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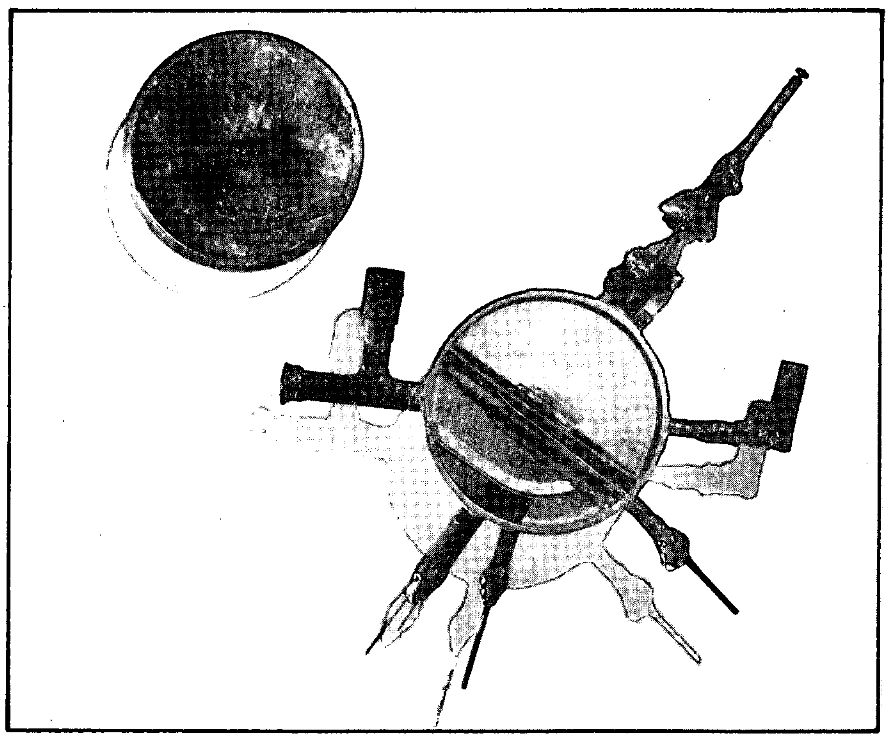

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DISCLAIMER

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Estimation of Neutron Dose Equivalent at the Mezzanine of the Advanced Light Source and the Laboratory Boundary using the ORNL Program MORSE

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Abstract — **To investigate the radiation effect of neutrons near the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory, with respect to the neutron dose equivalents in nearby occupied areas and at the site boundary, the neutron transport code MORSE, from ORNL, was used. These dose equivalents resulting from both skyshine neutrons transported by air scattering and direct neutrons penetrating the shielding. The ALS neutron sources are a 50-MeV linear accelerator and its transfer line, a 1.5-GeV booster, a beam extraction line, and a 1.9-GeV storage ring. The total occupational dose equivalent rate in the center of the ALS mezzanine, 39 m from the ALS center, was found to be less than 1 mSv per 2000-h "occupational" year, and the total environmental dose equivalent rate at the ALS boundary, 125 m from the ALS center, was found to about 0.25 mSv per 8760-h calendar year.**

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INTRODUCTION

Initially, the potential usefulness of synchrotron radiations, produced by parasitic energy loss at electron synchrotrons and storage rings in which charged particles traveling at relativistic speeds were accelerated by bending magnets, was not recognized. Later, these intense ultraviolet and x-ray beams were found to be very useful for scientific and technological studies. In recent years, scientists have striven to maximize the intensity and brightness of synchrotron light sources by means of wigglers and undulators inserted into the straight sections of storage rings. As a third-generation radiation facility, the Advanced Light Source project (ALS) at Lawrence Berkeley Laboratory (LBL) is a 1–2 GeV synchrotron designed to produce beams of high intensity, extreme brightness, short pulse length, and laserlike coherence, as described in the Conceptual Design Report, CDR, (LBL 1986). The ALS will be a powerful tool for study in the fields of material science, biology and medicine, atomic and molecular physics, chemical processes, and many others. The facility will provide scientists and engineers from all over the world with unexcelled opportunities for carrying out research and development projects (Perera and Thompson 1989, Bienenstock 1989).

One of the most important radiological problems related to the ALS complex is the neutron dose equivalents in nearby occupied LBL areas and at the Laboratory boundary at its nearest point to the complex, 125 m from the center of the ALS (NCRP 1971, NCRP 1977). These dose equivalents, which result from both skyshine neutrons transported by air scattering and direct neutrons that penetrate the shielding, were investigated using the neutron transport code MORSE from ORNL (ORNL 1984, Emmett 1975).

The layout of the ALS complex and the parameters of the four active components will be briefly described. Those components consist of a linear accelerator (LINAC) with a beam transfer line, a booster ring, a beam extraction line, and a storage ring. All of them will be shielded with concrete of various thicknesses (McCaslin and Swanson 1986, ICRP 1973, NBS 1964).

In the implementation of the MORSE code, only neutrons generated by the four active components are considered. Although this code allows choices for various complicated process, general simplifications were made, e.g. there were no albedo calculations or Russian roulette games. The MORSE results are used to calculate the annual neutron dose equivalent rates for the ALS, which are listed in a table. Results are discussed in the Conclusion section.

DESCRIPTION OF LBL ADVANCED LIGHT SOURCE COMPLEX

Advanced Light Source Complex

A general description of the ALS is available in the CDR (LBL 1986), whence most data used in our calculation were quoted.

The layout of the ALS is shown in Fig. 1. The complex, arranged within the circular dome structure (Building 6) that once contained the 184-Inch Cyclotron, is surrounded by a mezzanine and auxiliary buildings. The four active ALS components considered for radiation problems (see Fig. 2) are listed below.

