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ACCELERATOR BOUNDARY DOSES AND SKYSHINE*

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ABSTRACT

Beginning this year, AEC contractors are being required to submit dose evaluations as low as 1.7 mrem per year to the surrounding public from their installations. This small incremental dose exists within the framework of a natural background of about 130 mrem per year. Some of the pitfalls in estimating these small doses, especially with regard to skyshine, are discussed. It is shown that, for any accuracy at all, better data must be generated for the neutron-vs-distance curve. However, the need for measuring, or even estimating, such small doses is brought into question.

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I. Introduction

The AEC requires a detailed dose evaluation from its contractors when it is probable that the potential exposure to an individual or population group for a calendar year exceeds one percent of the relevant AEC 0524 dose standards. For individuals and population groups outside an accelerator boundary, the relevant dose standard could be either 1% of 500 mrem, or 1% of 170 mrem. For practical purposes, the larger value often is applied to commercial areas that are occupied only for 8 hours a day, while the smaller value is reserved for residential, or bedroom areas. As the Stanford Linear Accelerator Center (SLAC), in common with other accelerators, is bounded by both residential and commercial areas (see Fig. 1), we are required to submit a detailed report on doses that exceed 1.7 mrem per year.

A recent EPA report (Klement, Jr., et al., 1972) summarizes measurements of the radiation doses within the United States due to natural background (cosmic ray and terrestrial in origin). For the United States, the average annual whole-body dose is about 130 mrem per year. The 1.7 mrem per year reportable dose required by the AEC is only 1.3% of natural background.

While measuring 1.7 mrem with any accuracy may be difficult it certainly is not impossible. There are sensitive TLD materials which will measure integrated doses as low as 1 mrem, and ion chambers that will measure microrem doses. However, to detect an incremental dose of 1.7 mrem in the presence of 130 mrem is a formidable problem indeed. When the effects of seasonal fluctuations, fallout from weapons testing in the atmosphere, and local variations due to atmospheric changes such as rain, inversion layers, etc., are included, the effects of which may alter background by as much as 20% (Adams and Lowder, 1964; McLaughlin, 1972), the 1.7 mrem produced by an accelerator would seem impossible to detect.

There are several ways of approaching the problem. For example, measurements may be made closer to the source where doses are larger, and simply extrapolated to large distances provided that the shape of the dose-vs-distance curve is well understood. In the case of non-continuous sources, instantaneous rates may be large enough to measure even though the total integrated doses are small. Also, gated and ungated counters may be compared in the case of pulsed accelerators.

Any method of measuring small doses in the presence of much larger doses means increasing the complexity of measurements, and should be done only when there is a genuine need for the information.

II. Skyshine (Neutrons)

It is only through the caprice of nature (neutrons are non-ionizing and therefore _must_ be measured separately) that it is possible to measure accelerator-produced doses that are such a small fraction of naturally occurring background with any certainty. Of the naturally occurring 130 mrem per year in the United States, 60 mrem comes from external and 25 mrem comes from internal terrestrial radiation, while 45 mrem comes from cosmic rays which consist of electrons, protons, muons, pions and neutrons (Klement, Jr., _et al._, 1972). A detector measuring only external ionizing radiation will detect about 100 mrem per year. The dose from naturally occurring neutrons at sea level and 50° longitude in the U.S. is about 7 mrem per year (Lowder and O'Brien, 1972). 1.7 mrem per year represents a 24% increase in this natural dose which can be detected without resorting to special equipment.

Neutrons comprise the largest measurable dose at the boundaries of most high energy accelerators (Rindi and Thomas, 1973). This is certainly true of SLAC. These neutrons are called 'skyshine', having been backscattered from the atmosphere. The term 'skyshine', refers to neutron sources which have been shielded laterally, but which are not shielded adequately from above. The effect is due primarily to giant resonance neutrons having energies of a few MeV, though at very large distances, these neutrons will be removed and only high energy neutrons ($E > 150$ MeV) will survive. The attenuation length for giant resonance neutrons is about 800 feet in air, while it is about 3300 feet in air for high energy neutrons.

Skyshine has been measured at many laboratories and reported extensively in the literature. Unfortunately the measurements don't agree. Upon reading these reports, one notes that there isn't a single unified theory that will explain the discrepancies. For neutrons at large distances, Lindenbaum (Lindenbaum, 1961) originally generated an empirical formula of the form, $D = Ke^{-r/\lambda}/r$ where D is the neutron dose, K is a source term, r is the distance in feet, and λ is given as 830 feet, the attenuation length for neutrons of a few MeV in air. He noted that high energy neutrons should not contribute much to dose except at quite large distances. Unfortunately when we are measuring 1.7 mrem/yr, we are usually speaking of quite large distances.

Ladu et al. (Ladu et al., 1968) at Frascati performed a Monte Carlo analysis of the diffusion of giant resonance neutrons, assuming skyshine is due only to neutrons in this energy region. In their analysis, there was no source term of high energy neutrons. They found that the dose-vs-distance curve could be fit by an exponential of the form, $D = K e^{-r/\lambda}$, with λ on the order of 200 meters. Bathow et al. (Bathow et al., 1966) at The Deutsches Elektron En-Synchrotron (DESY) measured skyshine out to 600 meters and fit their data with an expression of the form, $D = Ke^{-r/\lambda}/r$, the same as Lindenbaum but with $\lambda = 140$ meters. At Brookhaven, Distenfeld and Colvett (Distenfeld and Colvett, 1966) fit their measurements with an expression of the form $D = K e^{-r/\lambda}/r^2$ where $\lambda = 600$ meters. Their measurements extend to 900 meters. For large distances, the Lawrence Berkeley Laboratory (LBL) (Thomas, 1973) used $D = K e^{-r/\lambda}/r^2$ but with $\lambda = 3280$ feet which is the attenuation length for high energy neutrons. Each of these authors uses a different value for the source term, K, and some throw in modifiers to explain the behavior at close distances, but these don't alter the shapes of the curves at distances beyond a few hundred feet or so. The measurements beyond 1200 feet usually suffer from poor statistics which, in a sense, is like good and bad news. The good news is that accelerators simply aren't allowed to generate enough radiation to give good data at large distances, while the bad news is that without better data, it is impossible to make accurate estimates of small doses at large distances.

