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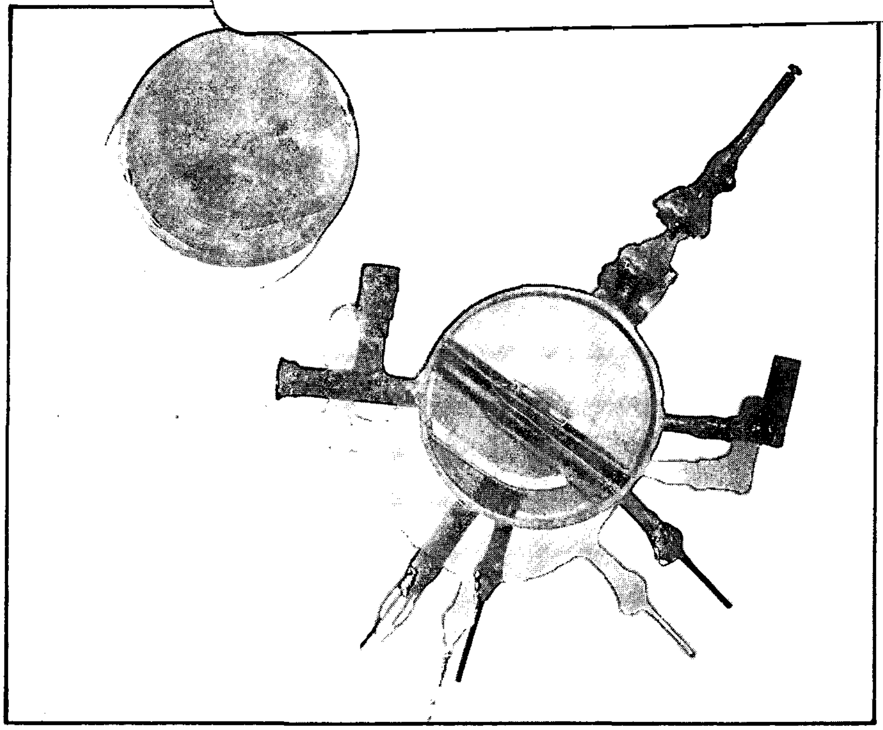

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Abstract

The Advanced Light Source (ALS) complex at the Lawrence Berkeley Laboratory (LBL) is located within the circular dome structure of the decommissioned 184-Inch Synchrocyclotron, Building 6 in Fig. 1, and is surrounded by a mezzanine and auxiliary buildings. The main active components are a 50-MeV linear accelerator, a 1.5-GeV booster and its beam extraction line, and a 1.9-GeV storage ring. An important radiological problem is the neutron dose equivalent in nearby occupied areas, e.g. mezzanine, and at the LBL site boundary. Both the direct and air-scattered (skyshine) components of the neutron dose equivalents generated by ALS active components are evaluated using the neutron transport code MORSE, from Oak Ridge National Laboratory (ORNL). The shielding was designed using an empirical method based both on data scaled from a 1977 SLAC experiment at 15 GeV and on a compilation of experimental and theoretical material relevant to shielding of electron accelerators.

From the MORSE calculation, the total occupational dose equivalent rate in the center of the ALS mezzanine was found to be less than 1 mSv (100 mrem) per shift year (2000-hr), and the total environmental dose equivalent rate at the ALS boundary, 125 m from the storage-ring center, was found to about 302 μSv (30 mrem) per year. A comparison of the dose equivalents shows that the calculated

MORSE-code values agree well with those estimated by the empirical method. That is, dose equivalents (H) obtained by the empirical methods are of the same order of magnitude as the corresponding MORSE values.

I. Introduction

The Lawrence Berkeley Laboratory (LBL) actively applies the U. S. Department of Energy (DOE) regulatory radiation safety limits to ensure minimal risk to the general public and LBL personnel from operation of the LBL Advanced Light Source (ALS).

To ensure that no member of the general public will receive a dose equivalent (H) over a DOE long-term-limit of 1 mSv yr^{-1}, an administrative action level of 250 μSv yr^{-1} will be observed along with a ALS design goal of less than 100 μSv yr^{-1}. Levels of occupational exposure will be limited to 50 mSv yr^{-1} and, as design goals, to 10 mSv per calendar year (8760-hr) and 2.5 mSv per shift year (2000-hr).

II. General Description of the ALS Complex

The ALS complex consists of several active components arranged within the circular dome structure of the decommissioned 184-Inch Synchrocyclotron and surrounded by a mezzanine and auxiliary buildings, Fig. 2. The four groups of active components that are the main sources of radiation are briefly described as follows:

(1) A 50-MeV linear accelerator (LINAC), 4 m long, is connected to a Linac-to-booster (LTB) transfer line, 17 m long, through a collimator. The LINAC has an intensity of 8.00×10^{10} e^{-} $cycle^{-1}$. For this study, pulse rate of operation for the ALS system is assumed to be 4 Hz (a conservative value; normal operation is expected to be at 1 Hz). A shielded beam dump is provided for beam disposal during tuneup. The LINAC system has a loss (for the collimator and LTB), of 4.80×10^{10} e^{-} $cycle^{-1}$ and will deliver to the booster 3.20×10^{10} e^{-} $cycle^{-1}$. Fig. 3 shows the intensity, (e^{-} $cycle^{-1}$), in the active components, and Fig. 4 shows their losses.

(2) A 1.5-GeV booster ring (BR) has a radius R_{BR} of 11.94 m. A well-shielded beam dump accommodates long-term beam disposal. The tuneup time for each filling cycle is 1 hour at 25% intensity followed by 0.25 hour at full intensity. The BR itself has a loss of 0.93×10^{10} e^- $cycle^{-1}$, and will deliver 2.27×10^{10} e^- $cycle^{-1}$ to the extraction line.

(3) A 1.5-GeV booster-to-storage (BTS) extraction line is 20 m long. It has an internal loss of 0.65×10^{10} e^- $cycle^{-1}$ and will deliver 1.62×10^{10} e^- $cycle^{-1}$ to the storage ring.