- A relatively short electron linear accelerator (LINAC), with a LINAC-to-booster transfer line (LTB), that transports 50-MeV electrons to the booster ring (BR).
- The booster ring, a synchrotron that accelerates electrons from 50 MeV up to 1.5 GeV before injecting them into the storage ring (SR).
- A booster-to-storage extraction line (BTS) that transfers electrons from the booster to the storage ring at an energy of 1.5 GeV.
- The storage ring, the larger-diameter ring that stores electrons at energies of 1.5 to 1.9 GeV.

The concrete shielding walls for the storage and booster rings were polygonal, and the outer shielding wall of the storage ring has a ratchet-shaped circumference. To construct an appropriate model of the ALS geometry by means of the combinatorial geometry modules used in the MORSE code, the shapes and dimensions of some components must be modified to be slightly different from, but still close to, the originals. The geometric model of the ALS used for the MORSE code is shown in Fig. 3. Circular shapes were chosen for all shielding walls, and the mean radii of the storage-ring beam and booster-ring beam given in Appendix A of the CDR (LBL 1986) were used. The specifications for the concrete shielding and tunnel dimensions are from Table 6-1 in the CDR (LBL 1986).

In the following sections, the energy losses in the four active components are calculated. These global energy losses (in terms of joules uniformly lost around each component's perimeter) are later used to calculate the neutron dose equivalent (D.E.) rate per year.

Parameters of the LINAC

The ALS LINAC is 4 m long and is located within a room 5.5 m long by 1.8 m wide. The electron beam, which is 1.4 m above the floor, will be transferred from the LINAC to the booster through the LTB, which is equipped with a collimator. The LINAC and LTB are shielded by walls, 2.44 m high and 1.22 m thick, and a roof, also 1.22 m thick (see Fig. 3).

The LINAC is on when the booster is being tuned. It delivers 8×10^{10} electrons per cycle at 50 MeV. During the tuneup the LINAC complex will have a loss of 50% at the collimator and 20% in the LTB, for a total loss of 4.8×10^{10} electrons per cycle. It is assumed that, at a pulse rate of 4 Hz, the LINAC fills the booster with a beam at 25% of the maximum beam intensity, $0.25 \times I_{max}$, for 1 h, then at full beam strength, I_{max}, for 0.25 h. Thus, the LINAC complex will have a loss of

$$2 \times (0.24 \times 4.8 \times 10^{10} \times 4 \times 3600) = 3.47 \times 10^{14}$$

electrons per fill, corresponding to an energy loss per fill of

$$50 \times 10^{6} \times 3.47 \times 10^{14} \times 1.602 \times 10^{-19} = 2.78 \times 10^{3}\ \text{J}$$

per fill.

Assuming that there are two fills per shift, 250 shifts per year for a 2000-h "occupational" year (used for calculating occupational dose equivalent) and 1095 shifts per year for a 8760-h calendar year (used for calculating the dose equivalent at the Laboratory boundary) for environmental loss, we have a 2000-h year loss of

$$2.78 \times 10^{3} \times 2 \times 250 = 1.39 \times 10^{6}\ \text{J}$$

and a 8760-h year loss of

$$2.78 \times 10^{3} \times 2 \times 1095 = 6.09 \times 10^{6}\ \text{J}.$$

Parameters of Booster Ring

The booster ring, with a beam energy of 1.5 GeV, has a radius of $R_{BR} = 11.94$ m and a beam height above the floor of 1.4 m. Two shielding walls were assumed to be 0.762 m thick and 2.44 m high and to be covered with a circular-ring concrete roof 0.762 m thick. The walls are equidistant from the beam and separated by a tunnel 2.74 m wide.

During the tuneup the booster ring will have a loss of 3.2×10^9 electrons per cycle. As with the LINAC, the tuneup occurs at a pulse rate of 4 Hz and takes 1 h at 25% of the beam maximum and 0.25 h to fill at full beam strength. The booster ring will then have a loss of 2.4×10^{13} electrons per fill, which corresponds to an energy loss of

$$1.5 \times 10^9 \times 2.4 \times 10^{13} \times 1.602 \times 10^{-19} = 5.77 \times 10^3 \text{ J}.$$

Given two storage-ring fills per shift, for 250 shifts per year and 1095 shifts per year, the annual losses are

$$5.8 \times 10^3 \times 2 \times 250 = 2.88 \times 10^6 \text{ J},$$

and

$$5.8 \times 10^3 \times 2 \times 1095 = 1.26 \times 10^7 \text{ J},$$

respectively. This analysis assumes that the useful beam is directed into a dump that is shielded to prevent significant extraneous neutron production.

Parameters of the Extraction Line (BTS)

The BTS will transfer 1.3×10^{10} electrons per cycle at an energy of 1.5 GeV from the BR to the SR. It takes 254 cycles to fill the storage ring to 0.8 A (3.3×10^{12} stored electrons). The sum of the losses along the BTS and at the injection point is 6.4×10^9 electrons per cycle (i.e. 3.2×10^9 for each of these two parts), which corresponds to an energy loss of

$$1.5 \times 10^9 \times 6.4 \times 10^9 \times 1.602 \times 10^{-19} = 1.54 \text{ J cycle}^{-1}.$$

The annual 2000-h loss with 254 cycles per fill, two fills per shift, and 250 shifts per year is

$$1.54 \times 254 \times 2 \times 250 = 1.95 \times 10^5 \text{ J},$$

and the annual 8760-h loss with 1095 shifts per year becomes

$$1.54 \times 254 \times 2 \times 1095 = 8.57 \times 10^6 \text{ J}.$$

Parameters of the Storage Ring

The beam of the SR at an energy of 1.9 GeV has a radius of $R_{SR} = 31.32$ m and a height above the floor of 1.4 m. Two shielding walls, one on either side of the ring, were assumed to be 0.457 m thick and 2.44 m high and to be covered with a circular-ring concrete roof 0.305 m thick. The walls are equidistant from the beam and separated by a tunnel 3.05 m wide.

