Submitted to Health Physics

LBL-3604 Rev.
Preprint c.1

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

Ralph H. Thomas

August 1975

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48

LBL-3604 Rev.

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

Ralph H. Thomas

Health Physics Department
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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 surrounding population, is reviewed. The radiation environments and the environmental impact of the four particle accelerators are discussed. 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. The collective dose to personnel involved in accelerator operations and maintenance has shown a small decline.

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 $85 per man-rem. For the 88-inch cyclotoron, projections over 10 years estimate the cost of the provision of additional roof shielding to be between $200 and $450 per man-rem.

---

*An abbreviated version of Lawrence Berkeley Laboratory Report LBL-3604.

"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.

INTRODUCTION

The principle that radiation exposures should be maintained as low as practicable is not new. It has underlain the responsible practice of health physics at research laboratories, in hospitals, and in industry for many years. Taylor (1971), in his history of radiation protection standards, places the first discussions of the "as low as practicable" principle within the National Committee on Radiation Protection (NCRP) as early as 1949. The evolution of the principle can be traced in the publications of the International Commission of Radiological Protection (ICRP) (ICRP, 1955, 1959, 1966a), which has recently discussed the principle extensively and given some guidelines for its practical implementation (ICRP, 1973a).

In determining radiation levels that are as low as practicable, the ICRP has become 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. Recently several papers have appeared in the literature discussing the sechniques of "risk-benefit analysis," (COHEN, 1970, 1971; DUNSTER, 1970, 1973; HEDGRAN and LINDELL, 1970; OTWAL _et al._, 1970; LEDERBERG, 1971; SAGAN, 1972). These studies now make it partly possible to examine radiation safety programs for cost effectiveness.

In this paper we describe the last 25 years at the Lawrence Berkeley Laboratory at which this principle has been endorsed and applied. Although a decrease in environmental radiation levels concurrent with an increasing potential source of radiation does not, of itself, necessarily prove that radiation levels are "as low as practicable," such an ongoing record is achieved only by continuous efforts to minimize radiation levels.

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 and 800 ft above sea level. The Laboratory, as shown in Fig. 1, is bounded on the north and south by densely populated residential areas of Berkeley and Oakland; the major part of the Berkeley Campus of the University of California lies to the west. To the east, on the hills above, are the Lawrence Hall of Science, the Space Sciences Laboratory, uninhabited land, and Tilden Regional Park.

THE PARTICLE ACCELERATORS AT LBL

Radiation to which the general population surrounding LBL and Laboratory personnel are exposed comes from the operation of the four particle accelerators: The Bevatron, a 6-GeV proton synchrotron that has been operating since 1954; the SuperHILAC, a heavy-ion linear accelerator, producing heavy-ion beams up to 8 MeV/amu in energy; the 184-Inch Synchrocyclotron, and the 88-Inch Cyclotron. Because these accelerators are used in research, they present many new and novel radiation problems -- their radiation environments are themselves a subject of some research. Such studies have always formed an integral part of accelerator development at LBL (FREYTAG, 1972, PATTERSON and THOMAS, 1973, ZAITSEV et al., 1971).

The simultaneous operation of four particle accelerators leads to a complex variation of radiation intensity, compounded by the flexibility in modes of accelerator operation demanded by a research program. Different experiments may require radiation intensities which vary by several orders of magnitude.

THE ENVIRONMENTAL MONITORING SYSTEM

Radiation intensities within the Laboratory were extensively measured when it became apparent that the Bevatron was an intense neutron source (PATTERSON, 1962). These studies led to the establishment of a permanent environmental monitoring program.

Since 1964, radiation levels at ten locations (Fig. 1) have been continuously monitored, and are now recorded at a central location by means of a telemetry system. Both the rate and time-integrated intensity of radiation exposure are monitored (STEPHENS and DAKIN, 1972). These locations were strategically selected close to each accelerator and at the Laboratory perimeter. Two stations (at Olympus Gate and adjacent to the 88-Inch Cyclotron) are specifically located to record the highest radiation levels at the Laboratory boundaries. The Olympus Gate station is in direct view of the Bevatron, and its recorded radiation levels most directly relate to conditions at that accelerator. The monitoring station adjacent to the 88-Inch Cyclotron responds to radiation from both that accelerator and the Bevatron. The stations 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 Synchrocyclotron. It is possible to estimate the relative contribution from each accelerator by noting the change in radiation levels during shutdown periods of the different accelerators.

SOURCES OF PENETRATING RADIATION

The sources of penetrating radiation due to LBL operation have recently been analyzed (STEPHENS and THOMAS, 1974). During 1972 roughly 80% of accelerator-produced radiation was from the Bevatron when it accelerated high-energy protons. Of that Bevatron-produced radiation, approximately one-half came from roof leakage when protons strike components of the beam extraction system, and the balance was due to the operation of external proton beams -- with about 75% being due to one particular mode of split beam operation (Table 1). It is clear that in 1973 the greatest potential reductions in radiation levels at site boundaries could have resulted from shielding modifications to, or changes in operation of the Bevatron.

MONITORING THE RADIATION LEVELS

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 LBL 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. Figures 2 and 3 show the annual dose equivalent reported for the four environmental stations as a function of time.

The Bevatron, operating since 1954, has had substantial changes in accelerator intensity, mode of operation, and shielding. Figure 4 shows the number of protons accelerated in the Bevatron each year in the period 1954 - 1973 (HARTSOUGH and LOTHROP, 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. Since 1969, the 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.

Radiation levels at the Olympus Gate Station have shown an overall decline since 1959 when estimates were first made. The decrease in 1962 - 1963 was due to modification and shutdown of the Bevatron; a further decrease in 1964 - 1965 was from added shielding and operation improvements; however, and increase in 1966 was due to increasing intensity of the proton beam, but a decrease in 1967 related to extra shielding added to the straight sections. Since 1970, radiation levels have declined due to increased acceleration of heavy ions at relatively low intensity. In 1972 when the Bevatron was accelerating protons for 75% of the time, the maximum, annual, site-boundary level was less than

55 millirem--to be compared with a value of 190 millirem that would have been predicted at this beam intensity by Moyer (MOYER 1962).