All of these expressions have been combined on one graph (Fig. 2), normalized at a distance of 600 feet to show how great a difference there is between the various expressions at distances larger than 1200 feet or so. It is impossible to fit all the measurements at each of the laboratories with a common expression, even with the uncertainties included in the measurements. In part, this may be due to topography. For example, LBL sits in the side of a hill. Measurements going up the hill aren't properly skyshine at all, but should be a combination of direct and reflected radiation. This problem is common to other accelerators.

A further uncertainty comes from an assessment of dose equivalence, i.e., converting from flux to dose. This wasn't a problem at Frascati where the computer simply followed all neutrons and their energies. However, they started with a source of only a few MeV in energy. The other laboratories made dose assessments in various ways. Brookhaven used a 12-inch sphere with a quasi-rem response. DESY used two polyethylene spheres with Li^6 crystals with the larger giving a quasi-rem response. They also used a moderated BF_3 counter to measure flux, and applied a QF to find dose. Their two methods agreed quite well.

LBL found an average neutron energy at fairly short distances from the bevatron, using nuclear emulsions, of 0.5 to 2 MeV. DESY calculated 0.5 MeV for the average energy after 5 collisions assuming a starting energy of 1 MeV. They measured 0.2 MeV. Frascati reported 0.24 to 0.4 MeV, Harwell 0.7 MeV, Dubna 0.7 to 3 MeV, Saclay 0.9 to 4 MeV and The Organisation Européenne pour La Recherche Nucléaire (CERN) 10 MeV. (Bathow et al., 1966). Within this energy region, the QF changes by some 30%.

To compound the problem further, so-called rem counters, either 10, 12-inch polyethylene spheres or the Anderson-Braun counter, have responses which only approximate the dose curve.

III. Measurements at SLAC

SLAC has a series of monitoring stations (PMS) along its periphery to measure boundary doses. The locations are shown in Fig. 1. Each station consists of neutron and ionizing radiation detectors with their associated electronics inside a wooden enclosure. The outputs of the electronics feed remote printers back at the Health Physics lab. There are eight PMS's at SLAC, seven of which surround the research area where the only measurable radiation levels are found. They range in distance from 1300 to 2400 feet from the research area. Each PMS has a Geiger counter and a moderated BF_3 counter for measuring neutron fluxes. Pulses from both counters are stored in scaling circuits and the raw data summed for 24 hours and then converted to dose. Every quarter, the daily doses are plotted as shown in Fig. 3, with the neutron and photon doses shown separately.

Photon doses. Under typical running conditions, it is impossible to measure any photon contribution to natural photon background at the boundary. However, a photon dose rate due to machine operation has been measured during unusual running conditions, such as occurred some years ago (see Fig. 3). At that time, the normal photon dose rate due to natural background increased by about 25% when the neutron dose rate increased by about 2800%. If we assume that this neutron-to-photon dose ratio (about 112-to-1) remains constant for the various running conditions (which would be the case if the photons come primarily from neutron capture), then a contribution from accelerator operation to the annual photon dose may be inferred from neutron measurements. For a natural photon background of 100 mrem per year, when the neutron dose from the accelerator doubles the annual neutron dose, the photon dose from the accelerator will be increased by 0.9%, or 0.9 mrem per year.

Neutron doses. As was noted earlier, in order to make an accurate estimate of small doses at large distances, the dose-vs-distance curve must be well known. Furthermore, reports from other labs are sufficiently in variance with each other at large distances that choosing the proper expression is impossible without additional information. Measurements taken at SLAC with a thick-wall, no-roof configuration can be fit with the DESY formula, $D = K\, e^{-r/\lambda}/r$ with $\lambda = 140$ meters, out to 600 feet. This is shown in Fig. 4. However, beyond 600 feet the slope changes, though statistics weren't sufficient to determine the exact shape. Data beyond 800 feet, taken when the beam dumped inside a tunnel with 3-foot-thick walls and roof, can be fit either with the Lindenbaum or the LBL formula (Fig. 5). The annual PMS data for 1971 can be fit with the LBL curve while the 1972 data is best fit with the Lindenbaum curve (Fig. 6).

The reason for these apparent differences may lie in the topography of SLAC. Figure 7 is an artist's sketch of SLAC showing the escarpments that surround the research area. These act as thick walls to the surrounding community, leaving an unshielded roof, so to speak. The only line of sight exists between three PMS's and the roof of End Station A (ESA). These three stations will receive a direct as well as scattered component of radiation whenever ESA is a source. There will be no direct radiation whenever End Station B (ESB), The Storage Ring (SPEAR) or the ESA tunnel are sources (see Fig. 1). Figure 8 is an elevation view of the research area and surrounding hills, clearly showing the efficacy of the berms in shadowing the environs of SLAC.

In 1971, ESA was the primary source of radiation at the boundary. The effect of removing the direct component of radiation at the PMS locations is to steepen the curve, bringing it closer to the Lindenbaum curve. In 1972, ESB was the primary source of radiation, and so no adjustment of the curve would be possible. It remains best fitted by the Lindenbaum formula.