The ring will store 3.3×10^{12} electrons per fill, which corresponds to an eventual energy loss of

$$1.9 \times 10^{9} \times 3.3 \times 10^{12} \times 1.602 \times 10^{-19} = 1 \text{ kJ}.$$

In addition, there is a distributed loss of 8.1×10^{11} electrons per fill, which amounts to a 12.5% loss of injected beam. The total loss per fill is, therefore, 1245 J. With two storage-ring fills per shift, 250 shifts per year for occupational loss, and 1095 shifts per year for environmental loss, the annual 2000-h loss is

$$1245 \times 2 \times 250 = 6.23 \times 10^{5} \text{ J},$$

and the annual 8760-h loss is

$$1245 \times 2 \times 1095 = 2.72 \times 10^{6} \text{ J}.$$

IMPLEMENTATION OF THE MORSE COMPUTER CODE

General Description of the Code

In the implementation of the MORSE code, point-detector estimators were chosen. The media used in the various geometry regions were vacuum, impervium, air, and concrete with a density $\rho = 2.26$ g cm^{-3}. The multigroup cross sections for these media were available from ORNL (ORNL 1979) and SLAC.*

The main MORSE program had to be 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 sources, i.e., the four active components, each of which is assumed to be a giant resonance neutron source.

Input Data File for the Code

The input data files account for the geometry model of the ALS complex that includes the four active components and their shielding with walls and roofs as a whole unit; the media in various regions, e.g.

* Jenkins, T.M. Personal communications. Stanford CA: SLAC; 1988.

walls, roofs, spaces, etc.; the compositions of the media; and the locations of the point detectors.

The geometries used for the calculation are as follows:

- The LINAC and LTB were assumed to be two straight sections about 17 m long and joined at the location of the collimator. The concrete walls and roofs of the LINAC room and the LTB tunnel were 1.22 m thick.
- The BR was assumed to be circular with a mean radius of 11.94 m, walls 0.76 m thick, roof 0.76 m thick, tunnel inside dimensions 2.44 m high and 2.74 m wide, and beam height above floor 1.4 m.
- The BTS was assumed to be one straight line 20 m long, walls 0.89 m thick, roof 0.76 m thick, and inside dimensions 2.44 m high, 10 m wide, and 5.7 m deep.
- The SR was also assumed to be circular with a mean radius of 31.32 m, walls 0.46 m thick, roof 0.305 m thick, tunnel inside dimensions 2.44 m high and 3.05 m wide, and beam height above floor 1.4 m.
- All roof sections join to form a single piece.

In the input data file the arbitrary spectrum-weighted factors that convert neutron fluence to dose equivalent had been modified to give the dose equivalent in units of Sv per J of beam power consumed. The modification was based on the assumption that 1 J of energy yields 1×10^9 neutrons (Swanson 1978, Swanson 1979).

In the implementation of the MORSE code, which allows choices for various complicated process, only general simplifications were made. Therefore, albedo calculations were not tried, and Russian roulette games were not included.

Output Files of MORSE Code

To run the code properly, first a test input file was used for a short run, e.g., 5 min, to check the correctness of the input data. Thereafter, the input file was modified to do a run of 100 neutrons in each of 10 batches and then a run of 1000 neutrons in each of 10 batches. In general, the latter case gave better statistical results, but it could take several hours to complete, depending on the number of estimators specified in the input file.

Several types of response functions are available to convert the output fluence results. The most important functions are

- The neutron fluence, normalized to one source photoneutron, with the assumption of an uniform ring source or linear source, in units of neutron cm^{-2} $neutron^{-1}$.
- The neutron dose equivalent, normalized to the uniform electron beam loss, with the same assumption described above, in units of Sv J^{-1}.
- The neutron dose in water, normalized to one photoneutron, with the same assumption described above, in units of Gy $neutron^{-1}$.

RESULTS OF CALCULATION

In the vicinity of the ALS, the neutron radiation at any point results from two transport paths: through the air by scattering and through the shielding by penetration. With a proper thickness of shielding and sufficient distance, the direct component is usually small compared with the skyshine. 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.

With point detectors set at various locations, the MORSE results show the dose equivalent value, in Sv J^{-1}, for each detector. Since the total losses, in J y^{-1}, for the four active components are known (see above describing the ALS complex) the dose equivalent per year at the specified locations can be determined.

In Figs. 4 – 6, four curves are given in each plot to show the dose equivalents, in Sv J^{-1}, due to the radiation of the LINAC, the BR, the BTS, and the SR, respectively. Figure 4 shows the dose equivalents, at a constant height (2.44 m) but at various distances from the ALS center, up to 200 m, along a line joining the centers of the BR and the SR. Figure 5 shows the quantities at a constant distance (39 m) but at various heights up to 20 m. Figure 6 shows the quantities as a function of azimuth angle at a constant distance of 39 m from the ALS center around the circumference and at a constant height of 6 m above the ground floor, at the elevation of the mezzanine. The azimuth angle is taken in a clockwise direction, starting with north as zero degrees.

There are two locations that must be considered:

- Location (1), 39 m from the ALS center along the line joining the two centers and 6 m above the ground floor.
- 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.

Location (1) is inside the mezzanine at the point nearest to both rings; therefore, its values of dose equivalent, in Sv J^{-1}, will be used for the evaluation of the annual occupational dose equivalent (2000-h). The values at location (2) will be used for the annual LBL boundary dose equivalent (8760-h). Table 1 shows the results of calculated annual D.E. rates.

