RADIATION PROBLEMS IN THE DESIGN
OF THE LARGE ELECTRON–POSITRON COLLIDER (LEP)

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ABSTRACT

This is a comprehensive review of the radiation problems taken into account in the design studies for the Large Electron-Positron collider (LEP) now under construction at CERN. It provides estimates and calculations of the magnitude of the most important hazards, including those from non-ionizing radiations and magnetic fields as well as from ionizing radiation, and describes the measures to be taken in the design, construction, and operation to limit them. Damage to components is considered as well as the risk to people. More general explanations are given of the physical processes and technical parameters that influence the production and effects of radiation, and a comprehensive bibliography provides access to the basic theories and other discussions of the subject. The report effectively summarizes the findings of the Working Group on LEP radiation problems and parallels the results of analogous studies made for the previous large accelerator. The concluding chapters describe the LEP radiation protection system, which is foreseen to reduce doses far below the legal limits for all those working with the machine or living nearby, and summarize the environmental impact. Costs are also briefly considered.
PREFACE

The present report was initiated by the LEP Radiation Working Group (RAWOG) as a compilation of the studies made and the results obtained by its members. The situation of the project presented here is essentially the same as it was in June 1983. This is particularly so for parameters such as machine energies and beam intensities.

W.P. Swanson, of the Stanford Linear Accelerator Center, who spent nine months in the Radiation Protection Group of CERN as a Scientific Associate, re-wrote or edited most of the text, incorporating the results of many draft notes and internal reports by the co-authors. After his departure, M. Höfert took over the task of finalizing the publication, with the invaluable help of the staff of the CERN Scientific Reports Editing Section.

I hope that this comprehensive presentation of radiation problems considered in the planning of LEP will not only serve to assist those who design and build this facility but also others who might one day be confronted with related problems. It is for this purpose that reference is also made to many unpublished papers and personal communications. Our gratitude is due to all who helped with and contributed to this work.

K. Goebel
CERN Radiation Protection Group
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1. INTRODUCTION

In 1981 the European Organization for Nuclear Research (CERN) issued a Radiation Protection Policy Statement (CER81) which is the internal document on which the LEP Radiation Protection System is based. In addition, CERN has concluded agreements with the Swiss and French authorities; these agreements govern the documents have been prepared in order to demonstrate to the authorities of the host countries that the principles of regulations (CER81, CER83) are being followed in the design of LEP. The present description is intended as a more technical document, summarizing the results of calculations and outlining the measures envisaged for monitoring and controlling the radiation environment of LEP.

Although the LEP project represents a significant expansion of CERN facilities, it should be emphasized that the particles to be accelerated to high energies are electrons and positrons, whereas all previous CERN accelerators are proton accelerators. Although e± beams can produce stray radiation, the amount is far less than for proton accelerators of the same intensity.

The radiological safety aspects of high-energy electron beams have been extensively studied for several decades and are very well understood. Many radiological consequences can be adequately estimated by simple scaling of the experience gained at accelerators in other laboratories. However, it is worth while to point out two aspects of LEP that are unprecedented in the development of high-energy accelerator facilities:

i) The importance of synchrotron radiation from e± beams at LEP energies. The consequences of this are higher doses to components, to air within the tunnel, and concomitant radioactivation and production of secondary neutrons.

ii) The geographical situation of LEP, its enormous physical scope, and its close proximity to habitable areas and areas of other traditional human activity. These aspects require that careful consideration be given to access control, limitation of environmental effects, and to public understanding and acceptance.

The LEP Radiation Protection System is designed to protect the staff, the environment, and the public, as well as the equipment, against all radiation-caused risks. In order to determine the salient radiation parameters, such as dose rates in areas of concern, assumptions regarding the future operating parameters of LEP must be made:

i) For areas where protection of human beings is the consideration, these assumptions must be conservative in order to allow for a reasonable safety factor.

ii) Where protection of materials and installations is of concern only, the LEP management has decided to base the protection measures on expected average values, for obvious reasons of economy.

Whenever data are given in this report, the basic assumptions are repeated in order to avoid confusion between these two aspects of radiation protection.

Consistent with recommendations of internationally recognized organizations, SI units (becquerel, gray, sievert) are used throughout this report, in place of the older system of special radiation units (curie, rad, rem). For the convenience of the reader, we repeat here that the becquerel (Bq) is the SI unit of radioactivity and is equal to 1 disintegration per second, 1 gray (Gy) equals an absorbed dose of 1 joule per kilogram (J/kg), and the dose equivalent in sieverts (Sv) is equal to the absorbed dose in tissue multiplied by the quality factor (and possibly other modifying factors). To convert to the old special units, it is convenient to remember: 1 Ci = 3.7 × 10¹⁰ Bq, 1 Gy = 100 rad, and 1 Sv = 100 rem.

Most of the calculations and estimates mentioned are the result of the work of members of a special committee, the LEP Radiation Working Group (RAWOG), and of the CERN Radiation Protection Group (RP Group). For the composition of the Radiation Working Group, see Appendix. The present document summarizes results originally given in many separate reports, which are cited at the appropriate places. We note here two longer reports which describe preliminary studies: “Design Study of a 22 to 130 GeV e±e- Colliding Beam Machine (LEP)” (LEP79) and “The radiological impact of the LEP Project on the environment” (Goe81). A shorter summary of this work has also been recently published (Swa83a).

2. RADIOLOGICAL REQUIREMENTS

2.1 The ICRP recommendations

The International Commission on Radiological Protection (ICRP) recommends a system of dose limitation, the underlying philosophy of which is expressed as follows (ICR 77, p. 3):

“(a) no practice shall be adopted unless its introduction produces a positive net benefit;
(b) all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account; and
(c) the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.”

It is convenient to remember these three aspects by the cachets “justification”, “optimization”, and “limitation”.

2
2.2 Regulations of the CERN host countries

The basic principles of radiation protection recommended by the ICRP have been adopted as the framework of radiation control legislation in most countries, including the host countries—France and Switzerland. In the past, however, most of the emphasis has been placed on the “limitation” of radiation exposures, rather than on “justification” or “optimization”. The regulations of the two host countries distinguish between persons professionally exposed to radiation, and individual members of the general public. The annual dose limits in both the French and Swiss regulations are 50 mSv and 5 mSv, respectively, for these two categories. In addition, the French law makes a distinction between the classes of persons professionally exposed to radiation: i) those directly involved in radiation work (dose limit 50 mSv/y), and ii) those indirectly involved (15 mSv/y). Table 1 summarizes these limits.

Table 1

<table>
<thead>
<tr>
<th>Population group affected</th>
<th>Recommended by ICRP (mSv/y)</th>
<th>As required by France (mSv/y)</th>
<th>As required by Switzerland (mSv/y)</th>
<th>CERN reference (mSv/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site boundary</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>Direct radiation at site boundary: 1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Airborne radiation at site boundary: 0.2</td>
</tr>
<tr>
<td>Individual members of the public outside CERN</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>All exposure pathways: 0.5</td>
</tr>
<tr>
<td>Persons visiting or working at CERN who are not individually monitored</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>CERN personnel who are individually monitored</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>Routine activities: 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>With special approval: 50</td>
</tr>
</tbody>
</table>

2.3 The internal CERN rules

CERN has essentially adopted the exposure limits of the two host countries. In addition, the document “Radiation Protection Policy” (CER81) defines so-called “Reference Levels” which are used at CERN (see Table 1). These are not considered as additional limits but are used as goals both for the design of new facilities and the operation of existing installations. Use of the Reference Levels ensures that the legal limits will be met with some margin of safety.

2.4 Individual members of the public

In the spirit of the Reference Levels, any person on CERN premises who is not individually monitored (whether an individual of the general public or member of the CERN personnel) is expected not to exceed an annual exposure of 5 mSv. Such a policy ensures a further limitation in exposure for those living outside the fenced CERN site. For consistency, the Reference Level of the fence-post dose from direct radiation is fixed at a value of 1.5 mSv/y.

In addition, the CERN internal rules specify that, taking stray radiation and all types of releases into account, the exposure of any individual living outside the CERN fence shall not exceed 0.5 mSv/y. A separate requirement limits the release of airborne radioactivity such that no person living near CERN receives more than 0.2 mSv/y from these releases alone. These rules, which limit doses that might be received by persons, are distinct from the fence-post dose limitation just mentioned.

Areas outside the fences have additional protection, beyond the formal limits outlined above; as for the release of radiation and of radioactive and noxious products into the environment, ALARA principles will be applied. This principle stipulates that all hazards will be kept “As Low as Reasonably Achievable”, taking social and economic factors into account. Observation of this principle is especially important for a project such as LEP, for which nearly all the surface areas are public.
2.5 Persons working in radiation-controlled areas

CERN personnel and outside contractors working under conditions where the possibility exists that their yearly dose-equivalent may exceed 5 mSv will be supplied with individual dosimeters. They may work in the presence of radiation provided that they have medical clearance and are properly instructed. The limit for annual exposures for these persons is 50 mSv/y (see Table 1). At CERN, exposure to any yearly dose-equivalent exceeding 15 mSv requires prior approval by the division leader concerned. Such a dose-equivalent, distributed over a year’s working time of 2000 h, corresponds to an average dose-equivalent rate of 7.5 µSv/h. This dose-rate limitation is the basic standard for the LEP shielding design for occupied areas.

2.6 Requirements for area and work control

All areas within the CERN fences are radiation-surveyed areas. Monitoring will ensure that the above limits at the fence and beyond it are respected. In the unlikely event that the monitoring system shows that an exposure limit might be approached under continued operation, appropriate measures will be taken. These would include increased shielding, or operation at reduced beam intensity, or both.

Areas where dose-equivalent rates in excess of 7.5 µSv/h are expected during normal operation, or areas where annual dose-equivalents are likely to exceed 5 mSv, will be classified as Controlled-Radiation areas. The boundaries of these areas are indicated by warning signs and access to them is regulated by administrative control. Areas where the annual exposure of workers may exceed 15 mSv are classified as limited-stay areas, and access and working conditions are subject to careful planning and strict control. Classification of areas according to radiation risk is summarized in Table 2.

Table 2
Classification of areas with regard to radiation levels

<table>
<thead>
<tr>
<th>Type of area</th>
<th>Dose-rate limits (µSv/h)</th>
<th>Maximum annual dose (mSv/y)</th>
<th>Condition of access and work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public area (outside CERN fence)</td>
<td>0.5</td>
<td>5b)</td>
<td>Free access</td>
</tr>
<tr>
<td>Surveyed area (all fenced CERN site)</td>
<td>7.5</td>
<td>5</td>
<td>Free access</td>
</tr>
<tr>
<td>Simple controlled area</td>
<td>100</td>
<td>50c)</td>
<td>Persons under the individual monitoring scheme must wear their personal dosimeter</td>
</tr>
<tr>
<td>Limited stay</td>
<td>2000</td>
<td>50c)</td>
<td>Persons must wear their personal dosimeter; time restrictions.</td>
</tr>
<tr>
<td>High radiation area</td>
<td></td>
<td>50c)</td>
<td>Persons must have special permission, an additional dosimeter, and warning devices.</td>
</tr>
<tr>
<td>Prohibited area</td>
<td>&gt; 105</td>
<td></td>
<td>No accessd)</td>
</tr>
</tbody>
</table>

a) Maximum dose rate (transient conditions).
b) The CERN radiation protection policy statement limits the fence-post dose to 1.5 mSv/y (150 mrem/y).
c) Annual doses must be kept below 15 mSv unless a higher exposure is authorized in advance by the Division Leader.
d) In very exceptional cases the Division Leader can authorize limited access to individuals after consultation with the RP Group Leader.

3. BRIEF DESCRIPTION OF LEP

3.1 The project as approved by the CERN Council

In June 1981 the CERN Council approved the proposal to build a Large Electron Positron Collider (LEP) adjacent to the present high-energy facilities of the Organization and situated across the frontier between France (Pays de Gex) and Switzerland (Canton de Genève). Figures 1 and 2 show the final positioning of the large collider ring. This project is an extension of the present high-energy physics programme which, until now, has been entirely based on proton accelerators and storage-ring facilities. During the last several years, these facilities have been modified and expanded to allow production and acceleration of antiprotons. The addition of the LEP facility will not only enlarge the
Fig. 1 Map of site showing location of environmental monitoring stations for LEP area. These are in addition to the extensive system which serves the existing sites. Downward arrow: air intake; upward arrow: air exhaust with air monitor; A: airborne radioactivity monitor; D: monitor for direct radiation (n and y); G: monitor for noxious gases. Water and fish samples will be taken from the rivers Allondon and Versoix (two locations) (W); domestic water samples will be taken at Versonnex. Diameter drawn (dashed line) connects LEP points of least and greatest depth below surface.