Although the first external beam at the 88-Inch Cyclotron was obtained in 1962, the radiation levels observed during 1962 - 1966 at this station correlate with the operation of the Bevatron. In 1967, however, the recorded levels indicate the increasing beam intensity at the 88-Inch Cyclotron; but the addition of shielded eaves caused a dramatic reduction in the radiation levels for 1971. The 88-Inch Cyclotron is now so well shielded that its adjacent monitoring station again reflects principally the Bevatron activity (GLEITER, 1973).

The station situated at Panoramic Way is in direct view only of the 184-Inch Synchrocyclotron and responds principally to that accelerator. High readings at this station may usually be directly attributed to unusual experimental conditions at the 184-Inch Synchrocyclotron. 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 systion are principally caused by skyshine from the Bevatron and 88-inch cyclotron.

The decline in radiation levels at the site-boundary is borne out by the decline in collective radiation exposures to Laboratory personnel and visitors as determined by their personal dosimeters. This is shown in Figure 4.

Influence of Hills on the Radiation Level. The environmental monitoring stations 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 2 summarizes average flux densities measured at these three stations during a period in which only the Bevatron was operating (McCASLIN, 1974). 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 suggests 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.

Accuracy of Environmental Monitoring. In the past, the 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.

The recent trend toward the quantitative definition of the "as low as practicable concept" requires an improvement in the accuracy of measurement of man-made radiation exposures, which in turn poses severe problems in measurement and data interpretation. But first a better understanding of natural background and the accelerator-produced radiation environment is needed.

Neutron Fluence to Dose-Equivalent Conversion. Several authors have discussed the conversion of measurements of neutron flux density to dose equivalent when the neutrons are distributed over a wide range of energy (GILBERT et al., 1968; SHAW et al., 1969; PATTERSON et al., 1971b; STEVENSON et al., 1972). If it should be required that the dose equivalent due to neutrons produced by high-energy accelerators be estimated to an accuracy better than 50%, then differential energy spectra must be determined (THOMAS, 1974) and detection with improved sensitivity in the 20 - 100 MeV energy region must be developed.

Dose Equivalent Due to γ-Rays. Estimates of man-made radiation to an accuracy of a few millirem/yr demand a corresponding understanding in natural background radiation levels. At the present time, the uncertainty in the photon component of natural background due to radioactivity of surrounding rocks and soils is about 15 millirem/yr because data on seasonal fluctuations in background are not yet available.

Effect of Shielding Modifications. Shielding studies have been an integral part of particle accelerator development at the Lawrence Berkeley Laboratory (PATTERSON and THOMAS, 1971a). As accelerator intensities have increased, shielding has been installed to maintain radiation levels below required radiation safety standards.

The original shielding for the Bevatron allowed the MPD of 500 millirem/yr (MOYER, 1961, 1962). Moyer recognized that site-boundary radiation levels, due to leakage from the shielding roof, when thick targets were operated in the accelerator straight sections, would present a limiting operational condition on the accelerator. However, the addition of shielding above the straight sections, as well as continued improvement in accelerator operation (especially beam extraction) have brought about significant reductions in site-boundary radiation levels despite increasing beam intensity.

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 at research accelerators must be rapidly demountable, access to experimental areas must be maintained, and the accelerator itself must be accessible. Radiation leakage occurs through access labyrinth ducts, penetrations, and cracks in shield walls. Further, 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 beneath. 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 ENVIRONMENTAL IMPACT OF HIGH-ENERGY PARTICLE ACCELERATORS

The environmental impact of high-energy accelerators is different from most types of nuclear installation: The possible magnitude of environmental contamination by accelerator-produced radionuclides has been studied at several accelerator laboratories around the world and has been shown to be negligible. (For a summary see PATTERSON and THOMAS, 1973). In particular, the environmental surveillance program of LBL has detected no significant changes in the radioactivity of water samples taken from surface streams around the Laboratory and no increase in radiation levels due to accelerator-produced gaseous radionuclides (WALLACE, 1974). Beyond the shielding the dose-equivalent is comprised $>$ 50% of neutrons between 0.1 and 20 MeV; 10 to 20% of γ-rays and low-energy neutrons; with the balance of neutrons greater than 20 MeV (PATTERSON and THOMAS, 1971a; RINDI and THOMAS, 1973; THOMAS, 1972).

POPULATION EXPOSURE FROM ACCELERATOR-PRODUCED PENETRATING RADIATION

In setting standards for 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:

$$M = \int HN(H)\,dH \quad ,$$

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 population dose.

Almost the entire urban population of the San Francisco Bay Area ($\sim$ 3 million people) lies within 80 kilometers of the Laboratory.* More importantly, it is estimated that the equivalent of 329,000 persons live or work within 8 kilometers of the Laboratory perimeter. The resulting population dose due to Laboratory operations is comparable in magnitude to the collective dose of radiation workers.** For example, in 1973, the population dose was reported as 60 man-rem (WALLACE, 1974), while the collective dose to Laboratory personnel was 102 man-rem.

The first estimates of the population dose, M , due to accelerator-produced penetrating radiation at LBL gave a value of 2150 D_0, where D_0 is the maximum annual dose-equivalent at the Laboratory site boundary (STEPHENS and THOMAS, 1973). More recent estimates that take account of the shielding effect of adjacent hills give a value of $M \approx 1000\ D_0$ (STEPHENS et al., 1975).

Table 3 summarizes the estimated population exposure due to LBL accelerator operation during the period 1963 - 1972.

---

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

**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.

COST EFFECTIVENESS OF SHIELDING MODIFICATIONS

In a cost-benefit study of radiological safety programs, one must define parameters that are measures of both the beneficial and detrimental impact. However, for research programs, it is difficult to determine an acceptable index of benefit because the ultimate consequences of scientific research cannot be accurately predicted. It is generally agreed that fundamental research is worthwhile and will lead to continuing benefits.

