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IMPLEMENTING THE REQUIREMENT TO REDUCE RADIATION EXPOSURE TO ". . . AS LOW AS PRACTICABLE AT THE LAWRENCE BERKELEY LABORATORY

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IMPLEMENTING THE REQUIREMENT TO REDUCE RADIATION EXPOSURE TO ". . . AS LOW AS PRACTICABLE AT THE LAWRENCE BERKELEY LABORATORY

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ABSTRACT

The work of the Health Physics Department of the Lawrence Berkeley Laboratory in limiting radiation exposures, over the past 25 years, both to Laboratory personnel and the general population, is reviewed. Because the radiation environments of particle accelerators used in fundamental research are often new and novel, a vital part of the LBL radiation protection program has been the fundamental study of the production, transmission through shielding, and measurement of accelerator-produced radiations. These topics are first briefly reviewed followed by a discussion of the environmental impact of high energy particle accelerators. The close proximity to the Laboratory of a large urban population and the University of California Campus resulted in the early establishment of an environmental monitoring system for the detection of penetrating radiation. Despite an increasing potential for the production of radiation with the beam intensity of the Bevatron increasing since its first operation in 1954, site boundary radiation levels have shown a steady decline since 1959.

Estimates of population dose are described and shown to be comparable with the collective dose to radiation workers. Unlike some other accelerator laboratories, the collective dose to personnel involved in accelerator operations and maintenance has not shown substantial increases with beam intensity--in fact, there has been a small decline in exposures.

Personal dosimeters indicate a small but gratifying decline with time in the collective radiation exposures to Laboratory personnel and visitors; however, examination of working habits and procedures indicate litte room for massive reductions in the collective dose to radiation workers.

Cost effectiveness studies of shielding show that the cost of removing radiation exposure by providing a roof shield for the Bevatron has been $40 to $100 per man rem. For the 88-inch cyclotron, projections over 10 years estimate the cost of the provision of additional roof shielding to be between $200 and $500 per man rem.

"Sir, are you grossly ignorant of human nature, as not to know that a man may be very sincere in good principles, without having good practice?" Attributed to Dr. Johnson, by James Boswell, Tour of the Hebrides, 25th October

1. INTRODUCTION

The principle that radiation exposures should be maintained as low as practicable is by no means new. It has underlain the responsible practice of health physics at research laboratories, in hospitals, and in industry for many years. In this paper we hope to give evidence of its application at the Lawrence Berkeley Laboratory for at least the past twenty-five years. As an example, Fig. 1 contrasts the increasing beam intensity of the Bevatron over the years with radiation levels estimated or observed at the site boundary of the Lawrence Berkeley Laboratory. Inspection of Fig. 1 shows that there has been an overall increase in accelerated protons of more than four orders of magnitude since 1954 (Hartsough 1971, Everette 1974). Since 1969 beam intensity increased by a factor of nearly 100, while radiation levels measured at the Environmental Monitoring Station closest to the Bevatron fell by a factor of 48--an overall improvement of nearly 5000. A decrease in environmental radiation levels concurrent with an increasing potential source of radiation do not, of themselves, necessarily prove that radiation levels are "as low as practicable"; such a record is only achieved by continuous efforts to minimize radiation levels.

In his history of radiation protection standards, Taylor places the first discussions of the "as low as practicable" principle within the National Committee on Radiation Protection (NCRP) as early as 1949 (Taylor 1961). The evolution of the principle can be traced in the publications of the International Commission of Radiological Protection (ICRP) (ICRP

1955, ICRP 1959, ICRP 1966a). Most recently the ICRP has discussed the principle extensively and given some guidelines for its practical implementation (ICRP 1973).

At the present time there are widespread efforts to define the "as low as practicable concept" in terms that will guide both the operational health physicist in his day-to-day judgments and the design team in their planning of new facilities.

In administering a radiation safety program it is well recognized that the operational health physicist must steer a middle course between the Scylla of fiscal irresponsibility and the Charybdis of unsafe working and environmental radiation levels. In determining radiation levels that are as low as practicable, the ICRP is keenly aware that social and economic factors must be taken into account (ICRP 1966b). A balance must be drawn between protecting public safety and, at the same time, permitting reasonable use of radiation in industry, medicine, and research.

In the past much attention has been devoted to the quantification of radiation exposures. Until recently few attempts have been made to place the "social and economic factors" on a quantitiative basis, which would enable rational judgments to be made as to both the benefits and detriments resulting from any particular application of activity which involves the use or production of ionizing radiation. Recently several papers have appeared in the literature discussing the techniques of such "risk-benefit analysis," (Cohen 1970, 1971; Dunster 1970, 1973; Hedgran 1970; Otway 1970; Lederberg 1971; Sagan 1972). These studies now make it partly possible to examine radiation safety programs for cost effectiveness.

2. THE LAWRENCE BERKELEY LABORATORY AND ITS LOCATION

The Lawrence Berkeley Laboratory (LBL) of the University of California is situated on the western slope of the most westerly range of hills parallel to the eastern side of San Francisco Bay. Elevation of the site varies between 400 ft. and 800 ft. above sea level. The Laboratory area is enclosed on the north and south sides by sparsely populated residential areas of the cities of Berkeley and Oakland. The major part of the Berkeley Campus of the University of California lies on the west side of the Laboratory. Higher up on the hills to the east are the Lawrence Hall of Science and Space Sciences Laboratory; beyond them lies uninhabited land and the Tilden Regional Park. The geographical setting is shown in the map (Fig. 2), and a good impression of the location of the Laboratory may be obtained from Fig. 3 which shows a general view of the western side of the Berkeley Hills with the Lawrence Berkeley Laboratory lying at the foot of the hills. The Berkeley Campus of the University of California is in the center of the photograph, while the city of Berkeley surrrounds the Campus and Laboratory in the foreground and to the right and left of the picture. Almost the entire urban population of the San Francisco Bay Area (∿3 million people) lies within 80 kilometers of the Laboratory.* More importantly, as we shall show later when we discuss the estimates of population exposure, it is estimated that the equivalent of 329,000 live or work within 8 kilometers of the Laboratory perimeter. This proximity of a large population to the Laboratory results in a population dose due to Laboratory operations comparable in magnitude to the collective dose of radiation

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*It is conventional to estimate population dose contributed by a nuclear installation out to a distance of 80 kilometers from the facility.

workers.** For example, in 1973 the population dose was reported as <60 man rem (Wallace 1974), while the collective dose to Laboratory personnel was 97 man rem (Section 8). These facts have led to special attention being given at LBL to population exposure since 1959.

The major source of radiation exposure, both to the general population and Laboratory personnel, is the operation of four particle accelerators engaged in fundamental research. These accelerators are: the Bevatron, a 6 GeV proton synchrotron; the SuperHILAC, a heavy ion linear accelerator, producing heavy ion beams up to 8 MeV/amu in energies; and the 184-inch and 88-inch cyclotrons. Because these accelerators are used in research, they present many new and novel radiation problems--their radiation environments are themselves to some extent a subject of research. Such studies have always formed an integral part of accelerator development at the Lawrence Berkeley Laboratory (Freytag 1972, Patterson 1973, Wallace 1965, Zaitsev 1971).

3. ACCELERATOR-PRODUCED RADIATION STUDIES AT THE LAWRENCE BERKELEY LABORATORY

Since the late 1940's the Health Physics Department has been responsible for accelerator radiation monitoring and shielding at the Laboratory. During this period extensive experience has been obtained with a variety of types of accelerators producing electrons, protons, and heavy ions over

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**This occurs because a large number of people in the general population receive very small average exposures due to LBL operations, whereas a comparatively smaller number of LBL employees and visitors receive a somewhat larger exposure. For example, in 1973 the average exposure to members of the general population (329,000 people) within 5 km of LBL was <0.18 millirem, while the average exposure to 4703 Lab visitors and employees was 21 millirem.

a wide range of energy.

The basic approach to the problems of accelerator radiation measurement has been analytical. The various components of the radiation field are identified, the intensity and energy distribution of the significant components are determined, and the dose equivalent then calculated. Such an approach has the advantage that sufficient information is obtained to implement many aspects of a health physics program--the anticipation and prior estimation of radiation intensities, their measurement and field estimation, and the design of shielding and operational procedures which ensure adequate safeguards but permit experimental flexibility.

The work of the group in radiation detector development and shielding measurements has been extensively described in the literature--most recently in several review articles. (Patterson 1971a, Rindi 1973a, Thomas 1972). From this work a general rule has emerged. Outside high energy accelerator shielding, neutrons between 0.1 and 20 MeV usually contribute more than half the total dose equivalent. γ-rays and low-energy neutrons together contribute 10-20%, with neutrons greater than 20 MeV making up the balance. In the past few years it has become possible to measure the energy neutron spectrum which exists outside accelerator shielding with adequate detail for radiation protection purposes. (For a more complete description see Thomas 1972).

The simultaneous operation of four particle accelerators leads to a complex variation of radiation intensity, both with time and distance from the Laboratory. This complexity is compounded by the flexibility in modes of accelerator operation demanded by a research program. Different experiments may require radiation intensities which vary by three orders of

magnitude or more. For example, large bubble chambers or spark chambers require neutron flux densities between one and two orders of magnitude below that required on radiation protection considerations alone. On the other hand, some experiments may require prolonged high intensity runs--with consequent high ambient radiation levels. A recent example of such an experiment at Berkeley was the production and identification of Element 106 at the SuperHILAC (Ghiorso 1974). Flexibility in experimental facilities--including radiation shielding--are essential if a successful research program is to be carried out around high energy particle accelerators.

The radiation phenomena at a research laboratory such as LBL are constantly changing and therefore, of necessity, under continuous review. The problems presented are always new and their solution requires constant alertness. For the past twenty years studies at Berkeley have principally centered around proton accelerators. Just at the time the radiation phenomena of such accelerators has become fairly well understood, the Laboratory's interests have changed direction with an increasing interest in high-energy, heavy-ion research. A whole new set of problems which require identification and solution is thus being presented to the health physicist.

4. THE ENVIRONMENTAL IMPACT OF HIGH ENERGY PARTICLE ACCELERATORS.

The environmental impact of high-energy accelerators is different in character from most types of nuclear installation. At accelerators the predominant source of population exposure is from the radiation field produced during operation, rather than from the leakage of radionuclides into the environment. The possibility of contamination of ground water in the vicinity of high energy accelerators has been carefully studied at several

laboratories. These studies all conclude that no significant ground water contamination is likely due to accelerator operation at beam powers presently feasible. This conclusion has been supported to date by the absence of any reports in the literature of any significant elevation in the radioactivity in water supplies close to accelerator laboratories. In particular, the environmental surveillance program of the Lawrence Berkeley Laboratory has detected no significant changes in the radioactivity of water samples taken from surface streams around the Laboratory (Wallace 1974).

The experience with the operation of diverse types of particle accelerators over many years makes it possible to conclude that the exposures resulting from radioactive gases or aerosols produced by particle accelerators are usually significantly lower than those due to the external radiation field. No elevation in radiation levels due to accelerator produced gaseous radioactivity has been observed by the Laboratory's environmental monitoring program. (For a more general discussion of the environmental impact of high energy accelerators see Patterson 1973 and the references given in Appendix II).

5. ENVIRONMENTAL MONITORING OF PENETRATING RADIATION

5.1. General

As we have seen (Section 2), the presence of a large urban area contiguous with the Laboratory's boundaries led to an early interest in environmental studies at the Lawrence Berkeley Laboratory. When it became apparent that the Bevatron was an intense neutron source, radiation intensities were first measured within the Laboratory (Patterson 1962). These studies led to the establishment of a permanent environmental monitoring program. (See Fig. 4).

Estimates of the contribution of dose equivalent at the Laboratory boundary due to accelerator operation have been made for many years. Figures 5-8 show reported site boundary penetrating radiation levels at the location on the Laboratory boundary. Radiation levels have been consistently below the maximum permissible dose-equivalent for non-occupational exposure.

Under certain operating conditions, any one of the Laboratory's accelerators may have a stray radiation field which can be detected at distances as far as a few thousand feet. The radiation intensity at a given location and time may consist of contributions from any one or all of these accelerators. Attempts to understand and predict the Laboratory's stray radiation field have in the past required combinations of stationary detectors and counting equipment that could not be read simultaneously. Many series of measurements were made with mobile counting equipment; each series lasted for a few hours and was scheduled during the infrequent times when only one of the accelerators was operating at a constant beam level. These measurements facilitated understanding of the contribution to the radiation environment of each accelerator and of the selection of permanent environmental monitoring locations.

Since 1964 radiation levels at ten locations have been continuously monitored (Fig. 4), (Stephens 1972). These locations were strategically selected to monitor the radiation output of the Laboratory's accelerators, both close to each accelerator and at the Laboratory perimeter. Two environmental monitoring stations (situated at the Olympus Gate and adjacent to the 88-inch cyclotron) are specifically located to record the highest radiation levels at the Laboratory boundaries, while two others--those at

Building 90 and at Panoramic Way--respond to skyshine from the Bevatron and the 88-inch cyclotron and to direct radiation from the 184-inch cyclotron respectively.

Radiation levels are continuously monitored and recorded at a central location by means of a telemetry system. Both the rate and time-integrated intensity of radiation exposure are monitored.

Neutrons are detected by means of a moderated BF_3 proportional counter. Moderator thicknesses are chosen to provide a flat energy response over the range of neutron energies from 0.25 to 20 MeV (Yamashita 1966). Neutron energies have been measured by a variety of techniques. These include proton recoil proportional counters (Moyer 1958), threshold detectors, and fission counters (Smith 1958). An energy compensated Geiger-Müller counter is used to detect and record gamma radiation (Jones 1962).

The monitoring system also provides a means for determining the relative contributions of each of the several accelerators to the total radiation environment by studying radiation levels during maintenance shutdown periods when radiation levels at remote locations are produced by different combinations of accelerator operating conditions.

In general, the response of each monitoring station is a complex function of the mode of operation of each and all the Laboratory's accelerators. With all accelerators operating simultaneously, it is not possible, at the present time, to assign accurately to particular accelerators their relative contributions to the radiation level at each station. Without more detailed study, only approximate assignments may be made.