Fig. 2 Schematic of LEP, showing its setting, entirely within the molasse. Average depth is about 70 m below the surface. The cut corresponds approximately to the diameter marked on Fig. 1. The minimum depth is 45 m, where LEP passes below the river Allondon above St. Genis. The vertical scale is exaggerated in relation to the horizontal.
range of available high-energy particles, but also provide a unique facility for studying $e^+e^-$ interactions at 100–200 GeV in the centre of mass. The $e^+e^-$ system only undergoes electroweak interactions, so that massive intermediate bosons, such as the $W$ or $Z^0$, can be produced and studied without the much more predominant strong interactions which always mask the electroweak component when hadrons, such as protons and antiprotons, interact.

The development of LEP is designed to utilize many of the existing CERN installations, while permitting the high-energy hadron physics programme to continue. The general facilities of the two CERN laboratories are available to LEP as it will be built nearby, and the existing accelerators will be used as injectors for the main ring.

The project comprises the construction of the LEP injector linacs (LIL) for electrons and positrons, an electron–positron accumulator ring (EPA), and the LEP main ring (MR), about 27 km in circumference, in which collisions of $e^+$ and $e^-$ will take place at very high energies inside the underground experimental areas to be built “around” the MR tunnel. The project also calls for the modification of the CERN Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) to allow $e^+$ and $e^-$ acceleration to 3.5 GeV and 20 GeV, respectively, as well as for construction of transfer tunnels from the SPS to the LEP-MR. Whereas in the injection system the electrons and positrons are accelerated separately (interleaved with proton pulses in the PS and SPS), the LEP-MR must provide for simultaneous acceleration of $e^+$ and $e^-$ and for enough RF power to keep these particles stored, without energy loss, in an elliptical vacuum chamber of 13 cm × 7 cm.

The most important technical problem of LEP is the compensation for energy loss by synchrotron radiation of the circulating $e^\pm$. As the RF power needed to compensate for this loss rises with the fourth power of $e^\pm$ energy and inversely with the radius, the project, as approved, is a compromise between size and installed RF power for a maximum $e^\pm$ energy of 86 GeV. The approved Phase I of the project should provide a minimum energy of 51.5 GeV. This energy will be achieved by means of four RF accelerating systems (two on each side of the ring) having a total installed RF power of 16 MW. Four halls, with facilities for supplying the needs of large detectors, will also be constructed for collider experiments. Modest detector and computer facilities will also be provided, although most of the experimental equipment will be furnished by the users.

Figure 3 shows the interconnection of the LEP accelerator system. In the first stage of the LEP injection linacs (LIL), electrons are accelerated to 200 MeV. At this point a converter of high-Z material is introduced when $e^+$ are to be produced for injection into the subsequent chain of accelerators. A small fraction (about 1/1000) of the positrons produced in the electromagnetic cascade in the converter are accepted by the second stage of the LIL in which they are accelerated to 600 MeV. For the acceleration of $e^-$ the converter is withdrawn, and electrons of about 10 MeV energy are injected into the second stage of the LIL from a second gun located near the converter.

From the LIL, $e^+$ and $e^-$ are accumulated in the electron–positron accumulator EPA in order to provide intense pulses of $e^+$ (and $e^-$) for injection into the PS for further acceleration. Figure 4 shows a plan of the LIL, EPA, and PS, and of the interconnecting tunnels. In the PS a modified RF system will accelerate pulses of $e^+$ or $e^-$ to 3.5 GeV. At this energy, synchrotron radiation losses in the PS are still very modest (the bending radius in the PS is 70 m). (The pulses of $e^+$ and $e^-$ are interlaced between proton pulses from the existing proton linac and booster, so as not to interrupt the on-going hadron physics programme.) After extraction from the PS and transfer to the SPS by means of the existing tunnels, the $e^+$ and $e^-$ are further accelerated to about 20 GeV. At this energy the synchrotron-radiation losses in the SPS (1100 m radius) start to become significant. The RF system of the SPS must be modified to provide power for compensating these losses. From the SPS the $e^+$ and $e^-$ are transferred separately to the LEP-MR.

![Diagram](image-url)
### Table 3
Parameters of the LEP system as of 30 June 1983

**Phase I (51.5 GeV)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>26,658.876</td>
</tr>
<tr>
<td>Average radius</td>
<td>4,242.892</td>
</tr>
<tr>
<td>Minimum diameter</td>
<td>8.405</td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>8.525</td>
</tr>
<tr>
<td>Bending radius</td>
<td>30,992.095</td>
</tr>
<tr>
<td>Number of intersections</td>
<td>4 + 4</td>
</tr>
<tr>
<td>Equipped experimental areas</td>
<td>4 (at P2, P4, P6, P8)</td>
</tr>
<tr>
<td>Number of lattice superperiods</td>
<td>4</td>
</tr>
<tr>
<td>Total number of lattice periods</td>
<td>256</td>
</tr>
<tr>
<td>Period length</td>
<td>79</td>
</tr>
<tr>
<td>Number of quadrupoles in lattice</td>
<td>504</td>
</tr>
<tr>
<td>Number of quadrupoles in insertions</td>
<td>372</td>
</tr>
<tr>
<td>Number of dipole magnets</td>
<td>3,328</td>
</tr>
<tr>
<td>Number of dipole magnets (weak)</td>
<td>64</td>
</tr>
<tr>
<td>Total magnetic length (dipole magnets)</td>
<td>19,427</td>
</tr>
<tr>
<td>Number of sextupole magnets</td>
<td>520</td>
</tr>
<tr>
<td>Maximum luminosity</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Energy at maximum luminosity</td>
<td>51.5 GeV</td>
</tr>
<tr>
<td>Experimentation possible up to</td>
<td>60</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>4</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$4.2 \times 10^{11}$</td>
</tr>
<tr>
<td>Circulating current per beam (average)</td>
<td>3 mA</td>
</tr>
<tr>
<td>Circulating current per beam (max. possible)</td>
<td>6 mA</td>
</tr>
<tr>
<td>Revolution time</td>
<td>88.924 µs</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>11,245 Hz</td>
</tr>
<tr>
<td>Number of straight sections with RF</td>
<td>2 (at P2 and P6)</td>
</tr>
<tr>
<td>Number klystrons and RF modules</td>
<td>$2 \times 8$</td>
</tr>
<tr>
<td>Klystron power output (nominal)</td>
<td>1 MW</td>
</tr>
<tr>
<td>RF frequency</td>
<td>352,209.14 MHz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>31,320</td>
</tr>
<tr>
<td>Installed RF power (P2 and P6)</td>
<td>16 MW</td>
</tr>
<tr>
<td>Number of five-cell RF cavities</td>
<td>$2 \times 64$</td>
</tr>
<tr>
<td>Active RF structure length</td>
<td>272.38 m</td>
</tr>
<tr>
<td>Synchrotron energy loss</td>
<td>200.5 MeV/turn</td>
</tr>
<tr>
<td>Synchrotron power (two beams)</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Required circumferential gradient</td>
<td>341.6 MV</td>
</tr>
</tbody>
</table>

**Phase II (86 GeV)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy at maximum luminosity</td>
<td>86 GeV</td>
</tr>
<tr>
<td>Circulating current per beam (average)</td>
<td>3.3 mA</td>
</tr>
<tr>
<td>Circulating current per beam (max. possible)</td>
<td>10.0 mA</td>
</tr>
</tbody>
</table>

**Phase III (100 GeV)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy at maximum luminosity</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Circulating current per beam (average)</td>
<td>5.5 mA</td>
</tr>
<tr>
<td>Circulating current per beam (max. possible)</td>
<td>10.0 mA</td>
</tr>
</tbody>
</table>
Table 3 contains an extensive list of parameters which shows the scope of LEP operation for the approved Phase I (51.5 GeV) operation (Pla82). This is followed by an abbreviated list for Phases II and III (86 and 100 GeV). From the table of parameters, two aspects are the most striking:
- the size and the large number of main components;
- the large amount of power required for compensation for the synchrotron radiation losses in view of the relatively low circulating currents of e+ and e-.

Where protection of personnel is the main consideration, the maximum possible currents (Fas82b) are assumed. These values are dictated by physical considerations such as inherent machine capability or electrical power demands. Where protection of equipment is the only consideration, the maximum average currents are assumed.

When averaged over a total LEP-MR filling and colliding cycle (∼4 hours), these e± currents are orders of magnitude smaller than the proton currents in the PS and SPS. An even more striking comparison can be made with currents circulating in the ISR, which are about 60 A. Values for 86 GeV concern the next development step for LEP, and the figures for 100 GeV are only given as the maximum achievable if and when new means for economic RF power generation become available and this new project extension is authorized.

3.2 Development of the project

The project, as authorized at the present time (Phase I), provides for all the basic facilities for colliding e± beams of 51.5 GeV. This energy is considered a minimum; it is expected that about 60 GeV will be reached in Phase I of the project, albeit with diminished luminosity.

A possible development for Phase II is the increase of e± energy to 86 GeV and/or the construction of new experimental halls. Increasing the energy to 86 GeV requires the installation of two additional accelerating structures and their RF supply (klystrons) in new klystron galleries. There would then be four accelerating facilities altogether, located at the even-numbered Access Points: 2, 4, 6, and 8. These can be partially constructed during LEP operation; the final installations would require a longer shutdown period. An even longer shutdown period is required for the addition of new experimental areas—probably of the order of one year.

These future developments can only be undertaken if the Council approves an amendment to the LEP project covering the additional costs.

A possible further development would be the provision of a proton bypass to allow p–e− or p–e+ collisions at one intersection point near Access Point 1. No new tunnels would be needed, only a new experimental area. Interest in these types of lepton–hadron interactions will also depend on world-wide developments in particle physics and experimental facilities over the next several years.

To increase the energy of e± beams above 86 GeV will require superconducting RF accelerating cavities in order to increase RF efficiency and to provide high enough accelerating gradients with a reasonable number of cavities. This development would also require approval by the Council as a new project or a project amendment. Safety aspects would then have to be reviewed in the light of the increased beam energy. The only implications which have been studied until
now for 100 GeV operation are those which depend on installations which cannot reasonably be modified at a later stage. This applies, for instance, to the impact of LEP on the environment at the location of the LEP-MR and at its access points. When assessing the potential impact of LEP on the environment, the 100 GeV stage at maximum intensity was considered.

3.3 Control and radiation safety responsibilities for LEP

The LEP control system will be linked to the control of other CERN accelerators in a twofold way:
- to operate the LEP-MR, the whole chain of accelerators must operate, and
- the electron–positron operation of the PS and SPS will be interlaced in time with proton operation.

Because of these interconnections, it has been decided that the LEP-MR control system be considered as an extension of the SPS control system; the two control centres will be merged to form an enlarged SPS-LEP Control Centre. At the same time, the LIL and the EPA will be integrated into the PS operating system, having a separate control centre.

All safety, including radiation safety, is the direct responsibility of the division concerned. Therefore for the PS complex, including the LIL and the EPA, responsibility for radiation safety for both p and e± operation will lie with the PS Division. Safety considerations for LEP will become the responsibility of the LEP-MR Division. Part of this responsibility may be delegated to the common SPS/LEP Controls Group.

In fulfilling its responsibilities, the RP Group has followed the practice of forming local Monitoring and Inspection Sections attached to important CERN facilities or accelerator divisions. During the design and construction phase of new CERN projects, the appropriate RP Section (or subsection) undertakes the task of collaborating with the design team to ensure that radiation safety aspects are incorporated. In this framework, the RP Group has delegated responsibilities for radiation protection as follows:
- radiation protection for the LIL and the EPA (for the design, construction, and operational phases) to the PS Section;
- radiation protection for the LEP-MR in the design and construction phases to the LEP/West Section.

From the table of parameters, two aspects are the most striking:
- the size and the large number of main components;
- the large amount of power required for compensation for the synchrotron radiation losses in view of the relatively low circulating currents of e+ and e–.

In order to assess the problems from stray radiation for the different facilities which constitute LEP, assumptions about the beam intensity, beam losses at various points, and the energy attained must be made. The basic assumptions are compiled in Table 4 (Hüb82) for 86 GeV operation (Phase II).