All of this isn't meant to suggest that the Lindenbaum formula, $D = K e^{-r/\lambda}/r$ with $\lambda = 830$ feet,is the proper one to use at distances greater than 800 feet or so. Actually, it is intended only to point out the complexity of the problem in the absence of good, reliable data. It also points up the effect of topography on skyshine measurements. What happens at great distances from SLAC probably won't hold for other laboratories. SLAC may be one of the few laboratories where true skyshine exists, i.e., where there is no direct component of radiation except when ESA is a source. Third, when there are a multiplicity of source locations as may exist at SLAC when SPEAR, ESA and ESB all operate at the same time, the shape of the curve becomes confused. For example, it can approach a curve of the form, $D = K e^{-r/\lambda}/r$ with $\lambda = 3300$ feet.

At SLAC, assuming a QF of 10, the cosmic ray neutron dose, measured when the accelerator is off, averages about 1.2×10^{-3} mrem/hr, and is constant from PMS to PMS. This gives about 11 mrem per year. While annual doses at the PMS locations from the accelerator may range from below 4 to almost 15 mrem, the actual doses to populations are even less as the nearest dwellings are some 300 to 400 feet further distant. This is an increase in the natural radiation dose of about 10% in the highest case, and less than a few percent in the typical location. The question still remains as to what happens to these doses at distances greater than 3000 feet. (Chapter 0573 of the AEC Manual requires a contractor to estimate the man-rem dose to the whole body received by a population exposed within 50 miles of the facility.) It seems reasonable to assume that the curve will change, most probably into one containing λ equal to 3300 feet in one form or another. But without adequate data, it is impossible to know how this should be modified.

At considerable expense and perhaps an increase in dose to the surrounding population, the statistics of measurement at each laboratory could be increased. But the question still remains; is it really worth while when the doses in question are less than the variations in natural background? The requirement that one be able to state where he has added a 1.3% increment to natural radiation represents an exercise in futility for the conscientious health physicist. One need only remember that the annual dose rate increases by some 40 mrem, or more than 30% simply by moving from sea level to an elevation of 3000 feet (Gibson, 1964) before asking the question.

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Figure Captions

1. Overall view of SLAC and its immediate environs. Symbol X denotes a peripheral monitoring station.
2. Graphs of the various skyshine curves normalized at a distance of 600 feet.
3. Quarterly dose plot from a typical PMS during an early running period.
4. Skyshine measurements made at SLAC out to a distance of 600 feet. The solid line is the DESY formula, $D = K e^{-r/\lambda}/r$ with $\lambda = 140$ meters.
5. Measurements made along a line between ESA and one PMS, with the ESA tunnel as a source. Circles are points made along this line, triangles are data from various PMS which, except for one, are not along this measuring line (see Fig. 1). Solid Line — Lindenbaum; dashed line — LBL.
6. 1971 and 1972 annual PMS data at SLAC.
7. An artist's sketch of SLAC and the immediate environs.
8. Elevation view of the SLAC research area and surrounding environs.