Since the giant resonance source chosen for the MORSE code does not include the intermediate-energy and high-energy neutrons, we assume that the former would result in a radiation increase of 4.2% and the latter of 0.42%, according to suggestions by Jenkins (Jenkins 1979).

The annual occupational dose equivalent (2000-h), taken at location (1), is the sum of the D.E. from the four active components. Similarly, the annual environmental dose equivalent (8760-h) is also the sum of these four components.

CONCLUSION

The MORSE results were used to calculate the annual neutron dose equivalent rates for the ALS: 9.42×10^{-4} Sv y^{-1} for occupational dose equivalent on the mezzanine and 2.48×10^{-4} Sv y^{-1} for the LBL site boundary. The latter value is close to the DOE administrative reporting level regarding radiation exposure to the general public, of 2.5×10^{-4} Sv y^{-1}.

In the study of the annual D.E. rates, the LINAC was found to be the most significant active component; it contributes 66.4% of the occupational D.E. total and 70.3% of the environmental D.E. total. The calculations of D.E. are based upon 4-Hz operation, and the results indicate that the LINAC and its accessories, the LTB and a collimator, are marginally undershielded, as related primarily to the LBL boundary dose equivalent rate.

However, the data used by the MORSE code are extremely conservative. For example, in normal operation, it required only 0.4 A, not of 0.8 A, to fill the SR with an injection rate of 1 Hz, not 4 Hz. For the estimation of D.E. at the LBL boundary, the total time of ALS operation could be as low as 6000 h y^{-1} instead of 7680 h y^{-1}. In addition, some local shielding near the LINAC, collimators, and other parts, as well as the attenuation due to some components inside the ALS complex, were not considered. To summarize, the conservative assumptions for radiation shielding in the ALS are

- The assumed SR current 0.8 A is twice the nominal value of 0.4 A.
- The assumed injection rate of 4 Hz is four times the nominal value of 1 Hz.
- Attenuation due to magnets and other materials near all the beam lines were not considered
- Additional local shielding for the LINAC, collimators, and other components were not considered.

Therefore, the annual dose equivalent rates in nearby occupied areas of the ALS and at the LBL site boundary are estimated to be much lower than the allowed DOE regulatory limits for radiation exposure. It can be concluded that the ALS shielding was properly designed.

Acknowledgements — The author expresses his gratitude to individuals at Lawrence Berkeley Laboratory and other national laboratories whose efforts were most helpful in making these calculations with the MORSE code. The work was first suggested and started by the late W.P. Swanson, who spent much valuable time during his final year to bring about a workable MORSE code at LBL. He invited A. Fasso, CERN, to lecture on MORSE theory at LBL and contacted many experts nationwide to obtain solutions for MORSE. J.B. McCaslin, as leader of the LBL Health Physics Group, has continually given careful guidance. In using the MORSE code, I am very much indebted to T.A. Gabriel, ORNL, for his advice and, in particular, to T.M. Jenkins, SLAC, for his numerous suggestions and consultations. E.H. Sheena, Computing Services, ICSD, always helped to solve many difficult computer problems. A computer account for running MORSE was given by the AFRD for the ALS project. It is a great pleasure to thank J. Young for his support and R.H. Thomas for his continuous encouragement and valuable comments.

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Table 1. Annual dose-equivalent (D.E.) rates for ALS

Maximum Occupational D.E. on the Mezzanine

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

Quantities	Active Components				Total
	LINAC/LTB	BR	BTS	SR	
D.E. 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 D.E. rate ($Sv\ y^{-1}$)	5.98×10^{-4}	2.99×10^{-4}	2.59×10^{-6}	2.00×10^{-7}	—
Modified† Annual D.E. ($Sv\ y^{-1}$)	6.25×10^{-4}	3.13×10^{-4}	2.71×10^{-6}	2.09×10^{-6}	9.42×10^{-4}

Maximum Environmental D.E. at Boundary

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

Quantities	Active Components				Total
	LINAC/LTB	BR	BTS	SR	
D.E. 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 D.E. rate ($Sv\ y^{-1}$)	1.67×10^{-4}	6.88×10^{-5}	1.06×10^{-6}	5.66×10^{-7}	—
Modified† Annual D.E. ($Sv\ y^{-1}$)	1.75×10^{-4}	7.20×10^{-5}	1.11×10^{-6}	5.92×10^{-7}	2.48×10^{-4}

†Including 4.2% for intermediate-energy neutrons and 0.42% for high-energy neutrons.

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FIGURE CAPTIONS

Fig. 1 A plan view of the Advanced Light Source (ALS) complex, a 1–2 GeV synchrotron radiation source, Building No. 6 on the LBL Master Plan.