(4) A storage ring (SR), with a radius of 31.32 m, operates at energies of 1.5–1.9 GeV. The SR has an internal loss of 0.32×10^{10} e^- $cycle^{-1}$, which leaves 1.30×10^{10} useful electrons per cycle. If the current in the SR is 800 mA (a conservative assumption), the SR should store 3.3×10^{12} e^-, with the number of cycles per fill calculated to be $(3.3 \times 10^{12} / 1.3 \times 10^{10}) = 254$.

III. Shielding Design and Results

All the active components of ALS will be shielded with concrete walls and ceilings.

Design Methodology

Shielding designs for the ALS are based both on experimental data scaled from an 1977 experiment at 15 GeV at the Stanford Linear Center (SLAC) [1,2] and on a compilation of experimental and theoretical material relevant to shielding of electron accelerators [3].

In general, the photon component of the ambient radiation field will be much larger than the neutron component for the shielding thicknesses specified for the storage and booster rings. Both direct bremsstrahlung production in the target material and photons produced through neutron interactions in the concrete shield are considered in Eq. (1). Meanwhile, for the neutron dose equivalent from giant-resonance, mid-energy, and high-energy neutron, Eq. (2) is useful.

The unit for H_γ and H_n is $\mathrm{mSv^{-2}cm^2GeV^{-1}}$.

$$H_\gamma = 10^{-10} E_o \left[\frac{\sin\theta}{R}\right]^2 \left[\frac{133 \exp\left[-\frac{\mu}{\rho}\frac{\rho d}{\sin\theta}\right]}{(1-0.98\cos\theta)^{1.2}} + \frac{0.27 \exp\left[-\frac{\rho d}{\lambda_1 \sin\theta}\right]}{(1-0.72\cos\theta)^2}\right], \tag{1}$$

and

$$H_n = 10^{-10} E_o \left[\frac{\sin\theta}{R}\right]^2 \left[\frac{13.7 \exp\left[-\frac{\rho d}{\lambda_1 \sin\theta}\right]}{A^{0.65}(1-0.98\cos\theta)^{1.2}} + \frac{10 \exp\left[-\frac{\rho d}{\lambda_2 \sin\theta}\right]}{(1-0.75\cos\theta)} + 4.94\, Z^{0.66} \exp\left[-\frac{\rho d}{\lambda_3 \sin\theta}\right]\right] \tag{2}$$

where

H_γ	the dose equivalent (mSv) due to photons, per GeV-electron, normalized to 1 cm distance,
H_n	the dose equivalent (mSv) due to neutrons, per GeV-electron, normalized to 1 cm distance,
E_o	electron energy in GeV,
R	distance normal to the beam line to outer shield surface (cm),
μ/ρ	0.24 $\mathrm{cm^2\ g^{-1}}$, mass attenuation coefficient for the Compton minimum in the target material (8 MeV for iron),
d	shield thickness at 90° to beam direction (cm),
λ_1	120 $\mathrm{g\ cm^{-2}}$, the attenuation length of high-energy neutrons in concrete,
λ_2	55 $\mathrm{g\ cm^{-2}}$, the attenuation length of mid-energy neutrons in concrete, (1 tenth-value layer = 53 cm)
λ_3	30 $\mathrm{g\ cm^{-2}}$, the attenuation length of giant-resonance neutrons in concrete, (1 tenth-value layer = 29 cm),
ρ	density of ordinary concrete, 2.25 $\mathrm{g\ cm^{-3}}$, used in these calculations,
θ	angle with respect to beam direction,
A	the atomic weight of the target material, and
Z	the atomic number of the target material.

The angle with respect to the beam direction θ at which the dose equivalent is the maximum, θ_{max}, is not the same for neutrons as for photons. For purposes of calculating the H outside the shielding for point losses, the photon H at θ_{max} is added to the neutron H at that same angle (θ for neutrons, θ_{max} for photons). Extended uniform-loss calculations were made through application of the Moyer Model principles [4] to these point-loss calculations.

Calculated Results

The dose equivalents from the storage ring and the booster ring are calculated based on the uniform distributed loss round the rings and the loss at a point.

(1) Storage ring

For the point-loss case, the H is the value expected outside the shield wall, should a full ring of 0.8 A (3.3×10^{12} electrons for 1 kJ at 1.9 GeV) impact accidentally at a point. For the concrete shielding with the inner and outer walls of 45.72 cm (1.5 ft) and a ceiling of 30.48 cm (1 ft), the H would be 0.4 mSv per event at the outside surface of the wall.

For the uniform-distribution case, the H is determined as following. If 2 fills per shift are assumed, the integrated H outside the shield wall during each shift (for a uniform distribution of $2 \times 4.1 \times 10^{12} = 8.2 \times 10^{12}$ electrons lost around the ring) is calculated to be 8 μSv per shift or 2 mSv per 2000-hr shift year.

(2) Booster ring

For the point-loss case, it postulated that a 10-sec loss of full-beam intensity of 2.6×10^{10} electrons per cycle at a 4-Hz rate would be the maximum loss before detection and corrective action. With 76.2-cm (2.5-ft) concrete walls and ceilings for shielding, the H is about 8 μSv.

The distributed-loss case is based on the assumption that 12.5% of the accelerated beam, 3.2×10^{9} electrons per cycle, is lost uniformly around the booster ring during extraction. This results in a H of 16 μSv per shift or 4 mSv per 2000-hr shift year at the surface of the shield.

(3) 50 MeV LINAC

The LINAC and the beam dump are shielded with concrete walls f 91.44 cm (3 ft) thick and a ceiling 60.96 cm (2 ft) thick. At a repetition rate of 4 Hz, the power for the LINAC is $(4\ \text{Hz})\cdot(8 \times 10^{10}\ e^{-}\text{cycle}^{-1})\cdot(5 \times 10^{7}\ \text{V})\cdot(1.6 \times 10^{-19}\ \text{C}) = 2.5\ \text{W}$. With the assumption that the power incident on the dump is twice this amount, the H outside the shield will be 50 μSvhr^{-1}.

(4) Mezzanine radiation levels

Forty m from the center of the storage ring (OS), through the center of the booster ring, the calculated dose equivalent at the elevation of a 2nd-floor office is about 3.3 mSv per 2000-hr shift year. This corresponds to the highest expected level of H for uniform dose distribution around both rings, because it is closest to both rings at that point. The H at other positions at a radius of 40 m about the OS will be less.