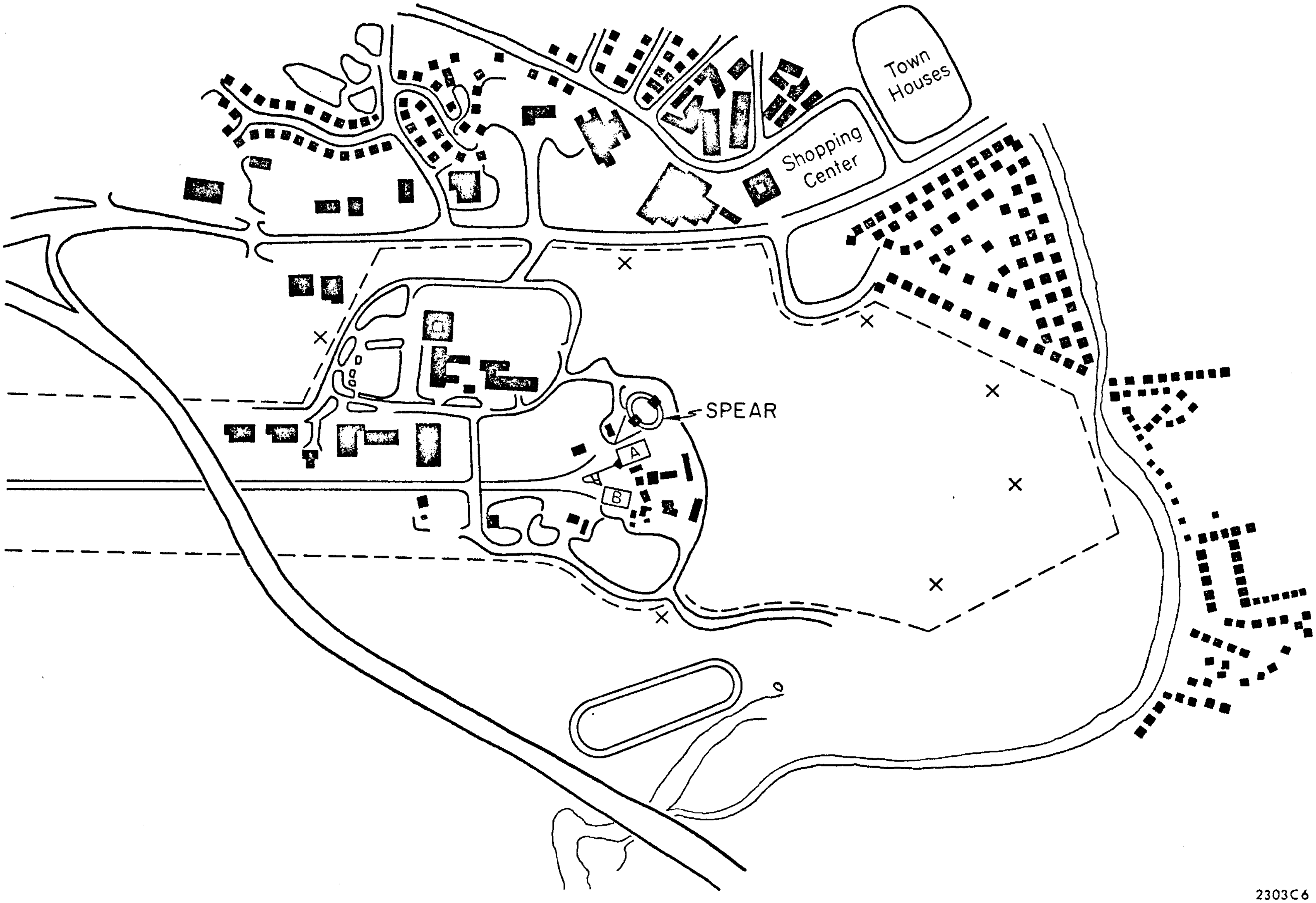


Fig. 1

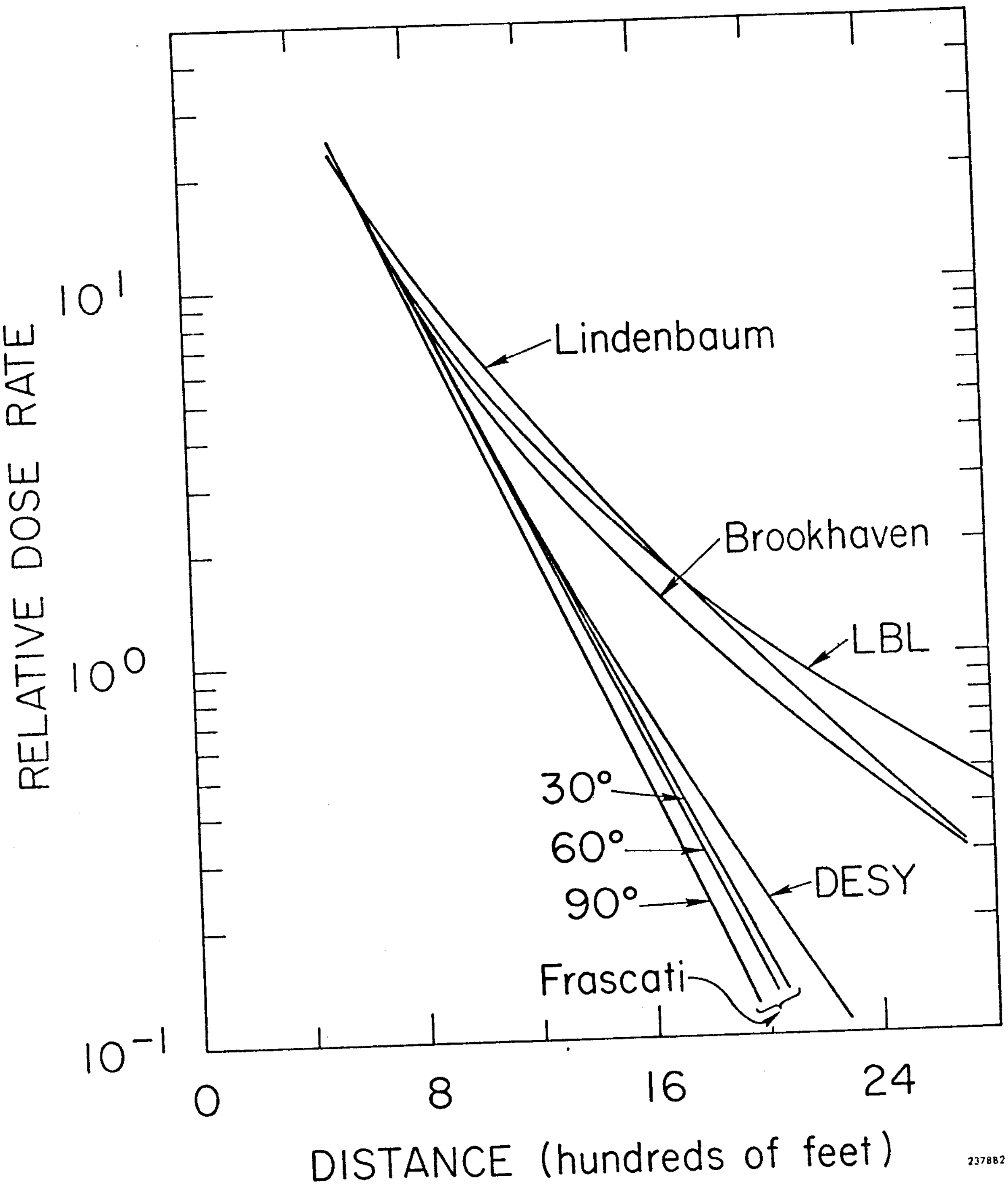

RELATIVE DOSE RATE
10^1
10^0
10^{-1}
Lindenbaum
Brookhaven
LBL
30°
60°
90°
DESY
Frascati
0
8
16
24
DISTANCE (hundreds of feet)
2378B2