5.2. Radiation Levels at the Laboratory Boundary, 1959-1973

The maximum permissible annual dose equivalent to which members of

the general population at the boundary of a laboratory such as Lawrence Berkeley Laboratory may be exposed is 500 millirem/year (MPD). It has been Laboratory policy to place considerable effort toward maintaining radiation levels well below this limit.

The environmental monitoring program of the Laboratory showed that approximately 80% of the accelerator produced radiation in 1972 was due to the operation of the Bevatron when accelerating protons (Stephens 1974a).

The Bevatron has a long history--having been in operation since 1954. During the past 19 years substantial changes have occurred in accelerator intensity, mode of operation, and shielding. Figure 1 shows the number of protons accelerated in the Bevatron each year in the period 1954-1973 (Hartsough 1971, Everette 1974). During this period the beam intensity of the accelerator, and, therefore, the potential radiation source, increased by a factor of more than 10,000. Radiation levels around the Bevatron have been controlled primarily by the addition of shielding, but also by improved techniques in beam control, extraction, and beam dumping into well shielded locations.

The existing shielding for the accelerator proper was designed in 1961 and installed in 1962 as part of an extensive accelerator improvement program. The shielding design was predicated upon a proton intensity of 10^{13} protons per pulse, repetition frequency of 10 pulses per minute, and a maximum permissible dose equivalent rate at the Laboratory boundary of 500 millirem per year (Moyer 1961, 1962). It was recognized at that time that site boundary radiation levels due to leakeage from the shielding roof, when thick targets were operated in the accelerator straight sections, would present a limiting operational condition on the accelerator..

Continuing improvements in accelerator operation--particularly with regard to beam extraction--and the addition of shielding above the accelerator straight sections have made significant reductions in site boundary radiation levels possible, despite increasing beam intensity. These techniques have resulted in a reduction in radiation levels.

Thus, in 1972 with a circulation proton beam intensity of 5×10^{12} protons per pulse and with the Bevatron accelerating protons for 75% of the time, the maximum annual site boundary level was less than 55 millirem--compared with a value of 190 millirem that would have been predicted in 1962 at this beam intensity.

Figure 5 through 8 show the annual dose equivalent reported for the four environmental stations as a function of time.

Radiation levels at the Olympus Gate Station have shown a steady decline since 1959 when estimates were first made. The Olympus Gate Station is in direct view of the Bevatron and most directly influenced by that accelerator. During late 1962 and early 1963 the Bevatron underwent a substantial modification and was out of operation for a significant time. This shutdown was, however, only partially responsible for the falling radiation level recorded. This falling trend continues through 1964 and 1965 because of the addition of shielding and improvements in accelerator operation--particularly the development of an extracted proton beam. Radiation levels through 1966 showed an increase due to increasing circulating proton beam intensity, but the decrease observed in 1967 was because of the installation of extra shielding to the straight sections of the Bevatron. Since 1970 radiation levels have declined due to increasing use of the Bevatron to accelerate heavy ions, and this trend is expected to

continue.

The monitoring station adjacent to the 88-inch cyclotron responds to radiation from both the Bevatron and the 88-inch cyclotron. The 88-inch cyclotron was completed in 1961 and the first external beam obtained in 1962. During the period 1962-1966 the radiation levels observed at this station closely reflect the operation of the Bevatron (see Figs. 5 and 6). In 1967, however, the increasing intensity at the 88-inch cyclotron is reflected in the higher radiation levels recorded at this station. The addition of new shielded eaves to the roof during the latter part of 1970 resulted in a dramatic reduction in the radiation levels for 1971, and the 88-inch cyclotron is now so well shielded that its adjacent monitoring station now principally responds to the Bevatron (Gleiter 1973).

The station situated at Panoramic Way is in direct view only of the 184-inch cyclotron and responds principally to that accelerator. High readings at this station may usually be directly attributed to unusual experimental conditions at the 184-inch cyclotron. Reduced use of this accelerator will result in a decline in readings at this station. The residual levels measured will be largely due to skyshine radiation from the Bevatron.

Radiation levels recorded at the Building 90 environmental monitoring station are principally caued by skyshine from the Bevatron and 88-inch cyclotron (compare Figs. 5, 6, and 8).

5.3. Accuracy of Environmental Monitoring

In the past dose equivalent reported by the LBL environmental monitoring program has been overestimated. The overestimation was due to (a) a conservative choice of neutron fluence to dose equivalent conversion

factors and (b) an underestimate of natural background subtracted from monitoring station readings. In the past this uncertainty in the reporting of LBL site boundary levels has been of little consequence, because it was possible to demonstrate that, even with a conservative estimate of site boundary annual dose equivalent, radiation levels were below the MPD. The ICRU suggested that when the maximum dose equivalent is considerably less than the MPD, an uncertainty of as much as a factor of three in estimation of the dose equivalent is acceptable (ICRU 1971). However, there is increasing tendency by regulatory agencies to require improved accuracy in the measurement of man-made radiation. Lowder and Gogolak have clearly drawn attention to the implications of this requirement for increased accuracy:

> "The recent trend toward the quantitative definition of 'as low as practicable' guidelines pertaining to the release of radionuclides to the environment for nuclear facilities and the resulting dose places a significantly increased burden on environmental surveillance programs. It was previously believed that adherence to the admonitions of expert bodies such as the ICRP (ICRP 1964) to limit unnecessary radiation exposure was achieved by demonstrating that such exposure was well below the recommended 'maximum permissible' annual levels of 500 mrem to individuals or 170 mrem to a 'suitable sample' (FRC 1960). U.S. regulatory agencies are now preparing numerical limitations on environmental radiation dose to man from light-water power reactors and the nuclear power fuel cycle (Fed. Reg. 1971, EPA 1973). 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 operation 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 population 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." (Lowder 1973).

This requirement for improved accuracy poses severe problems both of measurement and data interpretation at high energy accelerator laboratories, and it will be necessary to have a much better understanding of natural background and the accelerator-produced radiation environment than hitherto.

5.4. Neutron Fluence to Dose Equivalent Conversion

We have seen that the major component of accelerator-produced radiation is due to neutrons. Neutrons up to an energy of 20 MeV may be readily measured with a moderated BF_3 counter, and the neutron fluences at the site boundary in this energy region may be determined with good

accuracy. Conversion of this fluence to dose equivalent is, however, a more difficult matter. The evaluation of dose equivalent is limited by a general lack of knowledge in radiobiology; however, the evaluation consists of two steps: a physical measurement capable of good accuracy, and the conversion of this physical measurement to units appropriate to radiation protection. The assignment of the appropriate conversion factors is to some extent an administrative judgment. The problem is compounded by the fact that the accelerator-produced neutrons are distributed over a wide range of energy and neutrons greater than 20 MeV in energy may make a significant contribution to the dose equivalent.

Although the ICRP have published fluence to dose equivalent conversion factors for monoenergetic neutrons (ICRP 1973b), several authors have drawn attention to the fact that there is no official guidance as to how such factors should be used for neutrons distributed in a continuous energy spectrum (Shaw 1969, Patterson 1971b, Stevenson 1972). The relative numbers of high energy (greater than 20 MeV) to low energy neutrons in a spectrum can greatly influence the biological potency of the overall neutron fluence. For example, the biological potency of neutrons in the cosmic ray spectrum is lower than that of neutrons emerging from the shielding of the Bevatron by a factor of 1.5 (Gilbert 1968).

For neutron spectra the dose equivalent at the maximum of the dose equivalent-depth distribution in the body should be used to calculate fluence-dose equivalent conversion factors. Shaw et al. (1969) have reported calculations at the conversion factors for a variety of spectra for both unilateral and multilateral irradiation. Table 1 summarizes these values and compares them with conversion factors that were, until 1972, routinely used

at LBL in reporting environmental monitoring data.

Table 1. Dose Equivalent per Unit Fluence for Cosmic Ray and Bevatron Neutron Spectra.

Neutron Spectrum	Shaw et al. [Unilateral Irradiation] ($remn^{-1}$ cm^2)	Shaw et al. [Multilateral Irradiation] ($remn^{-1}$ cm^2)	LBL (prior to 1973) ($remn^{-1}$ cm^2)
Cosmic Ray (Hess et al.)	2.0×10^{-8}	1.3×10^{-8}	2.3×10^{-8}
Bevatron	2.3×10^{-8}	1.9×10^{-8}	3.2×10^{-8}

Table 1 shows that for a given neutron fluence wide variations are possible in the reported dose equivalent, depending upon the assumptions made in determining the conversion factor. If estimates of dose equivalent to an accuracy of better than about 50% are to be made, Table 1 shows that it is important that the neutron differential energy spectrum be measured.

Neutrons with energy greater than about 50 MeV can be measured by means of a bismuth fission counter (McCaslin 1970). The most sensitive bismuth fission chamber in operation is in use at LBL. At a neutron dose equivalent due to accelerator operation of 10 millirem/year the corresponding neutron fluence is about 6×10^5 n cm^{-2}, of which about 2×10^5 n cm^{-2} might have energies above 50 MeV. The corresponding counting rate in the bismuth fission chamber would then be $\sim$2000 counts/year. To be able to report dose equivalent to better than 50%, will be necessary to discriminate between 1000-4000 count/year, against a background counting rate due to noise $\sim$several

thousand counts/year in existing counters. It is therefore clear that this is a formidable task and will require significant technical improvement of bismuth fission counters. At dose equivalent rates below 10 millirem/year it seems unlikely that, without the development of very large and sensitive high energy neutron detectors--such as spark chamber arrays (Rindi 1974a)--, an accuracy of better than about 50% is possible in dose equivalent evaluation for a given neutron fluence.

5.5. Dose Due to γ-Rays

Measurements outside the shielding of the accelerators in operation at LBL show that, with the exception of the SuperHILAC, the dose equivalent due to photons is usually less than 10% of that due to neutrons. At radiation levels comparable with the maximum permissible dose-equivalent (MPD) of 500 millirem/year the photon component would therefore be 50 millirem/year or less. The intensity is comparable with fluctuations in the radiation component because of terrestrial radioactivity at LBL. Natural background at LBL amounts to between 70-110 millirem/year, made up as follows:

Natural radioactivity surrounding earth	approx. 40-80 millirem/yr.	(Smith 1974)
Cosmic rays - μ mesons	approx. 30 millirem/yr.	(O'Brien 1972,
neutrons	approx. 3 millirem/yr.	(United Nations 1972)
Total	approx. 70-110 millirem/yr/	

The component from natural radioactivity shows wide fluctuations from place to place, due both to geological and human causes, e.g., outcrop of granitic rocks, presence of large buildings, or paved roads (Eisenbud 1973). Table 2 summarizes some field measurements of radiation levels due to terrestrial

radioactivity made around the Lawrence Berkeley Laboratory site. Fluctuations of more than a factor of two are evident.

In addition to variations in natural γ-background from place to place, the background at a particular place may show secular variation of as much as 30%. Figure 9 shows measurements of exposure rates at several locations near New York City (Burke 1974). Seasonal fluctuations are evident and these have been largely attributed primarily to fluctuations in water content of surrounding soils. Burke and her colleagues have developed a climatic-exposure model which gives a fair description of these fluctuations in exposure rate (see Fig. 9).

Such direct measurements of temporal variations of exposure rate are not yet available at sites around the Lawrence Berkeley Laboratory, although indirect evidence has been available for some time. Figure 10 shows the correlation between exposure rates measured in the field and those calculated from laboratory radio-assays of soil samples taken at sites around the San Francisco Bay Area (Wollenberg 1969). Agreement between calculated and measured exposure rates is good, but it is evident from Fig. 10 that field measurements made when the soil is wet are generally depressed. This observation is in accordance with the conclusion of Burke and her colleages. Measurements of radiation levels due to accelerator produced photons to an accuracy of better than about 30 millirem per year therefore requires an accurate assessment of natural background because of terrestrial radioactivity. This may be achieved by preoperational radiation surveys in the field, measurements during periods of accelerator shutdown, or by the laboratory radio-assay of soil samples taken in the field and the calculation of environmental exposure rates. At Berkeley preoperational survey data is

Table 2. Measurements of Natural Background from terrestial radioactivity at the Lawrence Berkeley Laboratory (Smith 1974).

Location	Dose Equivalent Rate		Comments
	μrem/hr	mrem/yr	
Building 90 Parking Lot	1.9-3.6	17-32	Asphalt Surface
Building 90 Environmental Monitoring Station	4.8-5.4	42-47	∿100 ft. West Environmental Station at fence--above earth
Fence Gate North of NE Corner, Building 90	4.2	37	
Blackberry Canyon Parking Lot	4.8-6.5	42-57	Asphalt Surface
South Turnout Building 72	4.2	37	On grass at SW edge of road
Road Bank Building 72	3.2	28	Conglomerate (Orinda formation) 30 ft. from previous location

not available and recourse must be made to the latter two methods.

All the LBL accelerators are turned off for a few days during the Christmas-New Year's Day holidays, and the gamma ray background measurements have been made at this time. Because this period occurs during the rainy season of Northern California, the background levels subtracted from environmental monitoring station data are probably too low (by as much as 20 millirem/year). Consequently, photon exposure rates reported by the LBL environmental monitoring program are probably too high, by up to 20 millirem/year. Inspection of the environmental monitoring system data reported since 1964 tends to confirm this supposition. An extensive program to obtain a better understanding of γ-ray background is presently under way at LBL. Even with a good understanding of the radiogenic composition of the soil in the vicinity of the LBL environmental monitoring stations, an estimate of average exposure rates will be limited in accuracy to about 10-15 millirem/year until good data on seasonal fluctuations in background is obtained.

6. POPULATION EXPOSURE RESULTING FROM ACCELERATOR-PRODUCED PENETRATING RADIATION

In any cost-benefit study of radiological safety programs, it is first necessary to define parameters which are measures of both the beneficial and detrimental impact.