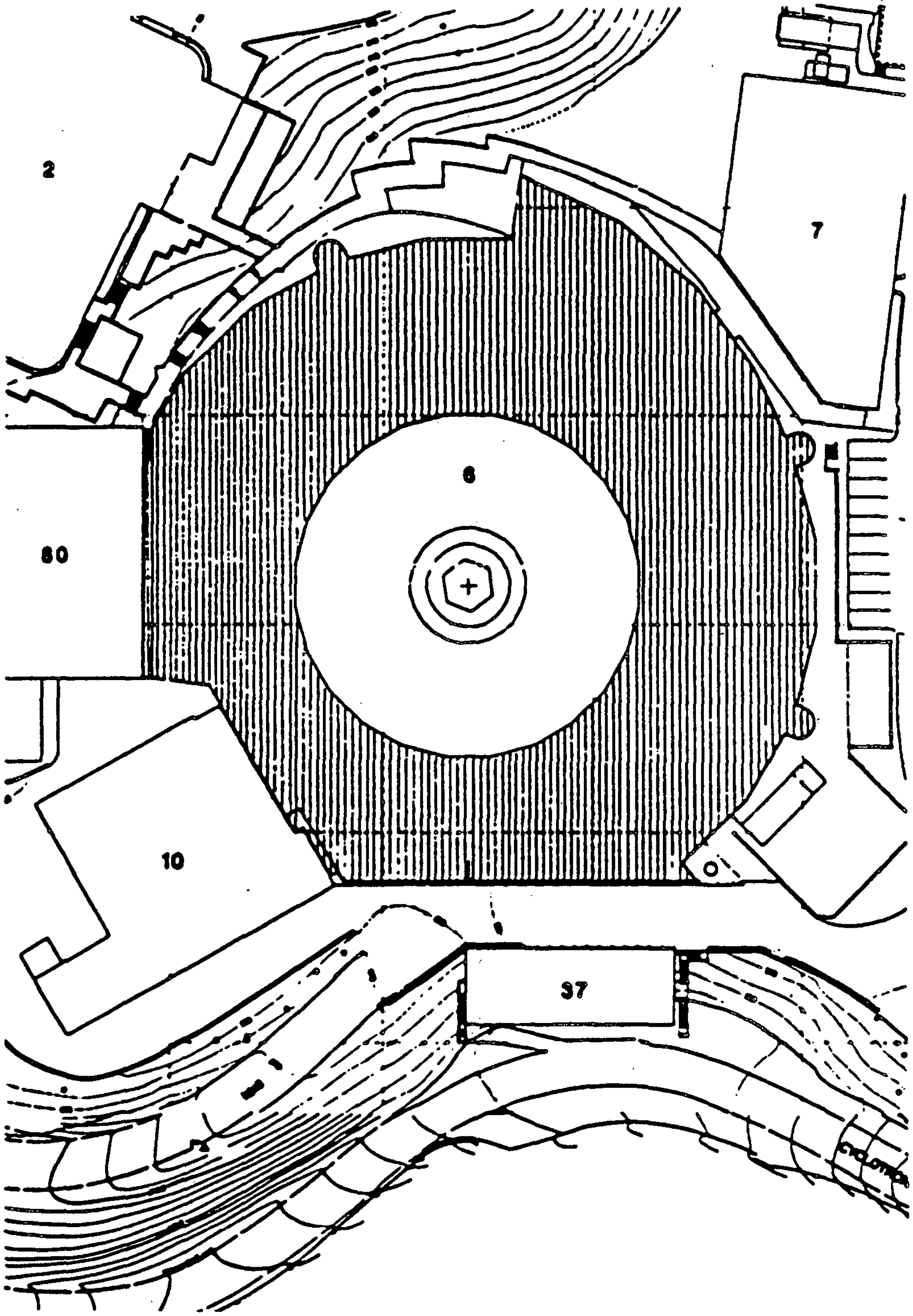
Fig. 2 A detailed layout of the ALS research facilities, showing the injection system, the booster, the storage ring, insertion devices, and locations of beam extraction lines.

Fig. 3 The geometric model of the ALS research facilities used for the MORSE code calculation. This model is slightly different from, but still close to, the detailed layout shown in Fig. 2.

Fig. 4 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 SR. The results are shown by four curves.

Fig. 5 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 (see Fig. 3).

Fig. 6 Neutron dose equivalent as a function of azimuth angle at a height of 6 m above the floor and a distance from the ALS center of 39 m (see Fig. 3).



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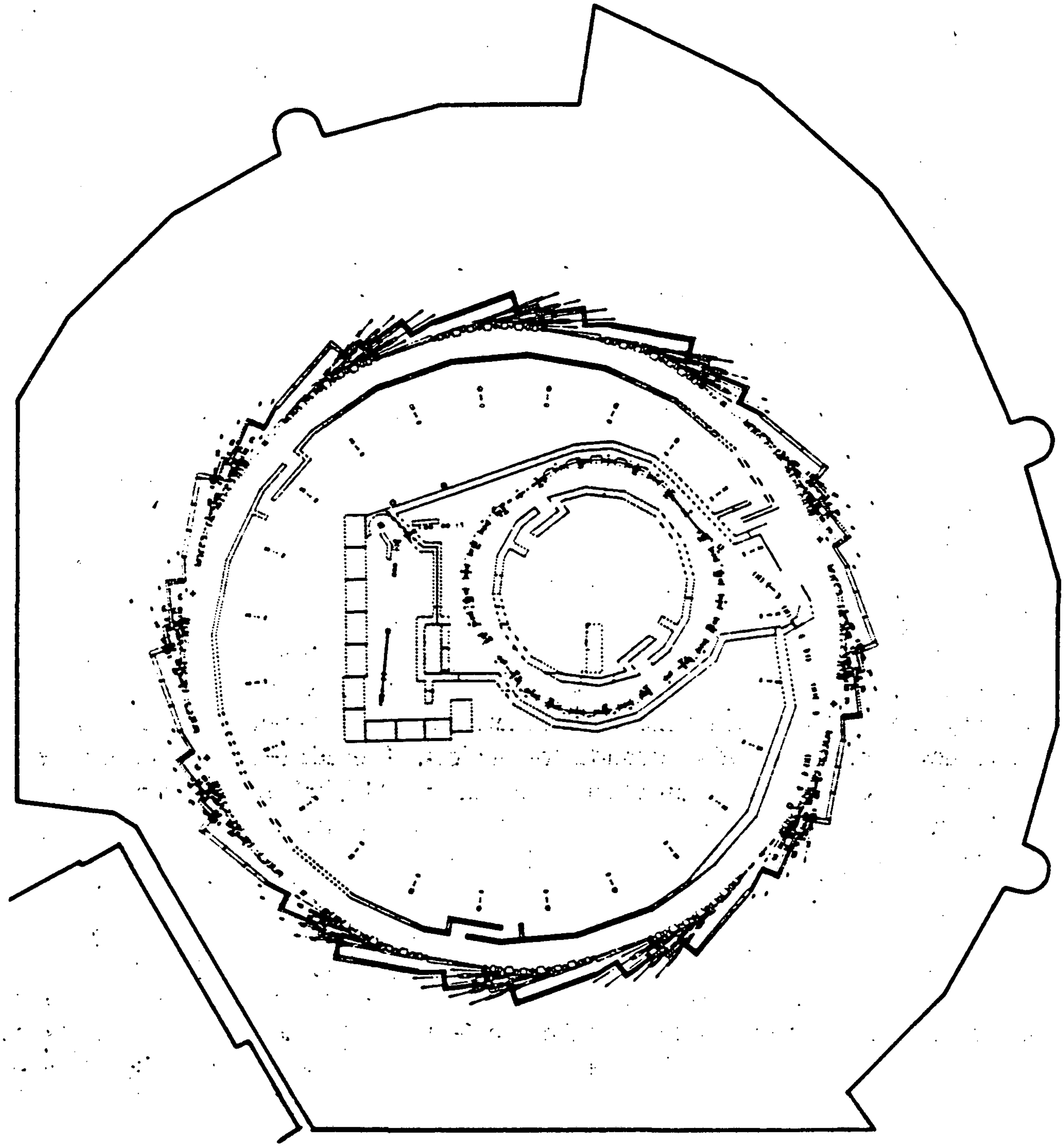