(5) Environmental radiation levels

Calculations that assume a single-scattering approximation for photons [5] show that the LBL site boundary yearly dose equivalent from photons is 10 μSv for the entire ALS due to photon skyshine. For neutrons, the ALS is expected to contribute 100 μSv per year through skyshine [6]. The total dose equivalent of 110 μSv per year at the boundary (125 m from OS), is a small fraction of the natural radiation background of about 800 μSv per year for this location.

Although the H values shown here do not reflect the possible increase of a factor of two in neutron quality factor,[1] such a change would increase the local determination of H by about 50% (since in present terms, the H is approximately equally divided between neutrons and photons). At the site boundary, where the H is due essentially to the neutrons only, the reported H would be doubled.

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[1] The International Commission on Radiological Protection (ICRP) has recently (1985) recommended that the quality factor for neutrons be doubled. DOE has not yet followed this recommendation.

IV. MORSE Code Calculation

In using the MORSE code [7], point-detector estimators were chosen. The media used in the various geometry regions were vacuum, air, and concrete with a density $\rho = 2.25$ g cm^{-3}. The main MORSE program was modified into four versions of its subroutine SOURCE so that the code could be run for the LINAC, the BR, the BTS, and the SR, individually. These subroutines account for the positions and the shapes of the four active components that are the sources of radiation. The geometric model of the ALS complex used for the MORSE-code calculation is shown in Fig. 5.

Input and Output Files

The input file data give details of the geometry model of the ALS complex, which includes active components and their shielding with walls and ceilings as a whole unit, the media in various regions, and the locations of the point detectors. In using the MORSE code, only general simplifications were made that do not include albedo calculations and Russian roulette games. A giant-resonance spectrum was chosen as the source.

In the output file, the resulting neutron dose equivalents for point detectors are normalized to the uniform electron beam loss, in units of Sv per J of beam power consumed, with the assumption that 1 J of energy yields 1×10^9 neutrons.[2]

In the results the typical fractional standard deviations are about ± 0.25 for the long productive runs, with 1000 neutrons per batch for 10 batches, and about ± 0.45 for the short test runs, with 100 neutrons per batch for 10 batches.

Results of Calculation

The main program of the MORSE code has been arranged so that the point detectors show the total neutron radiation at that point, i.e., the sum of skyshine and direct neutrons. Two locations must be considered:

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[2] This important assumption comes from IAEA 188 [3], page 87, Fig. 34, which shows the neutron yields from infinitely thick targets, per kw of electron beam power, as a function of electron beam energy, disregarding target self-shielding. We are using Cu or Fe above 100 MeV for the MORSE calculation.

- Location (1), inside the mezzanine 39 m from the ALS center along the line joining the BR center and the OS and 6 m above the ground floor, where the annual occupational dose equivalent (2000-hr) is considered.
- Location (2), the LBL boundary at its nearest point to the ALS complex 125 m from the ALS center and 2.4 m above the ground, on the south side of the complex, where the environmental dose equivalent (8760-hr) is considered.

The annual occupational dose equivalents (2000-hr) at location (1) and the annual environmental dose equivalents (8760-hr) at location (2) are summarized in Table 1 [7], Figs. 6 and 7.

V. Comparison and Conclusion

In Section III, some estimated values for dose equivalent in various locations are given under the subsection ***Calculated Results***, where in items (1)–(3) the H values for the individual active components are calculated without taking into account of all the shielding in the ALS complex. Those H values will not be used for comparison. In item (4) the occupational H value is given as 3.3 mSv per 2000-hr shift year which is comparable to the MORSE H value of 1.14 mSv per 2000-hr shift year. Also, in item (5), the environmental H value at the LBL boundary is obtained as 110 μSv per calendar year, which is also comparable to the MORSE H value of 302 μSv per year.

The discrepancy of the H-values seems to be quite considerable, but one must keep in mind that those values obtained from the empirical method are based upon the shield thickness for individual components without accounting for the geometry of the whole complex. On the other hand, the neutron-yields of 1×10^9 neutrons per Joule is assumed at an electron beam energy above 100 MeV. The yields could be much less at an energy of 50 MeV, (about 20–50% for Cu or Fe), which is the energy for the LINAC and LTB. Therefore, the contribution to H by these two active components can be much less than that given in Table 1, and the discrepancy of the H-values between the MORSE and the empirical model would be reduced. After all, the H values for either occupational or environmental dose are the same order of magnitude, and a factor of 2 or 3 is quite common for the dose-equivalent estimation.

The beam-loss data used by the MORSE code are extremely conservative. For example, in normal operation, it will require only 0.4 A, not 0.8 A, with a pulse rate of 1 Hz, not 4 Hz, and the total time of ALS operation could be as low as 6000 h y^{-1}, not 8760 h y^{-1}. If all these factors are considered, a reduction factor of (0.4 / 0.8)(1 / 4)(6000 / 8760) = 0.086 could be applied to the H values obtained above. Therefore, the annual dose equivalent rates in nearby occupied areas of the ALS and at the LBL site boundary would be estimated to be much lower than the allowed DOE regulatory limits for radiation exposure, as illustrated by Table 2 [7]. In addition, some local shielding near the LINAC, collimators, and other components, and the shielding effect of equipment, furniture, partitions, etc., inside the ALS complex, were not considered; consequently, the calculated dose equivalents are higher than those expected to be observed. It can, therefore, be concluded that the ALS shielding was adequately designed, and complies both with radiological protection and environmental dose limits.

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[5] J. C. Courtney, Editor, Handbook of Radiation Shielding Data, Louisiana State University, Baton Rouge, LA, 1976.

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Table 1. Annual dose-equivalent (H) rates for ALS (most-conservative values).