### Table 4
Assumptions made concerning beam currents and losses in the LEP accelerator chain (86 GeV operation)

<table>
<thead>
<tr>
<th>Location</th>
<th>Average current e+ (µA)</th>
<th>Average current e± (nA)</th>
<th>Loss (%)</th>
<th>Average energy (MeV)</th>
<th>Average power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output gun</td>
<td>–</td>
<td>5.5</td>
<td>55</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>Output buncher</td>
<td>–</td>
<td>5.2</td>
<td>10</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Output 1st linac</td>
<td>–</td>
<td>2.2</td>
<td>100</td>
<td>200</td>
<td>–</td>
</tr>
<tr>
<td>Output 2nd linac</td>
<td>18 nA</td>
<td>18 nA</td>
<td>40</td>
<td>300</td>
<td>440</td>
</tr>
<tr>
<td>Output (resolved)</td>
<td>11 nA</td>
<td>11 nA</td>
<td>81</td>
<td>600</td>
<td>5.4</td>
</tr>
<tr>
<td>Output EPA</td>
<td>2.1 nA</td>
<td>2.1 nA</td>
<td>20</td>
<td>600</td>
<td>0.26</td>
</tr>
<tr>
<td>Trapped by PS</td>
<td>1.7 nA</td>
<td>1.7 nA</td>
<td>20</td>
<td>3500</td>
<td>1.2</td>
</tr>
<tr>
<td>Trapped by SPS</td>
<td>1.4 nA</td>
<td>1.4 nA</td>
<td>10</td>
<td>20000</td>
<td>5.6</td>
</tr>
<tr>
<td>Output transfer</td>
<td>1.2 nA</td>
<td>1.2 nA</td>
<td>70</td>
<td>20000</td>
<td>17</td>
</tr>
<tr>
<td>Trapped by LEP</td>
<td>0.37 nA</td>
<td>0.37 nA</td>
<td>0.37</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Colliding in LEP</td>
<td>3.3 mA</td>
<td>3.3 mA</td>
<td>100</td>
<td>86000</td>
<td>42 kJ</td>
</tr>
</tbody>
</table>

a) Except for the first three lines, data in the last four columns describe losses estimated to occur between locations listed at left.
b) Power is averaged over 20 min intervals, except for last line, where the total energy of circulating beams is given.
c) Current “colliding in LEP” is the total charge multiplied by 11245 orbits per second.
The amount of beam power lost at various stages is an index of the amount of stray radiation and induced radioactivity. The beam power lost in the pre-injector system is higher than in the subsequent accelerators, and most of the activity will be produced there. Because of the relatively smaller power losses, as well as the nature of the $e^\pm$ interactions, the production of radioactivity in the PS and SPS will be negligible compared to that from proton operation. In the LEP-MR, at 86 GeV the total remanent radioactivity will be of the order of a few GBq.

The PS, SPS, and their transfer tunnels are already shielded and designed to cope with $5 \times 10^{12}$ protons per second at energies of 26 and 450 GeV, respectively. The $e^\pm$ beam power in these parts of the injector system will be orders of magnitude smaller than the beam power for protons. Electromagnetically interacting particles will make no significant contribution to the radiation fields that already occur outside the shielding of the facility; the shielding has already been determined by the more severe requirements of proton operation. The LIL and the EPA must be sufficiently shielded to limit their contribution of stray radiation on the site and at the fence-post.

4. HIGH-ENERGY ELECTRON (POSITRON) INTERACTIONS WITH MATTER

4.1 Introduction

The primary $e^\pm$ beams, when transported normally, are totally contained within the vacuum system and are therefore completely inaccessible. However, these beams can produce secondary radiation by two principal mechanisms (see Table 5).

i) When $e^\pm$ beams are lost from their orbits, whether by accident or deliberately, they will strike materials such as the vacuum chamber, converters, collimators, or other components. When this happens, the particles radiate photons by a process known as "bremsstrahlung" (literally "braking-radiation", referring to the fact that it is the act of deceleration which causes the radiation). The bremsstrahlung photons in turn produce $e^\pm$ pairs which in turn produce more bremsstrahlung. The whole process multiplies, producing an electromagnetic cascade (or electromagnetic shower; see Fig. 5). These cascades, which may involve many particles, contain a spectrum of photons extending from zero to the kinetic energy of the incident $e^\pm$. For the purpose of this report, these radiations, together with all forms of resulting secondary radiation (discussed below) are collectively called "high-energy radiation".

ii) When $e^\pm$ of high energy traverse magnetic fields, photons are radiated by means of an effect called "synchrotron radiation" (SR). Although it does not require the immediate presence of matter, SR is closely related to bremsstrahlung in that acceleration of charge is involved. However, SR differs considerably in the spectrum of photons radiated; for LEP conditions, the spectrum extends from the range of visible light to a maximum intensity in the range of a few hundred keV, followed by a rapid decline in the spectrum as the photon energy increases above a few MeV.

The electromagnetic cascade deposits a radiation dose in the materials in which it occurs, but, in addition, the photons interact further to induce radioactivity and release other forms of direct secondary radiation. At the energy of the LEP facility, these secondary radiations include giant-resonance neutrons, high-energy hadrons, and muons.

These secondary radiations are attenuated to negligible levels by the thickness of concrete and earth above the LEP tunnel. The radiation dose to air and cooling water can produce induced activity and radiogenic noxious gases.

| Table 5 |
| Qualitative nature of the radiations expected in LEP |

<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bremsstrahlung: when $e^\pm$ from the beam strike components</td>
<td>Electromagnetic cascade containing many secondary high-energy photons, electrons and positrons. Secondary high-energy radiation, consisting of neutrons, other hadrons (especially pions), muons. Radioactivity induced in components, air and cooling water. Ozone and oxides of nitrogen produced in air.</td>
</tr>
<tr>
<td>Synchrotron radiation: when $e^\pm$ are deflected by magnetic fields</td>
<td>Photons, typically of low energy. Neutron production. Radioactivity induced in components. Radioactivity induced in air. Ozone and oxides of nitrogen produced in air.</td>
</tr>
</tbody>
</table>
4.2 Electromagnetic cascade showers

4.2.1 Mechanisms of the cascade

At very high electron energies (compared to the rest mass), the importance of energy loss by radiation greatly exceeds loss by ionization. The average distance an electron travels in order that its energy be reduced by an average factor of 1/e approaches a constant value called the radiation length $X_0$, which depends on the atomic number of the medium in an approximate way ($X_0$ in g/cm$^2$):

$$X_0 \approx 716 A(Z + 1) \ln(183 Z^{-1/3})^{-1}, \tag{4.1}$$

where $A$ and $Z$ are the atomic weight and atomic number, respectively. In the situation where a photon is moving through a medium, the probability of $e^\pm$ production rises to a constant value such that the average distance the photon must traverse to materialize into an $e^\pm$ pair becomes equal to $9X_0/7$. This near equality of the two characteristic distances comes about because bremsstrahlung and pair production are different manifestations of the same underlying physical interaction involving two electrons with a real photon. The twin processes of bremsstrahlung and pair production together make possible the phenomenon of the electromagnetic cascade shower (Fig. 5). This is a complex phenomenon in which bremsstrahlung, followed by pair production, followed in turn by more bremsstrahlung, rapidly disperses the incident electron's kinetic energy among a myriad of photons, electrons, and positrons. At very high energies, other mechanisms of energy dispersal, although present, are almost negligible in comparison.

As the average energy lost by radiation $dE/dX_{rad}$ is about proportional to the particle energy, the radiated energy will rapidly decline, approximately exponentially with the number of radiation lengths of the medium traversed. At the same time, the amount lost by ionization $dE/dX_{10n}$ varies slowly with energy. Below a value of kinetic energy called the "critical energy" $E_{crit}$, radiation is no longer the dominant mechanism for energy loss. The electron is brought to rest without playing an important role in the shower, once its energy declines below $E_{crit}$.

Values of $E_{crit}$ are characteristic of the medium and are approximately given by

$$E_{crit} = 800/(Z + 1.2), \tag{4.2}$$

where $E_{crit}$ is in MeV, and $Z$ is the atomic number of the medium. Values of $E_{crit}$ for representative materials used in the construction of LEP are shown in Table 6. Extensive tables of these parameters can be found in Swa79a, pp. 297–310. For current values of $X_0$, see Tsa74.

The cascade shower builds up rapidly in the first layers of the medium, approximately doubling the number of $e^\pm$ in each successive radiation length until a broad maximum is achieved. The maximum number of particles and the depth at which the maximum is achieved depend on the incident energy $E_0$ and the medium, via $E_{crit}$. The location $X_{max}$ of the maximum is given approximately by

$$X_{max} = 1.01 X_0 [\ln (E_0/E_{crit}) - 1]. \tag{4.3}$$

\* This type of "critical energy", which plays a role in the electromagnetic cascade, is distinct from $\epsilon_c$, which is characteristic of the synchrotron radiation spectrum. See Section 4.6.
Table 6

<table>
<thead>
<tr>
<th>Material</th>
<th>Air</th>
<th>H$_2$O</th>
<th>Concrete</th>
<th>Al</th>
<th>Cu</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ (or $Z_{eff}$)</td>
<td>7.2</td>
<td>6.6</td>
<td>11.6</td>
<td>13</td>
<td>29</td>
<td>82</td>
</tr>
<tr>
<td>$X_0$ (g·cm$^{-2}$)</td>
<td>36.61</td>
<td>36.08</td>
<td>25.71</td>
<td>24.01</td>
<td>12.86</td>
<td>6.37</td>
</tr>
<tr>
<td>$E_{crit}$ (MeV)</td>
<td>102</td>
<td>92</td>
<td>51</td>
<td>51</td>
<td>24.8</td>
<td>9.51</td>
</tr>
<tr>
<td>$E_{comp}$ (MeV)</td>
<td>45</td>
<td>55</td>
<td>25</td>
<td>21.6</td>
<td>8.4</td>
<td>3.6</td>
</tr>
<tr>
<td>$\mu_{comp}$ (cm$^2$·g$^{-1}$)</td>
<td>0.0160</td>
<td>0.0166</td>
<td>0.0209</td>
<td>0.0215</td>
<td>0.0304</td>
<td>0.0419</td>
</tr>
</tbody>
</table>

Thus for LEP energies (51.5–100 GeV), the maximum occurs near 8 $X_0$ if the shower develops in a high-Z material. The average number of shower particles can be very large—of the order of 500–1000 for $e^\pm$ incident on a high-Z medium at LEP energies (51.5–100 GeV) (Ros52, p. 257, Jak70, Mue70).

At much greater depths than the shower maximum, the shower is gradually absorbed as its energy is deposited in the medium. At such depths there are few electrons remaining above the critical energy and the photons tend to have a spectrum greatly enhanced towards low energies. The character of the photon spectrum is influenced by the behaviour of the photon attenuation coefficient as a function of photon energy, in such a manner that a relative enhancement occurs near the “Compton minimum”. This is the photon energy for which the photon attenuation coefficient has its minimum value (see Table 6). Although it is almost too great a simplification, it is convenient to imagine that the photon spectrum in the shower tail is concentrated near the Compton minimum. Indeed, shielding experiments designed to measure the attenuation of electromagnetic showers at 0° tend to confirm that the effective attenuation coefficient for the shower “tail” is close to these values, typically differing from $\mu_{comp}$ by about 10–20%.

The electromagnetic cascade shower is an important phenomenon for all high-energy electron facilities, including LEP. The shower ensures that the particle energy is dissipated within a reasonable distance. Behaviour of the shower must be taken into account for radiation protection in all parts of the LEP system, the following considerations being foremost:

- shower-induced radiation doses to occupied areas;
- shower-induced radiation doses to sensitive components;
- production of secondary radiation;
- production of induced activity;
- production of noxious radiogenic gases.

General properties of the electromagnetic cascade shower are well described in the literature, particularly in writings by Rossi (Ros41, Ros52). Tabulations of shower properties have been published in several papers (e.g. But60, Mes70; see also a listing in Swa79a, pp. 38–39). Particular problems encountered in the design of a facility such as LEP are generally well handled by Monte Carlo techniques, as is done using the programs EGS and MORSE (For78, Emm75).

4.2.2 Doses from external bremsstrahlung

If an electron beam strikes an object in any portion of the LEP system, bremsstrahlung will be produced. This radiation gives rise to doses in the vicinity which must be evaluated, and appropriate shielding or other protective measures must be planned. One can correctly imagine that such doses are imparted by the electromagnetic cascade shower which originates in the first object struck, but then continues well beyond the dimensions of that object to propagate itself through air, concrete, earth, or other shielding material present. However, it can also be generally assumed that the main focus of the shower takes place within or very close to the object struck. Therefore in planning radiation shielding, one can assume that it is the characteristics of the greatly attenuated shower that are relevant. It has been mentioned above that the attenuation properties of shielding materials have been found to be close to the attenuation coefficient at the Compton minimum for the shower at 0° to the beam direction. As convenient rules of thumb for shielding calculations, the following have been found useful:

\[
\dot{D}(0^\circ) = 300 E_0 \quad (4.4)
\]
\[
\dot{D}(90^\circ) = 100 \quad (4.5)
\]

where the dose rates are in units of Sv/h at 1 m, per incident kW of electron beam power, and $E_0$ is in MeV. These rules of thumb are the same as those proposed by Swanson (Swa79a), except that the rule adopted here for 90° radiation has been increased by a factor of 2 from 50 to 100 [Eq. (4.5)]. As expressed in Eq. (4.5), the absorbed dose rate at large
angles (90°) is believed to be approximately proportional to electron beam power, independent of beam energy. This amount represents the more penetrating radiation component to be considered in the shielding design. Dose rates at 90° near an unshielded target may be significantly higher because of the contribution of softer radiation components, which are rapidly attenuated and so do not contribute significantly to doses outside of very thick shielding. It is also the case that doses in the vicinity of a target depend considerably on the specific geometry. For example, wide, re-entrant targets will absorb much radiation which would otherwise be emitted at large angles. On the other hand, higher doses at large angles can be obtained by a glancing incidence of the beam on a surface because, in this case, self-absorption in the target, in the sideward direction, is minimal (Din77). Figure 6 shows the relationships of these doses from external bremsstrahlung to doses from other types of radiation fields surrounding a thick high-Z target.