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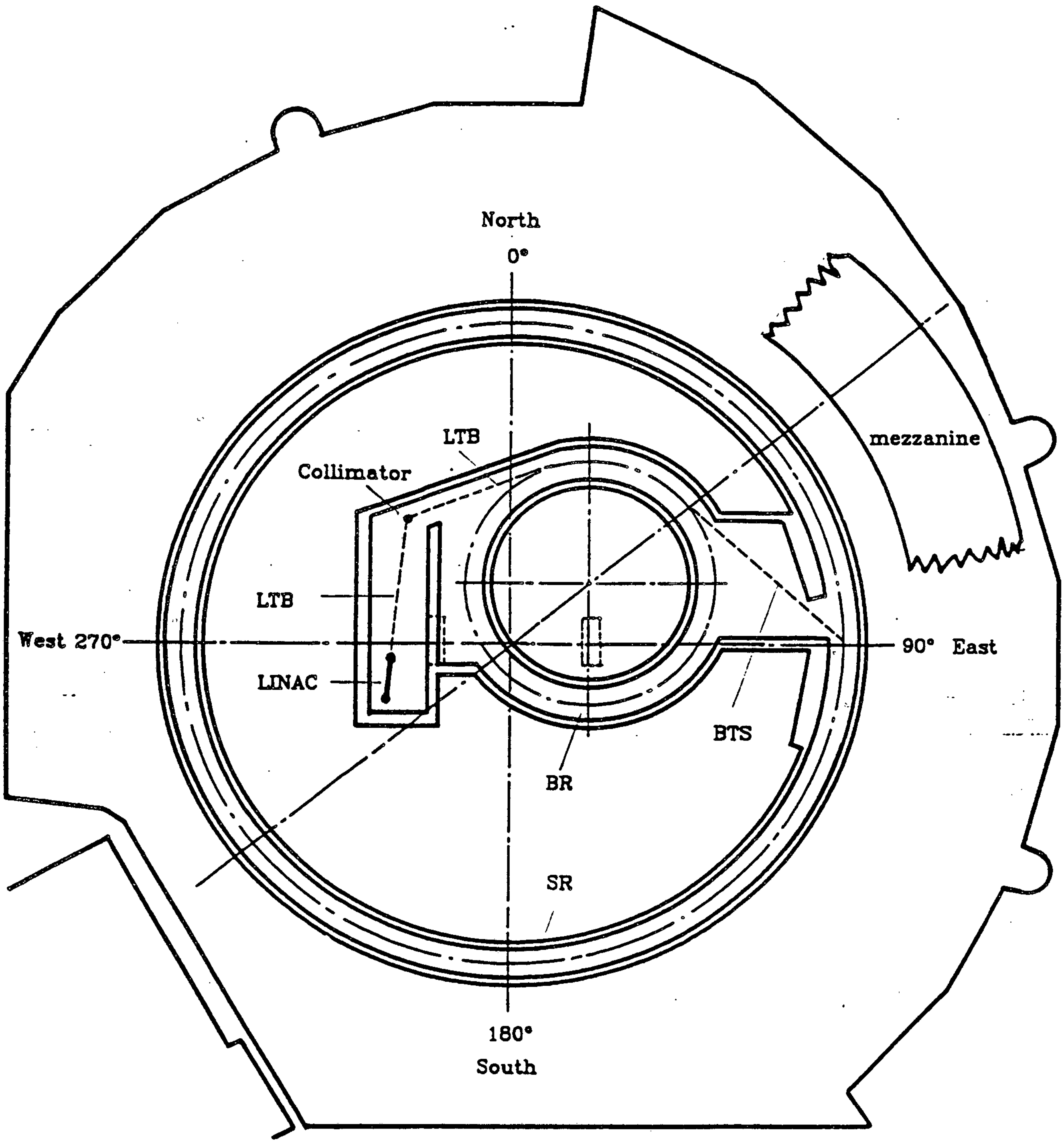

