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Publication Date
2018-01-09

Submitted to Health Physics

LBL-3826
Preprint

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March 1975

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

Then, rising with Aurora's light,
The Muse invoked, sit down to write;
Blot out, correct, insert, refine,
Enlarge, diminish, interline.

from "On Poetry"
by Jonathan Swift 1667-1745

A MODEL FOR ESTIMATING POPULATION EXPOSURES DUE TO THE OPERATION OF HIGH-ENERGY ACCELERATORS AT THE LAWRENCE BERKELEY LABORATORY*

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ABSTRACT

A model is described from which population exposure resulting from high-energy accelerator operation at the Lawrence Berkeley Laboratory can be estimated. The model takes account of variations in population density around the Laboratory and includes a rough estimate of the influence of surrounding hills, but the value of population dose-equivalent obtained is believed to be somewhat conservative (high). For a dose-equivalent H_0 at the Laboratory boundary, the population dose-equivalent is calculated to be $< 1000\ H_0$ man rem—approximately a factor of two lower than earlier estimates.

*Work done under the auspicies of the U.S. Energy Research and Development Administration.

1. INTRODUCTION

The Lawrence Berkeley Laboratory of the University of California is unusual among high-energy accelerator laboratories, in that it is contiguous with fairly densely populated areas. The Laboratory is situated on the western slope of hills running along the eastern side of the San Francisco Bay. The Berkeley Campus of the University of California is immediately adjacent on the west, while to the north and south, the Laboratory is surrounded by residential areas. To the east lie largely uninhabited watershed lands and Tilden Regional Park.

The equivalent of 168,000 people live or work within about 5 kilometers from the Laboratory. The proximity of a large urban population to the Laboratory has led to the close surveillance of the environmental impact of the Laboratory's activities.[1]

The largest radiological environmental impact is due to the operation of four high-energy particle accelerators: the Bevatron, the Super-HILAC, and the 88-inch and 184-inch cyclotrons. Stephens et al.[2] have discussed the radiological impact of these accelerators and have shown that the major source of radiation exposure of the general population is the production of whole-body ionizing radiation during accelerator operation. Neutrons are the dominant component of the radiation environment at large distances from the accelerators at Berkeley.

In a previous paper,[2] the present authors described a model that could be used to estimate the population exposure around a high-energy particle accelerator laboratory. This model assumed a uniform population distribution around the facility and took no account of either the shielding of the population from the accelerator by surrounding hills or of the shielding of buildings. Hills around the Lawrence Berkeley Laboratory (LBL) have a significant influence on the propagation of neutrons, and consequently the simple model[2] overestimates population exposure resulting from LBL accelerator operation. This paper refines the earlier model, takes account of population density variation, and includes shielding corrections resulting in a more accurate estimate of population exposure due to the operation of accelerators at LBL.

2. POPULATION DOSE

The population dose-equivalent, M, is defined by the equation:[3]

$$M = \int H\, N(H)\, dH \qquad (1)$$

where N(H)dH is the number of people receiving a dose-equivalent between H and H+dH.

In the urban area surrounding the Lawrence Berkeley Laboratory, it is plausible that the population density at a given location may be considered constant when averaged over long periods of time.[2] This should not result in serious error in the estimate of population exposure, provided the intensity of accelerator operation is uncorrelated with fluctuations in population (e.g. high intensity operation is not restricted to times of known low population). If this assumption is made, equation (1) may be simplified to

$$M = \int_{r_0}^{R} H(r)\, N(r)\, dr \qquad (2)$$

where H(r) is the annual dose-equivalent to a person at a distance from r to r + dr from the accelerator. The closest and farthest distances of approach to the accelerator are r_0,R, respectively; r_0 will correspond to the distance of the Laboratory bounary from the source of radiation. It is conventional to estimate population dose-equivalent out to a distance of 80 kilometers from the facility.

3. DISTRIBUTION OF POPULATION AROUND LBL

Thomas[4] has studied the distribution of population around LBL, using data from the U.S. Department of Commerce 1970 census[5] and from the University of California, Berkeley Campus statistics for 1972/73.[6] Figure 1 shows the regions investigated. Concentric circles at 1000-ft intervals were drawn around the Bevatron at the Laboratory, at distances between 1000 to 16,000 ft. The residential population within each ring was obtained by summing the census data of the blocks located inside each circle. Table 1 summarizes the data so obtained.