4.2.3 Track-length distributions and secondary interactions

It must be realized that, although an electron initiates the electromagnetic cascade shower, electrons themselves do not interact to a significant extent with nuclei of the shower medium. The photons have much larger nuclear cross-sections and give rise to the overwhelming majority of secondary particles, especially neutrons, and, at LEP energies, to mesons together with other hadrons and muons. Radioactivation of materials results from these photonuclear reactions. To estimate the yield of reaction products, it is necessary to know not only the photonuclear cross-section \( \sigma(k) \) for particle production as a function of photon energy \( k \), but also the total length of medium traversed by photons of each energy. The track-length dependence on photon energy is expressed as the differential track-length distribution \( dL/dk \), representing the total track length of all photons having energy in the interval \( (k, k + dk) \).

The yield of secondary particles per incident electron \( Y(E_0) \), of energy \( E_0 \), is obtained by an integration over the photon energy \( k \):

\[
Y(E_0) = (N_A \rho / A) \int_0^{E_0} \sigma(k) |dL(k)/dk| \, dk ,
\]

using the production cross-section \( \sigma(k) \) for the secondary reaction in question and the differential track-length distribution just explained. \( N_A, \rho, \) and \( A \) are Avogadro's number, the medium density, and the atomic weight, respectively.

For electrons of high energy \( E_0 \) incident on very thin targets (of thickness \( X \)), the photon differential track-length distribution is approximately

\[
dL/dk = (1/2)(X^2/X_0 k) ,
\]

valid for \( X \ll X_0, k < E_0, \) and \( E_0 \gg E_{\text{crit}} \). In Eq. (4.7), \( L \) will have the same units as \( X_0 \) and the target thickness. Equation (4.7) is only useful for radiation protection calculations where it is known that a thin target will be presented to the beam. This is seldom the case, and the assumption is generally made that an object struck by the beam is so thick that the maximum possible yield of secondary particles is produced. It is conservative radiation protection practice to neglect the possible attenuation that the same thick target might afford.
A number of approaches to handling the more difficult problem of the photon track-length distribution in thick targets are used. Some of these are described in Swa79a. By far the simplest formulation is that given by Approximation A of analytical shower theory (Ros41, Ros52). This approximation applies to an infinitely thick target, considers only pair production and bremsstrahlung, and assumes constant cross-sections at the high-energy limit for these processes. The distributions are written:

\[
\frac{dL}{dk} = 0.572 \left( X_0 E_0 / k^2 \right) \quad (\text{photons})
\]

\[
\frac{dL}{dE} = 0.437 \left( X_0 E_0 / E^2 \right) \quad (\text{electrons}),
\]

where \( L \) has the same units as \( X_0 \), and \( k \) and \( E_0 \) are conveniently expressed in MeV. Conditions on the validity of Approximation A are: the medium must be thick enough to absorb nearly all the energy of the shower, \( E_0 \) and \( k \) are both greater than \( E_{\text{crit}} \), and at the same time \( k \) is not too close to \( E_0 \) : \( (E_0 - k) > E_{\text{crit}} \). Approximation A is well suited to many problems associated with LEP, except those related to giant-resonance production, for which the important photon energies are not high compared to \( E_{\text{crit}} \), and the track-length distribution is overestimated by Approximation A.

Other analytical forms of the track-length distributions have been proposed, particularly that of Clement and Kessler (Cle63, Cle65), and adaptations of Approximation B. Approximation B is similar to Approximation A, except that electron energy loss by ionization is also considered and thus uses \( E_{\text{crit}} \) as a parameter. Approximation B is more accurate at all energies, but it has the disadvantage that numerical integrations must be made. Discussions of the use of a version of Approximation B with additional corrections are given in Swa78 and Swa79b (see Fig. 7).

The most satisfactory general approach to handling the photon track-length distribution is through Monte Carlo calculations. These accommodate all the major physical processes accurately and can be done for any shape, composition, or thickness of target, whereas the analytical forms described above refer only to infinitely extended targets of a single material.

**Fig. 7** Photon differential track length for lead for incident electron energies \( E_0 \) up to 100 MeV, calculated using Approximation B. The dimensionless units for the ordinate scale are used for clarity. The Approximation A prediction is indicated at 0.572 for comparison. The photoneutron cross section (in barns) is also shown to illustrate the calculation of photoneutron production. Also shown is a Monte Carlo calculation by Alsmiller et al. (Al66) (from Swa79a).

### 4.3 The photon–nucleon interaction

Above a threshold energy of about 6 MeV for heavy nuclei and about 12 MeV for most light nuclei (but which is 2.2 MeV in deuterium and 1.7 MeV in beryllium), neutrons are produced in the interaction of a photon with a nucleus. For photon energies up to some 30 MeV, the neutron production arises from the "giant photonuclear resonance"; the photon induces an oscillation in the nucleus in which the protons, acting as a group, move in an opposite direction to the neutrons, also acting as a group.

The giant-resonance process results in a neutron spectrum containing two components; the first component arises from the absorption of the photon to form a compound excited nucleus. This gives the standard evaporation spectrum

\[
\frac{dn}{dE_n} = \left( E_n / T^2 \right) \exp\left( - E_n / T \right),
\]

where \( E_n \) is the neutron kinetic energy and \( T \) is a parameter that is usually called the nuclear "temperature" (Swa79a, p. 73).
The agreement with measured spectra for heavy nuclei (tantalum for example (see Fig. 8)), is good, but the model on its own is insufficient to describe neutron production from beryllium (see Fig. 9) (Als70). The high-energy tails in the spectra shown constitute a second component attributable to an additional photonuclear process, that of direct photoneutron emission.

Above photon energies of about 25 MeV the interaction of a photon with the nucleus can be described by the quasi-deuteron model, i.e. absorption by a neutron–proton pair within the nucleus. The probability of this process is given approximately by the expression of Levinger (Lev51)

$$\sigma_{\text{qd}} = \sigma_0 D(A-Z)/A,$$

where \((A-Z)Z\) is the number of quasi-deuteron pairs, \(A\) is the atomic number, \(\sigma_{\text{qd}}\) is the photodeuteron cross-section, and \(D\) is the quasi-deuteron constant which is a measure of the probability that a quasi-deuteron pair is within a suitable interaction distance of the photon. The recommended values of \(D\) appearing in the literature range from 7 to 12 (Gab69 and Gab75). The proton or neutron resulting from this process then creates an intranuclear cascade, and the emitted neutron spectrum is typical of this cascade.

Above 140 MeV the cross-section for photonuclear reactions again rises because of the onset of photopion production. There are a number of resonance peaks at energies below 1.1 GeV caused by nucleon isobar formation. The largest peak is the first, centred at about 300 MeV with a width of about 110 MeV. Above 1.1 GeV the \(\gamma p\) and \(\gamma n\) total cross-sections both decline slowly towards an asymptotic value close to 100 \(\mu\)b. Neutrons are emitted from both the nucleus struck by the photon (which becomes highly excited and gives rise to intranuclear cascade and evaporation particles) and from the extranuclear cascade generated by the photopions.

A qualitative picture of photonucleon cross-sections as a function of photon energy is given in Fig. 10 (Swa79b). The cross-sections for all three processes are shown: giant-resonance, quasi-deuteron, and photopion. Also given are cross-sections weighted by the multiplicity of neutrons produced.

It is important to realize that the cross-sections for neutron production depicted as a function of photon energy are to be folded together with a photon spectrum which falls rapidly with photon energy in most practical situations. The
Fig. 10 Qualitative picture of photoneutron-producing mechanisms, expressed as cross-section per target nucleon, as a function of photon energy. To the left is the giant-resonance peak which produces most of the neutrons. To the right is the photopion production cross-section and in the centre the pseudodeuteron effect. The photopion mechanism produces the highest energy neutrons which most readily penetrate the shielding (Swa79a).

thin-target bremsstrahlung spectrum falls approximately as 1/E, that of thick target bremsstrahlung as 1/E^2, and that of the high-energy tail of the synchrotron radiation spectrum as exp(−r)/r^0.5, r being the ratio of the photon energy to the critical energy (subsection 4.6). The trends of such spectra strongly enhance the importance of the giant-resonance mechanism relative to the other mechanisms of low-energy neutron production and the first photopion resonance at 300 MeV for the production of higher-energy neutrons.

For electrons incident on a thick target, the maximum neutron yield is obtained by allowing the full development of the electron–photon cascade and by assuming minimum shielding of the produced neutrons. The total neutron yield as a function of energy is given in Fig. 11 (Swa79a). Experimental data on low-energy neutron production for electrons incident on a thick copper target as a function of electron energies up to 100 GeV are given in Fig. 12, taken from Ste83b. The increased yield observed at energies above 20 GeV is as yet unexplained.

4.4 Radioactivation by electron beams

Radioactivity may be induced in solid components, as well as in air and water, to an extent that depends on the electron energy, beam power, and type of material. Activation can be produced in all parts of the LEP system, as electron energies are above the thresholds for activation everywhere except very close to the LIL pre-injectors. Precise thresholds for various activation reactions can be found in How64. Three types of photon-induced reactions produce most of the activity:

i) The giant photonuclear resonance,

ii) the quasi-deuteron effect, and

iii) high-energy photospallation reactions.
The components to be most suspected for activation are those that absorb most of the beam energy, in particular:

i) beam dumps,

ii) targets (converter),

iii) collimators.

Areas where steering is particularly critical, such as where beam transfer between elements of the LEP accelerator chain occurs, are subject to electron beam losses which will lead to activation of components.

The subject of induced radioactivity has been extensively treated by Barbier (Bar69), and a shorter review of the subject has been published by Gollon (Gol76). Predictions of radioactivity at electron accelerators have been tabulated by Swanson (Swa79a, Ch. 2.6). Although the overwhelming majority of the activity is produced by photon-induced reactions, significant activity may be induced by secondary neutrons if the beam power is high enough to release large neutron fluences.

To set a scale for the amount of activity induced, the following remarks are useful.

i) By far the most copious radioactivity-inducing reactions are the \((\gamma, n)\) reactions. The maximum possible saturation activity (in Bq) is therefore always close to (but less than) the photoneutron production rate (in neutrons per second). Approximate saturation rates are shown in Table 7. These values assume that only a single target isotope is present, and that all the energy of the electromagnetic shower induced by the incident electron beam is absorbed in that material. These values set an upper limit to the amount of radioactivation that is possible. This upper limit generally will not exceed about 2000 GBq per kW of electron beam power lost, under the most unfavourable conditions; these are rarely found in practice.

ii) Saturation radioactivity produced by \((\gamma, 2n)\) reactions amounts to about 5% of these values for light nuclei (C–Fe) and about 10% for heavier nuclei (Au, Pb).

iii) Saturation radioactivity produced by all other processes combined, including spallation, is of the same order of magnitude as that induced by \((\gamma, 2n)\) reactions.

iv) Although the above remarks set a useful scale for the amount of radioactivity possible, the practical result will always be considerably less, for two reasons: many reactions do not lead to radioactive end products; and those that do may have half-lives that are either too short or too long to be of any concern. One may generally ignore half-lives that are shorter than 10 minutes because these radionuclides decay before personnel have time to enter into their vicinity. Similarly, half-lives greater than 10 years may usually be ignored because saturation is not achieved during the lifetime of the facility.

Casual observation at high-energy electron facilities suggests the qualitative groupings of common materials shown in Table 8. It is evident that lead, concrete, and aluminium are preferred materials, from the standpoint of radioactivation, and that fissionable materials, such as uranium, are undesirable in terms of activation potential.