Maximum occupational dose equivalent on the mezzanine

(39 m from ALS center and 6 m above ground floor, 2000-hr y^{-1})

Quantities	Active components				Total
	LINAC/LTB	BR	BTS	SR	
H from MORSE ($Sv\ J^{-1}$)	4.30×10^{-10}	1.04×10^{-10}	1.33×10^{-11}	3.22×10^{-13}	—
Annual energy loss ($J\ y^{-1}$)	1.39×10^{6}	2.88×10^{6}	1.95×10^{5}	6.23×10^{5}	—
Calculated H rate ($Sv\ y^{-1}$)	5.98×10^{-4}	2.99×10^{-4}	2.59×10^{-6}	2.00×10^{-7}	—
Modified[a] annual H ($Sv\ y^{-1}$)	7.62×10^{-4}	3.82×10^{-4}	3.31×10^{-6}	2.55×10^{-6}	1.14×10^{-3}
Annual H estimated with empirical formula, item (4) ($Sv\ y^{-1}$)					3.30×10^{-3}

Maximum environmental dose equivalent at boundary

(125 m from ALS center and 2.4 m above ground, 8760-hr y^{-1})

Quantities	Active components				Total
	LINAC/LTB	BR	BTS	SR	
H from MORSE ($Sv\ J^{-1}$)	2.74×10^{-11}	5.46×10^{-12}	1.24×10^{-13}	2.08×10^{-13}	—
Annual energy loss ($J\ y^{-1}$)	6.09×10^{6}	1.26×10^{7}	8.57×10^{6}	2.72×10^{6}	—
Calculated H rate ($Sv\ y^{-1}$)	1.67×10^{-4}	6.88×10^{-5}	1.06×10^{-6}	5.66×10^{-7}	—
Modified[a] annual H ($Sv\ y^{-1}$)	2.13×10^{-4}	8.78×10^{-5}	1.35×10^{-6}	7.22×10^{-7}	3.02×10^{-4}
Annual H estimated with empirical formula, item (5) ($Sv\ y^{-1}$)					1.10×10^{-4}

[a] Including 25% for intermediate-energy neutrons and 2.5% for high-energy neutrons.

Table 2. Annual dose-equivalent (H) rates for ALS (realistic).

Maximum occupational dose equivalent on the mezzanine

(39 m from ALS center and 6 m above ground floor)

Quantities	Active components				Total
	LINAC/LTB	BR	BTS	SR	
H from MORSE (Sv J^{-1})	4.30×10^{-10}	1.04×10^{-10}	1.33×10^{-11}	3.22×10^{-13}	—
Annual energy loss[a] (J y^{-1})	1.22×10^{5}	2.52×10^{5}	1.07×10^{4}	5.45×10^{4}	—
Calculated H rate (Sv y^{-1})	5.15×10^{-5}	2.62×10^{-5}	2.27×10^{-7}	1.75×10^{-8}	—
Modified[b] annual H (Sv y^{-1})	6.67×10^{-5}	3.34×10^{-5}	2.90×10^{-7}	2.23×10^{-7}	1.00×10^{-4}
Annual H estimated with empirical formula, item (4) (Sv y^{-1})					3.30×10^{-3}

Maximum environmental dose equivalent at boundary

(125 m from ALS center and 2.4 m above ground)

Quantities	Active components				Total
	LINAC/LTB	BR	BTS	SR	
H from MORSE (Sv J^{-1})	2.74×10^{-11}	5.46×10^{-12}	1.24×10^{-13}	2.08×10^{-13}	—
Annual energy loss[a] (J y^{-1})	5.33×10^{5}	1.10×10^{6}	7.50×10^{5}	2.38×10^{5}	—
Calculated H rate (Sv y^{-1})	1.46×10^{-5}	6.02×10^{-6}	9.27×10^{-8}	4.95×10^{-8}	—
Modified[b] annual H (Sv y^{-1})	1.86×10^{-5}	7.68×10^{-6}	1.18×10^{-7}	6.31×10^{-8}	2.65×10^{-5}
Annual H estimated with empirical formula, item (5) (Sv y^{-1})					1.10×10^{-4}

[a] Calculation with SR current 0.4 A, injection rate 1 Hz, and use factor 0.7.

[b] Including 25% for intermediate-energy neutrons and 2.5% for high-energy neutrons.