In the particular case of fundamental research programs, it is extremely difficult to determine an index of benefit which would be acceptable to all because the ultimate consequences of scientific research cannot be accurately predicted. Experience has shown that scientific research has, on balance, resulted in substantial benefits to mankind, and it is

generally agreed that fundamental research is worthwhile and will lead to continuing benefits.

On the other hand, for research programs which result in the production of ionizing radiation, such as those at LBL, it is fairly easy to obtain an upper limit to the possible concomitant human detriment.

In setting standards for radiation protection, it is assumed that biological effects are linearly related to the dose equivalent. With this assumption a useful index of the possible detriment from the uses of ionizing radiation is the total population exposure resulting from a given activity, M, defined by the equation:

$$M = \int HN(H)dH \qquad (1)$$

where N(H)dH is the number of people receiving a dose equivalent between H and H + dH, and the integration is carried out over the entire dose equivalent distribution and population exposed. M is usually expressed in the unit man-rem and is termed the <u>population dose</u>.

Several estimates of the monetary equivalent of the detriment from a population exposure of 1 man-rem have recently appeared in the literature (Cohen 1970, 1971; Dunster 1970, 1973; Hedgran 1970; Otway 1970; Lederberg 1971; Sagan 1972). These estimates fall in the range \$10-\$250 and are helpful in determining the sums of money that might prudently be used in eliminating radiation exposures.

An upper limit to the annual population dose equivalent, M, due to accelerator-produced penetraing radiation at LBL, has been reported as 2150 D_0, where D_0 is the maximum annual dose equivalent at the Laboratory boundary (the fence post dose equivalent) (Stephens 1973).

Under the conditions obtained at LBL with an urban area contiguous with the Laboratory's boundaries, the population dose is entirely due to people living or working within about 5000 meters from the Laboratory.

Three factors that could greatly reduce the estimated upper limit of population dose are:

a. The value of the attenuation length of accelerator-produced neutrons is not well known. Many measurements of dose equivalent around a variety of particle accelerators have been published. These measurements have recently been reviewed and critically evaluated (Rindi 1974). No measurements have been reported beyond a distance of 1500 meters. Figure 11 shows typical data reported by several accelerator laboratories. Despite the poor accuracy of the data some consistent patterns are evident. At all accelerators the dose equivalent falls at least as fast as the inverse square of the distance. At distances beyond about 300 meters the variation of dose equivalent H (r), with distance, r, from shielded high energy accelerators is probably best expressed by:

$$H(r) = \frac{a\, e^{-r/\lambda}}{r^2} \qquad r \geq 300 \text{ meters} \tag{2}$$

where a is a constant.

The parameter $e^{-r/\lambda}$ is interpreted as due to air attenuation. The attenuation length, λ, depends upon the spectrum of neutrons entering the air from the accelerator shield. A lower limit would be that measured for fission neutrons of ≈ 225 meters (Stephens 1963). If the accelerator is capable of producing neutrons of energy greater than about 1000 MeV at large distances from the accelerator, when an equilibrium spectrum has been established in air, λ will take on the value corresponding to high energy neutrons.

The high energy attenuation length in air may be calculated as $\sim$95 gm cm^{-2}. Cosmic ray studies have measured the attenuation of strongly interparticles, produced in Extensive Air Showers and obtained values in the range 100-120 gm cm^{-2}. It is reasonable therefore to take an upper limit of λ as $\approx$100 gm cm^{-2} (850 meters). Although the measurements published in the literature do not determine the value of λ with any great accuracy, they are consistent with this interpretation. Values of λ between 240 and 1000 meters are reported. Measurements made at low energy accelerators, or at high energy accelerators whose leakage spectrum is rich in low energy neutrons, tend to show values of λ in the region of $\sim$ 250 meters. At other high energy accelerators values of λ between 600 and 1000 meters have been reported. There are anamolies in the literature, however, which will require further studies for their resolution (Rindi 1974b). These measurements, however, set the physical range of λ between 225 meters and 850 meters. The population dose varies approximately as $\lambda^{2/3}$ (Stephens 1974b). Such an uncertainty in λ gives rise to an uncertainty of nearly a factor 3 in population dose. Early measurements at the Bevatron give a value of λ of $\sim$270 meters (Thomas 1968), but under present shielding conditions a higher value would almost certainly be obtained. At the radiation intensities which presently prevail around the Bevatron, it is extremely difficult to make measurements which would determine λ with good accuracy. A recent review of the literature (Rindi 1974b) suggests that for a well shielded high-energy accelerator such as the Bevatron, a value of λ $\sim$850 meters should be used. This would reduce somewhat the population dose estimated by Stephens and Thomas, (who assumed a value for λ of 1000 meters) to $<$2000 D_0.

b. The dose equivalent to the surrounding population may be reduced because of shielding from the Laboratory of a large fraction of the area by hills. (See Figs. 3 and 4). The Bevatron sits in a basin and is shielded from almost all the urban area surrounding the Laboratory: Figs. 12 through 14 give examples of topographical profiles drawn from the Bevatron. The precise effect of such shielding is not yet known. Preliminary information obtained from the environmental monitoring stations at the Laboratory indicate that radiation levels are depressed by a factor of about two when hills intervene in the direct line-of-sight between detector and accelerator (McCaslin 1974) (see Appendix I). It is possible that the original population dose estimate of Stephens et al. may be reduced by about a factor of two because of hill screening or: $M < 1000\ D_0$.

c. Shielding due to buildings was not included in the estimates of population exposure. For light wooden frame buildings this is only a small factor. Assuming a wall thickness of 15 gm cm^{-2} neutron intensities would only be reduced by a factor of 0.87 and assuming an 80% occupancy factor the average shielding factor would be 0.89 in buildings of light construction. In concrete buildings with a 75 gm cm^{-2} the shielding factor is 0.50 and the time-averaged factor is 0.60 (again assuming an 80% occupancy factor). Students and staff of the University of California Campus contribute about 15% of the population dose estimated by Stephens and Thomas. Since the great majority of buildings on the Campus are of substantial construction, a shielding factor of 0.60 can be applied to the exposure to Campus residents.

These considerations would reduce the population dose to:

$$M < 1000\ (0.85 \times 0.89 + 0.15 \times 0.60)\ D_0$$

$$< 850\ D_0 \text{ man rem}$$

In addition to these three factors, the population dose will be further reduced by the daily movements of a large fraction of the nearby resident population. The net effect of this population movement is to areas of lower radiation intensity but is numerically difficult to evaluate.

In summary, our current best estimate of population dose equivalent due to LBL operations is

$$M < 850\ D_0 \text{ man rem.}$$

Table 3 summarizes the estimated population exposure due to LBL accelerator operation during the period 1963-1972. As we have seen these estimates are probably high by more than a factor of two.

7. REDUCTION OF LBL SITE BOUNDARY LEVELS BY SHIELDING

Shielding studies have been an integral part of particle accelerator development at the Lawrence Berkeley Laboratory (Patterson 1972a). As accelerator intensities have increased, shielding has been installed to maintain radiation levels well below required radiation safety standards. Most recently extensive shielding has been installed at the 88-inch cyclotron (in 1971) and is currently being added to the SuperHILAC.

The continued addition of shielding will not, however, result in continued reductions in radiation levels. Shielding design at accelerators used in fundamental research must often allow flexibility; rapidly demountable shielding is required, access to experimental areas must be maintained, and the accelerator itself must be accessible. Radiation leakage

Table 3. Reported Population Dose Equivlaent due to LBL Accelerator Operation.

Year	Average Fence Post Dose Equivalent background subtracted (rem/yr)*	Man Rem*
1963	0.134	288
1964	0.101	217
1965	0.051	110
1966	0.066	142
1967	0.071	153
1968	0.086	185
1969	0.129	277
1970	0.082	176
1971	0.127	273
1972	0.048	103
1973	0.028**	<60**

*1972 Reporting System. $M \leq 2150\ D_0$.

**Maximum Fence Post Dose Equivalent Quoted for 1973.

through access labyrinth ducts and penetrations and cracks in shield walls often place a practical limit on the addition of shielding. The use of high density shielding materials is limited by the load-bearing characteristics of floors and foundations of the facility or even of the earth and rock on which it is built. Finally, there is a point at which cost-effectiveness studies show the addition of shielding to be no longer an economic means of reducing ambient radiation levels.

The sources of penetrating radiation due to LBL operation have recently been analysed (Stephens 1974a). During 1973 roughly 80% of accelerator-produced radiation was from the Bevatron when it accelerated high energy protons. Measurements show that approximately half of the Bevatron produced radiation (40% of the total) is because of roof leakage when protons strike components of the beam extraction system of the Bevatron. The balance of Bevatron-produced radiation is due to the operation of external proton beams--with about 75% being due to one particular mode of split beam operation. (See Table 4).

Table 4. Relative Sources of Penetrating Radiation at LBL Site Boundary - 1973.

Accelerator	Percentage of Site Boundary Radiation Level	
Bevatron	Accelerator Roof	40%
	Split Beam Operation	30%
	Other External Beams	10%
184-Inch Cyclotron 88-Inch Cyclotron SuperHILAC		10%

It is clear from Table 4 that the greatest potential reductions in site boundary levels could, in 1973, therefore, have resulted from shielding modifications to, or changes in operation of the Bevatron. As we have seen (Section 5.2) the Bevatron was substantially modified in 1962-63. As part of this modification, roof shielding was constructed (see Figs. 15-17). The existing roof reduces radiation levels by a factor of 100 (Smith 1965) and was constructed at a cost of about $2.8M (Salsig 1974). From Table 3 we see that the total population dose reported for the ten years 1963-1972 was 1924 man rem of which roughly 770 man rem was due to leakage of neutrons through the Bevatron roof. If there had been no roof the population exposure would have been 7.7×10^4 man rem, and the cost of removing a man rem by addition of the Bevatron roof was therefore roughly $40 per man rem over these ten years.* This figure should be compared with recent estimates of the monetary value of avoiding the detriment possibly associated with a population dose of one man rem which falls in the range $10-250 per man rem (ICRP 1973). The expenditure of $3M on roof shielding for the Bevatron is seen to have been reasonably cost-effective.

Any further addition of shielding would, however, pose great technical difficulties. A careful study of floor loading would be necessary because the existing shielding foundations are presently stressed to their limit. Limited space would require the use of high density shielding. It is unlikely that steel could be used to replace the existing ferrophosphate high density aggregate concrete shielding because of magnet perturbations on the particle orbit in the accelerator. It would therefore be necessary to use expensive

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*The more recent estimate of population dose would increase this estimate to $\approx$$100 per man rem.

and inconvenient materials such as stainless steel or uranium, and the high floor loadings resulting from the use of such high density materials would probably make the addition of shielding impossible. Even if the addition of shielding were technically feasible, the cost would be prohibitively expensive because extensive structural modifications to the accelerator would be required. An engineering design study to examine feasibility, and (if feasible) to prepare a cost estimate would alone cost about $50,000 (LOU 1973). In view of the increasing use of the Bevatron to accelerate heavy ions, with the concomitant decrease in external radiation levels for the next few years, even the cost of a design study does not seem warranted.

The addition of roof shielding to the Bevatron was an extremely cost-effective measure because of the long period during which the shielding has been installed. Shielding changes which operate for only a year or so are much less effective. An example would be the cost of reducing population exposure due to external beam operation at the Bevatron. Approximately 30% of the site boundary levels in 1973 were due to split beam operation. Preliminary studies showed that the strategic addition of 1-foot of steel to the existing roof shielding over the septum magnet in the beam channel at a cost of $25,000 might lead to a reduction in site boundary levels of no more than 25%. The population dose for 1973 was reported as <60 man rem. Had shielding been placed above the septum magnet the cost of removing 1 man rem would have been greater than $1600 and may have been higher than $4000 (see Section 6). The decision not to add shielding is seen to have been cost effective since the cost of removing a man rem would have been about an order of magnitude more than its detrimental value.

The addition of shielding to the 88-Inch Cyclotron during 1970 and 1971 (Section 5.2) provides an example of the addition of shielding which is projected to be cost effective. Adding shielded caves to the roof of the 88-Inch Cyclotron at a cost of $330 K evidently reduced radiation levels at the 88-Inch Cyclotron environmental monitoring station by more than 0.25 rem per year (see Fig. 6).

Because the maximum energy of neutrons produced by the 88-Inch Cyclotron is about 30 MeV and the average energy is considerably lower, the population dose per fence post rem due to this accelerator is lower than that calculated for the Bevatron by the factor $(250/850)^{2/3}$ (see Section 6). Older estimates of M would then give $\sim 650\ D_0$, while newer estimates, including all the mitigating factors discussed in Section 6, give $M \approx 250\ D_0$. If ten years of operation similar to that observed in 1972 is assumed, the cost of removing a man rem by the addition of shielding to the 88-Inch Cyclotron was then between $200 and $550 per man rem.

In retrospect it can be seen, from the examples given, that estimates of the cost of removing a man rem by the addition of shielding to high energy accelerators is in the range from ∿$15 and ∿$550 per man rem. In the past the decision to add shielding has largely been determined by the need to reduce radiation levels close to the accelerators or at the Laboratory's boundaries. Somewhat fortuitously this has led to the cost of removing a man rem which is comparable to the estimates of the detrimental cost of a man rem. Bearing in mind that the upper values of the detrimental cost of a man rem are almost certainly extremely conservative, the use of shielding at LBL seems to have been reasonably cost effective.

8. PERSONNEL DOSIMETRY DATA

It has long been established policy at LBL that all permanent staff and temporary visitors are issued a β-γ film badge. In addition, those personnel working at particle accelerators carry a neutron track film. Staff are encouraged to carry their dosimeters with them at all times--even when not at work. This policy provides a convenient monitor of the LBL radiation protection program and of any incidental radiation exposures that might be incurred off site.

Table 5 summarizes personal dosimetry data for visitors to and staff of the Lawrence Berkeley Laboratory over the period 1959-1973. During this period there has been a general trend toward lower exposures. This may be crudely seen in the percentage of people in the 0-1 rem annual dose equivalent group which has steadily increased from about 95% to more than 99% in these 24 years. Concurrently, there has been a steady decline of the percentage of people exposed in the 1-2 and 2-3 rem groups (from 4.7% to 0.2% and from 0.7% to 0.1% respectively) (See Fig. 18). In the dose groups above 3 rem the number of people exposed is so small that statistical fluctuations make any general conclusions difficult.