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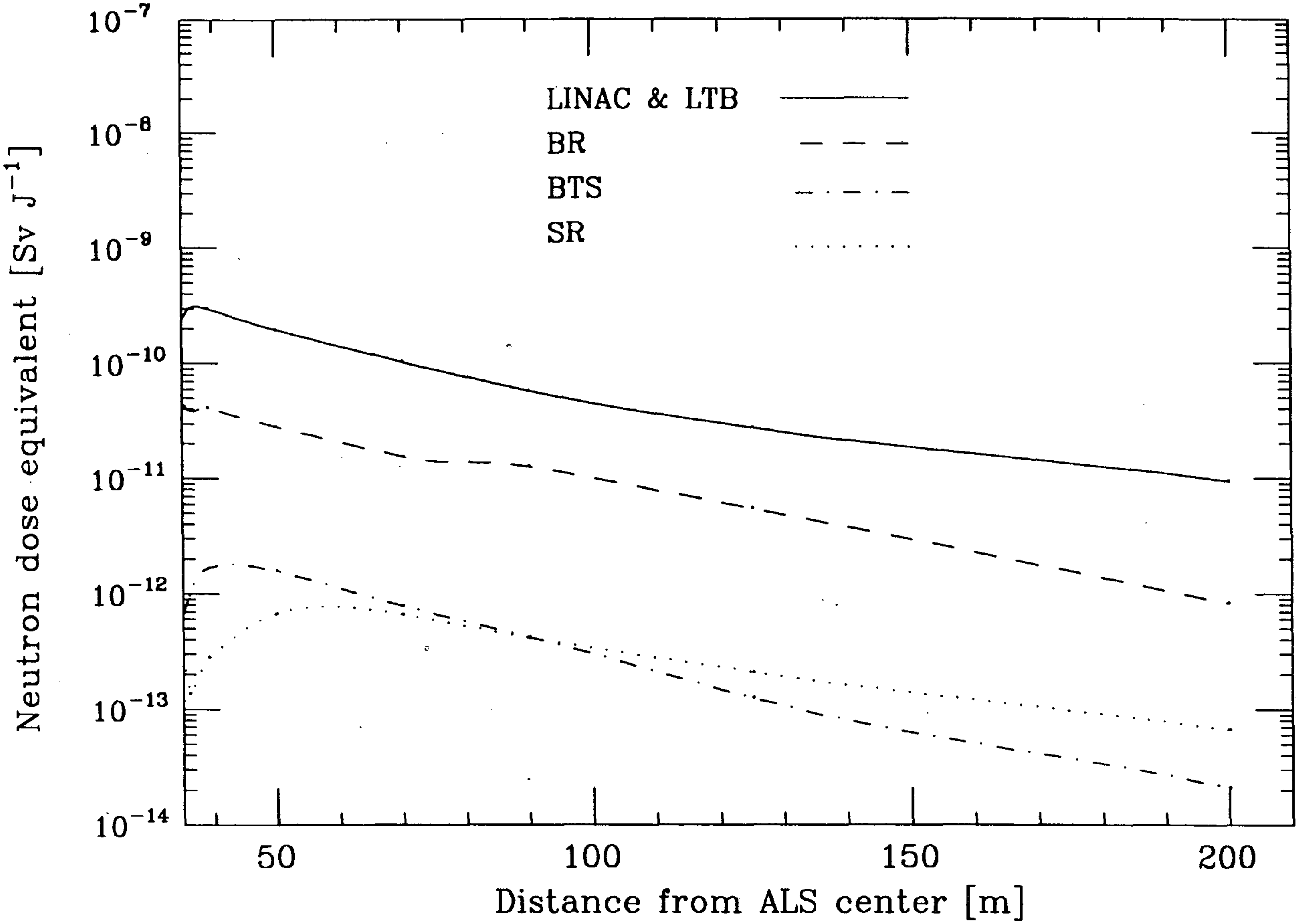

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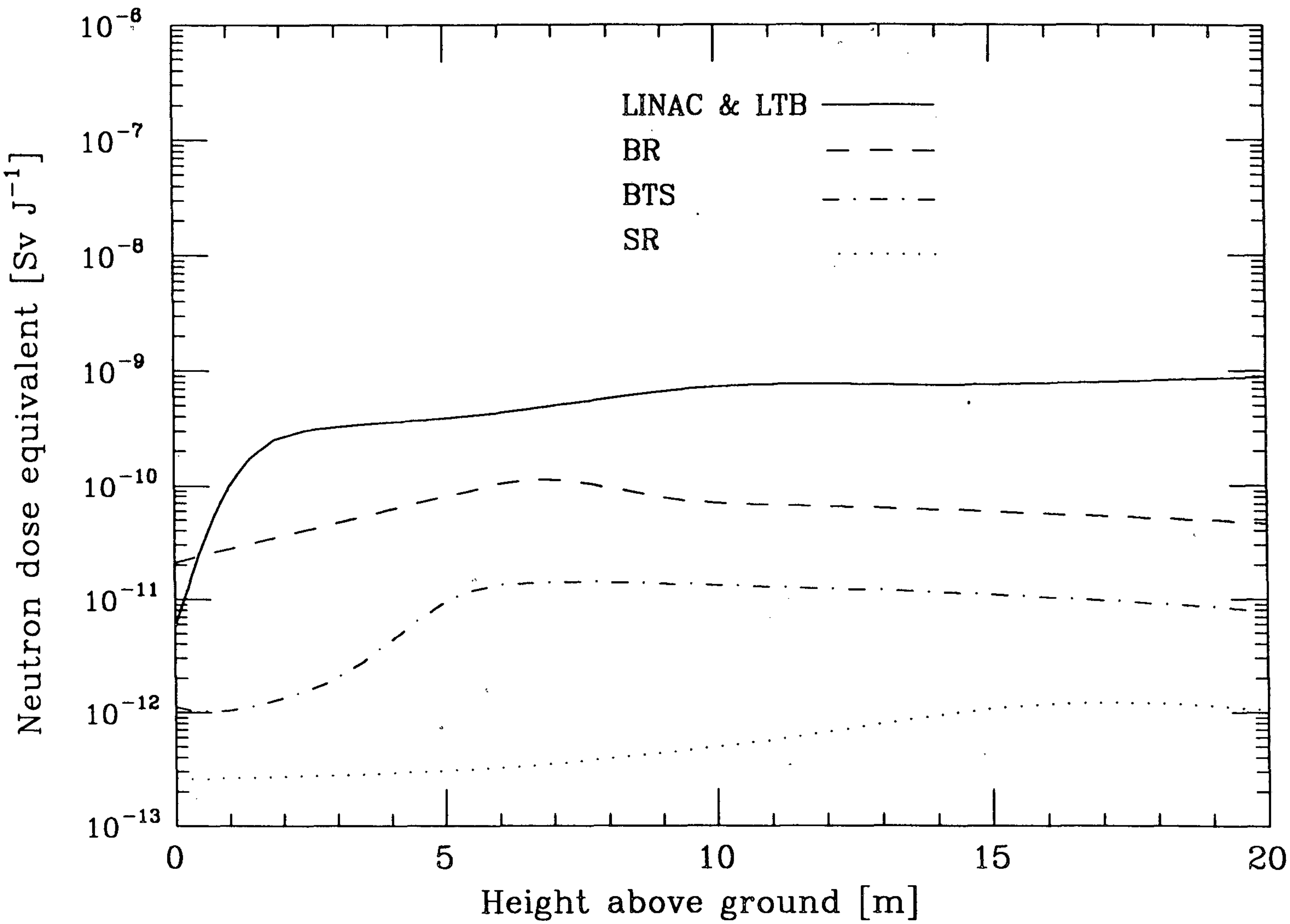