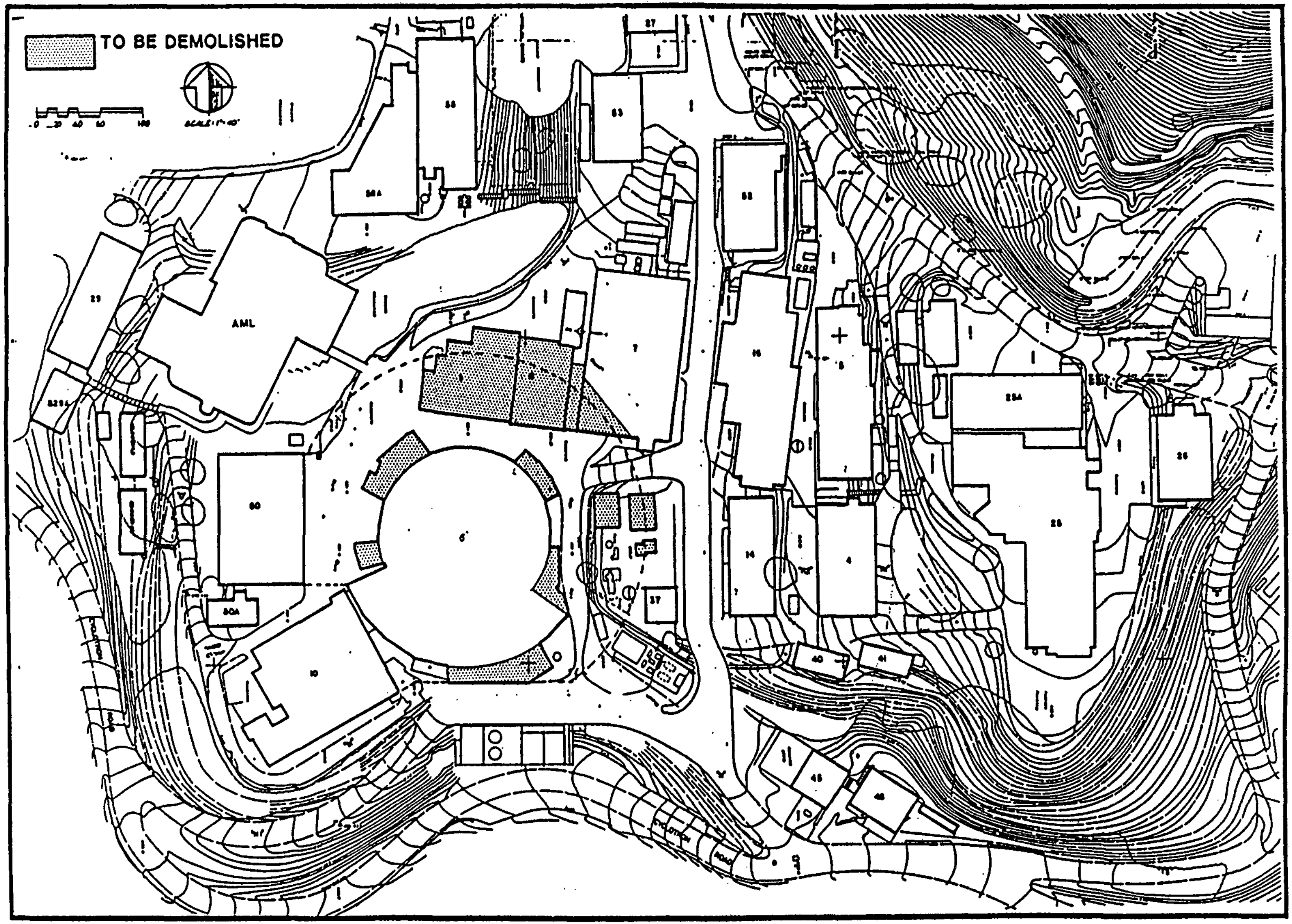


Fig. 1 A layout of the ALS in Lawrence Berkeley Laboratory

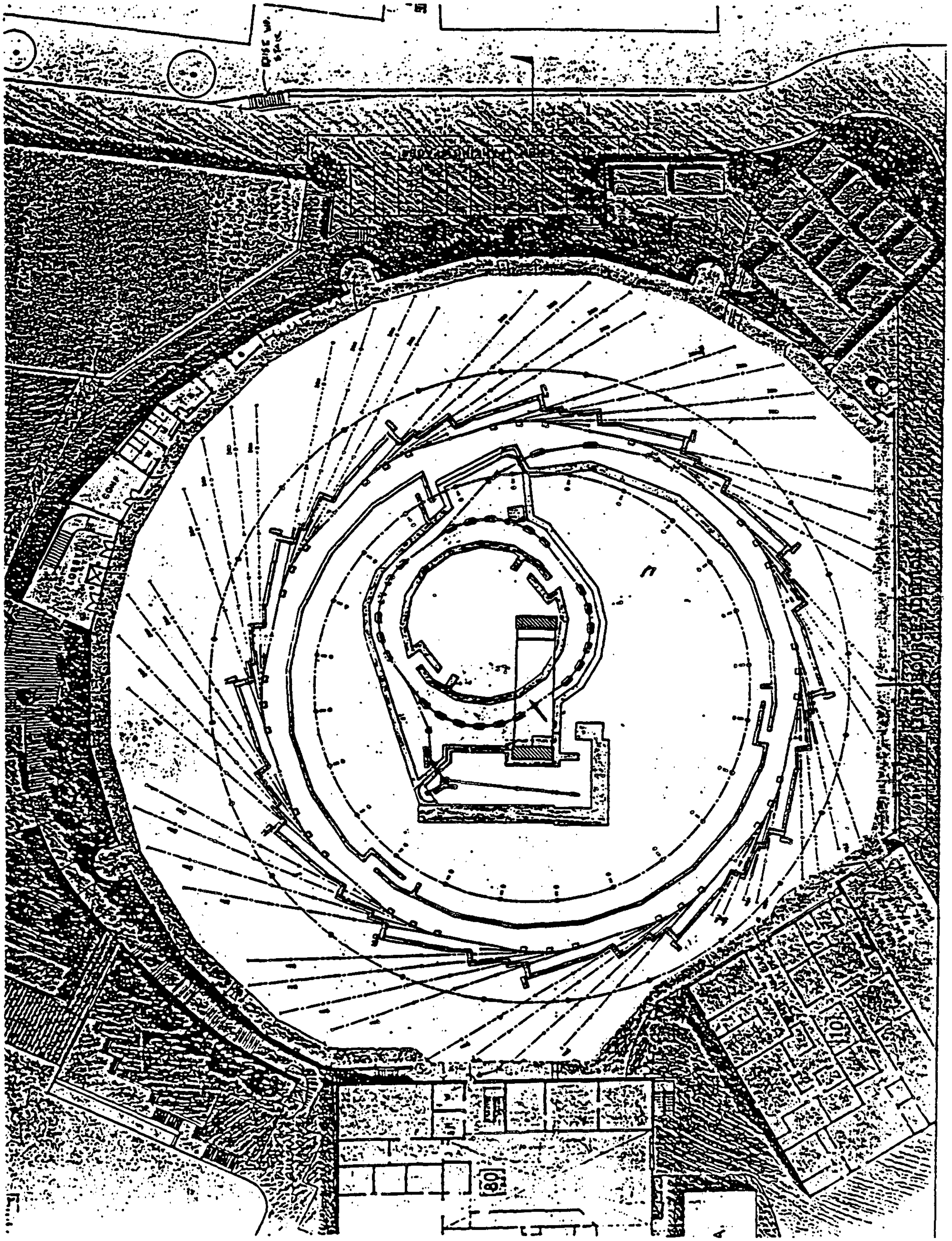
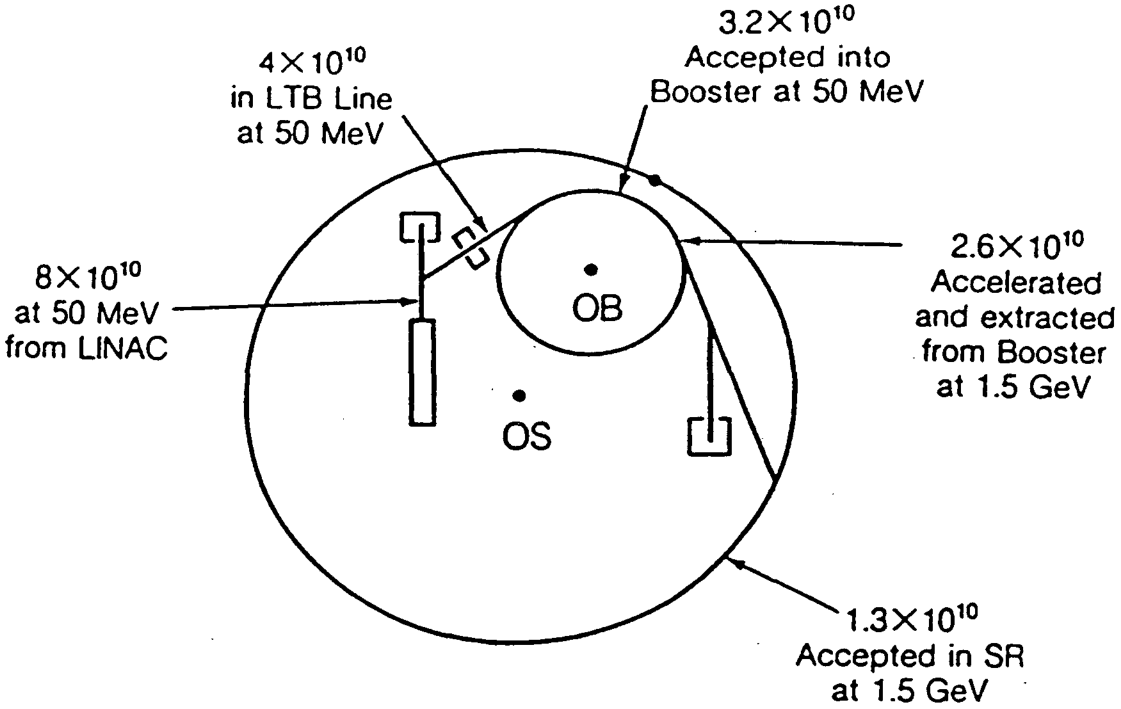