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Saturation radioactivity per electron beam power (GBq/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light elements (C–Al)</td>
<td>400–600</td>
</tr>
<tr>
<td>Medium elements (Fe–Ag)</td>
<td>800–1700</td>
</tr>
<tr>
<td>Heavy elements (Ba–Pb)</td>
<td>2000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Insusceptible</th>
<th>Moderately</th>
<th>Highly</th>
<th>Highly (fissionable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (antimony-free)</td>
<td>Iron (steel, ferrite)</td>
<td>Stainless steel</td>
<td>Uranium</td>
</tr>
<tr>
<td>Concrete</td>
<td>Copper</td>
<td>Tungsten</td>
<td>Plutonium</td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td>Tantalum</td>
<td>Thorium</td>
</tr>
<tr>
<td>Wood</td>
<td></td>
<td>Zinc</td>
<td></td>
</tr>
<tr>
<td>Plastics</td>
<td></td>
<td>Gold</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manganese</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cobalt</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nickel</td>
<td></td>
</tr>
</tbody>
</table>
4.5 Muon production

Above a photon energy of 211 MeV, muon pair production becomes possible by photons in the Coulomb field of target nuclei (Cle65, Kim73). This is a process analogous to ordinary $e^\pm$ pair production, except that the cross-sections are smaller by several orders of magnitude ($\approx 1/40000$), owing to the larger muon mass. The dominant process is one in which the target nucleus remains intact as it recoils from the interaction (coherent production), although some reactions involving nuclear break-up (a few per cent) also occur. Muons are also present as decay products of photoproduced pions and K mesons, but these additional sources are relatively small compared with the direct production of muon pairs, provided that the meson decay path is not too long.

The muon fluence is very highly peaked in the forward direction, with beam diameters (at half-intensity) of the order of only tens of centimetres outside of the thick shielding (Nel68, Nel74a, Nel74b). Figure 13 shows the $\mu^\pm$ fluence at $0^\circ$, integrated over all muon energies as a function of primary electron energy $E_0$ (Swa79a, pp. 142–147). The flux density per kilowatt of beam power is approximately proportional to $E_0$, and we may reasonably expect this linear trend to continue to higher values of $E_0$. Although the total number of muons produced per kilowatt does not rise very rapidly with incident electron energy, those produced tend to be more tightly collimated, which results in higher fluences at $0^\circ$.

Although similar in every respect to electrons, the larger mass of muons does not permit them to radiate energy as readily by bremsstrahlung. Thus they do not participate in the electromagnetic cascade shower. Being leptons, they also do not interact with nuclei via the hadronic interaction. The only remaining significant stopping mechanism is energy loss by ionization. Extensive tables of muon stopping power and ranges in various materials have been published by Barkas and Berger and Berger and Seltzer (Bar64, Ber66). Transport of muons through thick shielding has been studied at CERN by means of the program TOMCAT (Ste81b). Figure 14 shows a graph of muon range as a function of muon kinetic energy. Fluence-to-dose-equivalent conversion as a function of muon energy is discussed in Ste83a.

Muon production will not be a significant radiation problem at LEP, because of the generally low beam power (throughout the LEP system), the massive overburden of earth, and other geometrical factors. Dose rates from beam losses in various parts of the system range from about 20 mSv/h (at 1 m) for full loss of injected beam (17 W) at a point, to about 0.2 Sv (at 1 m) for complete loss of circulating beam at 86 GeV. As there will be nobody in the vicinity of these highly collimated muon beams, the muons will be harmlessly ranged-out in sufficient thicknesses of earth shielding and have no effect whatsoever.

![Fig. 13](image1.png) Muon production at $0^\circ$ from an unshielded thick iron target, as a function of electron energy $E_0$. Left-hand scale: muon flux density at 1 m, per unit electron beam power. Right-hand scale: unshielded dose-equivalent rate normalized to 1 m, per unit electron beam power.

![Fig. 14](image2.png) Range-energy curves for muons in various materials. Muons of the highest energy that can be produced by LEP remain close to the plane of the LEP ring and can penetrate only about 200 m of earth. Muons do not produce any residual radioactivity.

4.6 Synchrotron radiation

When the $e^\pm$ pass through the dipole magnets of the pre-injector or the LEP-MR, or through the fields of the focusing (quadrupole) magnets, they experience a centripetal acceleration designed to keep them in the proper orbit (Fig. 15). This type of acceleration is always accompanied by the emission of synchrotron radiation (SR). The spectrum of SR is typically of low energy, compared with that of bremsstrahlung produced by the same electrons, extending from the region of visible light through the energy range of ordinary diagnostic X-rays (hundreds of kiloelectronvolts) up to MeVs in the LEP–MR. The SR occurs where the beam particles undergo transverse deflection,
Fig. 15  Production of synchrotron radiation (SR) by electron beams transversely deflected by a magnetic field. (There is no scale and the amount of deflection is greatly exaggerated.) SR is emitted tangentially to the beam direction so that it remains close to the orbital plane, irradiating the vacuum chamber and other components in the vicinity. Positrons, transported in the opposite direction, would radiate towards the left in this figure.

Fig. 16  Synchrotron radiation in the SPS (bending radius 741.3 m). Left-hand scale, energy loss per e\(^{+}\) per orbit path length as a function of particle energy. Right-hand scale: Critical energy for the same conditions.
and this occurs primarily in the curved sections. By the nature of the SR, the dose rates in these areas will be of a steady, predictable nature that is easily calculable for a given value of beam current and magnetic field.

Two parameters are of primary importance in determining the effects of SR: the radiated power per unit beam path, and the critical energy $e_c$. The critical energy is defined as the median of the power spectrum and characterizes the "hardness" of the radiation. The SR emitted depends strongly on the beam energy and strength of the deflecting forces; the critical energy of the emitted photons increases as the third power of the particle energy and the radiation power emitted rises with the fourth power of the energy (Fig. 16).

The total energy loss per complete turn of an electron in a circular orbit is given by

$$\Delta E = \frac{4\pi}{3} m_e r_e \gamma^4 / \rho,$$

where $m_e$ and $r_e$ are the rest mass and classical radius of the electron, $\rho$ is the radius of the orbit, and $\gamma$ is the ratio of total energy $E$ to rest mass of the moving $e^\pm$. If $E$ is expressed in GeV and $L$ in metres, the total energy loss $\Delta E / \Delta L$, in keV/m, becomes

$$\Delta E / \Delta L = 14.08 \, E^4 / \rho^2.$$

The total power emitted in watts per turn for a circulating current $I$ (in mA) is then

$$P = 88.46 \, E^4 I / \rho.$$

The total power emitted in watts per turn for a circulating current $I$ (in mA) is then

$$P = 88.46 \, E^4 I / \rho.$$

The photon spectrum for a single radiating electron is given by the expression

$$d^2 N / d\varepsilon d\tau = \frac{\alpha}{\pi \sqrt{3 \hbar}} \left(1 / \gamma^2 \right)^{1/2} K_{5/3}(\eta) d\eta,$$

where $\varepsilon$ is the photon energy, $\alpha$ and $\hbar$ are the fine structure and Planck's constants, respectively, and the integrand is the modified Bessel function of order $5/3$. The lower limit of integration $r$ is the ratio of the photon energy to the critical energy $e_c$, the latter being given by

$$e_c = 2.218 \, E^3 / \rho \, (\text{keV}),$$

where $E$ is in GeV and $\rho$ in metres as before. Figure 17 shows examples of SR spectra at LEP energies.

![Fig. 17 Primary synchrotron radiation spectra at three LEP energies, in units of photons per MeV and metre.](image)
This means that a single electron radiates at a rate of
\[ \frac{d^2N}{d\varepsilon dt} = (5.32 \times 10^5 \frac{E}{E^2}) \int_{\eta}^{\infty} K_{Si}(\eta) d\eta \] photons per eV and s \hspace{1cm} (4.17)

or, since \( ds = c \, dt \), the loss along the orbit for a single electron is
\[ \frac{d^2N}{d\varepsilon ds} = \left( 1.775 \times 10^{-3} \right) \frac{E}{E^2} K_{Si}(\eta) \int_{\eta}^{\infty} d\eta \] photons per eV and m. \hspace{1cm} (4.18)

The total number of photons emitted by an electron per metre of orbit is
\[ \frac{dN}{ds} = 3.936 (\frac{E}{\rho}) \int_{\eta}^{\infty} K_{Si}(\eta) d\eta dr = 19.4 \frac{E}{\rho} \text{ photons per metre.} \hspace{1cm} (4.19) \]

There are very significant differences between the synchrotron-radiation spectrum in the EPA (600 MeV), the PS (3.5 GeV), and the SPS (20 GeV) on the one hand, as compared with the LEP ring at the highest energies (51.5–100 GeV) on the other. In the EPA ring, the SR lies in the energy region of infra-red light. This means that the radiation is of such low energy and power that no additional provisions for radiation protection are needed; the SR is too low in energy to produce any significant effect. In the SPS, the SR is of some concern because of possible damage to the components nearest the vacuum chamber. However, in the LEP ring, it is the main source of radiation. The dose to main-ring components and the production of \( \text{O}_3 \) and \( \text{NO}_x \) are the main effects of this radiation, becoming important at \( \text{e}^\pm \) energies of 86 GeV and above. At such energies, the critical energy is higher, about 0.4 MeV, which means that a substantial number of photons are above the threshold for photonuclear reactions. Although there is a very rapid decline in the spectrum above the critical energy, the high-energy tail extends beyond the threshold for photonuclear reactions and, for sufficiently high intensity, photoneutron production and photo-activation have to be taken into consideration for radiation protection. Table 9 shows basic parameters of SR at three LEP design energies.

**Table 9**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEP energy in GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>51.5</td>
</tr>
<tr>
<td>I (per beam) (mA)</td>
<td>3.0</td>
</tr>
<tr>
<td>Q (two beams) (C)</td>
<td>( 6.5 \times 10^4 )</td>
</tr>
<tr>
<td>Critical energy (keV)</td>
<td>97.8</td>
</tr>
<tr>
<td>Radiated power (two beams) (W/m)</td>
<td>62</td>
</tr>
</tbody>
</table>

a) Assuming 3000 h operation.

5. CHEMICAL INTERACTIONS

5.1 Introduction

Photons of an energy higher than a few electronvolts are capable of exciting oxygen molecules in air via the reaction

\[ h\nu + \text{O}_2 \rightarrow \text{O}_3. \] \hspace{1cm} (5.1)

This excitation is followed by rapid chemical reactions:

\[ \text{O}_3^* + \text{O}_2 \rightarrow \text{O}_3 + \text{O}, \] \hspace{1cm} (5.2)

\[ \text{O} + \text{O}_2 + \text{M} \rightarrow \text{O}_3 + \text{M}, \] \hspace{1cm} (5.3)

where \( \text{O}_3 \) is the ozone molecule and \( \text{O} \) the extremely reactive oxygen atom. The latter can react with an oxygen molecule to form another ozone molecule (a third body, \( \text{M} \), such as a nitrogen molecule, is necessary to take on the excess kinetic energy).

Accompanying reactions, such as

\[ \text{N}_2 + \text{O}_3^* \rightarrow 2\text{NO}, \] \hspace{1cm} (5.4)
will compete with the above reactions which form \( O_3 \). As soon as small concentrations of nitrogen monoxide (NO) are present in the atmosphere, a very fast reaction with ozone,

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2, \tag{5.5}
\]

will lead to appreciable quantities of nitrogen dioxide which, in the presence of water vapour, are transformed into strongly oxidizing nitric acids. It should be noted that, whereas reactions (5.2) and (5.3) produce ozone, the latter two reactions tend to reduce the concentration of ozone.

### 5.2 Radiolytic reactions

The same radiolytic products, i.e. ozone and oxides of nitrogen (generally named \( \text{NO}_x \)) and nitric acids, are also formed under the action of ionizing radiation. The possible reactions are more complex, however, owing to the presence of ionic species and free radicals (Wil70).

It is common to characterize the formation of these products globally by so-called “G-values”, i.e. the number of reaction products per 100 eV of ionizing radiation absorbed by the system. Measured G-values for the formation of ozone in air, reported in the literature, range from 7.4 to 10.3 molecules per 100 eV, depending on the dose rate. The theoretical value for the production of \( \text{NO}_2 \) is 4.8, whilst for the production of nitric acid an average value of 1.5 has been determined experimentally (Wil70, Les64).

### 5.3 Formation of ozone in the LEP tunnel

Synchrotron radiation penetrating the lead shielding of the vacuum chamber will lead to the production of ozone and nitrogen oxides. The dynamic model for the formation of ozone and its destruction by the action described above (Höf81b) leads to the following formulation for the concentration at saturation in a closed system with no ventilation:

\[
\text{N}_{\text{sat}} = \frac{IG}{(\alpha + k)I}, \tag{5.6}
\]

where
- \( I \) = mean energy deposited in air per unit time and volume (eV \( \cdot \) s\(^{-1} \) \( \cdot \) cm\(^{-3} \)),
- \( G \) = G-value for ozone formation (0.074 eV\(^{-1} \)),
- \( \alpha \) = decay constant for ozone inside the LEP tunnel (2.3 \( \times \) 10\(^{-4} \) s\(^{-1} \)),
- \( k \) = a constant describing the destruction of ozone by the action of radiation, estimated to be 1.4 \( \times \) 10\(^{-16} \) eV\(^{-1} \) \( \cdot \) cm\(^{3} \).