Fig. 2

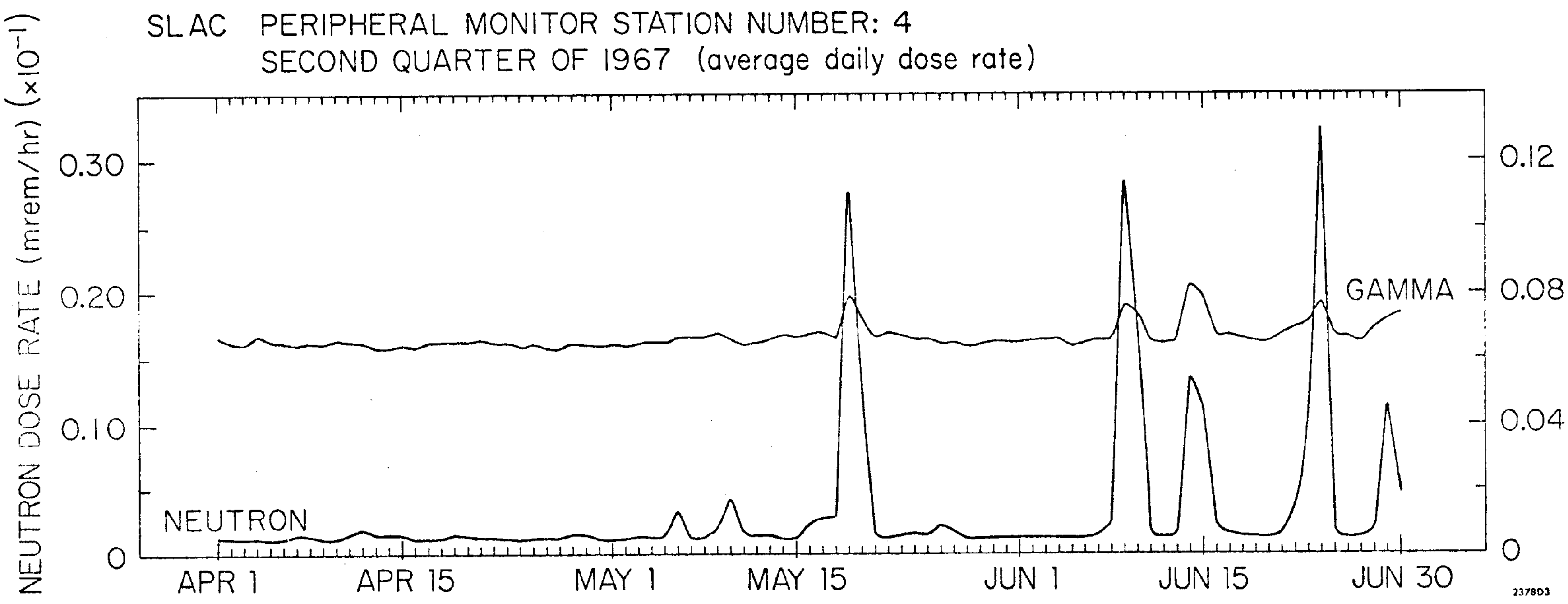