Fig. 2 A detailed layout of the ALS research facilities, showing the injection system, the booster, the storage ring, insertion.



To fill SR to 0.8 A:

$$\frac{3.3\times10^{12}\ \text{Electrons/Fill}}{1.3\times10^{10}\ \text{Electrons/Cycle}} = 254\ \text{Cycles}$$

Note: OB = Center of Booster Ring; OS = Center of Storage Ring.

Fig. 3 Intensity (electrons/cycle) in Booster and Storage Rings

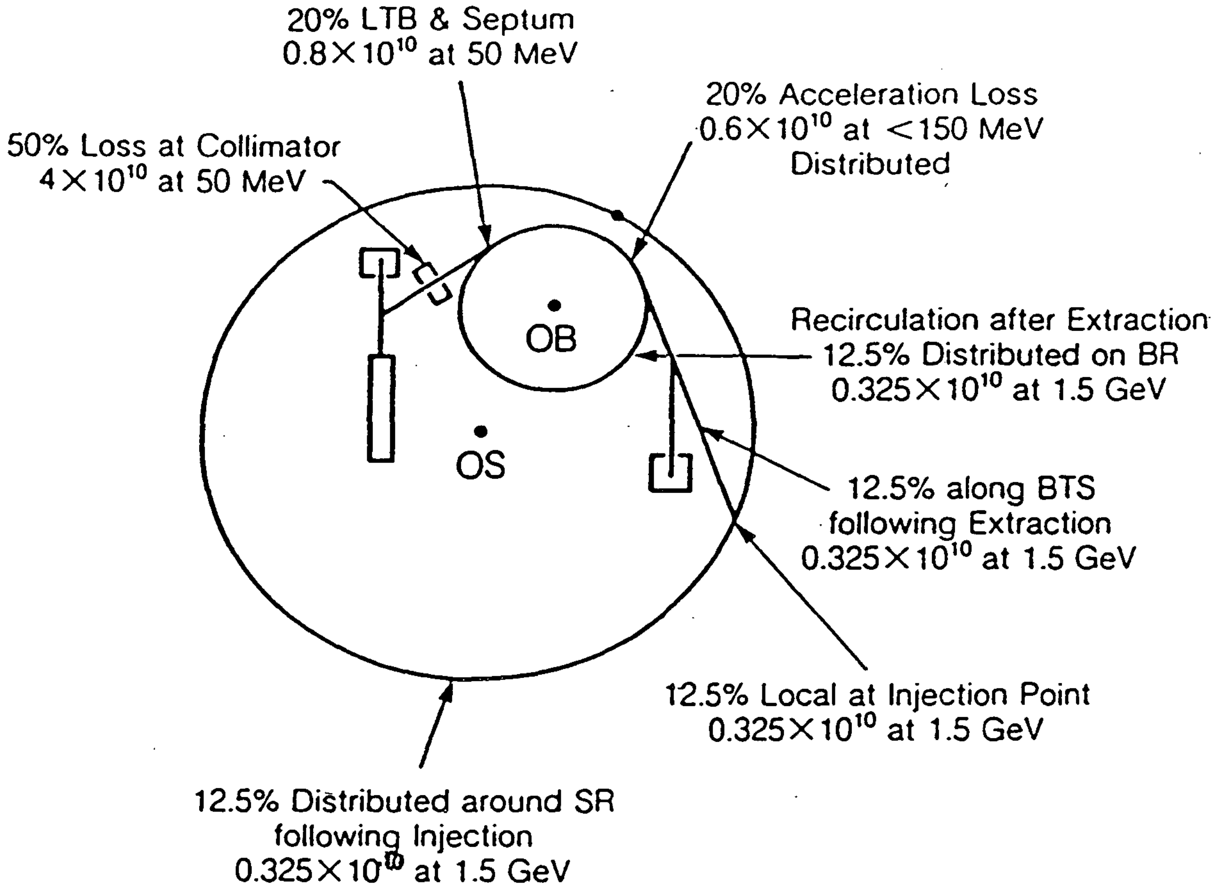


Fig. 4 Injection Losses in Booster and SR (electrons/cycle)