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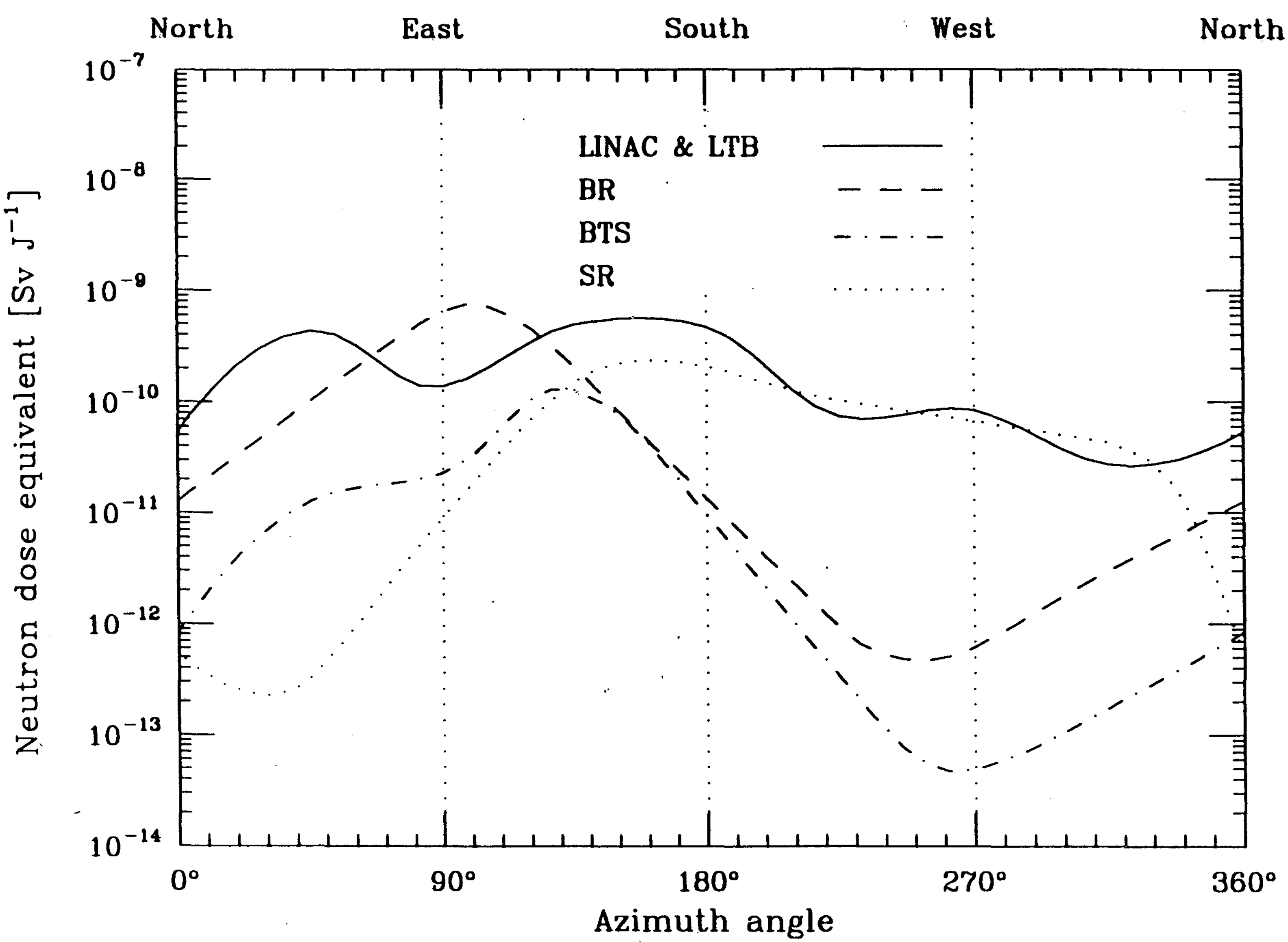

Fig. 6 Neutron dose equivalent per beam energy loss as a function of azimuth angle at a height of 6 m above the floor and a distance from the ALS center of 39 m (see Fig. 3).

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