On the other hand, for research programs that result in the production of ionizing radiation, such as those at LBL, it is farily easy to obtain an upper limit to the possible concomitant human detriment. Several estimates of the monetary equivalent of the detriment from a population exposure of one man-rem have recently appeared in the literature. These estimates fall in the range \$10 to \$250 and are helpful in determining the sums of money that might prudently be used in eliminating radiation exposures.

As a part of the Bevatron modification in 1962, roof shielding was constructed at a cost of about \$2.8 M (SALSIG, 1974) and reduced radiation levels by a factor of 100 (SMITH, 1965). From Table 3 we wee that the total population dose reported for the ten years 1963 - 1972 was 1924 man-rem, of which roughly 770 man-rem were due to leakage of neutrons through the Bevatron roof. Had there been no roof the population exposure would have been 7.7×10^4 man-rem, therefore, the cost of removing a man-rem by addition of the Bevatron roof was roughly \$40 per man-rem over these ten years.* When compared with the recent (ICRP,

*The more recent estimate of population dose would increase this estimate to ≈ \$85 per man-rem.

1973a) cost estimate of $10 to $250 per man-rem, to avoid the detriment associated with the population dose of one man-rem, cost of roof shielding for the Bevatron is considered reasonably cost-effective.

Any further addition of shielding would pose great technical difficulties because the existing shielding foundations are presently stressed to their limit. High-density shielding would be required because of limited space: Steel could not be used to replace the existing ferrophosphate high-density shielding because of magnet perturbations on the particle orbit in the accelerator and stainless steel or uranium would be too expensive and inconvenient. The high floor loadings resulting from the use of such high-density materials would probably make the addition of shielding impossible. An engineering design study to examine feasibility, and prepare a cost estimate alone would 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, even the cost of a design study does not seem warranted.

The addition of roof shielding to the Bevatron has been a cost-effective measure because of the long period during which the shielding has been in use. Sheilding changes which operate for only a year or so are much less effective, as for example 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 addition of one foot of steel over the septum magnet in the beam channel at a cost of $25,000 might reduce site boundary radiation levels to 25%. With a reported population dose for 1973 of < 60 man-rem, the cost of removing 1 man-rem by this addition would have been greater than \$1600 and may have been higher than \$3500. 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 one order of magnitude more than its detrimental value.

The addition of shielded eaves to the roof of the 88-Inch Cyclotron during 1970 and 1971 provides an example of the addition of shielding which is projected to be cost effective. The radiation levels at the 88-Inch Cyclotron environmental monitoring station were reduced by more than 0.25 rem per year at a cost of \$330 K (see Fig. 2). By projecting ten years of operation similar to that observed in 1972 the cost of removing a man-rem by the addition of this shielding is between \$200 and \$450 per man-rem.

Thus, it would seem that the cost or removing a man-rem by the addition of shielding to our high-energy accelerators ranges from ~ \$50 to ~ \$500. 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.

SUMMARY AND CONCLUSIONS

In any study to determine whether radiation levels are as low as practicable, it is necessary first 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 shileding 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 decreased steadily over the past 14 years, despite increasing beam intensities at our accelerators. In 1973, when the Bevatron accelerated protons, contributed about 80% of the maximum dose-equivalent observed at the Laboratory's site boundary: 28 millirem/year (WALLACE, 1974).

The declining site boundary radiation levels have in part been achieved by addition of shielding -- particularly to the Bevatron and 88-Inch Cyclotron roofs. The cost of removing radiation exposures has been in the range $40 to $550 per man-rem; this judged to be a cost-effective use of shielding since the estimated monetary value of detrimental effects of a man-rem ranges from $10 to $250. Examples of additional shielding judged to be too expensive by these criteria are given. Floor loading imposes physical limitations that prohibit additional shielding for the Bevatron roof and the external proton beams areas.

ACKNOWLEDGMENTS

The work reported here is the collective effort of many present and past members of the Health Physics Department. The author is grateful for the advice from and discussions with Joseph B. McCaslin, H. Wade Patterson, Alessandro Rindi, Alan R. Smith, Lloyd D. Stephens, and Harold Wollenberg, all of the Health Physics Department, LBL, and Hattie Carwell of the San Francisco Operations Office of the USAEC.

REFERENCES

COHEN J.J., 1970, Health Physics 19, 633.

COHEN J.J., 1971, A Suggested Guide Line for Low Dose Radiation Exposure to Populations, Based on Benefit-Risk Analysis, July, Lawrence Livermore Laboratory Report UCRL-72848.

DUNSTER H.J. and McLEAN A.S., 1970, Health Physics 19, 131.

DUNSTER H.J., 1973, Costs and Benefits of Nuclear Power, New Scientist, 18 October, p. 192.

EVERETTE W., 1974, Private Communication, Lawrence Berkeley Laboratory, October , 1974.

FREYTAG E., 1972, Radiation Protection at High-Energy Accelerators (in German), G. Braun, Karlsruhe.

GILBERT W.S., KEEFE D., McCASLIN J.B., PATTERSON H.W., SMITH A.R., STEPHENS L.D., SHAW K.B., STEVENSON G.R., THOMAS R.H., FORTUNE R.D., and GOEBEL K., 1968, CERN-LRL-RHEL Shielding Experiment at the CERN Proton Synchrotron, UCRL-17941, September.

GLEITER M.E., 1973, A Preliminary Determination of Environmental Radiation at Large Distances Due to LBL Operation, Lawrence Berkeley Laboratory Internal Note HPN/5, December.

HARTSOUGH W.D. and LOTHROP F.H.G., 1971, Bevatron Monthly Report for January; Lawrence Berkeley Laboratory Internal Report BeV-2003, February 2.

HEDGRAN A. and LINDELL R., 1970, Health Physics 19, 121.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1955, Brit. J. Radiol. Supplement 6. British Institute of Radiology, London.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, (ICRP) Publication 1, 1959 (Adopted 9 September 1958), London: Pergamon Press.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, (ICRP) Publication 6, (As amended 1959 and revised 1962), 1964 (Oxford: Pergamon Press).