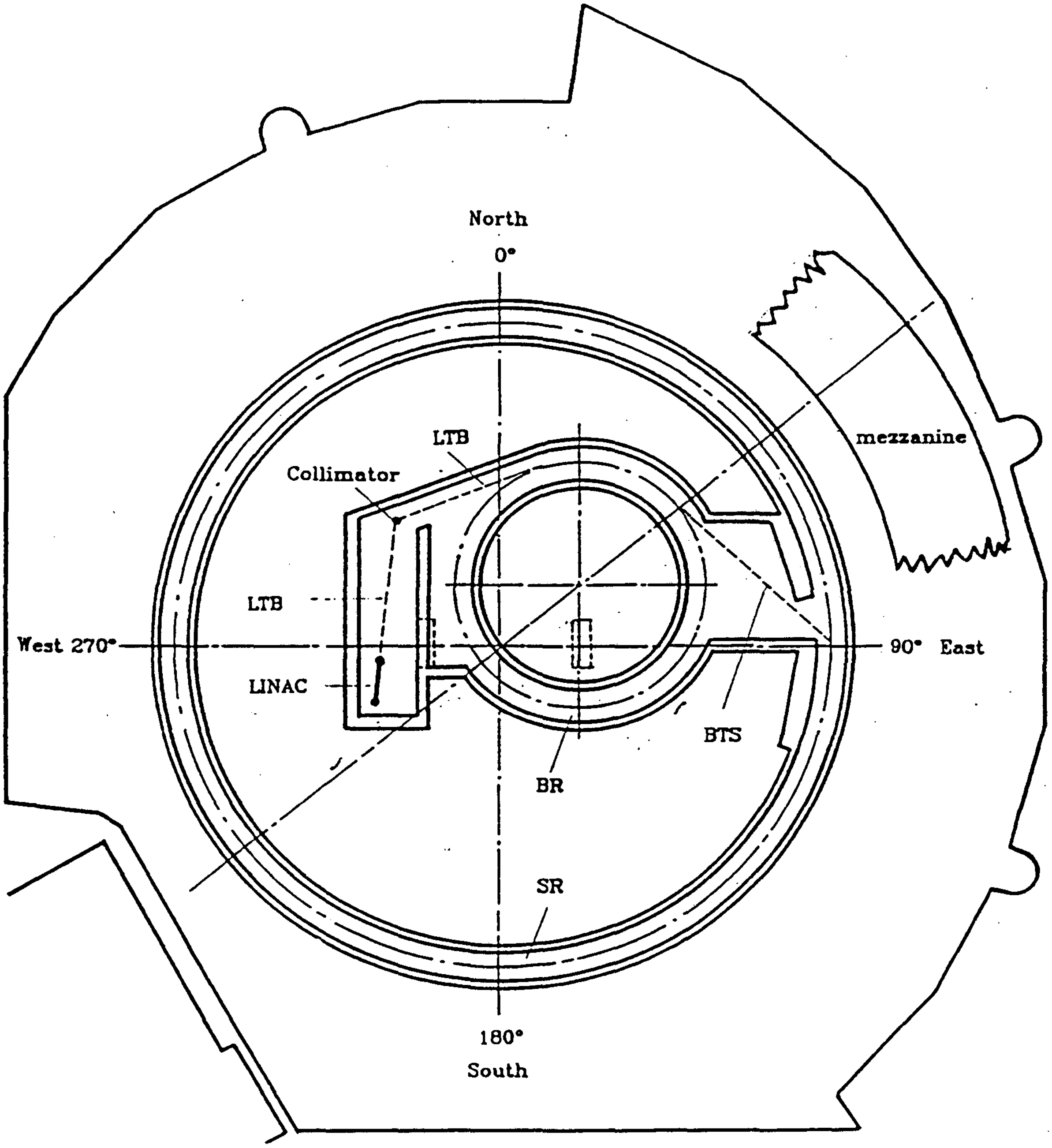


Fig. 5 The geometric model of the ALS research facilities used the MORSE code calculation. This model is slightly different from, but still close to, the detailed layout.