Maintenance of, or changes in, radioactive accelerator components is often the major cause of radiation exposure to personnel at accelerator laboratories. Figure 19 shows how the exposure to maintenance workers at Brookhaven 30 GeV Alternating Gradient Synchrotron has increased with the intensity of the accelerator. Operating experience at the 200 GeV proton sychrotron at Batavia has also shown an increase in the radiation exposures of maintenence crews with beam intensity.

In contrast, experience at LBL has not shown an overall increase in

Table 5. Personnel Dosimetry Data Lawrence Berkeley Laboratory

Period		# Monitored	# or Percentage of Accumulated Dose Equivalents in Range					
			rem					
			0-1	1-2	2-3	3-4	4-5	5-12
1959	#	2400	2264	112	17	1	0	0
	%	100	94.3	4.67	0.71	0.04	0	0.25
1960	#	2570	2681	48	12	2	1	6
	%	100	97.5	1.74	0.44	0.07	0.04	0.22
1961	#	3000	2918	64	10	3	2	3
	%	100	97.2	2.13	0.33	0.10	0.07	0.10
1962	#	3345	3299	35	11	0	0	0
	%	100	98.6	1.05	0.33	0	0	0
1963	#	3121	3081	31	7	2	0	0
	%	100	96.7	0.99	0.22	0.06	0	0
1964	#	3125	3080	82	19	2	2	0
	%	100	96.7	2.57	0.60	0.06	0.06	0
1965	#	3297	3207	72	13	3	1	1
	%	100	97.2	2.18	0.39	0.09	0.03	0.03
1966	#	3232	3144	68	14	3	2	1
	%	100	97.3	2.10	0.43	0.09	0.06	0.03
1967	#	3271	3237	25	9	0	0	0
	%	100	99.0	0.76	0.28	0	0	0
1968	#	3462	3401	51	6	0	0	0
	%	100	98.2	1.47	0.17	0.12	0	0
1969	#	4540	4458	66	13	3	0	0
	%	100	98.2	1.45	0.29	0.07	0	0
1970	#	4323	4231	71	11	5	5	0
	%	100	100	1.64	0.25	0.12	0.12	0
1971	#	4405	4358	35	12	0	0	0
	%	100	98.9	0.80	0.27	0	0	0
1972	#	4652	4612	25	11	4	0	0
	%	100	99.1	0.54	0.24	0.09	0	0
1973	#	4720	4703	11	4	2	0	0
	%	100	99.6	0.23	0.08	0.04	0	0

radiation exposures with increasing beam intensity of the Bevatron. Table 6 gives the collective exposure to personnel exposed to 1 rem or greater per year during the period 1959-1973 (Fig. 20). Exposures greater than 1 rem per year have been selected because exposures of this magnitude are carefully controlled and are deliberately incurred only when the need is well demonstrated. Table 5 shows that the number of people in this group is quite small, declining from 47 in 1971 to 17 in 1973. During this period approximately 2/3 of this group were accelerator operators or involved in accelerator maintenance--the remaining 1/3 was composed of radiation monitors or health physicists.

The collective exposure to personnel in the >1 rem category is approximately 1/3 of the total collective exposure to monitored personnel--Table 7.

Estimates of collective exposure are very sensitive to the dose distribution, which at LBL is falling steeply with increasing dose equivalent. Figure 21 shows the distribution for 1972 but the data of other years is very similar. Investigation of the distribution in the region 0-0.1 rem shows it to be still falling steeply (Stephens 1974). In 1972 70% of personnel issued a dosimeter received less than 10 millirem, 90% less than 100 millirem and 99% less than 1 rem. The percentage of people who received less than a given dose equivalent is shown in the upper curve (A) in Fig. 22. Curve (B) of Fig. 22 shows the percentage of the total collective exposure to personnel issued a dosimeter that is contributed by doses less than a given value. In 1972, 7% of the collective dose was due to exposures less than 10 millirem, 22% due to exposures less than 100 millirem, and 65% due to exposures less than 1 rem. Such data are helpful in determining any areas where improvement may be required in a radiation protection program.

Table 6. Man Rem from Exposures Greater than one Rem.*

Year	Man Rem Resulting from Dose Equivalents >1 Rem
1959	256
1960	162
1961	160
1962	80
1963	71
1964	186
1965	161
1966	162
1967	60
1968	106
1969	142
1970	174
1971	82
1972	79
1973	34

*In estimating the Man Rem, M, in Table 6 the midrange approximation has been used i.e.

$$M = 1/2 \sum_{i=1}^{5} N_i \, (D_{i+1} + D_i)$$

Footnote:

With a steeply falling dose distribution, man rem estimates made using a mid-range approximation maybe seriously in error. Table 7 shows the error of this assumption produced in the LBL 1972 personal dosimetry data. The error is greatest in the range 0-1 rem. Beyond 1 rem the approximation is quite accurate.

Table 7

1972 Man Rem Extimates
Lawrence Berkeley Laboratory
Personnel and Visitors

Dose Equivalent Range (rem)	Mid-Range Approximation	Actual
0 - 1	2306	146.2
1 - 2	37.5	34.9
2 - 3	27.5	27.6
3 - 4	14	14.1
0 - 4	2385	222.8*

Actual Man Rem	223 Man Rem
Assuming error + 10 millirem	198 Man Rem
Assuming error + 20 millirem	191 Man Rem
Population Dose Reported for 1972	103 Man Rem

If one is only concerned with mere bookkeeping reductions in collective exposure, it is often easier to remove the contribution from very small exposures. One could, for example, refine the accuracy of measurements of very low doses. Man rem estimates may also be in error if there is a systematic error in personal dosimetry records. For technical reasons there is inevitably an overestimate of about 10-20 millirem/year in the LBL dosimetry service. A systematic overreading of 10 millirem/year would lead to an overestimate of about 10% in collective dose, while a systematic overreading of 20 millirem/year would lead to an overestimate of about 14% (see Table 7). These exposures are very small.

Radiation exposures which are comparable in magnitude to fluctuations in natural background should be regarded as inconsequential. Such exposures contribute 10-20% of the collective exposures at LBL.

It is more profitable to examine the high exposure group. We have already seen that roughly 1/3 of the collective exposure is due to people exposed to more than 1 rem/year. This group largely consists of accelerator operators, maintenance crew and radiation monitors. Such personnel are routinely exposed to radiation as part of their work. Continuing review of work habits and procedures of personnel in this group is vital if radiation exposures are to be maintained at levels as low as practicable.

9. SUMMARY AND CONCLUSIONS

In any study to determine whether radiation levels are as low as practicable it is first necessary to quantify the degree of radiation exposure. This implies an understanding of the nature of the radiation environment produced by high-energy accelerators, how it is measured and

interpreted in terms of dose equivalent, and how it is propagated and transported through shielding and the atmosphere. Such studies are a vital part of the work of the Health Physics Department.

The environmental impact of accelerator operation at LBL is dominated by the production of neutrons. The close proximity of a large population around the Laboratory's borders led to an early interest in environmental monitoring of penetrating radiation. Radiation levels at the LBL site boundaries have steadily decreased over the past 14 years, despite steadily increasing intensities at our accelerators. In 1973 the Bevatron, when it accelerated protons, contributed about 80% of the maximum dose equivalent observed at the Laboratory's site boundary of 28 millirem/year (Wallace 1974).

The declining site boundary radiation levels has in part been achieved by addition of shielding--particularly to the Bevatron and 88-inch cyclotron roofs. In retrospect the cost of removing radiation exposures has been in the range $40 to $550 per man rem. This is judged to be a cost effective use of shielding since the monetary value of detrimental effects of a man rem have been estimated to be in the range $10 to $250. Examples of additional shielding judged to be too expensive by these criteria are given. The physical limitations imposed by floor loading to the addition of shielding to the Bevatron roof and external proton beams make further improvements in radiation levels by the mere addition of shielding unlikely.

The environmental monitoring system will report the maximum dose equivalent at the Laboratory's boundary as <15 millirem for 1974 (Stephens 1974d), with a corresponding population dose of <13 man rem. (To be compared with a population dose of approximately 33,000 man rem to the

population at risk from natural causes). This would suggest that the sum of money that might prudently be spent in eliminating population exposure at LBL might be $3,500 or less.

Personal dosimeters indicate a small but gratifying decline in the collective radiation exposures to Laboratory personnel and visitors. In 1973 the collective exposure was approximately 100 man rem of which a third was due to exposures obtained by personnel exposed to more than 1 rem. Roughly 20 man rem was due to trivial exposure (i.e., < ∿50 millirem). Examination of working habits and procedures indicate little room for massive reductions in the collective dose to radiation workers.

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APPENDIX I

Influence of Hills on the Radiation Level

The environmental monitoring stations situated at the Olympus Gate, Building 90, and the 88-Inch Cyclotron are all approximately 400 meters from the Bevatron. Only the first of these stations is in direct view of the Bevatron. Table A1 summarizes average flux densities measured at these three stations during a period in which only the Bevatron was operating (McCaslin 1974).

Table A1

Environmental Station	Distance from Bevatron (meters)	Observed average neutron flux density* ($n\ cm^{-2}\ sec^{-1}$)	Flux Density Normalized to 435 meters ($n\ cm^{-2}\ sec^{-1}$)
Olympus Gate	435	0.106	0.106
Building 90	421	0.063	0.058
88-Inch Cyclotron	385	0.080	0.059

*Normalized to an external proton beam intensity of 10^{12} ppp.

Column 4 shows the flux densities that would have been observed if all stations had been 435 meters from the Bevatron, assuming the flux density to vary with distance as:

$$\phi(r) \approx e^{-r/\lambda}/r^2$$

with λ taken to be 850 meters.

This rough measurement tends to suggest that radiation levels are depressed by the shadowing effect of hills, and that the magnitude of this reduction might be as much as a factor of two.

APPENDIX II

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FIGURE CAPTIONS

Fig. 1. Comparison between the increasing intensity of the Bevatron (Right Hand Scale) and the decreasing radiation levels of the Laboratory's site boundary and decreasing radiation worker collective exposure since 1959 (Left Hand Scale).

Fig. 2. Map of the San Francisco Bay Area Showing the location of the Lawrence Berkeley Laboratory.

Fig. 3. A general view of the eastern region of Berkeley with Lawrence Berkeley Laboratory lying on the side of the Berkeley hills.

Fig. 4. A view of the Lawrence Berkeley Laboratory showing the location of the environmental monitoring stations.

Fig. 5. Annual dose equivalent at the Olympus Gate Environmental Monitoring Station.

Fig. 6. Annual dose equivalent at the 88-Inch Cyclotron Environmental Monitoring Station.

Fig. 7. Annual dose equivalent at the Panoramic Way Environmental Monitoring Station.

Fig. 8. Annual dose equivalent at the Building 90 Environmental Monitoring Station.

Fig. 9. Comparison of exposure rates calculated from a climatic exposure model (solid lines) with monthly TLD measurements at residences near New York City (from Burke 1974).

Fig. 10. Comparison of calculated exposure rates with those measured in the field. (After Wollenberg and Smith).

Fig. 11. Intercomparison of neutron flux densities measured as a function of distance around several high energy accelerators. The parameter $4\pi r^2\ \phi(r)/Q$ is plotted as function of distance r where $\phi(r)$ is the measured flux density (n cm^{-2} sec^{-1}) and Q is the estimated source strength of neutrons leaking into the atmosphere (n sec^{-1}).

Fig. 12. Topographical profile in the direction 12°E from the Lawrence Berkeley Laboratory.

Fig. 13. Topographical profile in the direction due West from the Lawrence Berkeley Laboratory.

Fig. 14. Topographical profile in the direction N 33° W from the Lawrence Berkeley Laboratory.

Fig. 15. View of Bevatron roof shielding under construction.

Fig. 16. View of Bevatron roof shielding under construction.

Fig. 17. View of completed roof shield.