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, (ICRP) Publication 9, 1966a (Oxford: Pergamon Press).

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, (ICRP) Publication 9, 1966b, paragraph 52. (Oxford: Pergamon Press)

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, (ICRP) Publication 22, 1973a, "Implications of Commission Recommendations that Doses be Kept as Low as Readily Achievable (Oxford: Pergamon Press).

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, (ICRP) Publication 21, 1973b (Oxford: Pergamon Press).

LEDERBERG J., 1971, Squaring an Infinite Circle: Radiobiology and the Value of Life, Bull. Atomic Sci. 27, 43.

LOU, K., 1973, Mechanical Engineering Department, Lawrence Berkeley Laboratory, Private Communication, December.

McCASLIN J.B., 1974, Private Communication, Lawrence Berkeley Laboratory.

MOYER B.J., 1971, Evaluation of Shielding Required for the Improved Bevatron, Lawrence Berkeley Laboratory Report UCRL-9769, June.

MOYER, B.J., 1962,"Method of Calculating the Shielded Enclosure of the Bevatron", in Premier Colloque International sur la Protection Auprès des Grands Accelerateurs. (Paris: Presses Universitaires de France) p. 65.

OTWAY H.J., BURHAM J.B., and SOHRDING R.K., 1970, Economic vs. Biological Risk as Reactor Design Criteria. Presented at the IEEE Nuclear Science Symposium.

PATTERSON H.W., 1962, The Effect of Shielding on Radiation, in Proc. of the First International Conference on Shielding Around High-Energy Accelerators, Paris, January (Paris: Presses Universitaires de France) p. 95.

PATTERSON H.W. and THOMAS R.H., 1971a, Experimental Shielding Studies at High-Energy Accelerators -- A Review, Particle Accelerators 2, 77.

PATTERSON H.W., ROUTTI J.T., and THOMAS R.H., 1971b, "What Quality Factor?" Health Physics 20, 517.

PATTERSON H.W. and THOMAS R.H., 1973, Accelerator Health Physics (New York: Academic Press).

RINDI A. and THOMAS R.H., 1973, The Radiation Environment of High-Energy Accelerators, Ann. Rev. Nucl. Sci. 23, 315.

SAGAN L.A., 1972, Human Costs of Nuclear Power, Science 117, 487.

SALSIG W.W., 1974, Mechanical Engineering Department, Lawrence Berkeley Laboratory, Private Communication, December.

SHAW K.B., STEVENSON G.R., and THOMAS R.H., 1969, Evaluation of Dose-Equivalent from Neutron Spectra, Health Physics 17, 459.

SMITH A.R., 1965, Some Experimental Shielding Studies at the 6.2 Bev Berkeley Bevatron, in Proc. First Symposium on Accelerator Dosimetry and Experience, Brookhaven, November, CONF-651109, p. 365.

STEPHENS L.D. and DAKIN H.S., 1972, A High Reliability Environmental Radiation Monitoring System, in Proc. of the VIth International Congress of the Societe Francaise de Radioprotection, Bordeaux, France, March 27-31, p. 753.

STEPHENS L.D. and THOMAS R.H., 1973, Estimate of Population Exposure due to Operation of the Lawrence Berkeley Laboratory Particle Accelerators, Lawrence Berkeley Laboratory Report UCID-3602, April.

STEPHENS L.D. and THOMAS R.H., 1974, Radiation Levels at the Site Boundary of the Lawrence Berkeley Laboratory, Lawrence Berkeley Laboratory Internal Report, HPN-6, February 11.

STEPHENS L.D., THOMAS R.H., and THOMAS S.B., 1975, A Model for Estimating Population Exposure Due to the Operation of High-Energy Accelerators at the Lawrence Berkeley Laboratory, Lawrence Berkeley Laboratory Report LBL-3826, March.

STEVENSON G.R., HÖFERT M., NEUFELD J., RINDI A., ROUTTI J.T., and PRÊTRE S., 1972, Proposal for Standardizing the Fluence to Dose Equivalent Conversion Factors for Whole Body Neutron Exposures, in Proc. of IAEA Symposium on Neutron Monitoring, Vienna, December 11-15, Vol. 1, p. 177.

TAYLOR L.S., 1971, Radiation Protection Standards (Cleveland, Ohio: CRC Press) p. 26. See also: Letter to Editor, Nuclear News, November, 1973 issue, p. 43.

THOMAS R.H., 1972, Neutron Dosimetry at High Energy Particle Accelerators--A Review, in Proc. of IAEA Symposium on Neutron Monitoring, Vienna, December 11-15, Vol. 1, p. 327.

WALLACE R.W., 1965, Cyclotron Shielding, Lawrence Berkeley Laboratory Report UCRL-11315, August 11, and Engineering Compendium on Radiation Shielding, Section 10.7.2 (Berlin: Springer-Verlag, 1970).

WALLACE R. (Ed.), 1974, Annual Environmental Monitoring Report (For Calendar Year 1973), Lawrence Berkeley Laboratory, University of California, in Environmental Monitoring at Major U.S. Atomic Energy Commission Contractor Sites, Calendar Year 1973, Vol. 2, p. 1173, WASH-1259.

ZAITSEV L.N., KOMOCHKOV M.M. and SYCHEV B.C., 1971, The Basis of Accelerator Shielding (in Russian), (Moscow: Atomizdat).

Table 1. 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 Synchrocyclotron 88-Inch Cyclotron SuperHILAC		20%

Table 2. Average flux densities from Bevatron operation

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.

Table 3. Estimated population and radiation worker dose-equivalent due to LBL accelerator operation.