In addition to full-time residents, an estimate must be made of the time spent by students, faulty, and staff on the Berkeley Campus of the University of California. In this paper a resident is assumed to spend 8766 hr/yr in his home and a full time equivalent resident (FTER) is therefore defined as 8766 man hr/yr. An estimate of the total time spent by students, faulty, and staff on the campus enables the number of FTER's to be calculated. An estimate of the total time spent on campus by students is difficult to approximate in that non-instructional hours can vary with each student. Stephens and Thomas[7] estimated the average student spends 780 hr/yr on the Berkeley campus (based on the assumption that a student is on campus 4 hr/day, 5 days/week for 39 weeks/yr). Campus statistics for the University of California at Berkeley[6] show that a full-time-equivalent (FTE) student spends 450 hr/yr in classroom instruction, which will give a lower limit to the time spent on campus. An upper limit on campus attendance may be obtained from the University Catalogue which identifies an FTE student as one who takes 36 units/yr, each unit requiring 30 hr of instruction and preparation (3 hr/wk, 10wk/quarter), giving a total of 1080 hr/yr. Estimates of campus attendance for the average student may therefore range between 450 and 1080 hr/yr, with an average of 765 hr/yr, which is close to the estimate of 780 hr/yr given by Stephens and Thomas.[7] The value of 765 hr/yr has been used in the data of Table 1 in calculating the number of FTERs on the University campus. In a 1973 report[8] on "Administration, Academic and Staff Personnel Headcount," the total FTE Berkeley staff numbered 9,809. Assuming a full time employee works 40 hr/wk for 45 weeks, staff and faculty contribute 2,059 FTER. From the residential population data and the estimates of University campus FTER's, the average population density in each ring shown on Fig. 1 may be calculated.

The use of these estimates of total population or population density in calculating population dose-equivalent will give conservative (high) values for the following reasons:

a. Many students and staff members of the University of California, Berkeley, live close to the Campus. They will therefore be counted twice in this estimate.

b. The daily migration of population, other than UC students and employees, is towards work places, stores, schools, etc., and tends to be away from the Laboratory. Thus, for a significant fraction of the day the total residential population close to the Laboratory will be lower than that given in Table 1.

4. VARIATION OF DOSE EQUIVALENT WITH DISTANCE FROM LBL

Rindi and Thomas[9] have reviewed measurements of the variation of dose-equivalent with distance, made at many particle accelerators. Experimental data is limited to distances less than 1500 m from an accelerator, but at all accelerators the dose-equivalent beyond 300 m falls faster than the inverse square of the distance from the accelerator. These authors conclude from the data that, in direct line of sight of shielded accelerators, the dose-equivalent beyond 300 m is probably best expressed in the empirical form:

$$H(r) = a\frac{e^{-r/\lambda}}{r^2}, \text{ where } r \geqslant 300 \text{ m}. \quad (3)$$

The parameter $e^{-r/\lambda}$ is attributed to air attenuation, and λ may take values between 225 and 850 m. For accelerators capable of producing neutrons of energy greater than about 100 MeV, such as the 184-inch Synchrocylotron and the Bevatron, the higher value of λ should be used. Accelerators such as the SuperHILAC and 88-inch Cyclotron do not produce neutrons greater than about 50 MeV in energy, and so in this case, λ has a value of $\sim$ 250 m.

5. CALCULATION OF POPULATION DOSE-EQUIVALENT

Substitution of eq. (3) into the expression for population dose-equivalent gives

$$M = a \int_{r_0}^{R} N(r) \frac{e^{-r/\lambda}}{r^2} dr, \quad (4)$$

where "a" has to be determined.

If the dose-equivalent at distance r_0 from the Bevatron is H_0, substitution into eq. (3) gives

$$a = r_0^2 H_0 e^{r_0/\lambda}, \quad (5)$$

and eq. (4) becomes

$$M = r_0^2 \, H_0 \, e^{r_0/\lambda} \int_{r_0}^{R} \frac{N(r) e^{-r/\lambda}}{r^2} \cdot dr. \qquad (6)$$

Stephens and Dakin[10] have described the environmental monitoring program of LBL. Since 1964, radiation levels have been continuously measured at locations that were strategically selected to monitor the radiation output of the Laboratory's accelerators, both close to each accelerator and at the Laboratory's perimeter. From these measurements the dose-equivalent at the Laboratory's perimeter (the "fence-post" dose) may be determined.