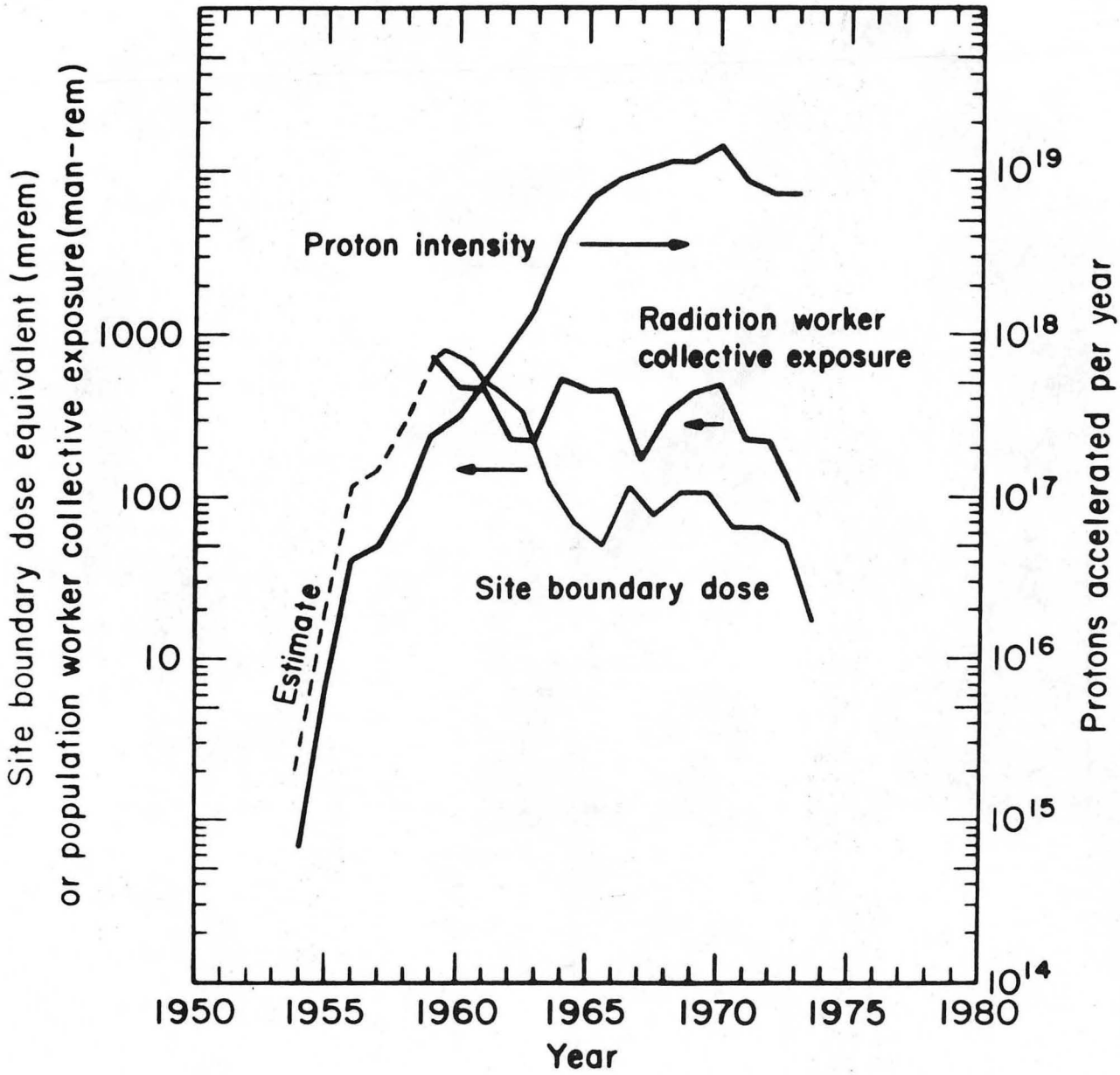
Fig. 18. Summary of personal dosimetry data, 1959-1973.

Fig. 19. Correlation between personnel exposures at the beam intensity of the Brookhaven National Laboratory 30 GeV proton synchrotron.

Fig. 20. Collective exposure to radiation workers at LBL exposed to >1 rem/year during the period 1959-1973.

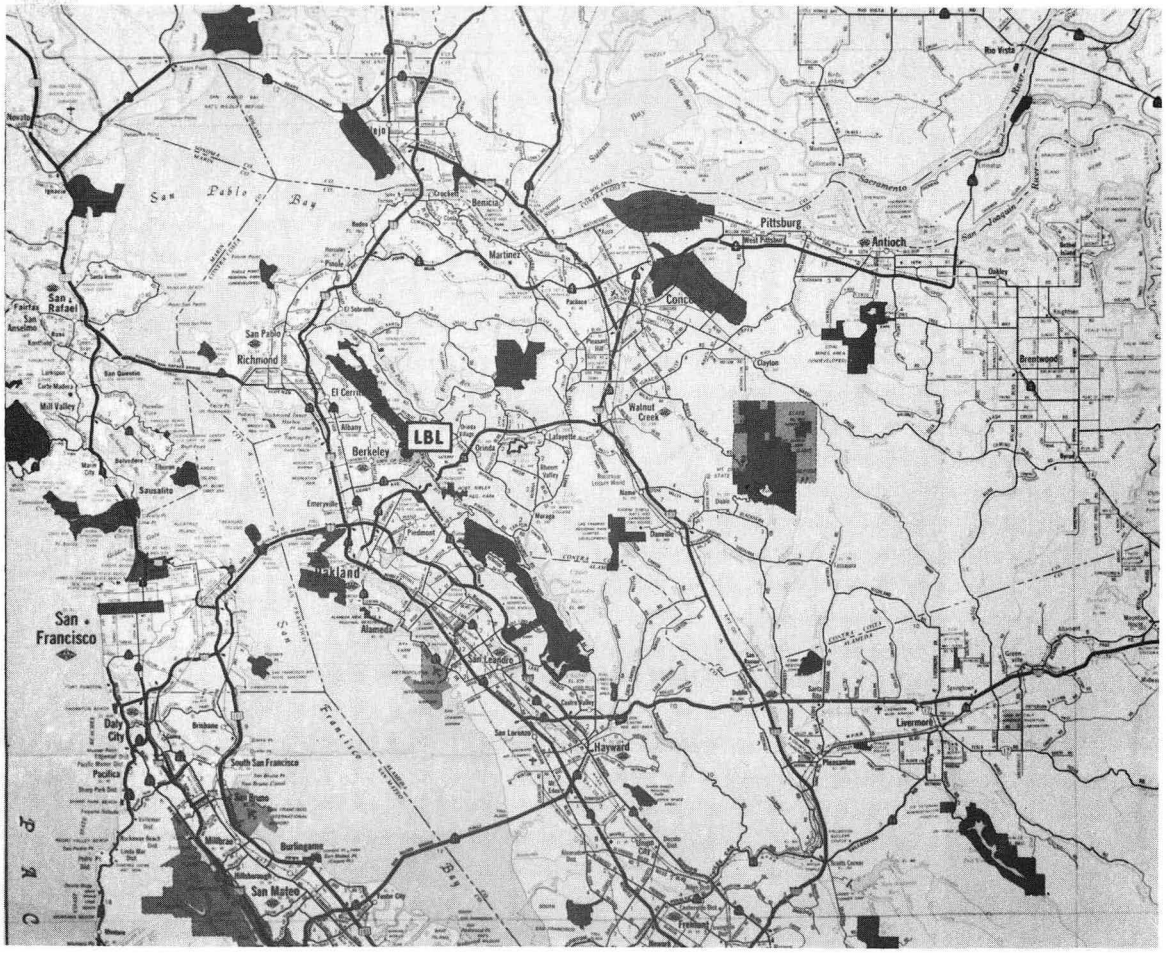
Fig. 21. Distribution of dose equivalents recorded by personal dosimeters at LBL - 1972.

Fig. 22. Percentage of LBL personnel exposed to less than a given dose equivalent (curve A) and the percentage of total radiation workers collective exposure contributed by dose equivalents less than a given dose equivalent (curve B).



CBB 752-1175

Fig. 1



XBC 749-6205

Fig. 2

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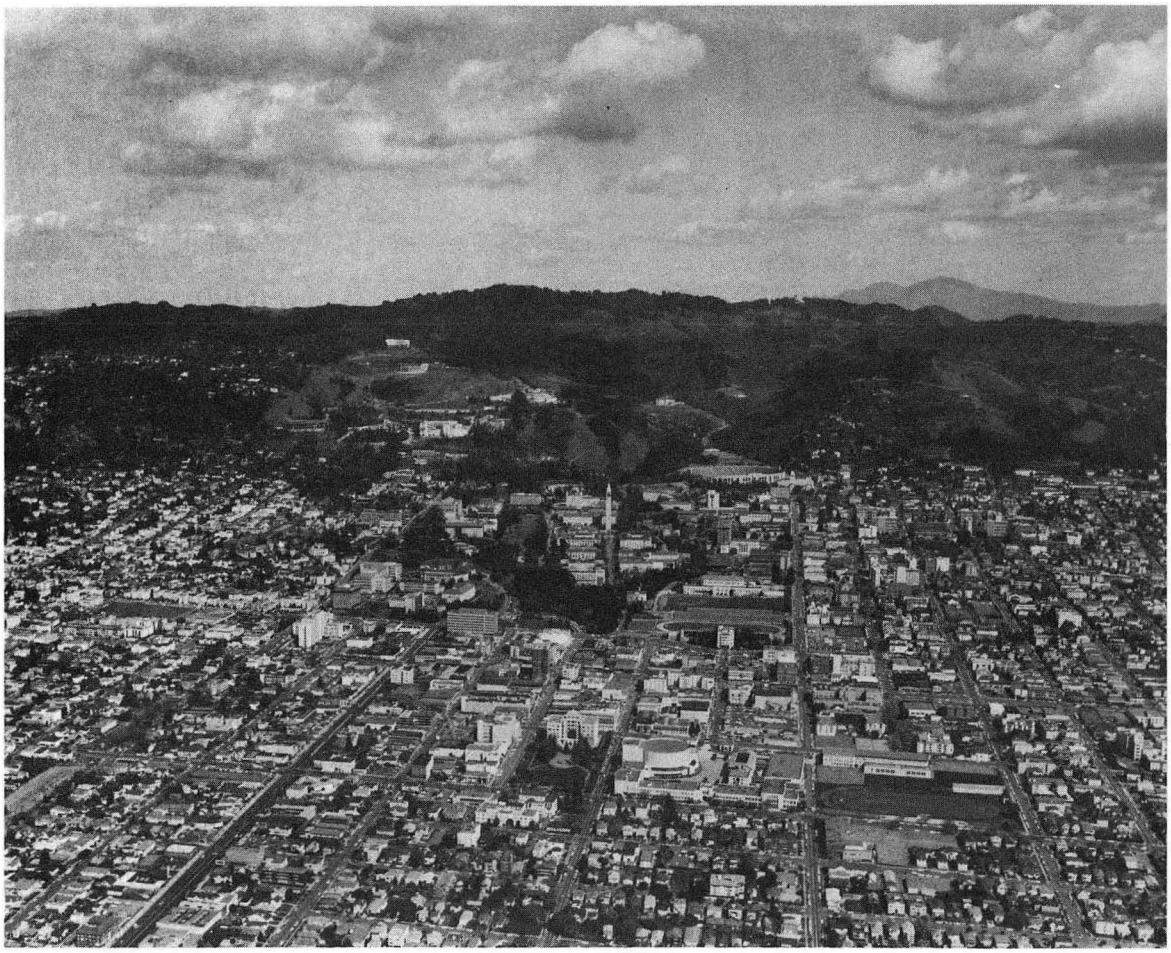
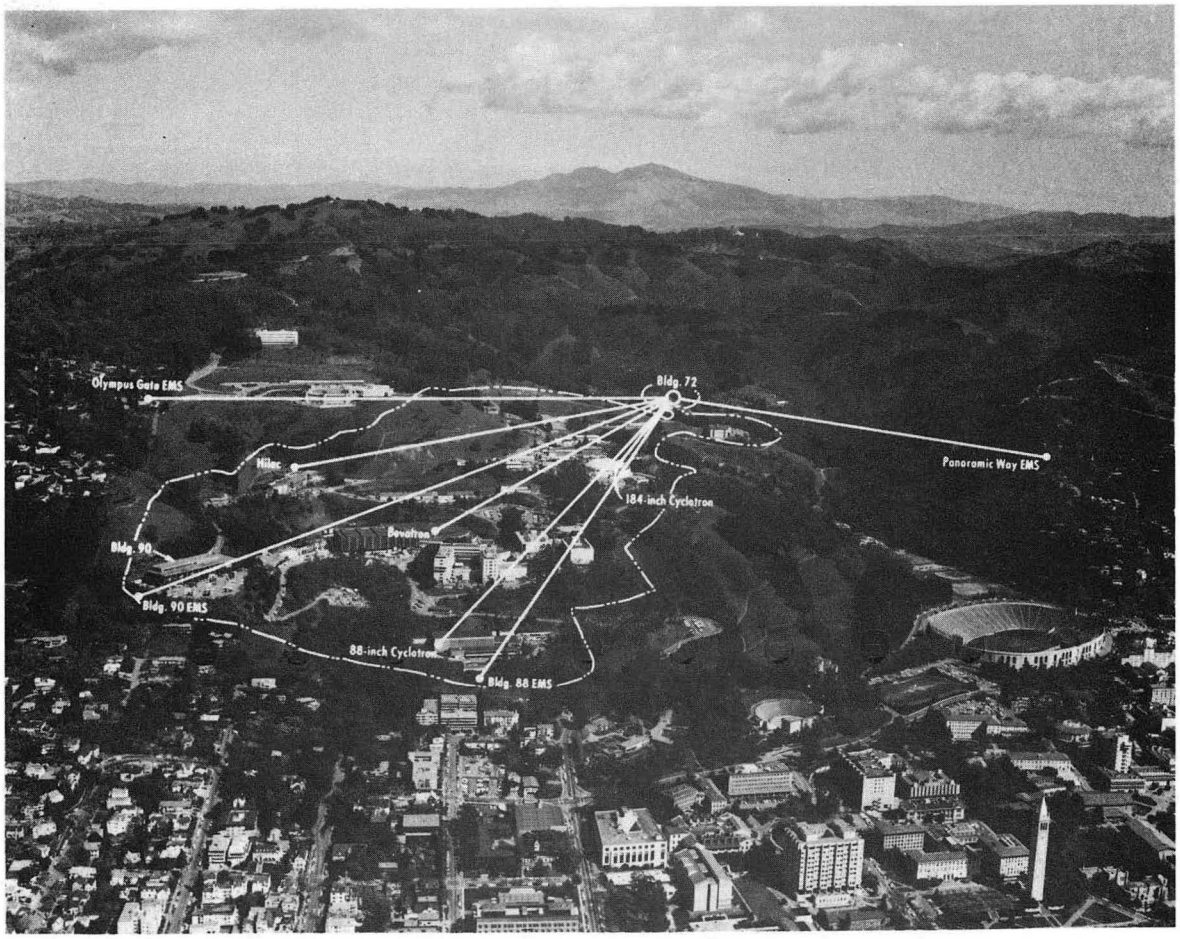