Year	Average Fence Post Dose-Equivalent, Background Subtracted (rem/yr)*	Estimated* Population Dose Equivalent (man-rem)	Estimated* Radiation Worker Dose-Equivalent (man-rem)
1963	0.134	288	213
1964	0.101	217	558
1965	0.051	110	483
1966	0.066	142	486
1967	0.071	153	180
1968	0.086	185	318
1969	0.129	277	426
1970	0.082	176	522
1971	0.127	273	246
1972	0.048	103	237
1973	0.028**	< 60**	102

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

**Maximum fence post dose-equivalent quoted for 1973.

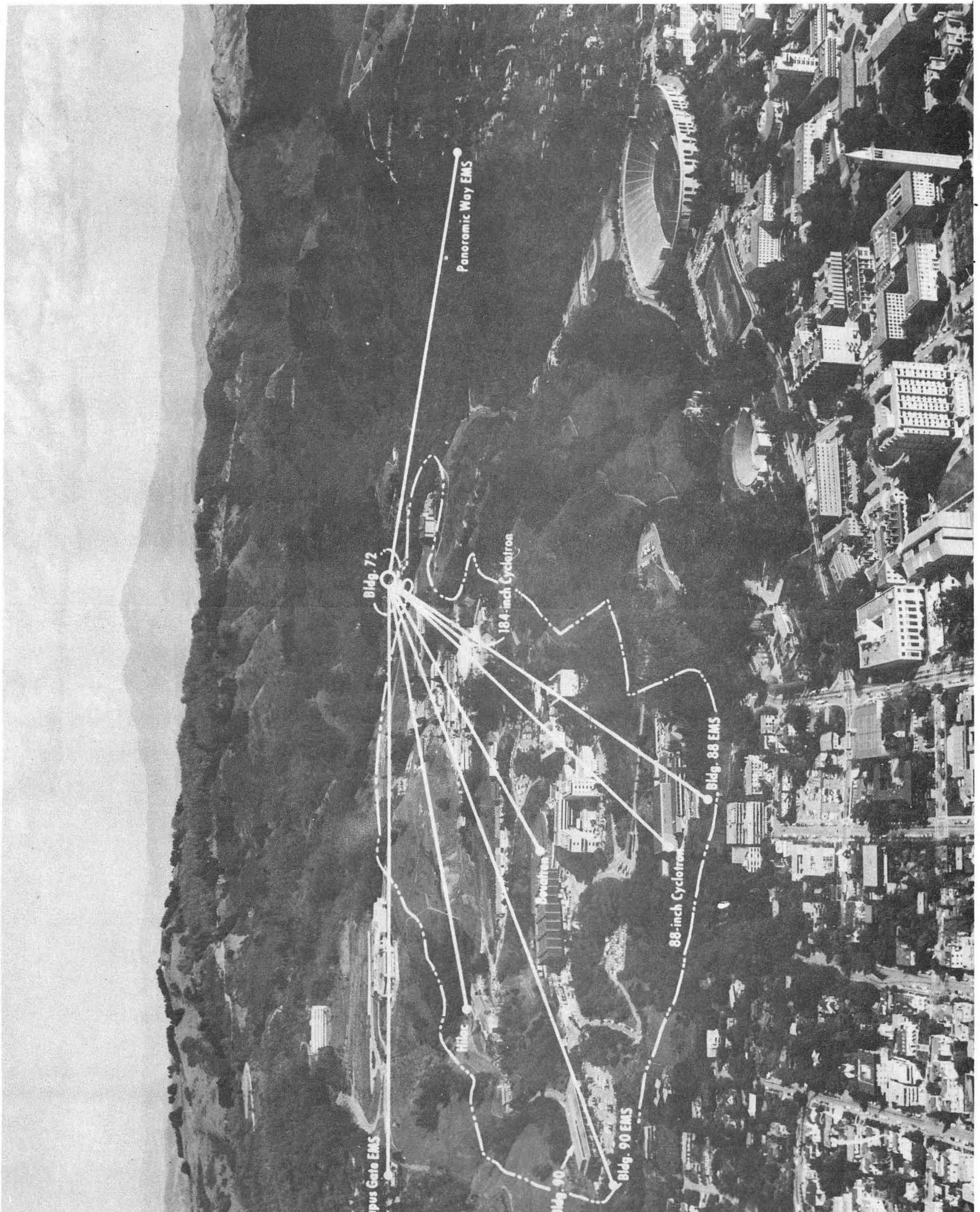
FIGURE CAPTIONS

Fig. 1. A view of the Lawrence Berkeley Laboratory showing the location of the environmental monitoring stations.

Fig. 2. Annual dose-equivalent at (a) Olympus Gate and (b) 88-Inch Cyclotron environmental monitoring stations.