Equation (6) does not allow for the shielding provided to a large fraction of the populated area by the hills surrounding the Laboratory or by the buildings which people occupy. To do so, Eq. (6) can be written

$$M = \frac{r_0^2 \, H_0 \, e^{r_0/\lambda}}{S_1 \, S_2} \int_{r_0}^{R} \frac{N(r) \, e^{-r/\lambda}}{r^2} \cdot dr, \qquad (7)$$

where S_1 and S_2 are shielding factors that take account of the shielding provided by hills and buildings, respectively. Only approximate estimates may be made for S_1 and S_2. Figure 2 shows three topographical profiles along different directions from the Laboratory from which it can be seen that the Bevatron is in a basin shielded from almost the entire urban area surrounding the Laboratory. Experimental data obtained by McCaslin[11] suggest that radiation levels are depressed by a factor of almost two when hills intervene (See Appendix.) From this preliminary data, $S_1 \approx 1.8$.

Thomas[1] has estimated the shielding factor for buildings to be $\approx$ 1.2 for the residential population and students and staff of the

University campus. This estimate is based on an assumed occupancy factor of 0.8 and the known types of buildings adjacent to the Laboratory. Thus, the product S_1S_2 has the value ≈ 2.2.

In our earlier paper[2] a uniform population density was assumed in estimating the population dose-equivalent, which limited the accuracy of the estimate. A more accurate value may be obtained by writing:

$$M = \frac{2\pi r_0^2 H_0 \, e^{r_0/\lambda}}{S_1 \, S_2} \int_{r_0}^{R} \frac{\sigma(r) \, e^{-r/\lambda}}{r} \, dr. \tag{8}$$

The integral of Eq. (8) may numerically be evaluated by assuming a uniform distribution of population within each ring drawn around the Laboratory (Fig. 1). M may then be approximated by:

$$M = \frac{2\pi \, r_0^2 H_0 \, e^{r_0/\lambda}}{S_1 \, S_2} \sum_{i=1}^{i=n} \sigma_i \int_{r_{i-1}}^{r_i} \frac{e^{-r/\lambda}}{r} \, dr, \tag{9}$$

where σ_i is defined by:

$$\sigma_i = \frac{N_i}{\pi (r_i^2 - r_{i-1})^2} . \tag{10}$$

Values of σ_i are given in Table 1.

The number of annuli, n, is determined by the convergence of the integral in Eq. (9). Population dose-equivalent, resulting from the operation of a nuclear installation, is a scalar quantity independent of distance from the installation, and should therefore be calculated out to infinity.

If we write

$$M(r') = \frac{2\pi\, H_0\, e^{r_0/\lambda}}{S_1\, S_2} \quad \frac{\sigma(r)\; e^{-r/\lambda}}{r}\, dr\ ; \qquad (9a)$$

in general

$$M(r') \rightarrow M$$

as $\quad r' \rightarrow R$.

It is conventional to assume that $M(r')$ has reached its convergent value, M, at a distance of 80 km from the installation.

In the case of high-energy accelerator operation at LBL, however, the integral of Eq. (7) rapidly converges[2] and it is necessary to extend integration out to a distance of about 5 km from the Laboratory. (See Fig. 3.) In the evaluation of the integral, the following values were used:

n	= 15
r_0	= 366 meters (1200 ft)
r_1-r_0	= 244 meters (800 ft)
r_i-r_{i-1}	= 304.8 meters (1000 ft) for $r \geqslant 2$
r_{15}	= 4,877 meters (16,000 ft)
λ	= 850 meters
S_1S_2	= 2.2 .

Substituting into Eq. (9a) we obtain:

$$M/H_0 = 5.875 \times 10^5 \sum_{i=1}^{15} \sigma_i \int_{r_i-1}^{r_i} \frac{e^{-r/850}}{r}\, dr, \qquad (11)$$

with r in meters,

σ_i in persons/m^2.

