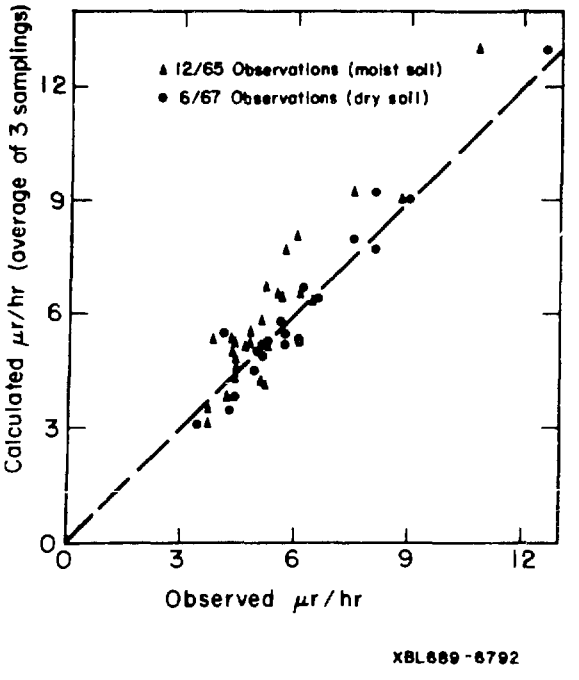

Fig. 15. Comparison of calculated exposure rates due to terrestrial radioactivity with measurements made in the field. Measurements made in the field are depressed when the soil moisture content is significant.

Figures 17 and 18 show data taken simultaneously at the same site in the Northeastern United States. Figure 17 shows data obtained with a 10 cm X 10 cm NaI(Tl) crystal in a counting time of 20 minutes. γ-rays from the fallout nuclides ^{137}Cs and ^{95}Zr-^{95}Nb are clearly resolved from γ-rays produced by naturally occurring radionuclides. Figure 18 shows the dramatic improvement in resolution that may be obtained using a Ge(Li) detector.[49]

For special problems which may require this good resolution, Ge(Li) detectors may be invaluable, but NaI detectors are generally adequate. Thus, for example: Nakamura has reported the use of a NaI detector to investigate the energy spectrum of "Skyshine" photons around accelerators at the Institute for Nuclear Study.[50]

Table 7. Characteristics of HASL Field Spectrometer Systems

	NaI (Tl)	Ge(Li)
Detector size	4 x 4 in. (820 cm^3)	60 cm^3
Detector geometry	rgt. circ. cyl.	closed coax. cyl.
Detector resolution (0.662 MeV)	53 keV (FWHM)	2.3 KeV (FWHM)
Detector efficiency (0.662 MeV)	36.5 cts/unit flux	2.2 cts/unit flux
Analyzer capacity	400 ch.	4000 ch.
Data accumulation times	10-20 min.	30-90 min.
Data recording	(1) magnetic tape (2) decimal printout	(1) magnetic tape
Data output	(1) peak areas (2) energy bands (4)	(1) peak areas

Phelps et al.[51] have used the environmental monitoring system developed at the Health and Safety Laboratory to make extensive in situ measurements of radionuclides in soil. This has been done at the Nevada Test Site and at several nuclear reactor sites. They have mounted their analytical equipment in a small van making field measurements very convenient.

Thermoluminescent dosimeters. Thermoluminescent dosimeters are preferred over film in the measurement of photon exposures above a few millirem. They are intrinsically more accurate and less subject to the problems of latent image fading found in film.

Several thermoluminescent materials are capable of the measurement of exposures below 1 mr with good accuracy. Thus, in 1974 de Planque Burke[30] reported the use of LiF and CaF_2:Mn to measure integrated environmental gamma exposures. Over exposure periods of 4 weeks and 2 weeks respectively accuracies of ±3 percent at exposures of 1 mR were reported. Lindeken et al.[31] reported measurements of the γ-exposure in houses in the Livermore Valley using CaF_2:Dy dosimeters in 1973.