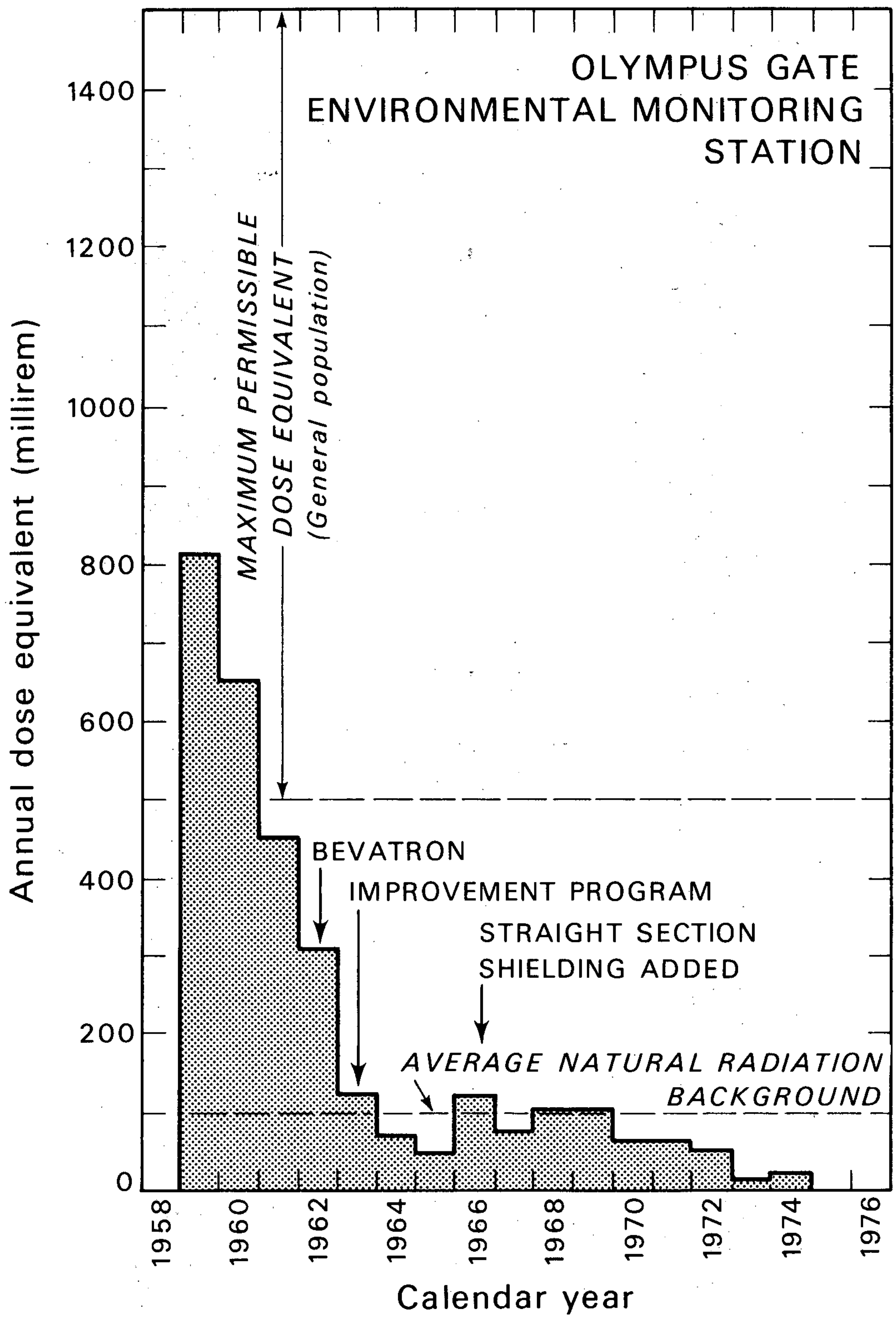
Fig. 3. Annual dose-equivalent at (a) Panoramic Way and (b) Building 90 environmental monitoring stations.

Fig. 4. 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).