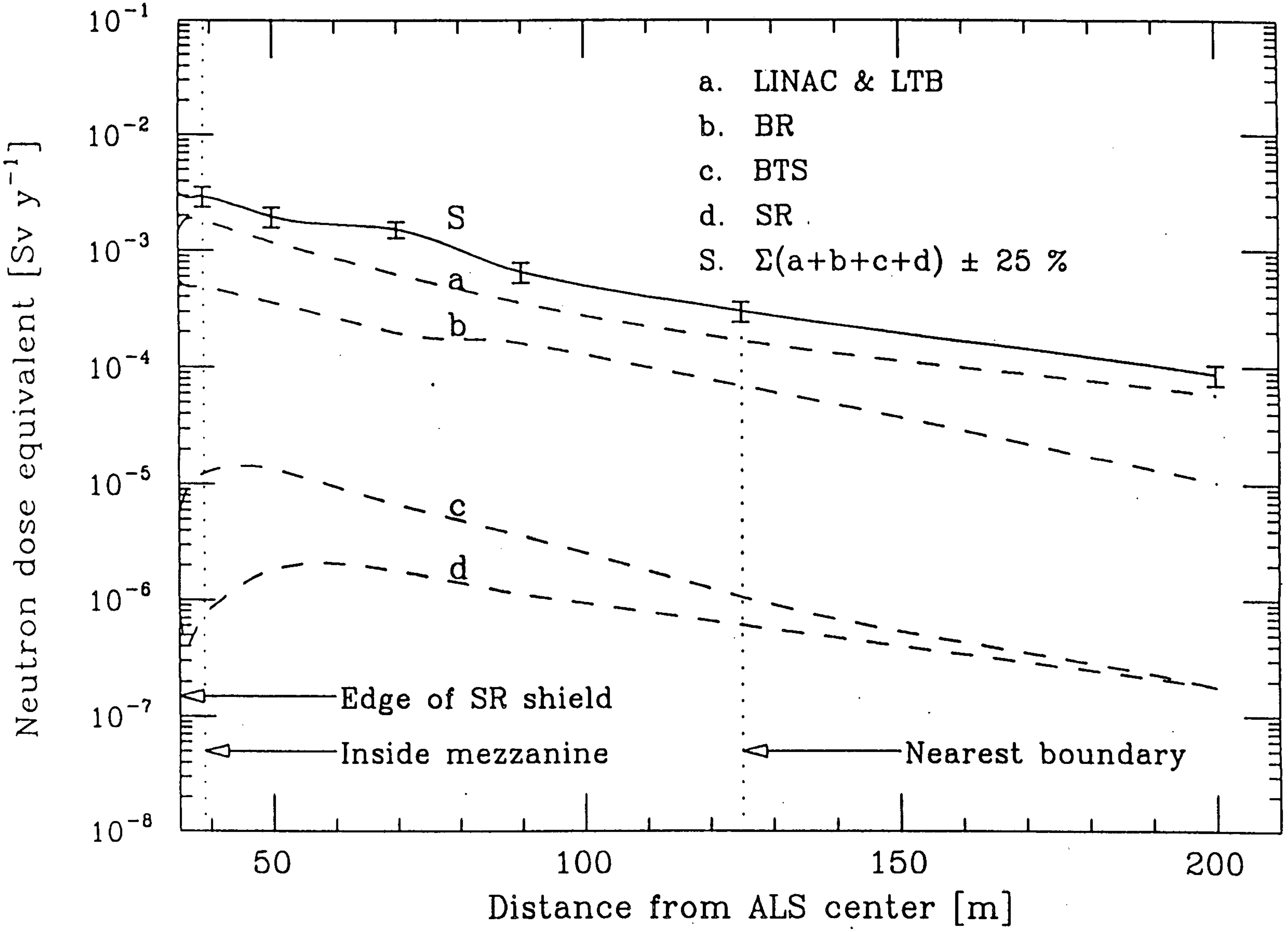


Fig. 6 Neutron dose equivalent per beam energy loss as a function of distance from the ALS center (i.e. SR center). Measurements were made with all estimators located at a height above the floor of 2.44 m, for the four active components: LINAC & LTB, BR, BTS, and

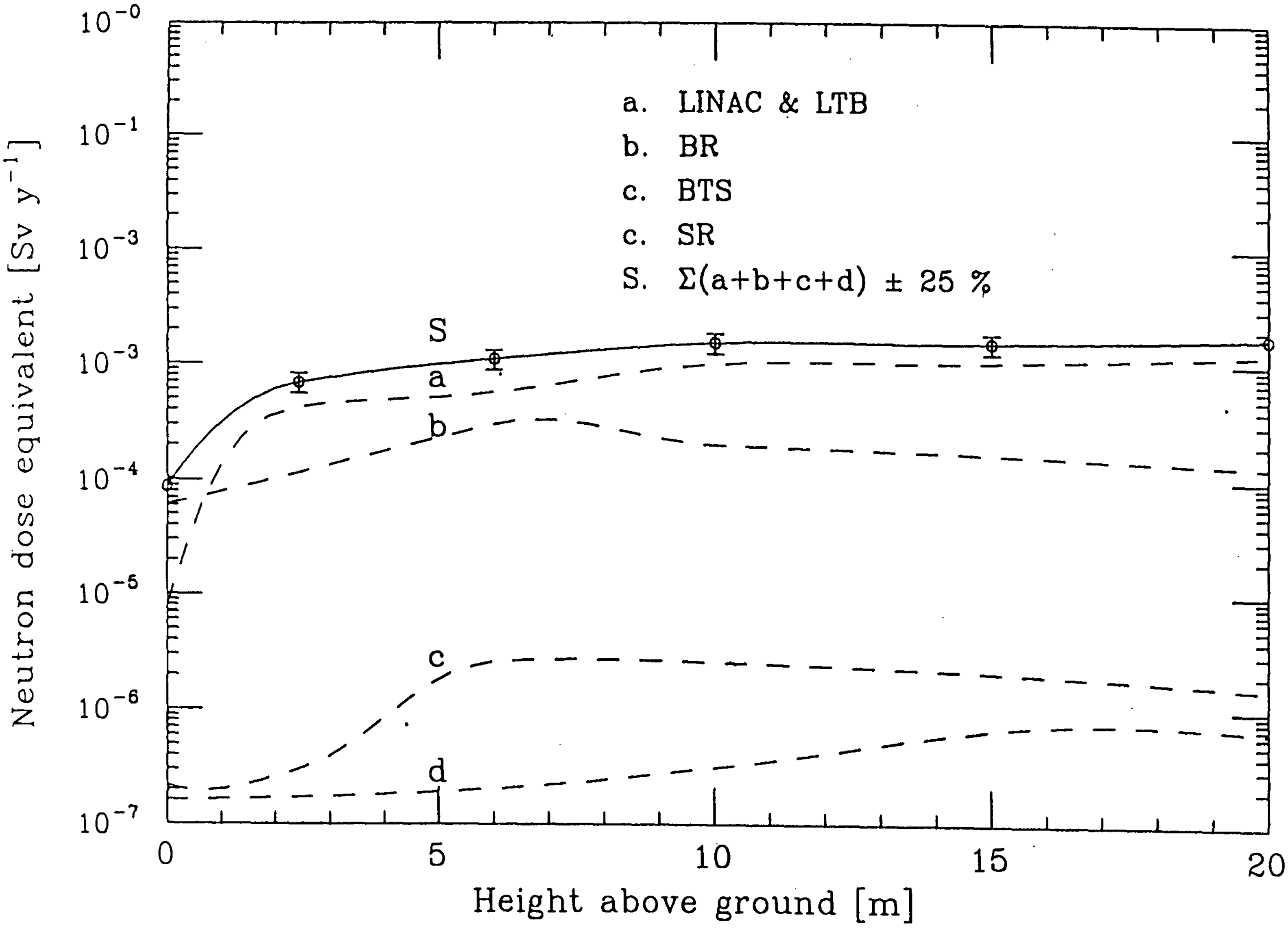


Fig. 7 Neutron dose equivalent per beam energy loss as a function of height above the floor at a constant distance of 39 m (mezzanine) from the ALS center, along a line joining the centers of the storage and booster rings.

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