Values of the integrands of Eq. (11) were obtained by numerical integration and are summarized in Table 2. The population dose equivalent due to LBL accelerator operation calculated using this model is then:

$$M/MH_0 \approx 1023 \text{ man rem/fence-post rem.}$$

In practice, this value will give an upper limit to the population dose equivalent because:

a. The population density estimates used in the calculation are conservative (Section 3).

b. The value of population dose-equivalent depends strongly upon the value of λ assumed.

In the calculations presented here, a value of λ = 850 meters has been used. This value is appropriate for that component of the fence-post dose-equivalent contributed by the Bevatron and 184-Inch Synchrocyclotron. The contribution of the SuperHILAC and 88-Inch Cyclotron to the population dose will be overestimated in the ratio $(\frac{850}{250})^{2/3}$ Ref.(2), or a little more than a factor of two. If these two acclerators contribute a proportion, f, of the minimum fence-post dose-equivalent, the population dose-equivalent is then more accurately written:

$$\begin{aligned} M &= 1000\ H_0 \left[(1-f) + \left(\frac{250}{850}\right)^{2/3} f \right], \\ &= 1000\ H_0\ [1-0.56f] . \end{aligned}$$

c. In calculating M the maximum value of H_0 is used. At the present time there are considerable uncertainties in the evaluation of the γ-component of the fence post dose equivalent--principally caused by uncertainties in the intensity of natural background to better than 20 millirem/yr.(1) This uncertainty is comparable to the annual fence post dose equivalent itself.(1)

For these reasons we feel justified in expressing the population dose-equivalent due to high-energy accelerator operation at LBL as:

$$M/H_0 < 1000 \text{ man rem/fence-post rem.}$$

APPENDIX

Influence of Hills on the Radiation Level Around LBL

Three environmental monitoring stations at the Laboratory are 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[10]).

Table A1. Average flux densities during Bevatron operation.

Environmental Station	Distance from Bevatron (meters)	Observed average neutron flux density* ($n\ cm^{-2}\ sec^{-1}$)	Flux density normalized to 435 meters ($n\ cm^{-2}\ sec^{-1}$)
1	435	0.106	0.106
2	421	0.063	0.058
2	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. The flux density is depressed by a factor of ~ 1.8 by the presence of hills.

Table 1. Distribution of population around the Lawrence Berkeley Laboratory

At distance(ft) from to	Residential population (Census data)	Average U.C. Berkeley FTER*	Total population
1,000-2,000	1,449	1,610	1,449
2,000-3,000	2,715	1,894	4,325
3,000-4,000	4,627	1,231	6,521
4,000-5,000	6,570		7,801
5,000-6,000	9,568		9,568
6,000-7,000	8,275		8,275
7,000-8,000	12,857		12,857
8,000-9,000	13,200		13,200
9,000-10,000	11,859		11,859
10,000-11,000	13.671		13,671
11,000-12,000	14,564		14,564
12,000-13,000	16,423		16,423
13,000-14,000	17,751		17,751
14,000-15,000	15,559		15,559
15,000-16,000	14,150		14,150
		Grand Total	167,973

*Full-time-equivalent resident.