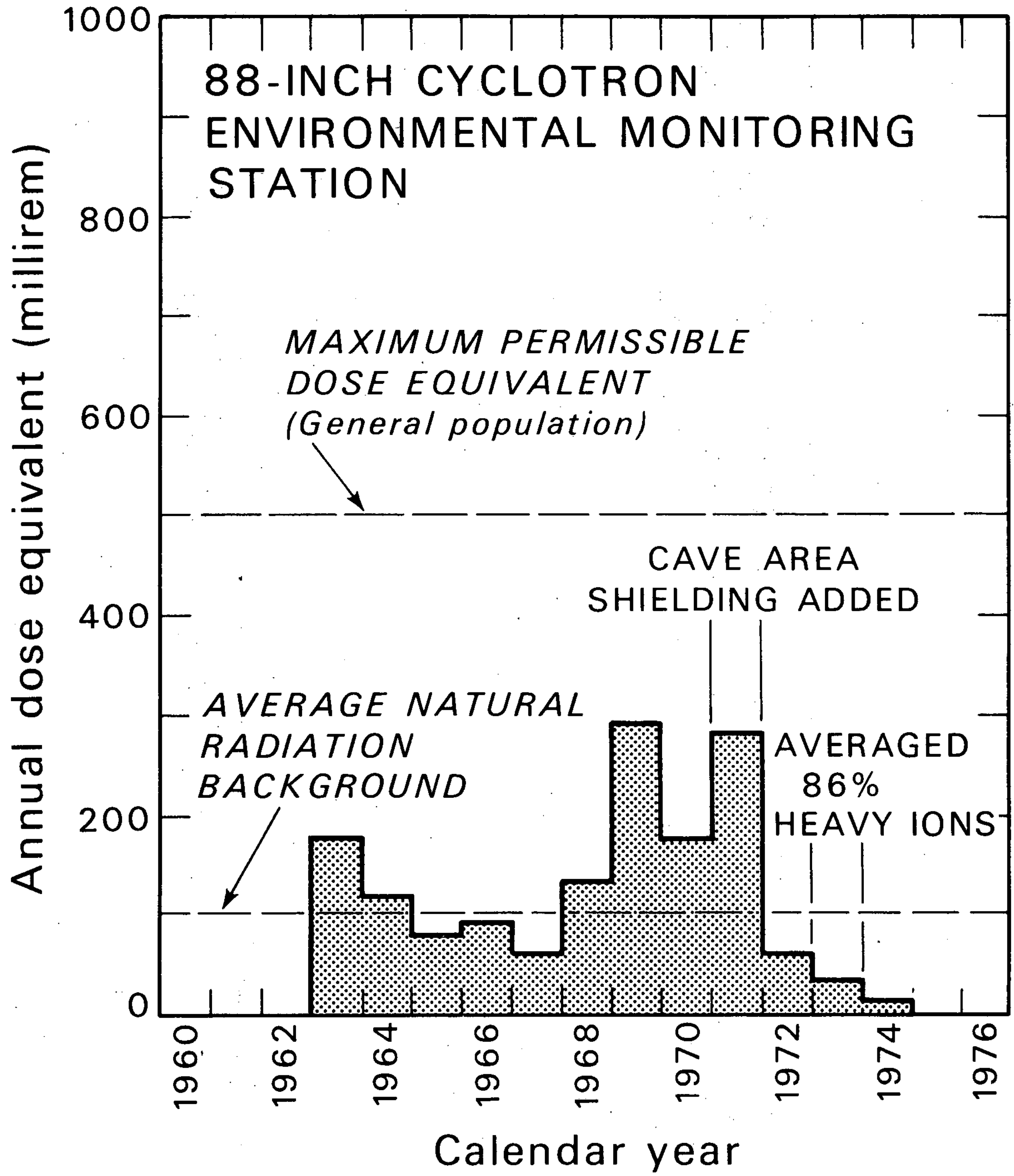
XBB 733-1830

Fig. 1



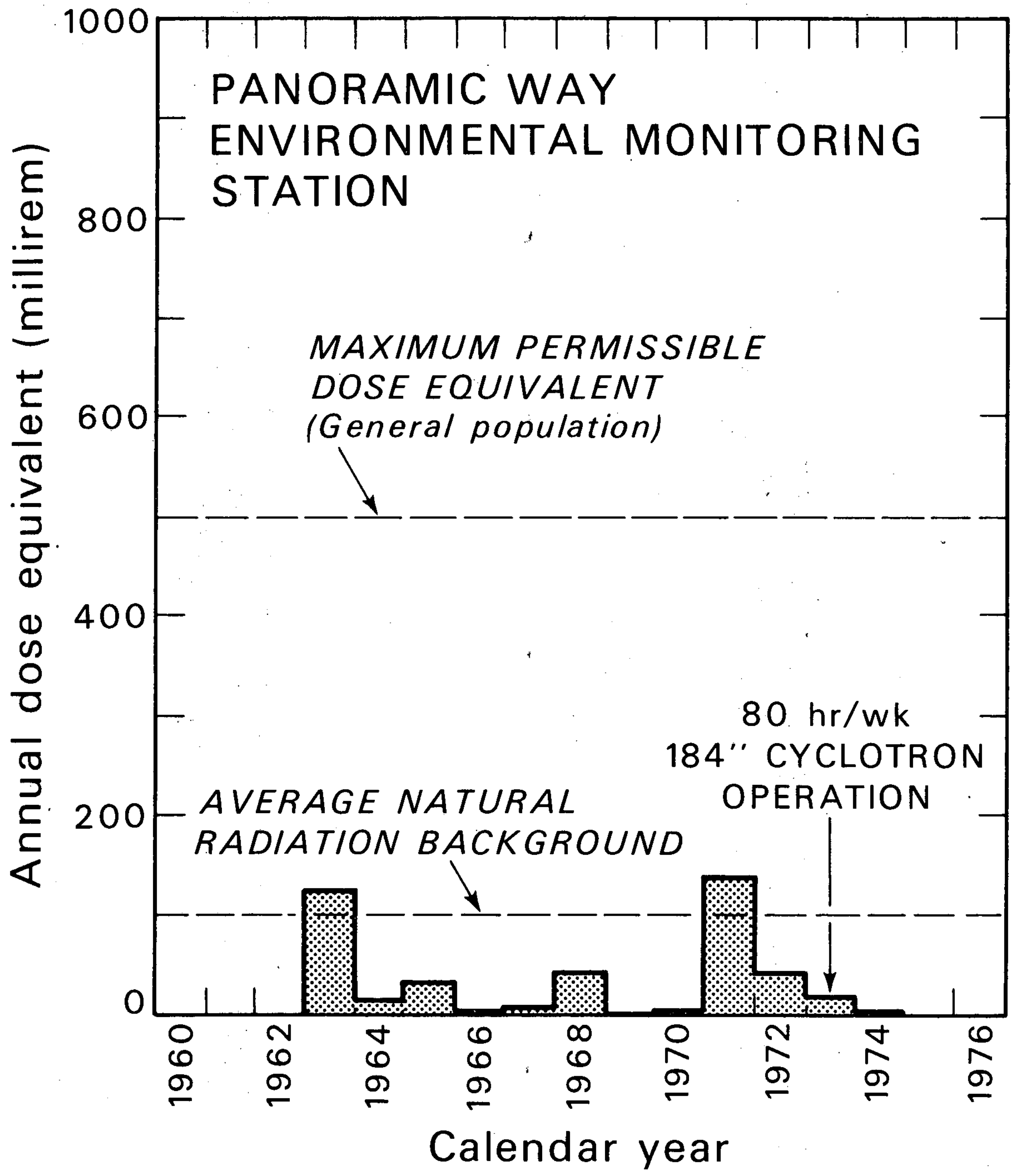
XBL 753-4766

Fig. 2a



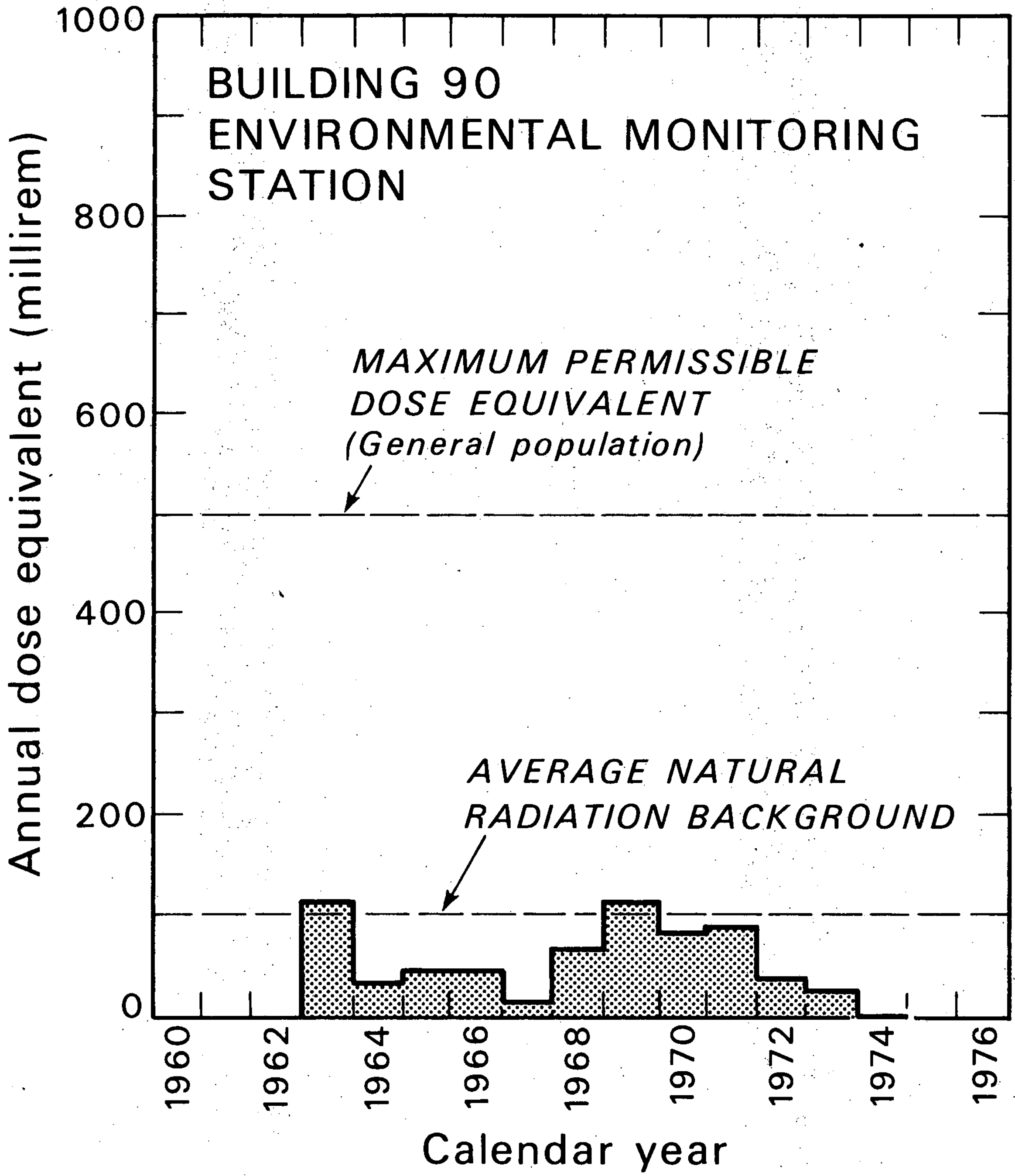