XBB 673-1730

Fig. 3



XBB 733-1830

Fig. 4

Fig. 5

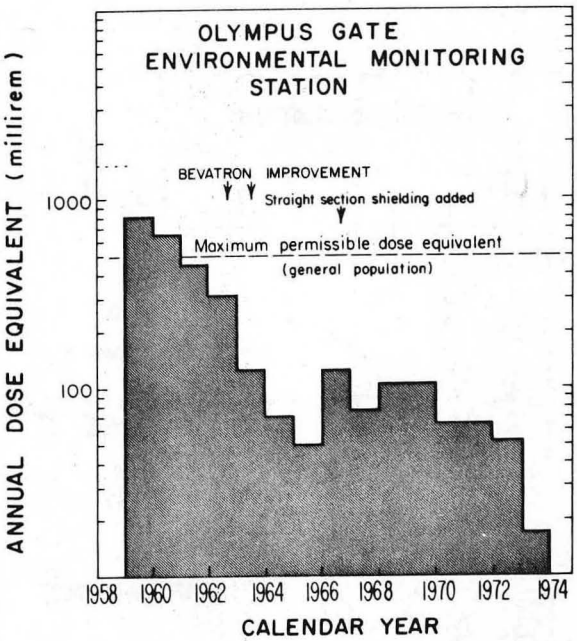
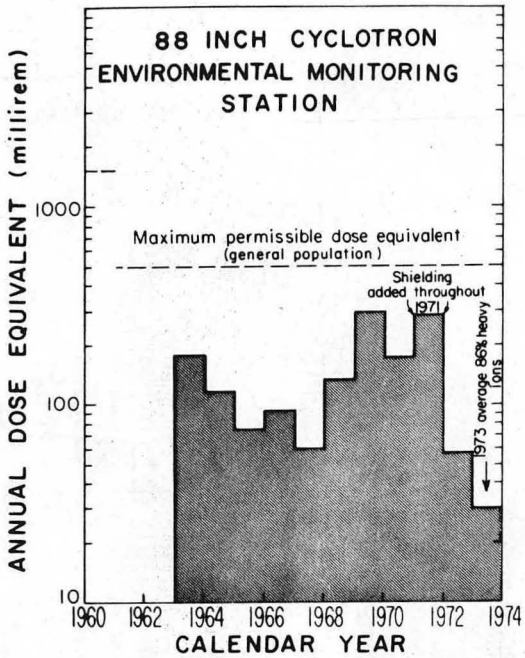
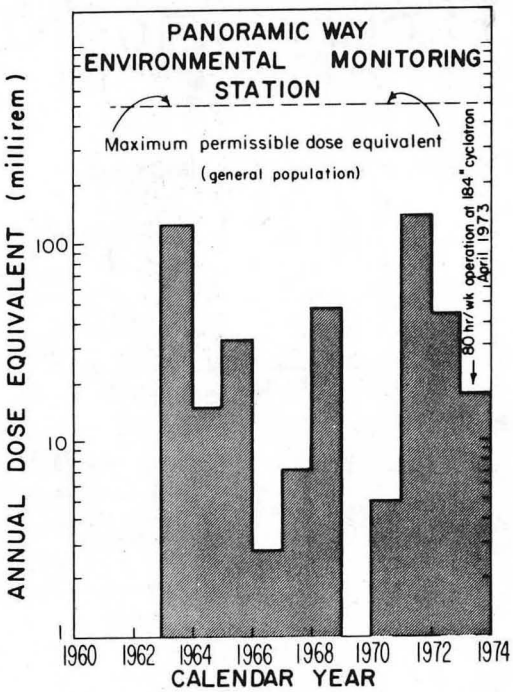
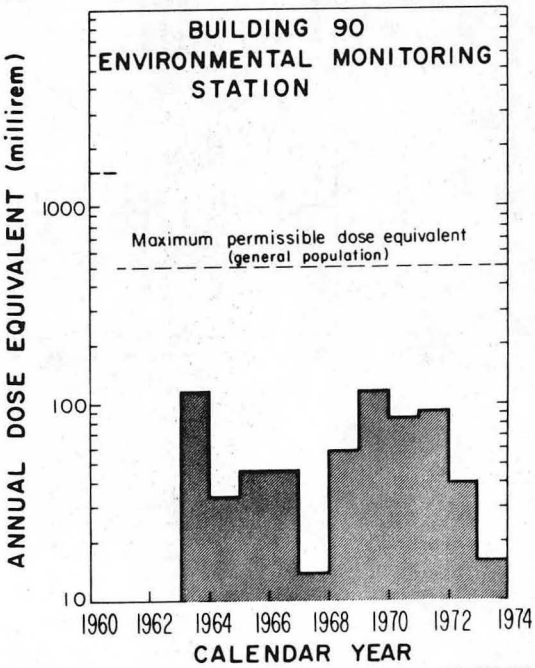


Fig. 6



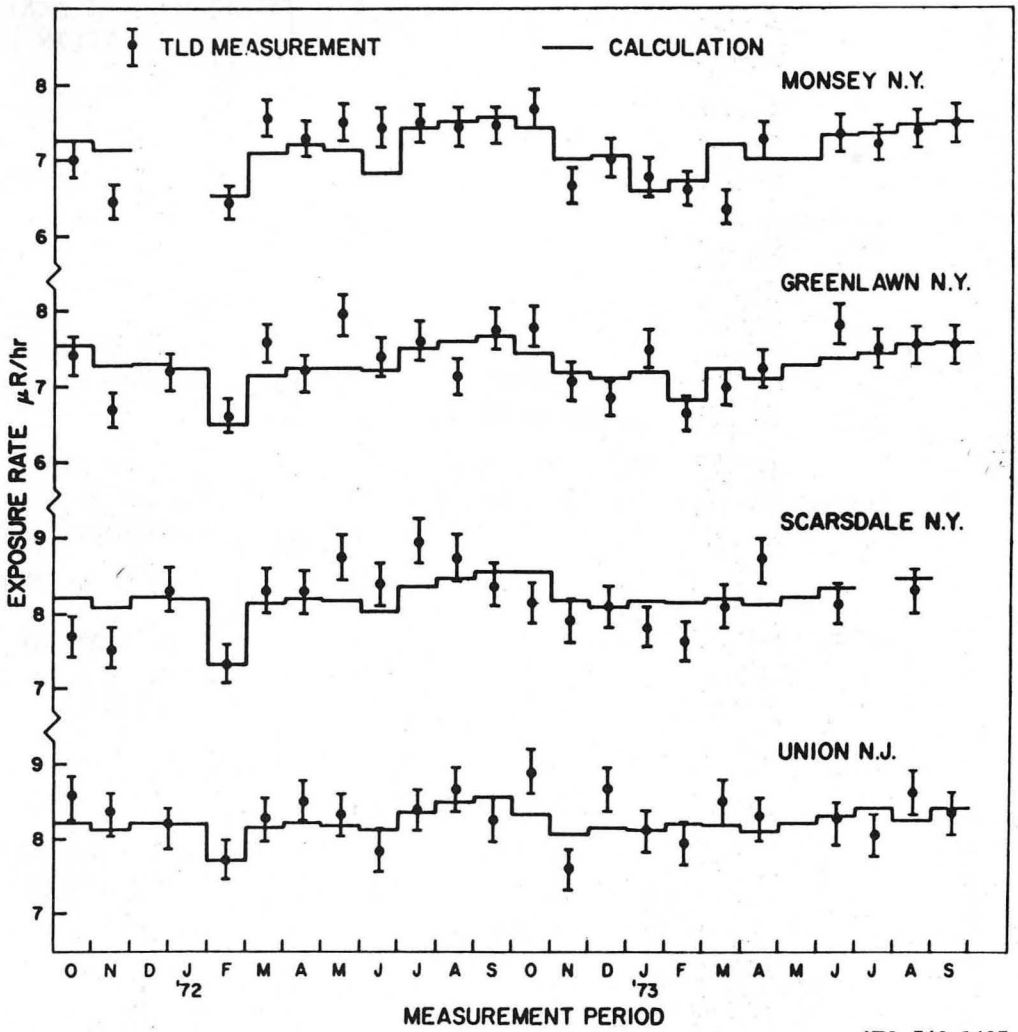




XBL 752-187

Fig. 7

Fig. 8

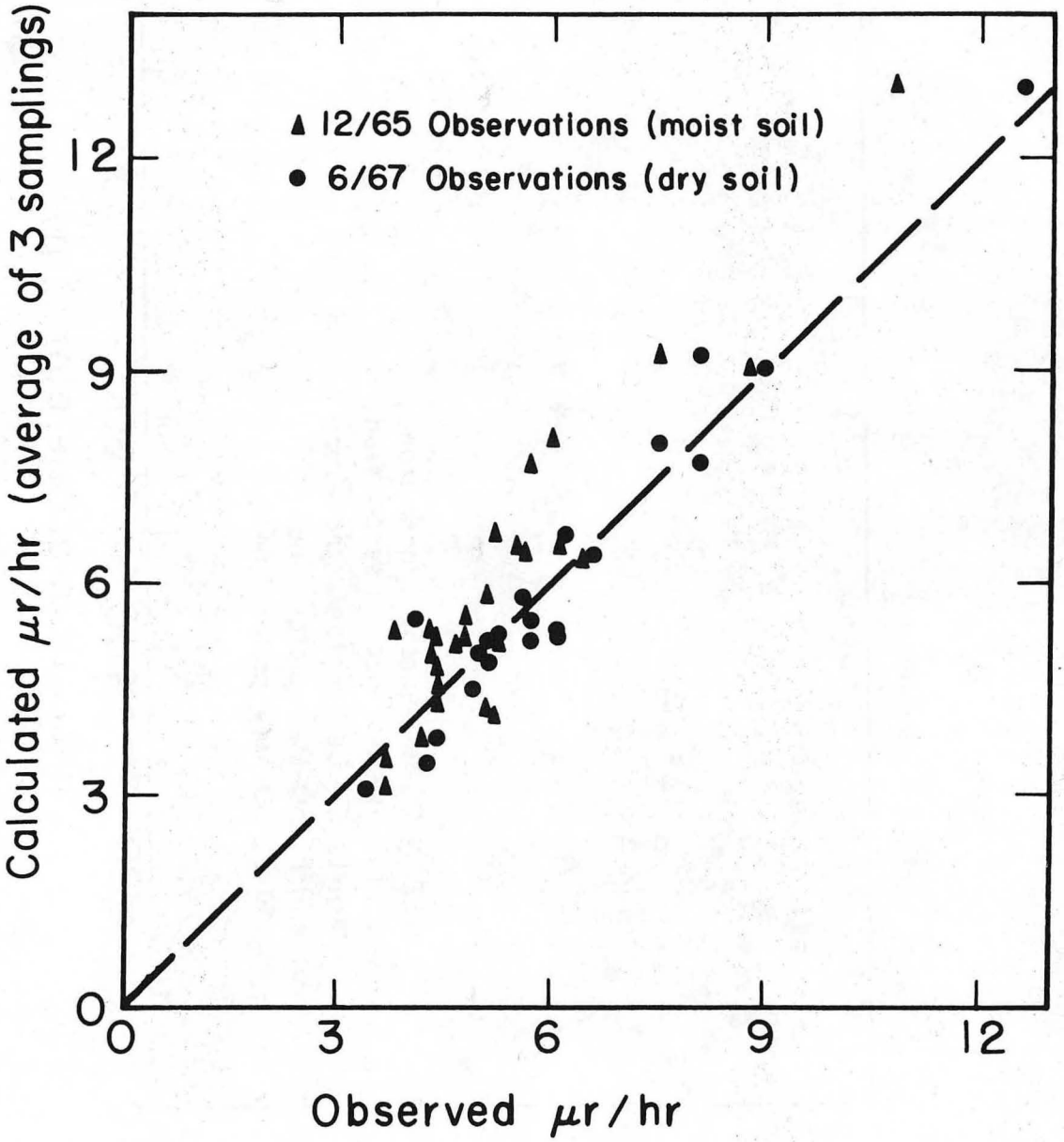


XBL 749-1487

Comparison of exposure rates determined by a climatic-exposure model (Equation 1) with monthly TLD measurements at residences near New York City.

Fig. 9

0 0 0 0 4 3 0 0 2 0 8



XBL689-6792

Fig. 10

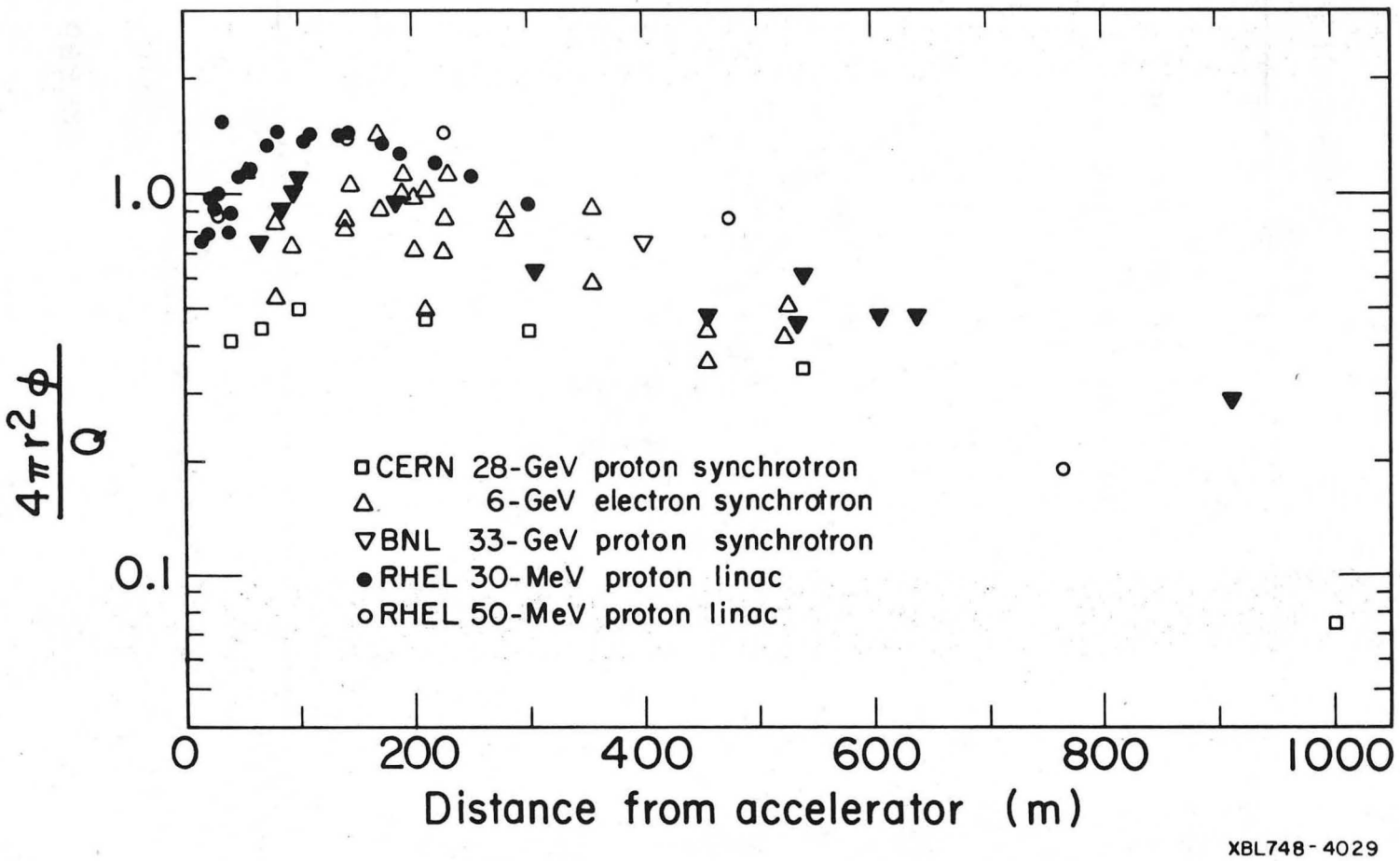

1.0
0.1
$\frac{4\pi r^2 \phi}{Q}$
CERN 28-GeV proton synchrotron
6-GeV electron synchrotron
BNL 33-GeV proton synchrotron
RHEL 30-MeV proton linac
RHEL 50-MeV proton linac
0
200
400
600
800
1000
Distance from accelerator (m)
XBL748-4029