Table 2: Values of the integrands

At distance (meters) from	to	σ_i (persons/m^2)	I_i^*	M_i/H_0 Man rem/ fence-post rem
366 (1,200 ft)	610 (2,000 ft)	$\sigma_1 = 1.94\times10^{-3}$	2.938×10^{-1}	341.1
610 (2,000 ft)	914 (3,000 ft)	$\sigma_2 = 2.96\times10^{-3}$	1.690×10^{-1}	299.2
914 (3,000 ft)	1219 (4,000 ft)	$\sigma_3 = 3.19\times10^{-3}$	8.343×10^{-2}	159.2
1219 (4,000 ft)	1524 (5,000 ft)	$\sigma_4 = 2.97\times10^{-3}$	4.511×10^{-2}	80.2
1524 (5,000 ft)	1829 (6,000 ft)	$\sigma_5 = 2.98\times10^{-3}$	2.571×10^{-2}	45.8
1829 (6,000 ft)	2134 (7,000 ft)	$\sigma_6 = 2.18\times10^{-3}$	1.5174×10^{-2}	19.8
2134 (7,000 ft)	2438 (8,000 ft)	$\sigma_7 = 2.94\times10^{-3}$	9.177×10^{-3}	16.1
2438 (8,000 ft)	2743 (9,000 ft)	$\sigma_8 = 2.66\times10^{-3}$	5.652×10^{-3}	9.0
2743 (9,000 ft)	3048 (10,000 ft)	$\sigma_9 = 2.14\times10^{-3}$	3.531×10^{-3}	4.5
3048 (10,000 ft)	3353 (11,000 ft)	$\sigma_{10} = 2.23\times10^{-3}$	2.2309×10^{-3}	3.0
3353 (11,000 ft)	3656 (12,000 ft)	$\sigma_{11} = 2.17\times10^{-3}$	1.422×10^{-3}	1.8
3656 (12,000 ft)	3962 (13,000 ft)	$\sigma_{12} = 2.25\times10^{-3}$	9.141×10^{-4}	1.2
3962 (13,000 ft)	4267 (14,000 ft)	$\sigma_{13} = 2.25\times10^{-3}$	5.911×10^{-4}	0.8
4267 (14,000 ft)	4572 (15,000 ft)	$\sigma_{14} = 1.84\times10^{-3}$	3.844×10^{-4}	0.4
4572 (15,000 ft)	4877 (16,000 ft)	$\sigma_{15} = 1.56\times10^{-3}$	2.512×10^{-4}	0.2

$$^*I_i = \int_{r_{i-1}}^{r_i} \frac{e^{-r/850}}{r}\, dr$$

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FIGURE CAPTIONS

Fig. 1. Region around LBL. The concentric circles are drawn around the Bevatron at 1000-foot intervals.

Fig. 2. Topographical profile taken at three directions from the Bevatron.

Fig. 3. The percentage of population dose-equivalent at distances from the Lawrence Berkeley Laboratory.

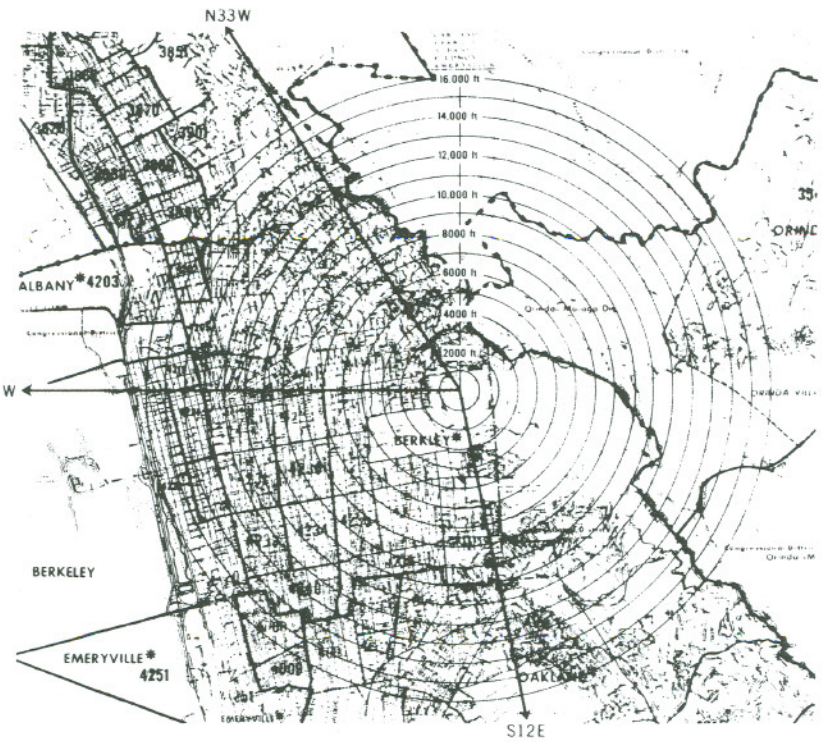

N33W
16,000 ft
14,000 ft
12,000 ft
10,000 ft
8000 ft
6000 ft
4000 ft
2000 ft
ALBANY*4203
W
BERKELEY
EMERYVILLE*
4251
S12E