XBL 753-4767

Fig. 2b



XBL 753-4769

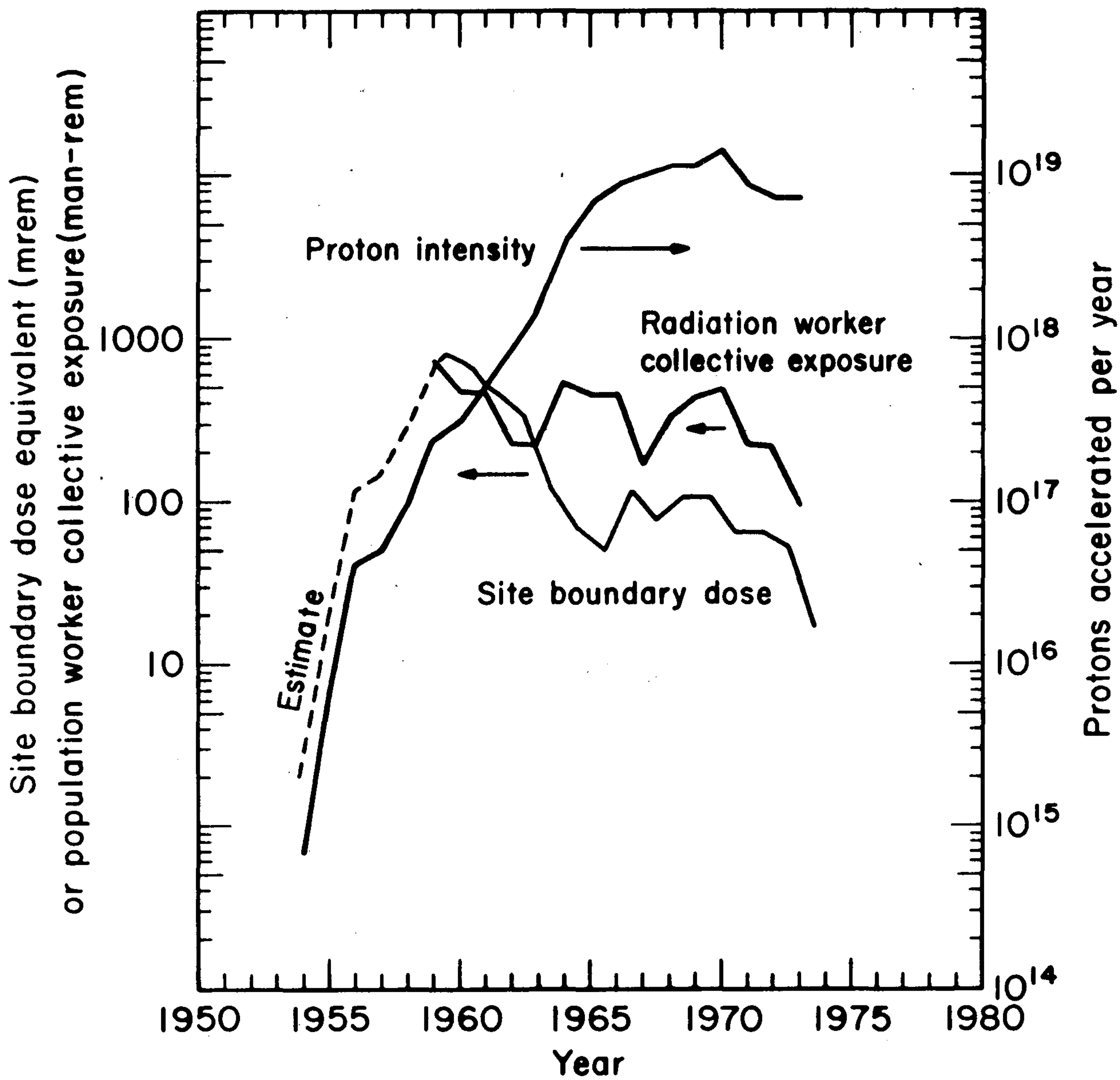
Fig. 3a



XBL 753-4768

Fig. 3b

0 0 · 4 3 0 0 2 3 1



CBB 752-1175

Fig. 4

U U 4 3 J U 2 3 2