Fig. 11

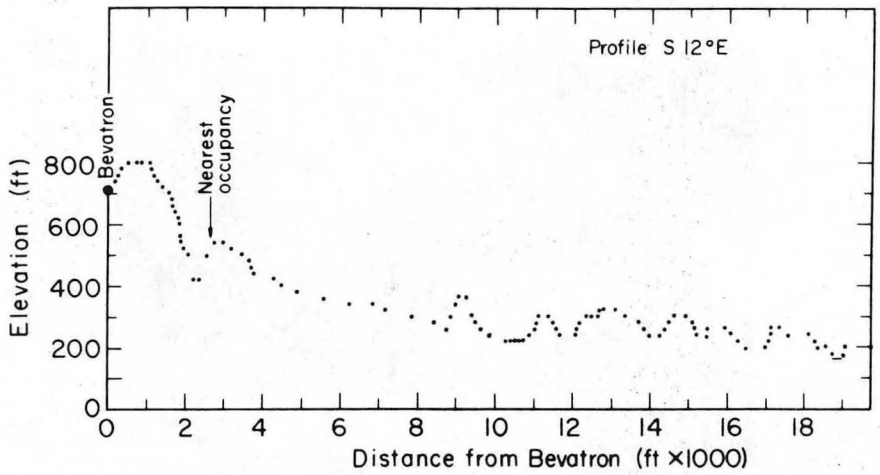


Fig. 12

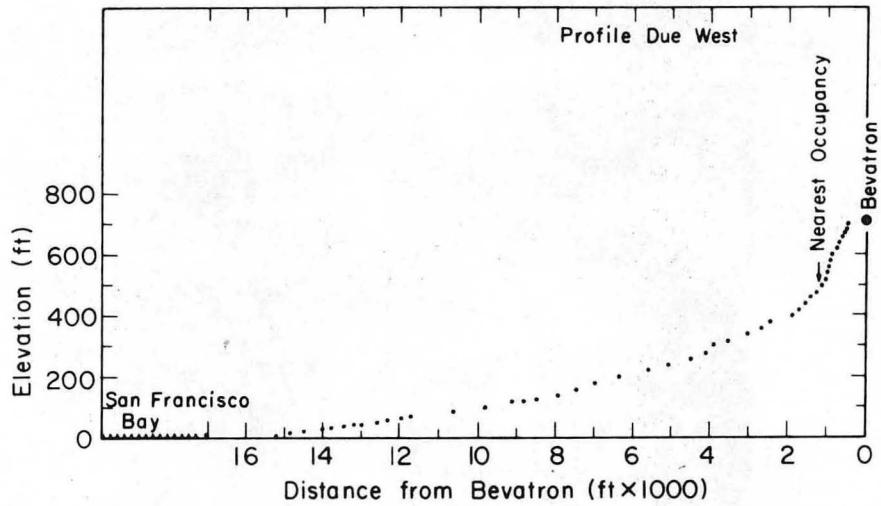


Fig. 13

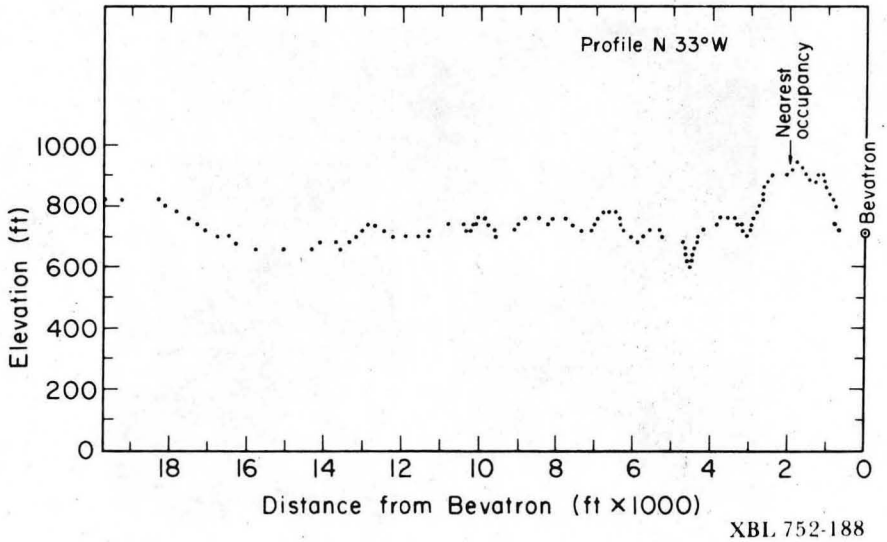


Fig. 14

XBL 752-188

Fig. 15

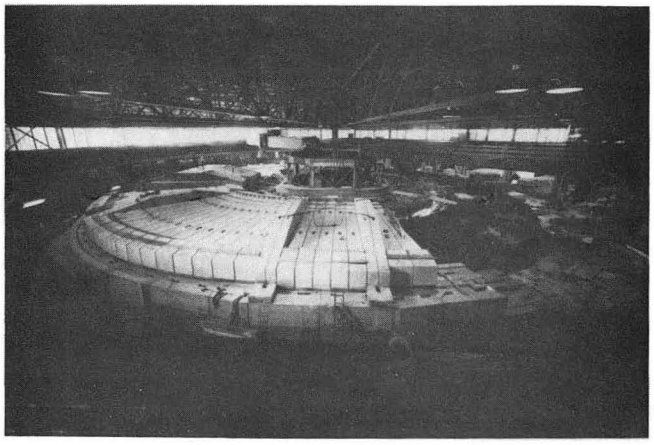


Fig. 16

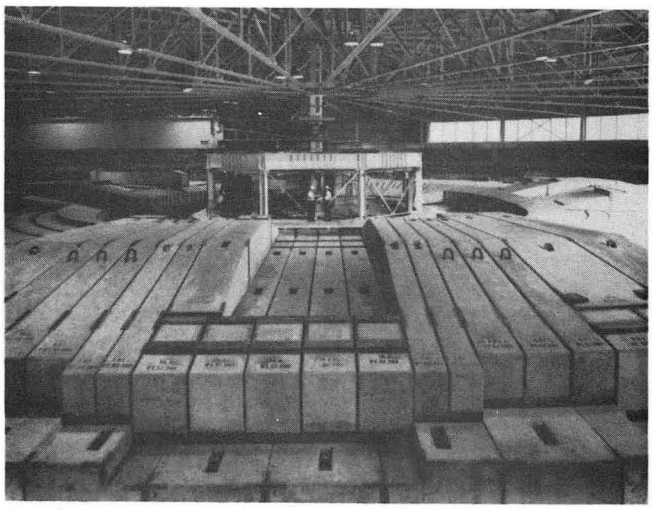


Fig. 17

XBB 752-1282

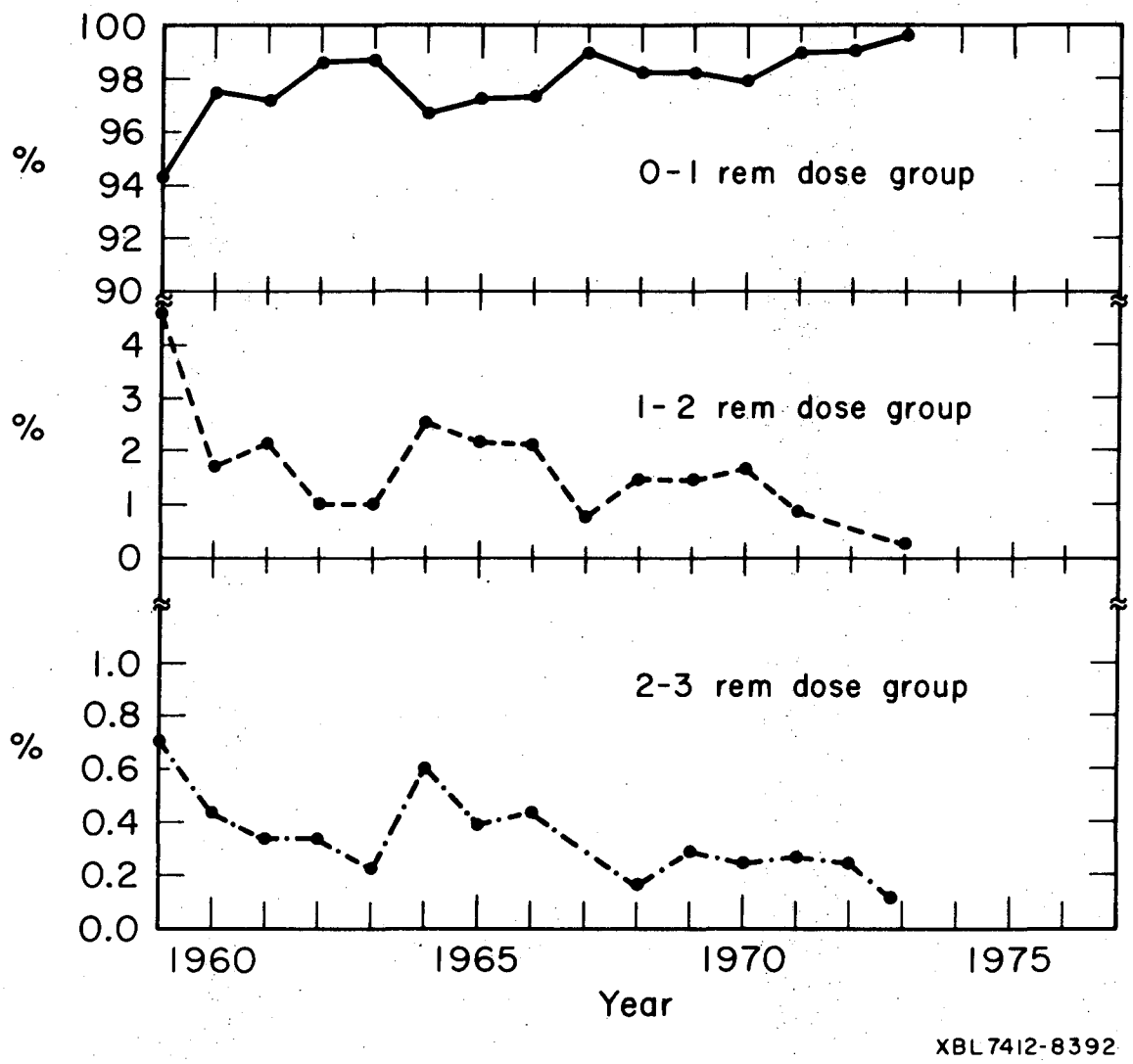

100
98
96
94
92
90
%
0-1 rem dose group
4
3
2
1
0
%
1-2 rem dose group
1.0
0.8
0.6
0.4
0.2
0.0
%
2-3 rem dose group
1960
1965
1970
1975
Year
XBL7412-8392