For G, the most reliable value from the literature is taken (Wil70), the decay constant \( \alpha \) corresponds to a “half-life” for ozone of 50 minutes (Geo65), whilst \( k \) is derived from an experiment performed at Frascati under conditions which approximate those of the LEP tunnel (Cav79). For power densities of less than \( I = 10^{13} \) eV \( \cdot \) cm\(^{-3} \) \( \cdot \) s\(^{-1} \) deposited in the air, the increase in ozone concentration was found in this work to be approximately proportional to \( I^{0.8} \). The concentration of ozone at saturation in a closed system is plotted in Fig. 18 as a function of dose rate. In this figure one may compare the measurements obtained at Frascati (dashed line) with the predictions of Eq. (5.6).

![Fig. 18](image-url)
The LEP tunnel is, however, not a closed system but is ventilated. The transport of air through the tunnel leads to the following build-up term by which the saturation concentration estimated by Eq. (5.6) is to be multiplied:

\[ 1 - \exp\left(-\frac{(\alpha + k)I}{\nu}\right), \]

where the \( \alpha, k, \) and \( I \) terms are defined above, \( L \) is the length of the bending section of a LEP octant, and \( \nu \) the ventilation speed in m/s. Taking \( L \) to be 2787 m and the ventilation speed to be 1 m/s, the above build-up term is of the order of 0.5. In this model it is assumed that, over the last 250 m following a bending section, the ozone concentration reached will remain stable since possible decay is compensated by a small production due to synchrotron radiation streaming down the long straight section.

Weak concentrations of natural ozone are found in the ambient atmosphere — of the order of 0.025 to 0.045 ppm by volume. Ozone is an unstable gas, which decomposes slowly at ordinary temperatures. The facility with which ozone decomposes makes it a powerful oxidizing agent. Its oxidizing reactions are enhanced by the presence of humidity. Its decomposition is accelerated in the presence of certain catalysts. Most metals are attacked by ozone, with the exception of gold and platinum. Stainless steel and aluminium resist its action rather well. Many plastics and elastomers are degraded by ozone. Results on the concentration of noxious compounds expected for the operation of LEP are given in Section 12.4.

Although several chemical species result from radiolytic reactions, ozone production is the limiting factor, owing to its much lower maximum acceptable concentration (see later Table 44), high radiolytic yield, and its chemical reactivity. Provisions for mitigating the effects of radiogenic noxious gases are the same as those for reducing the concentrations of radioactive gases, and include, primarily, reducing the average radiation dose to the air.

6. METHODS OF ESTIMATING RADIATION PARAMETERS

6.1 Estimates from measured data

6.1.1 Introduction

The shielding requirements for high-energy electron accelerators and storage rings have been extensively discussed in various publications (Swa79a, Pat73), and have been reviewed for LEP in Hof81a. A frequent approach has been to distinguish three different radiation components: the electromagnetic, the giant-resonance neutron, and high-energy hadron contributions. Owing to substantial differences in the attenuation of these three components, it is generally observed that behind shielding thicknesses of about 2 m of concrete, or the equivalent of earth or a similar material, the high-energy particle component propagating the nuclear cascade dominates and determines the basic shielding requirements. Hence for thick shields, electron accelerators can be treated similarly to high-energy proton machines. For thin shields, however, the more abundant production of other components, especially the electromagnetic component, more than compensates for the shorter attenuation lengths. Parameters adopted for the LEP shielding design, describing the strength of the radiation sources as well as attenuation in concrete, are given below.

It should be noted that, at least for the direction at 90° to the beam, the strength of these three radiation components scales approximately as electron beam power (i.e. as beam energy, for constant current).

A fourth significant radiation component, consisting of muons, is different in two respects — it is important only in a narrow cone of radiation in the forward direction, and it scales in a more complicated manner. Muons are discussed in Sections 4.5 and 6.4.

Although more accurate results can, and have been, obtained through the use of computer transport programs, the results of “hand-calculations” based on these parameters are often extremely useful, both as design information in themselves, and as a check on the reasonableness of answers obtained by more sophisticated methods.

6.1.2 Source terms

a) High-energy component

The production of high-energy particles from high-energy electrons and photons interacting in copper targets has been studied by various authors, both theoretically and experimentally (DeS68, Bat67, Als73). Since the quantitative description of the source is of prime importance in the determination of shielding requirements, various published results have been analysed and presented in a consistent form in Table 10.

The assumption is frequently made that the total high-energy particle yield \( Q \) scales linearly with energy for constant beam current. Hence the data in Table 10 have been normalized to 1 GeV. The correspondence between experiment and theory is rather good in the GeV range, whilst the calculated value at 400 MeV is significantly lower.

In estimates for LEP, we employ a high-energy particle yield at 90° based on the highest reported experimental figure. The measurements of Bat67 (Table 10), interpolated to 90°, give a value of \( 1.3 \times 10^{-3} \) high-energy particles per electron per steradian. When multiplied by a fluence-to-dose-equivalent conversion factor of \( 9.3 \times 10^{-10} \) Sv \( \cdot \) cm\(^2\) \( \cdot \) GeV\(^{-1}\), the dose-equivalent source term becomes \( 1.2 \times 10^{-12} \) Sv \( \cdot \) cm\(^2\) \( \cdot \) GeV\(^{-1}\).
Table 10
High-energy particle yields (> 25 MeV) per electron on a thick copper target per steradian at different angles and for various incident electron energies, and production yield Q integrated over all solid angles. Data are normalized to 1 GeV incident energy.

<table>
<thead>
<tr>
<th>Energy</th>
<th>400 MeV</th>
<th>6.3 GeV</th>
<th>7 GeV</th>
<th>10 GeV</th>
<th>20 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>2.5 x 10^{-4}</td>
<td>3.8 x 10^{-2}</td>
<td>1.8 x 10^{-1}</td>
<td>2.2 x 10^{-1}</td>
<td>7.4 x 10^{-2}</td>
</tr>
<tr>
<td>0-60</td>
<td>2.1 x 10^{-4}</td>
<td>1.5 x 10^{-2}</td>
<td>9.0 x 10^{-3}</td>
<td>-</td>
<td>2.7 x 10^{-2}</td>
</tr>
<tr>
<td>60-120</td>
<td>1.2 x 10^{-4}</td>
<td>8.1 x 10^{-3}</td>
<td>6.2 x 10^{-3}</td>
<td>-</td>
<td>1.9 x 10^{-2}</td>
</tr>
<tr>
<td>120-180</td>
<td>8.1 x 10^{-5}</td>
<td>4.9 x 10^{-3}</td>
<td>5.1 x 10^{-3}</td>
<td>-</td>
<td>1.6 x 10^{-2}</td>
</tr>
<tr>
<td>Yield Q</td>
<td>4.3 x 10^{-3}</td>
<td>1.9 x 10^{-2}</td>
<td>1.5 x 10^{-2}</td>
<td>-</td>
<td>1.4 x 10^{-2}</td>
</tr>
</tbody>
</table>

a) Als73, b) Bat67, c) DeS68.

Table 11
Yield of giant-resonance neutrons

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>Cu</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (neutrons per GeV and electron)</td>
<td>0.18</td>
<td>0.35</td>
<td>0.42</td>
</tr>
</tbody>
</table>

b) Giant-resonance neutrons
As for the high-energy particles, it is generally assumed that the yield of giant-resonance (GR) neutrons is proportional to the electron energy. It is also assumed to be isotropic, but there is some dependence on target material. A comparison of published values (Jen78, Tes79, Bat67, Swa79a, Din72, Bat65, Hof78, Jen76, Als70, Han75, Swa79b, Swa78) has led us to adopt the values of GR neutron production set forth in Table 11. These are consistent with results of a systematic study by Swanson (Swa79b). For other materials, the GR neutron yield can be obtained by interpolation, assuming a dependence on atomic number Z of the form Z^0.66 (Swa79b).

c) Electromagnetic
The attenuation of the electromagnetic (e.m.) component in shielding at 90° to the electron beam direction has been extensively studied by Dinter and Tesch (Din77). The source term at 90° of this component used for shielding calculations is smaller than that measured at 90° to an unshielded target because of the abundance of low-energy electrons which do not penetrate into the shielding. In the following we consider only the effective source which gives rise to the penetrating component. This source function is strongly dependent on the development of the cascade. This is seen in Table 12 which demonstrates a strong dependence on the angle of grazing incidence.

Table 12
Determinations of the electromagnetic radiation source term at 90°, from electrons striking a target

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Target thickness (cm)</th>
<th>Electromagnetic radiation yield (Sv · cm² · GeV⁻¹ per electron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1° grazing angle a)</td>
<td>0.2 Cu</td>
<td>1.23 x 10^{-12}</td>
</tr>
<tr>
<td>2° grazing angle a)</td>
<td>1 Cu</td>
<td>9.2 x 10^{-12}</td>
</tr>
<tr>
<td>High-Z b)</td>
<td>“thick”</td>
<td>2.2 x 10^{-11}</td>
</tr>
<tr>
<td>“Glancing angle” c)</td>
<td>“thick”</td>
<td>1.8 x 10^{-11}</td>
</tr>
</tbody>
</table>

a) Din77, b) Swa79a, c) Jen78.
As there is considerable spread in these values, stemming from varying target configurations, we have adopted the conservative choice of $2.2 \times 10^{-11}$ Sv · cm$^2$ · GeV$^{-1}$ per electron (or $50$ Sv · m$^2$ · kW$^{-1}$ · h$^{-1}$) as the e.m. source term for the LEP shielding design at $90^\circ$.

6.1.3 Attenuation lengths

The attenuation length $\lambda$ of 115 g/cm$^2$ in concrete has been adopted for shielding of the high-energy component of radiation. This is consistent with various published values which lie in the range 105 to 120 g/cm$^2$, and is also based on experience in shielding the CERN high-energy proton accelerators. For comparison, the value 120 g/cm$^2$ is recommended by the ICRU (ICR 78).

Concerning the attenuation length of GR neutrons, there is considerable disagreement among various published values for concrete (see Table 13). After consideration of these values, we have adopted 40 g/cm$^2$ as a conservative compromise for the LEP design.

The attenuation length for e.m. radiation at $90^\circ$ was measured by Dinter and Tesch for concrete and found to be 44 g/cm$^2$ (Din77). We have adopted this value for LEP shielding. This is somewhat less than the length based on attenuation at the Compton minimum (50 g/cm$^2$), but is reasonable considering the softening of the spectrum towards $90^\circ$.

6.1.4 Summary and precautions

In using these source terms to determine the lateral shielding, we have conservatively chosen geometrical conditions which maximize the source. For example, we utilize the e.m. source term, which corresponds to the case where the electron beam impinges at grazing incidence on a target. This situation gives maximum doses from the bremsstrahlung photon component. At the same time we assume that the shower develops sufficiently to give the maximum neutron dose. In a particular loss situation these conditions might not apply, but it would be imprudent, in our opinion, not to use conservative assumptions when making specifications for the LEP shielding.

To summarize, we have recommended the parameters shown in Table 14 to calculate the dimensions of bulk concrete shielding around LEP.

The relative importance of these terms is indicated in Fig. 19. It is seen that bremsstrahlung (e.m.) radiation dominates at all depths up to about 2 m of concrete; deeper in the shielding the high-energy component dominates. Where protection of the personnel is the primary concern, rather than merely protection of equipment, an additional safety factor is applied in cases where it seems appropriate (see Section 11 on the LEP pre-injector shielding).

### Table 13
Attenuation length for giant-resonance neutrons for concrete

<table>
<thead>
<tr>
<th>Neutron source</th>
<th>$\lambda$ (g/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3 GeV electron bremsstrahlung</td>
<td>49$^{\text{a)}$</td>
</tr>
<tr>
<td>15 GeV electron bremsstrahlung</td>
<td>32</td>
</tr>
<tr>
<td>Neutrons from AmBe</td>
<td>47$^{\text{a)}$</td>
</tr>
<tr>
<td>55–85 MeV electron bremsstrahlung</td>
<td>37–43</td>
</tr>
</tbody>
</table>

$^{a)}$ Din72, b) Jen76, c) NCR 77, d) for heavy concrete.