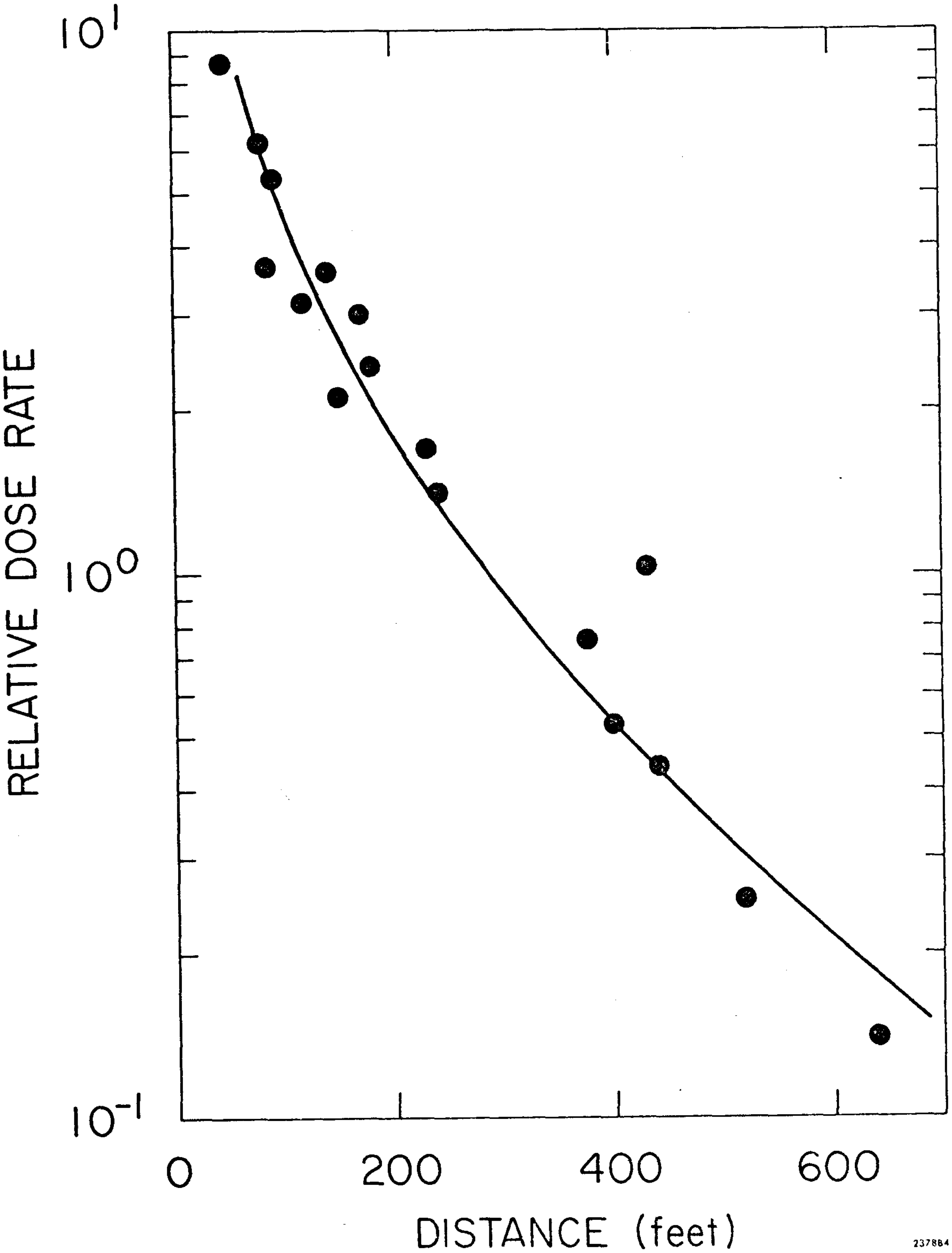
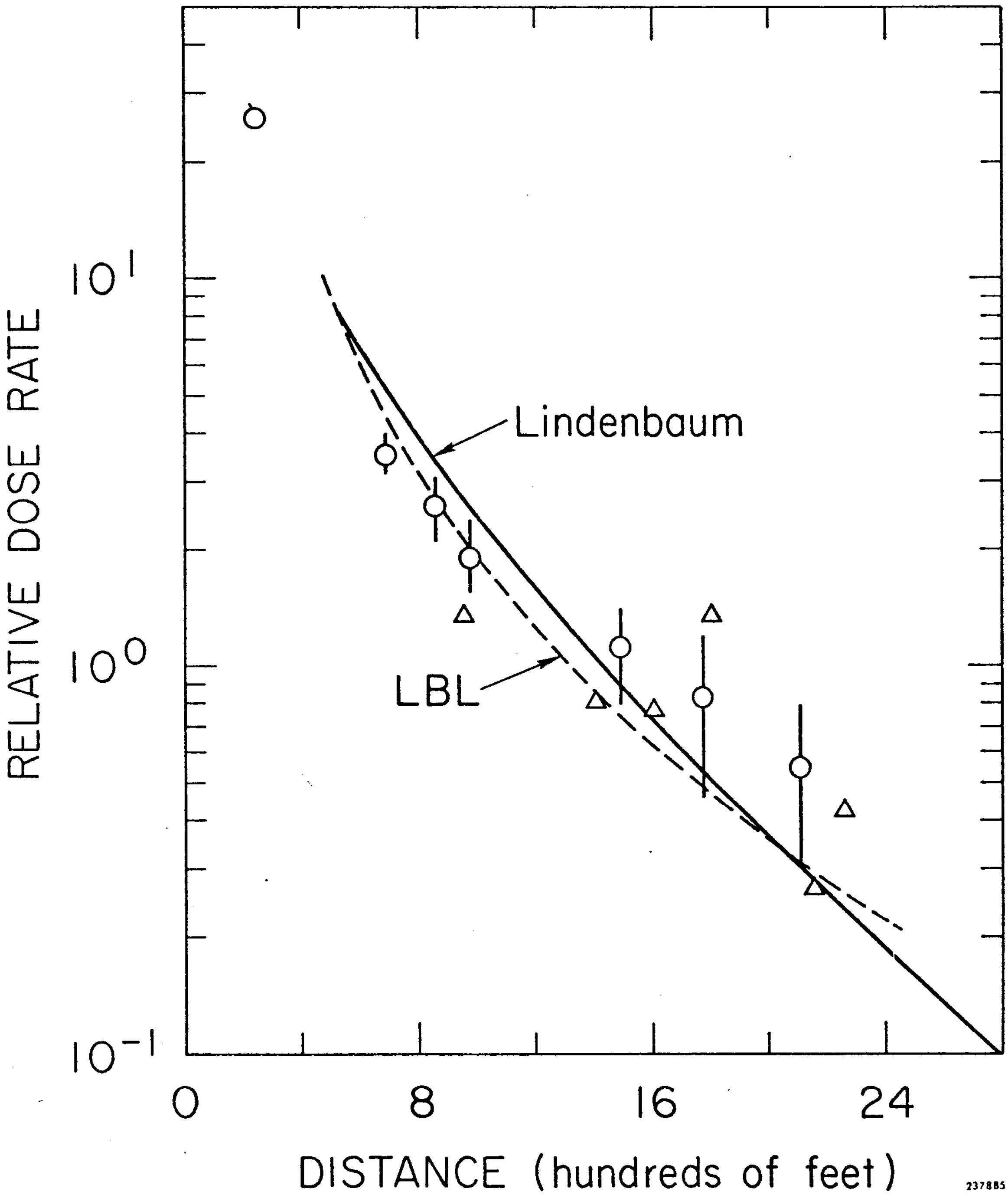