Fig. 18

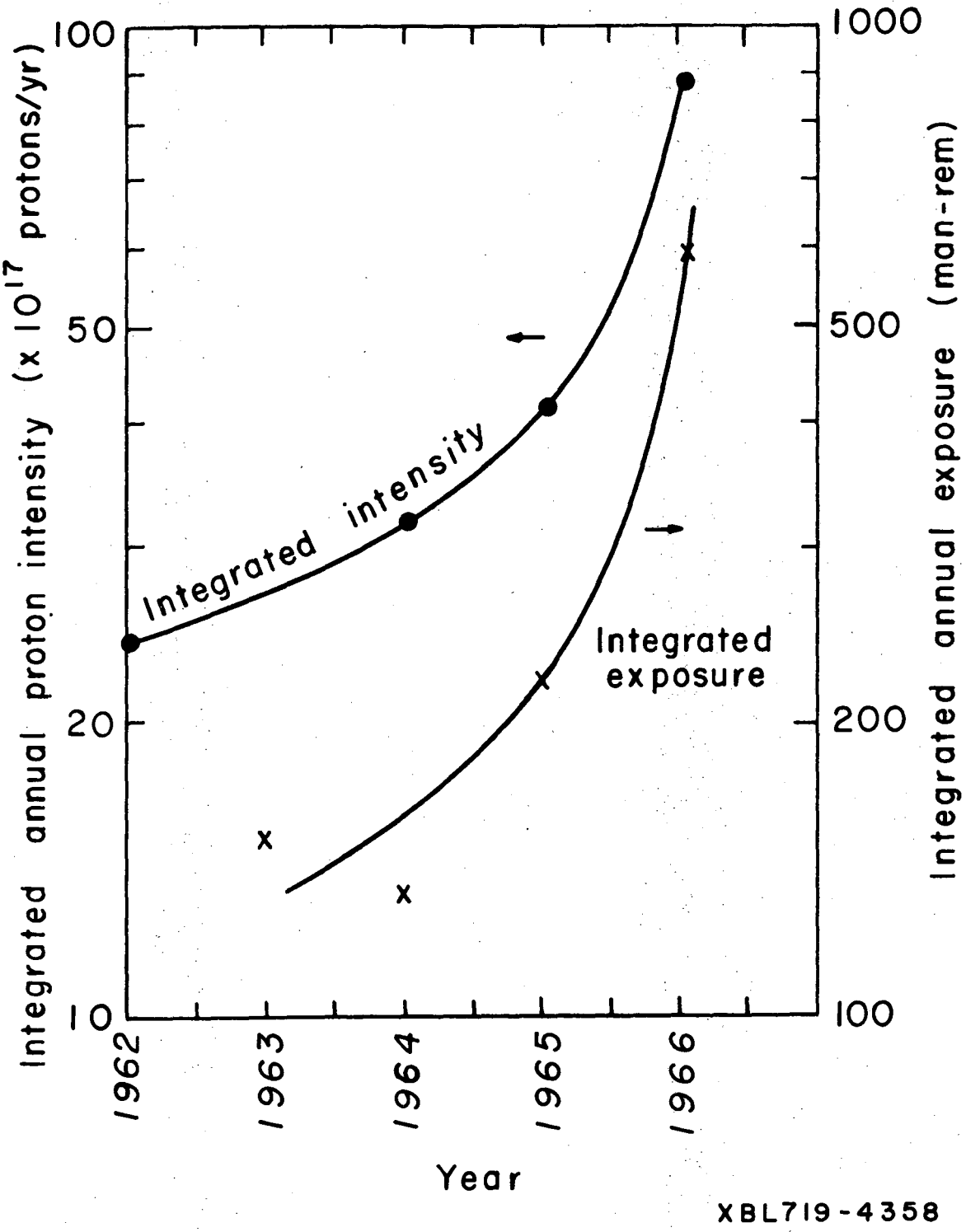

Integrated annual proton intensity (x 10^17 protons/yr)
100
50
20
10
1000
500
200
100
Integrated annual exposure (man-rem)
Integrated intensity
Integrated exposure
1962
1963
1964
1965
1966
Year
XBL719-4358

Fig. 19

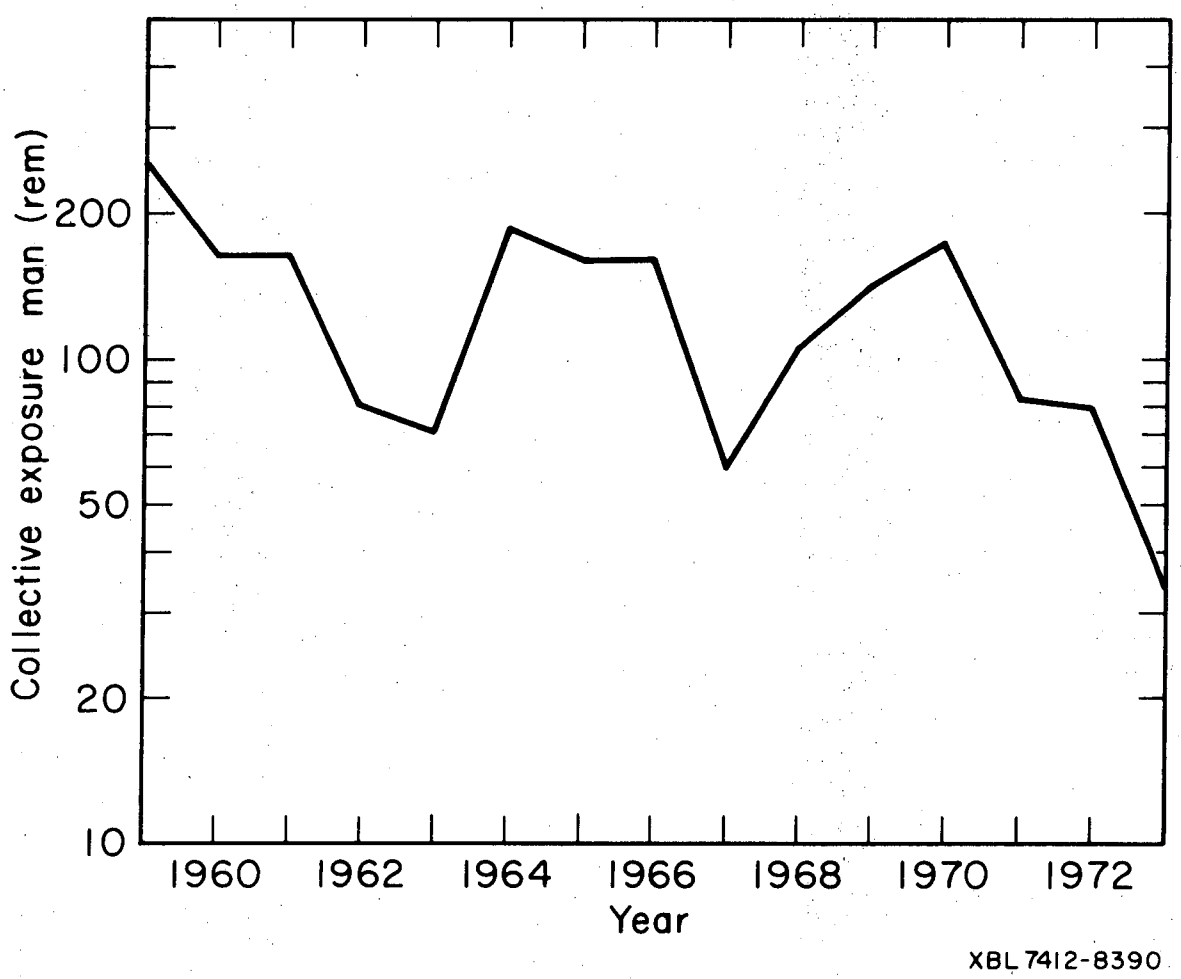

Collective exposure man (rem)
200
100
50
20
10
1960
1962
1964
1966
1968
1970
1972
Year
XBL 7412-8390

Fig. 20

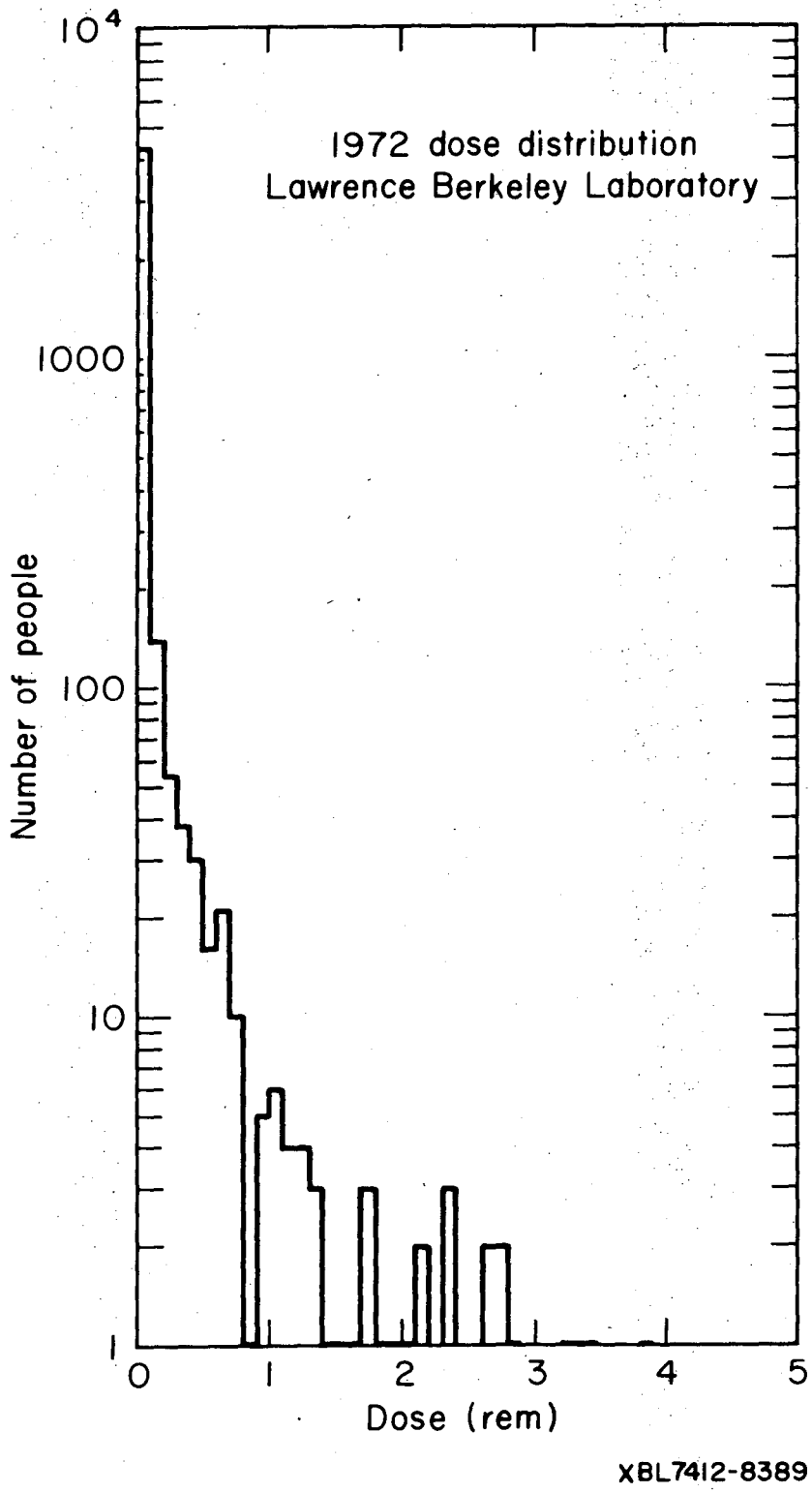

1972 dose distribution
Lawrence Berkeley Laboratory
Number of people
10^4
1000
100
10
1
0
1
2
3
4
5
Dose (rem)
XBL7412-8389

Fig. 21

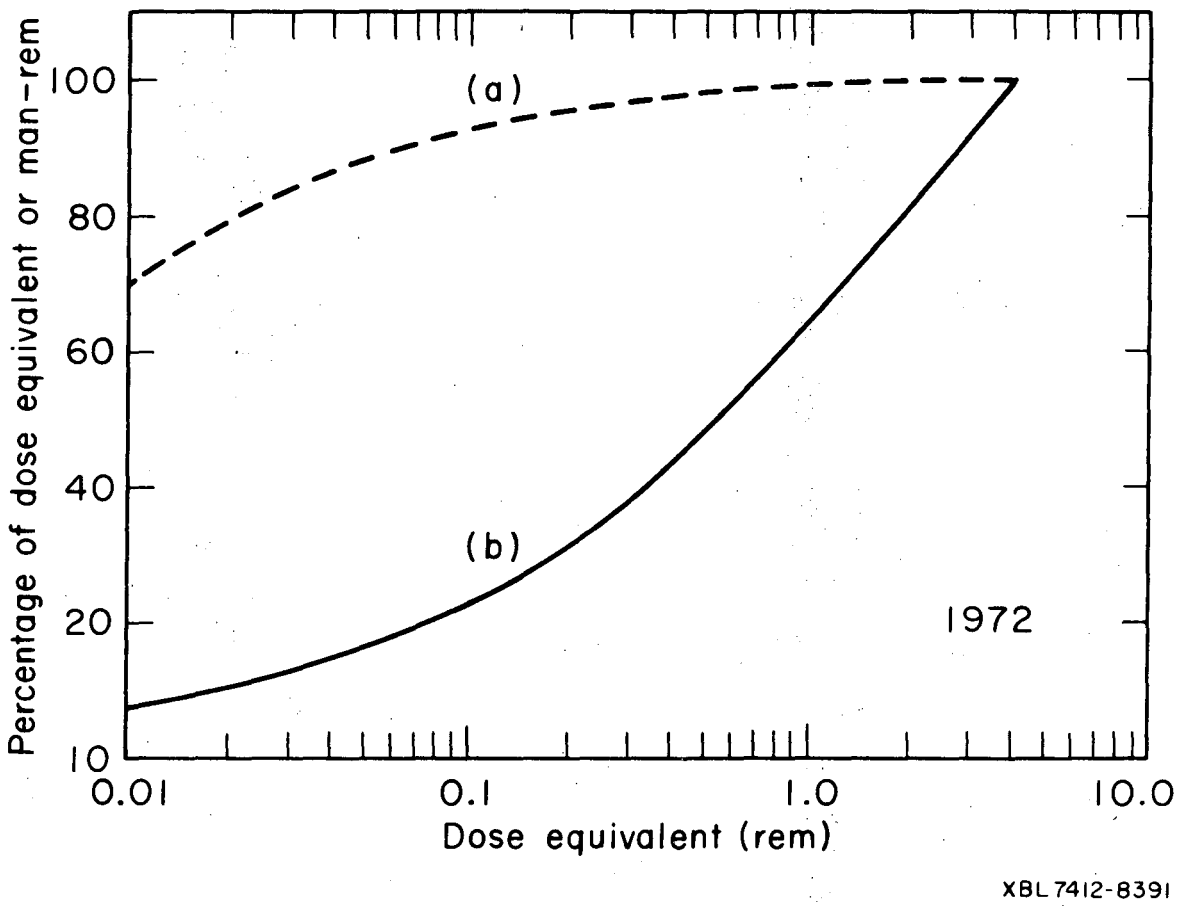

Percentage of dose equivalent or man-rem
100
80
60
40
20
10
(a)
(b)
1972
0.01
0.1
1.0
10.0
Dose equivalent (rem)
XBL 7412-8391

Fig. 22

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