### Table 14
Source terms and attenuation length in concrete for the principal radiation components produced at $90^\circ$ at LEP

<table>
<thead>
<tr>
<th>Radiation component$^{a)}$</th>
<th>Source term (Sv · cm$^2$ · GeV$^{-1}$ per electron)</th>
<th>Attenuation length (g/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>$2.2 \times 10^{-11}$</td>
<td>44</td>
</tr>
<tr>
<td>Giant-resonance neutrons</td>
<td>$1.0 \times 10^{-11}$</td>
<td>40</td>
</tr>
<tr>
<td>High-energy</td>
<td>$1.2 \times 10^{-12}$</td>
<td>115</td>
</tr>
</tbody>
</table>

$^{a)}$ For muons, see subsections 4.5 and 6.4.
Fig. 19 Attenuation of components of radiation produced by e⁺ beams incident on a high-Z target, at 90° to the incident beam direction, as a function of concrete shielding thickness. Values are normalized to 1 kW electron beam power and to 1 m distance from target by inverse-square scaling. The curves for bremsstrahlung and giant-resonance neutrons are the same for all electron energies in the range used by the LEP system. The hatched bands for neutrons show the dose equivalents for the lowest energy in question (lower limit of band: 200 MeV for the LIL converter) to the maximum LEP energy (upper limit: 86–100 GeV).

6.1.5 Bulk shielding calculations

In this report we use the following equation for the dose equivalent penetrating the transverse shielding:

\[ H = \sum_i (S_i E_i r^2) \exp(-d/\lambda_i), \]

where \( S_i \) is the source term for the component \( i \) in the angular region around 90° in Sv · cm² · GeV⁻¹ per electron (Table 14);
\( E_i \) is the electron energy in GeV;
\( r \) is the source-to-outer-shielding thickness in cm;
\( \lambda_i \) is the attenuation length for concrete for the relevant component \( i \) (Table 14); and
\( d \) is the shielding thickness in g/cm².

The dose equivalent is then given in Sv per incident electron.

We have further standardized our basic assumptions for calculating shielding thickness by adopting the values for material density given in Table 15.

6.1.6 Assumptions on beam losses and resulting doses

Assumptions on beam losses in the various reports written (e.g., Pot80, Bac80) differ somewhat. We have standardized our assumptions for this report, and unless otherwise stated, the values used are:
1) Injection loss: Worst case is the local loss of 1.55 × 10¹⁰ electrons or positrons per second at 20 GeV.
2) Continuous loss due to normal beam decay: A figure of 1 × 10⁹ electrons per second lost in the ring at an energy of 86 GeV.
3) Total loss of two beams of 10 mA each at a point: 1.1 × 10¹³ e± at an energy of 86 GeV (from Table 3).

Table 15

<table>
<thead>
<tr>
<th>Shielding material</th>
<th>Density (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary concrete</td>
<td>2.35</td>
</tr>
<tr>
<td>Baryte concrete</td>
<td>3.40</td>
</tr>
<tr>
<td>Earth (molasse or moraine)</td>
<td>1.95</td>
</tr>
</tbody>
</table>
6.2 Monte Carlo program EGS for electron–photon showers

The EGS code system is a Monte Carlo computer program which simulates the development of electromagnetic cascade showers in media chosen by the user. Developed at SLAC by Nelson and Ford (For78), EGS is well suited for the solution of problems associated with LEP. Some of the features which enhance its usefulness are listed below:

i) Showers can be simulated in any element, compound, or mixture. Media can include elements 1 through 100.

ii) An extremely wide energy range is covered. The upper energy limit is 100 GeV. The lower limit is 1.5 MeV (total energy) for e± and 0.001 MeV for photons.

iii) Particles are transported in random rather than discrete steps.

iv) Positrons may annihilate either in flight or at rest, and their annihilation photons are followed to completion.

v) Electrons and positrons are treated separately, and the appropriate, exact formulae are used for Möller and Bhabha scattering.

vi) EGS is a subroutine package with user interface. This allows the user great flexibility without requiring him to be familiar with the internal workings.

vii) The geometry is specified by user-written subprograms.

viii) Provision is made for variable density of media.

By writing his own main program, as well as a geometry subroutine and an output routine, the user can specify the geometry of the problem and the type of output he desires (i.e. energy deposition, doses, particle spectra).

The Monte Carlo technique provides a much better way of solving the shower generation problem than do the analytical techniques, not only because all the fundamental processes can be included, but because arbitrary geometries can be treated. In addition, other minor processes, such as photoneutron production, can be added as a further generalization. Another fundamental reason for using the Monte Carlo method to simulate showers is their intrinsic random nature. Since showers develop randomly according to the quantum laws of probability, each shower is different. For many applications of interest, shower-by-shower fluctuations, rather than just averages over many showers, are important. The Monte Carlo method is ideally suited to such problems.

In radiation studies for LEP, the following categories of problems, involving either e± interactions or synchrotron radiation transport, were solved using the EGS program:

i) dose distributions near targets struck by electrons;

ii) energy deposition in machine components with regard to radiation damage;

iii) energy deposition in machine components with regard to cooling requirements;

iv) photon spectra subsequently used as input for studies of transport within ducts;

v) transport of photons through ducts;

vi) neutron production in thick targets.

In the development of programs for these studies, subroutine packages were adapted or developed for the following geometries:

i) Cartesian geometry, both two- and three-dimensional,

ii) cylindrical geometry,

iii) spherical geometry.

The problems studied for LEP consist mainly in determining the energy deposition in machine components from synchrotron radiation. In the case of solid components, this is usually done directly within EGS by summing the energies deposited by individual particles. In some cases, because of the small number of interactions per unit volume (e.g. in air), the direct assessment of energy deposition is subject to large random fluctuations. In these cases a record is generated of the photon spectrum traversing the medium in question. This spectrum permits the calculation of the kerma, which is an estimate of the absorbed dose (in all cases relative to LEP).

A typical geometry which simulates a dipole magnet in EGS is shown in Fig. 20 (in cross-section). Synchrotron radiation impinges, at a grazing angle, on the inner surface of the vacuum chamber. The latter is inserted into the magnet yoke, which provides, in addition to the lead sheath around the vacuum chamber, a shielding towards the outside of the machine. After preliminary studies had been made, it became clear that the critical point with respect to shielding was the open (inner) side of the magnet gap. This open side is nearly as strongly irradiated as the closed side, where the synchrotron radiation impinges directly.

In order to arrive at meaningful results with computer runs of reasonable duration, the number of regions was reduced by replacing three-dimensional geometry by an equivalent two-dimensional problem: in Cartesian coordinates, the principal axis extended along the direction of the dipole magnet pole-face from $-\infty$ to $+\infty$, and in cylindrical coordinates no azimuthal cuts were made (Bur82a, Fas82b).

The energy deposition in defined regions of interest can be easily transformed into average absorbed dose. In regions where the energy deposition is small, i.e. in air volumes, or if it is necessary to determine surface doses, the spectrum of photons traversing the region is utilized by EGS in the following manner: Kerma is defined as the integral

$$K = c \int \phi E \eta/\rho(E) \, dE \quad \text{(Gy)} , \tag{6.2}$$
Fig. 20 Example of geometry used in EGS to simulate a dipole magnet, including aluminium vacuum chamber (with lead shield), iron concrete magnet yoke, coils, and air.

where $\phi_E$ is the spectral fluence in $\text{MeV}^{-1} \cdot \text{cm}^{-2}$, $E$ is the photon energy in MeV, $\eta/p(E)$ is the mass energy transfer coefficient in $\text{cm}^2/\text{g}$, $c = 1.602 \times 10^{-6} \text{g} \cdot \text{Gy} \cdot \text{MeV}^{-1}$.

If $F_E$ is the fraction of energy carried by photons per energy interval in MeV (from EGS), the spectral flux density $\phi_E$ in photons per cm$^2$, s and MeV through a region of dimension $d$ in centimetres can be deduced from:

$$\phi_E = 6.242 \times 10^{10} F_E \frac{E}{P} d,$$

where $E$ is the energy of the interval in MeV and $P$ is the synchrotron power lost in W/m.

Replacing the above integral by a sum, the kerma rate can finally be calculated to be

$$\dot{K} = (10P/d) \sum E F_E \eta/p(E) \Delta E \quad (\text{Gy/s}).$$

Since the sum is already directly calculated in EGS, and $P$ is determined from LEP operating parameters, only the dimensions of the region traversed by the photons finally enter into the estimate of the kerma rate.

6.3 Neutron–photon transport code MORSE

6.3.1 Description of MORSE

The Monte Carlo neutron and photon transport code MORSE was developed in the late nineteen-sixties by the Neutron Physics Division of the Oak Ridge National Laboratory. First released in 1970 (Str70), it has since undergone several modifications. The version used at CERN is essentially the MORSE-CG version distributed by the Nuclear Energy Agency of the OECD, and by the Oak Ridge Radiation Shielding Information Center for IBM machines, with some additions which will be described below. A detailed description can be found in the revised MORSE manual (Emm75). However, some of the features described there (boundary crossing estimator, albedo...
option, energy biasing after scattering) are not actually implemented in the distributed version. A good introduction to the code and its applications has been made by Gabriel (Gab80).

The main features of MORSE include the use of multigroup cross-section sets, anisotropic scattering treated by means of Legendre expansion, time-dependence option, three-dimensional geometry, forward or adjoint calculation, extended importance sampling and biasing devices. Neutrons and photons can be transported separately, but coupled neutron–photon calculation is also possible. Other capabilities of the code, such as that of treating fission and criticality problems, are not of interest in the CERN environment.

Rather than a single code, MORSE must be considered as a modular code system, the individual modules being to a large extent independent of each other and easily replaceable according to the user's requirements. Of the five modules of which MORSE consists — source, random walk, cross-section, geometry, and analysis — only the random walk or transport module can be considered as fixed.

The standard cross-section module uses ANISN-type multigroup cross-section sets (Eng67), which can be obtained with the code through RSIC or NEA. Several such sets exist, each of which has been optimized for a given class of problems. Neutron cross-section sets are in general available up to 20 MeV, but recently a set has been made available for neutrons up to 400 MeV. Photon cross-section sets, however, are limited to a maximum energy of 14 MeV because of the problems encountered in treating pair production. Below this energy, pair production is simply taken into account by "scattering" down to the 500 keV energy group.

The Combinatorial Geometry package, originally developed for military purposes (Gub67) but at present widely used in many Monte Carlo codes, is now preferred by most MORSE users to the original Generalized Geometry package from the older O5R code. The latter package, based on analytical description of quadratic surfaces, is in fact no longer maintained by RSIC.

Combinatorial Geometry describes "zones" (portions of space distinct by their material properties) and "regions" (distinct by their importance) by means of a set of bodies (cylinders, spheres, etc.) and of three operations: addition, subtraction, and intersection.

Special supplementary programs are available to help in setting up the input for the geometry module and in debugging. Two are used at CERN: program PICTURE (Irv70), which is distributed with the main code and described in the same manual, produces line-printer plots of any selected plane section of the geometry; PLOTGEOM (Jaa73) has been obtained from the Ispra Joint Research Centre and gives similar information on a graphics terminal.

SAMBO is the name of the standard MORSE analysis module. Its flexibility allows, in principle, several kinds of estimators to be calculated for fluence or current-like quantities, as integral values and as energy-, angle-, or time distributions. Reaction rates, kerma and similar quantities can also be obtained.

In reality, however, only a point detector (next-event estimator) is implemented in the distributed version of MORSE. Such an estimator can be very useful in particular problems presenting one preferred path for particle transport, but presents several disadvantages (singularities at the detector positions, asymmetry of the probability distribution function, point responses rather than responses averaged over volumes or surfaces). Because of such characteristics, it is not well adapted to a system having pronounced linear symmetry, such as an accelerator tunnel.

6.3.2 Implementation of MORSE for LEP

MORSE was modified at CERN in order to allow the use of several other scoring methods. A track-length density estimator and a boundary-crossing current estimator were implemented as in MORSE-E (Pon76), the Ispra version of the code (also available from NEA), but the structure of the SAMBO analysis module, which is more flexible and easier to use, was retained. In addition, a collision density estimator and a boundary-crossing fluence estimator were provided. All the mentioned scoring techniques can be applied simultaneously in the same run without substantial increase of computer time.

MORSE is a non-analog Monte Carlo code: in other words, it does not solve the Boltzmann transport equation for the given problem by direct numerical simulation of the physical processes, but rather attempts to identify and solve an equivalent problem where the expectation values for the quantities of interest (fluences or doses in given phase-space regions) are the same, although having narrower probability distributions. Whilst this allows one to solve even deep penetration problems within reasonable computer time, it leaves to the user the responsibility for the proper choice of the equivalent problem. This is accomplished by biasing more or less vigorously the random walk at its different stages, which can only be done on the basis of physical judgment, previous experience with the code and, in general, any extra available information.