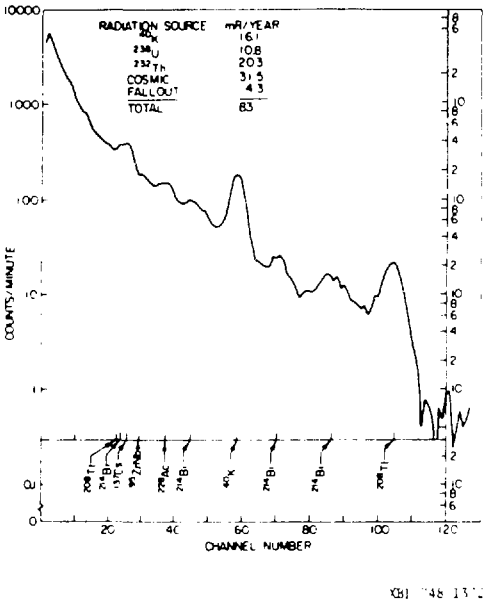

Fig. 16. Typical preoperational γ spectrum at reactor site. This spectrum, a conjunction with a pressurized ion chamber measurement of the total γ dose rate, can be reduced to provide the portion of the total dose contributed by the five sources of background radiation (Environmental Analysis Inc.).

The use of thermoluminescent dosimeters for environmental radiation measurement is now widespread and the results of an intercomparison of dosimeters under both field and laboratory conditions with 85 participants from 26 countries has recently been published.[52] Tuyn et al.[53] have used LiF thermoluminescent dosimeters to determine contours of equal dose equivalent from γ-rays and neutrons around the complex of accelerators at CERN.

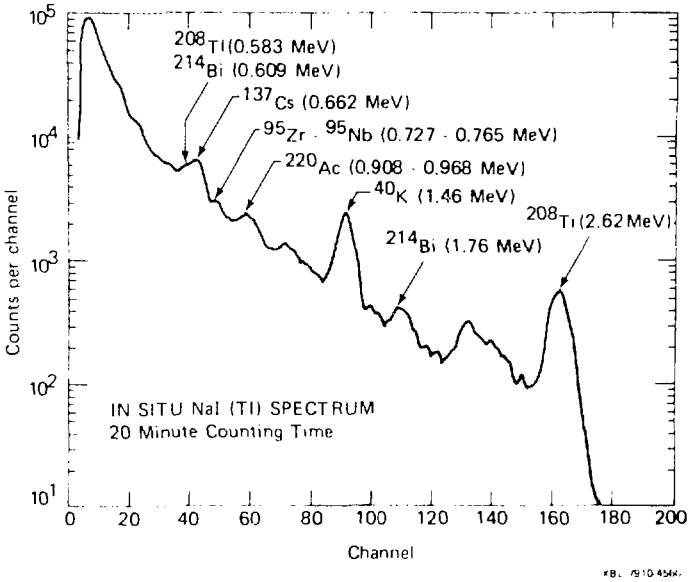

Fig. 17. In situ spectrum, northeastern U.S.A. location, taken in 1971 with a 10 cm by 10 cm NaI (Ti) crystal, 20 min counting time.

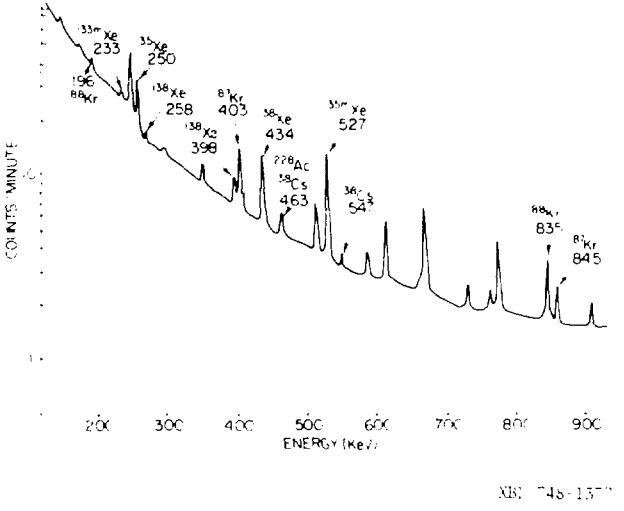

Fig. 18. In situ Ge(Li) spectrum taken near stack of BWR power plant with relatively short noble gas holdup (<1 hr). Peaks not identified are due to natural and fallout emitters (Harold Beck, U. S. Atomic Energy commission, Health and Safety Laboratory).

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