Fig. 1

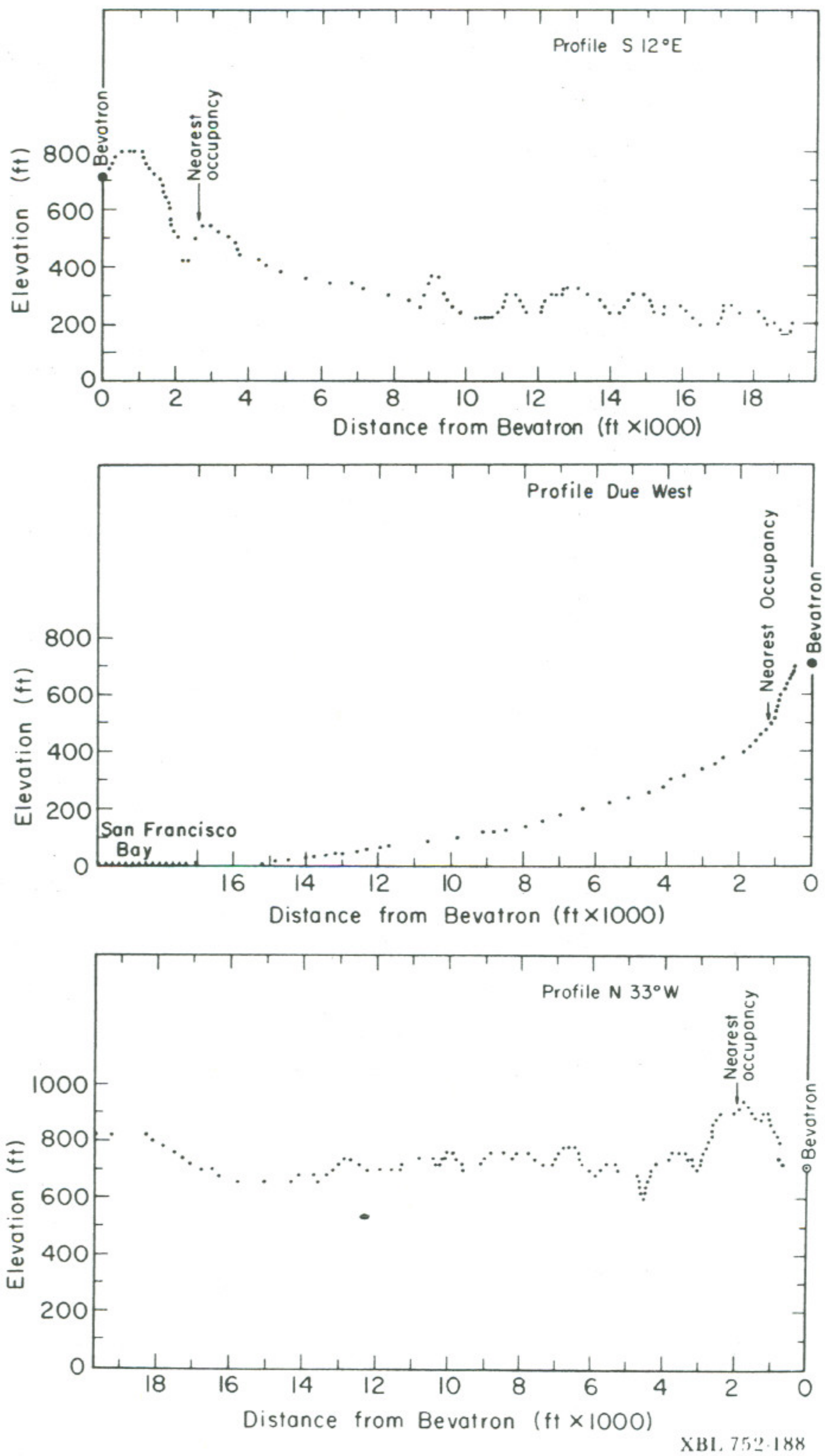
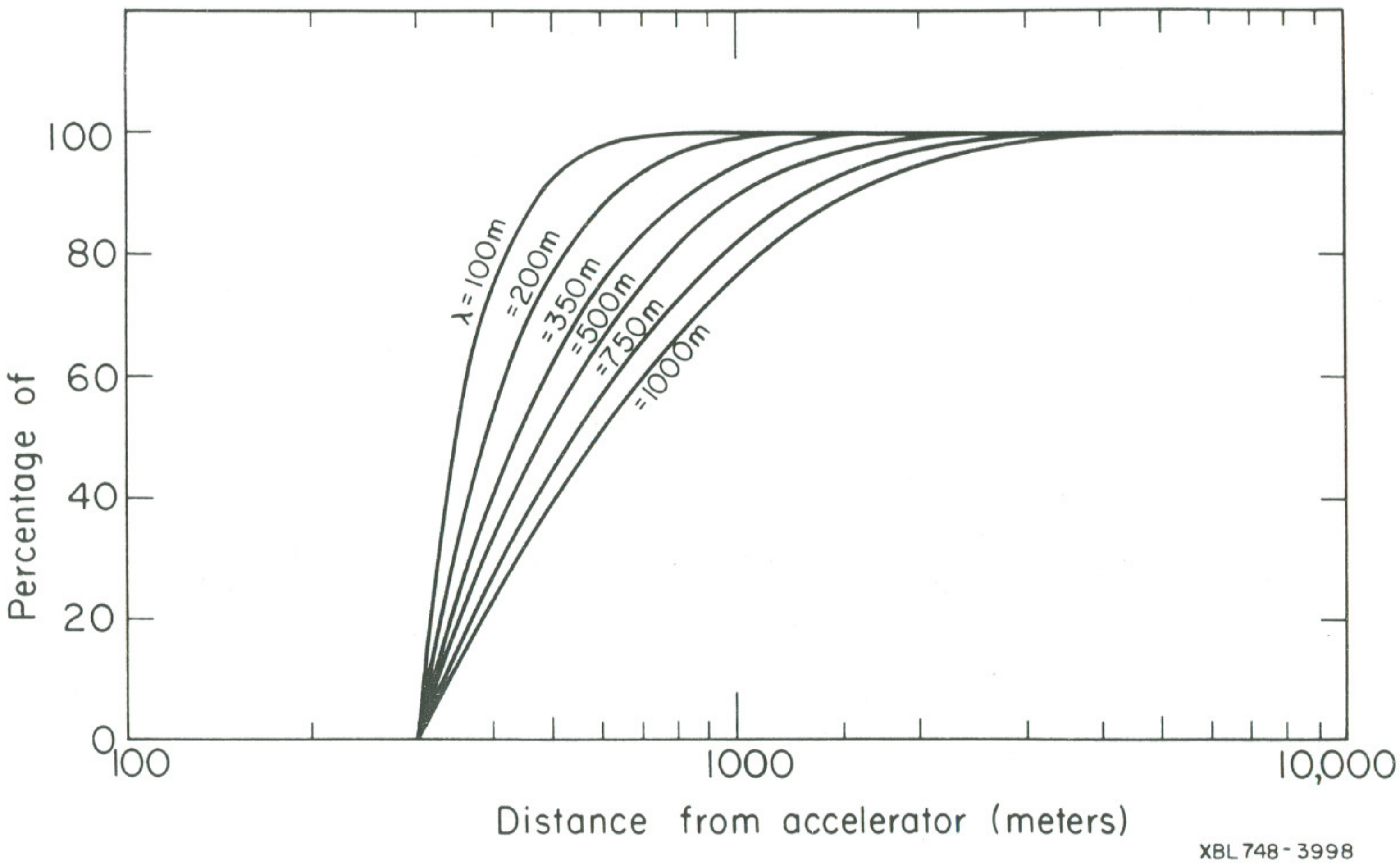

Profile S 12°E
Bevatron
Nearest occupancy
Elevation (ft)
Distance from Bevatron (ft ×1000)
Profile Due West
Nearest Occupancy
Bevatron
San Francisco Bay
Elevation (ft)
Distance from Bevatron (ft×1000)
Profile N 33°W
Nearest occupancy
Bevatron
Elevation (ft)
Distance from Bevatron (ft × 1000)
XBL 752-188

Fig. 2.



100
80
60
40
20
0
Percentage of
100
1000
10,000
Distance from accelerator (meters)
λ = 100m
=200m
=350m
=500m
=750m
=1000m
XBL 748-3998

Fig. 3