SLAC PERIPHERAL MONITOR STATION NUMBER: 4
SECOND QUARTER OF 1967 (average daily dose rate)
NEUTRON DOSE RATE (mrem/hr) (×10⁻¹)
0
0.10
0.20
0.30
GAMMA DOSE RATE (mrem/hr) (×10⁻¹)
0
0.04
0.08
0.12
NEUTRON
GAMMA
APR 1
APR 15
MAY 1
MAY 15
JUN 1
JUN 15
JUN 30
2378D3

Fig. 3



10^1
10^0
10^{-1}
RELATIVE DOSE RATE
0
200
400
600
DISTANCE (feet)
237884

Fig. 4



RELATIVE DOSE RATE
10^1
10^0
10^{-1}
Lindenbaum
LBL
0
8
16
24
DISTANCE (hundreds of feet)
237885

Fig. 5

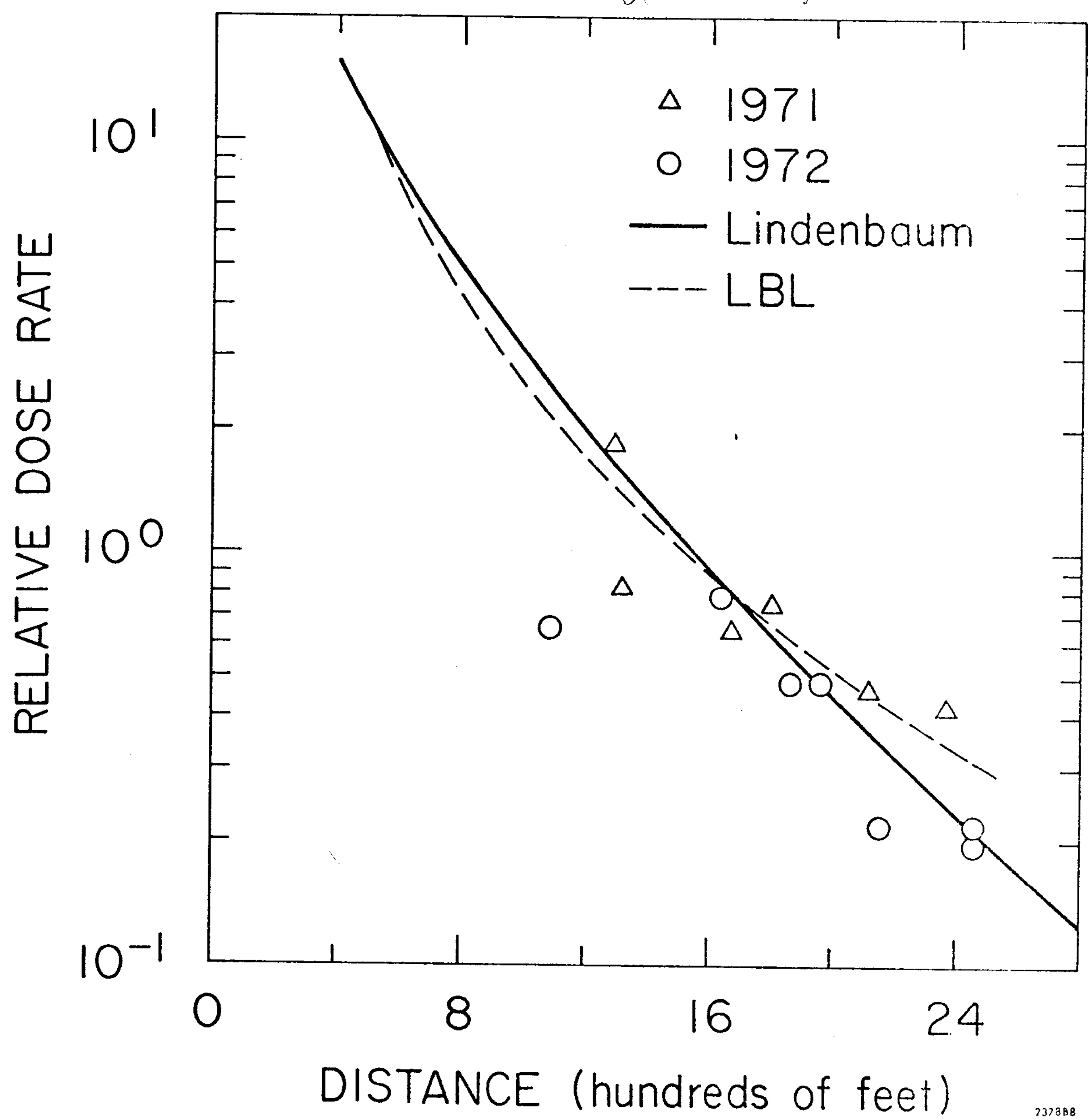

1971
1972
Lindenbaum
LBL
RELATIVE DOSE RATE
10^{1}
10^{0}
10^{-1}
0
8
16
24
DISTANCE (hundreds of feet)

Fig. 6

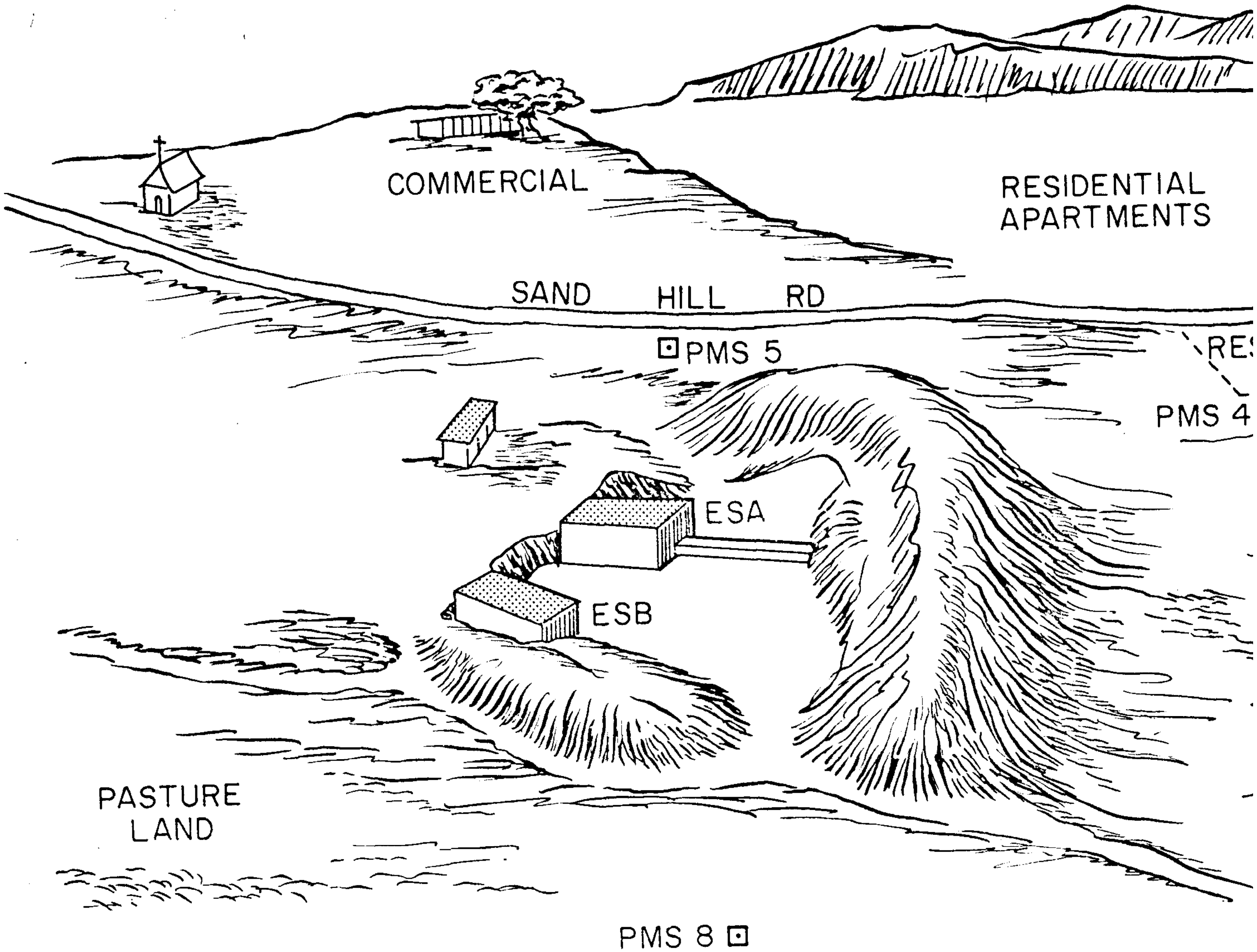

COMMERCIAL
RESIDENTIAL
APARTMENTS
SAND HILL RD
PMS 5
PMS 4
ESA
ESB
PASTURE
LAND
PMS 8

Fig. 7

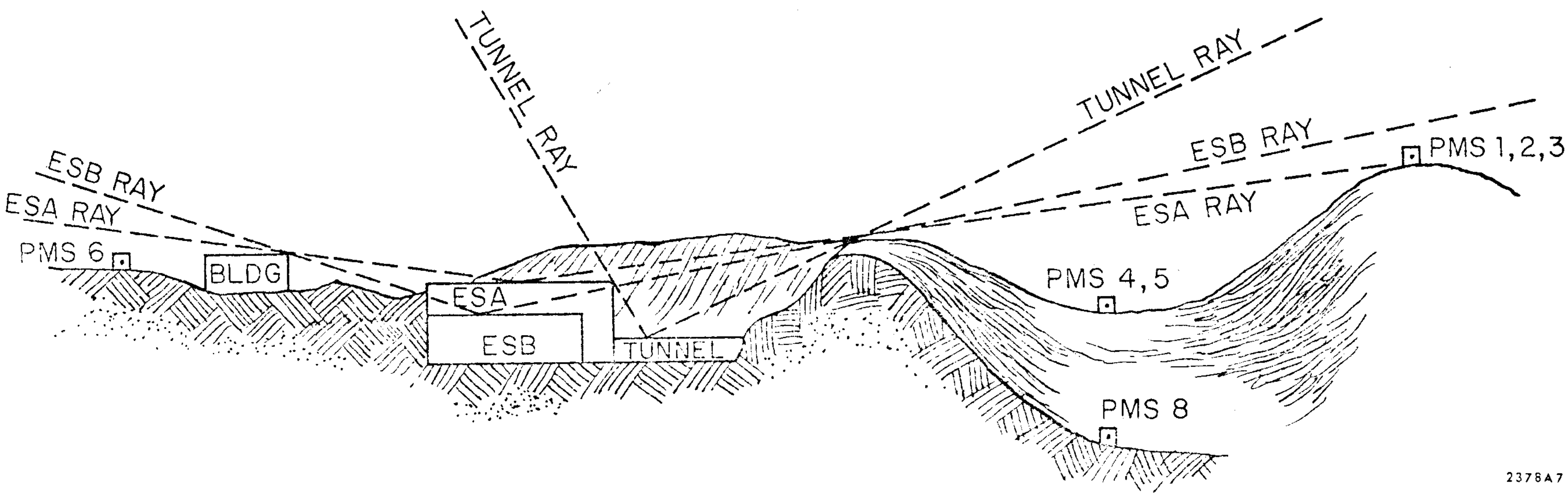

TUNNEL RAY
ESB RAY
ESA RAY
PMS 6
BLDG
ESA
ESB
TUNNEL
TUNNEL RAY
ESB RAY
ESA RAY
PMS 1,2,3
PMS 4,5
PMS 8
2378A7

Fig. 8