A non-negligible risk exists, however, that a wrong judgement could lead to a biased result, especially when, as in the case of synchrotron-radiation transport in the MeV range, practical experience is very poor. It is a common practice in such circumstances to use results from other codes, such as ANISN (Eng67) or DOT (Rho73), as a first guideline for importance sampling and at the same time to provide a reciprocal check. It is also possible to pursue the same aim by making preliminary runs while switching off most of the biasing facilities in MORSE itself.

Both such procedures were followed: programs EGS and DOT were used for this purpose in the first stages of the calculations. The agreement was encouraging enough to permit most of further calculations to be done with MORSE, in order to fully exploit its advantages (speed, three-dimensionality).
Importance sampling was first of all used to generate source particles in the different energy groups. The importance of each group was assessed as a function of both the quantity and the region of interest after a few short runs with mono-energetic photons.

"Russian roulette" and splitting were used extensively in all calculations, making it possible to estimate attenuation factors up to $10^4$ with good precision. The intense use of these two biasing techniques is indeed typical of MORSE, where particles are never absorbed but rather decreased in weight at every collision according to the absorption probability. Particle "killing" and weight adjustment are therefore necessary in order to avoid unnecessarily long particle histories and large fluctuations.

Exponential transform (or path stretching) was also tried but failed to improve the results. No use was made of other biasing facilities available in MORSE.

Owing to the lack of any cross-section set expressly designed for synchrotron radiation problems, the existing FEWG1 library (37 neutron, 21 gamma-ray coupled groups, P3 angular expansion) (Bar77) was employed. Preparation of a proper file would be possible by collapsing a larger thin-group cross-section set. However, such a manipulation could be quite time consuming, and a different set should probably be prepared for each LEP energy. Concerning the level of Legendre expansion, a check was made by comparing results with those obtained using the EPR cross-section set (coupled 100-group neutron, 21-group gamma-ray, P8 angular expansion) (For76). No significant difference was found, whilst computer time increased considerably.

In the geometry input, a LEP bending section, approximately 30 m long, was simulated, including tunnel wall and floor, three bending magnets, two inter-magnet gaps, inner and outer coils, vacuum chamber with lead shield, three water channels, and an ionic pump (NEG) channel.

Track-length density estimators were used for all calculations. In addition, collision density was scored in aluminium, lead, and water, and boundary crossing was used to estimate surface doses and activities. Next-event estimators were only used in a first stage. Agreement among different scoring techniques was excellent.

MORSE was applied to the following problems in connection with LEP:

- estimate of doses to dipole coils, cables, and other auxiliary equipment inside the main tunnel;
- ozone production in the main ring, around the intermagnet gap bellows and in the SPS ring;
- dose-rate effects on the pick-up electrodes (time-dependent calculation);
- activation of air, water, vacuum-chamber, and dipole components;
- neutron production in the main ring;
- neutron shielding in the experimental areas;
- radiation streaming in the alcoves, in the waveguide ducts connecting the ring with the klystron galleries, and in the long straight sections.

6.4 Program TOMCAT for muon transport

This section gives a brief description of the muon diffusion theory contained in the TOMCAT transport program. This program was initially developed to calculate the muon fluxes downstream of secondary beams in the SPS experimental areas (Ste81b), and has subsequently been adapted for LEP problems. The initial need was for calculations of the muon flux distribution downstream of high-momentum targets, to determine the possible intensity limitations needed.

The TOMCAT program was developed to meet the need for a fast, simple, but accurate transport program in slab geometry where the muon transport is determined by analytic methods, but the incident muon distribution is determined by Monte Carlo methods. The following gives a brief description of the analytical calculations of muon diffusion and the program output and gives some examples of the use of TOMCAT.

6.4.1 The distribution function

The spatial and angular distributions of a beam of particles which, on passing through a layer of matter, undergoes multiple scattering, are described in a theory developed by Rossi and Greisen (Ros41) and extended by Eyges (Eyg48) to account for the slowing down of particles. From the results of Eyges, it can be shown that the radial distribution of particle fluence at a given depth in the scattering material, independent of angle to the beam axis, is given by

$$\phi(r) = N_0 \exp\left[-r^2/(4A_2)\right]/(4\pi A_2), \quad (6.5)$$

where $r$ is the radial distance off axis, $N_0$ is the number of particles incident in a pencil beam, and $A_2$ is given by the following integral:

$$A_2 = \int_0^z \chi^2(t)(z-t)^2 \, dt \quad (6.6)$$

where $z$ is the depth of the plane of interest in the shielding for scattering material and $\chi^2$ is one quarter of the mean square scattering angle per unit distance. The dependence of $\chi^2$ on the position in the shield, $t$, is given through the
momentum of the particle at that position. In this theory, all range straggling is ignored and the range–momentum relationship is considered to be monotonic. All scattering is considered to be the sum of many individual small-angle scattering processes. Equation (6.6) is also rigorously true for shielding consisting of slabs of different materials.

6.4.2 Scattering of muons

An essential part of the use of the Fermi–Eyges distribution function is the determination of the mean square angle of scattering per unit distance. There are four principal scattering processes for high-energy muons:

i) Coulomb scattering from nuclei and electrons,
ii) bremsstrahlung from muon–nucleon collisions,
iii) pair production from muon–nucleus collisions,
iv) muon–nucleus non-elastic collisions.

An accurate expression for Coulomb scattering, which takes account of both the screening of the nuclear field by the orbital electrons and the finite size of the nucleus, is:

\[ \chi_c^2 = 4\pi p N_A (Z^2/A) r_e^2 [m_u/p\beta]^2 \ln [196Z^{-1/3}(Z/A)^{1/6}] , \]  

(6.7)

where \( N_A \) is Avodadro's number, \( r_e \) is the classical radius of the electron, and \( p, Z, \) and \( A \) are the density, atomic number and atomic weight of the scattering medium, respectively. The additional effect of scattering by orbital electrons is taken into account by replacing the \( Z^2 \) of Eq. (6.7) by \( Z(Z+1) \).

The three remaining scattering processes differ from multiple Coulomb scattering in that they are low-probability processes but have the potential for large-angle scattering, coupled with significant energy loss of the muon. By an extension of the method of Alsmiller, we have treated these processes in the same manner as for Coulomb scattering but with different parameters. Parameters have been derived for iron and concrete (Als71). It has been observed that scattering from pair-production processes can be neglected. Nuclear scattering of muons is independent of the material (when thicknesses are expressed in g/cm²), in the approximation chosen.

Each of the three processes can be represented by a power law in muon momentum. Thus in TOMCAT the total scattering as a function of momentum \( p \) is represented by the sum

\[ \chi^2 = \alpha_c p^\beta_c + \alpha_{n} p^\beta_{n} + \alpha_{b} p^\beta_{b} \]  

(6.8)

Values of the parameters \( \alpha \) and \( \beta \) are listed in Table 16 for iron and concrete.

<table>
<thead>
<tr>
<th>Scattering parameter</th>
<th>Material</th>
<th>( \alpha ) (m²/kg)</th>
<th>( \beta )</th>
<th>( \alpha ) (m²/kg)</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulomb</td>
<td>Iron</td>
<td>7.8459 × 10⁻⁷</td>
<td>-1.9992</td>
<td>3.8888 × 10⁻⁷</td>
<td>-1.9994</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>6.9744 × 10⁻¹⁰</td>
<td>-0.8592</td>
<td>6.9744 × 10⁻¹⁰</td>
<td>-0.8592</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td></td>
<td>4.2963 × 10⁻¹⁰</td>
<td>-1.0406</td>
<td>2.3624 × 10⁻¹⁰</td>
<td>-1.0365</td>
</tr>
</tbody>
</table>

In considering energy loss, the slowing-down approximation is used in TOMCAT. This means that range-straggling is ignored, single large energy loss processes are averaged, and a single value of the range is assumed for any momentum value. The rate of momentum loss is approximated by linear relationships having different slopes above and below 50 GeV:

\[ \frac{dp}{dx} = a + b(p - g) , \]  

(6.9)

where \( p \) is the momentum (GeV/c). The parameters \( a, b, \) and \( g \) are taken from the work of Richard-Serre (Ric71) and are shown in Table 17. Operation of the program is considerably speeded up by the use of tables containing the range–momentum relationship.

6.4.3 The diffusion calculation

The integration of Eq. (6.6) is performed by Gaussian integration over each shielding slab separately and the result summed to give the \( A_2 \) parameter appropriate to the point of interest.

30
Table 17
Parameters used for muon range–momentum tables

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter and unit</th>
<th>Range of 1 GeV muon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a ([GeV/c] · kg⁻¹ · m²)</td>
<td>b (m²/kg)</td>
</tr>
<tr>
<td>Below 50 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>1.825 × 10⁻⁴</td>
<td>1.194 × 10⁻⁴</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.247 × 10⁻⁴</td>
<td>1.126 × 10⁻⁴</td>
</tr>
<tr>
<td>Earth</td>
<td>2.103 × 10⁻⁴</td>
<td>9.892 × 10⁻⁷</td>
</tr>
<tr>
<td>Above 50 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>2.350 × 10⁻⁴</td>
<td>7.054 × 10⁻⁷</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.746 × 10⁻⁴</td>
<td>4.297 × 10⁻⁷</td>
</tr>
<tr>
<td>Earth</td>
<td>2.542 × 10⁻⁴</td>
<td>3.729 × 10⁻⁷</td>
</tr>
</tbody>
</table>

a) c = velocity of light: 3 × 10⁸ m/s.

The muon distribution at the front face of the shielding can be simulated using analogue Monte Carlo techniques. These distributions depend on the nature and characteristics of the parent beam—its type (e.g. pion, kaon, or muon), its momentum distribution, its divergence and size, distance from the front face of the shielding and, in the case of pion and kaon beams, the distance available for decay of the beam particles.

In the treatment of LEP problems, muon sources are assumed to be of two types: direct muon-pair production by high-energy photons, and decay of photopions produced by high-energy photons. The sources of high-energy photons are, of course, the electromagnetic cascades initiated by LEP beams.

6.5 Estimate of synchrotron radiation from measured data

A direct estimate, from measured data, of dose values from synchrotron radiation to air (production of noxious gases) and components (radiation damage) in the LEP tunnel is difficult since the geometry of the bending magnet/vacuum chamber system with its lead shielding is complicated. Hence straightforward answers cannot be given, as the scattering phenomena for photons become more important compared with absorption at the higher energies encountered in the operation of LEP.

Comparisons between measured data and calculations are, however, possible for existing electron storage rings, and a cautious extrapolation to LEP energies can be attempted. Tables 18 and 19, as well as Fig. 21, are taken from

Table 18
Doses at 1 m distance from the open side of the bending-magnet yoke
as measured at PETRA and calculated for LEP and PETRA

<table>
<thead>
<tr>
<th>Machine</th>
<th>Measurement or calculation</th>
<th>Beam energy (GeV)</th>
<th>Critical energy (keV)</th>
<th>Shielding for open side of magnet yoke (mm of lead)</th>
<th>Dose (Gy·A⁻¹·h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETRA</td>
<td>M</td>
<td>15</td>
<td>39</td>
<td>3⁹</td>
<td>1 × 10²</td>
</tr>
<tr>
<td>PETRA</td>
<td>CE</td>
<td>17</td>
<td>57</td>
<td>None</td>
<td>6 × 10⁶</td>
</tr>
<tr>
<td>PETRA</td>
<td>CE</td>
<td>17</td>
<td>57</td>
<td>3⁹</td>
<td>3 × 10³</td>
</tr>
<tr>
<td>PETRA</td>
<td>CE</td>
<td>17</td>
<td>57</td>
<td>3⁹</td>
<td>2 × 10²</td>
</tr>
<tr>
<td>PETRA</td>
<td>M</td>
<td>17</td>
<td>57</td>
<td>3⁹</td>
<td>2 × 10²</td>
</tr>
<tr>
<td>LEP</td>
<td>CE</td>
<td>51.5</td>
<td>98</td>
<td>3</td>
<td>5 × 10¹</td>
</tr>
<tr>
<td>LEP</td>
<td>CE</td>
<td>86</td>
<td>455</td>
<td>3</td>
<td>4 × 10³</td>
</tr>
<tr>
<td>LEP</td>
<td>CM</td>
<td>86</td>
<td>455</td>
<td>3</td>
<td>8 × 10³</td>
</tr>
<tr>
<td>LEP</td>
<td>CM</td>
<td>86</td>
<td>455</td>
<td>8</td>
<td>3 × 10³</td>
</tr>
<tr>
<td>LEP</td>
<td>CE</td>
<td>100</td>
<td>716</td>
<td>3</td>
<td>5 × 10⁴</td>
</tr>
<tr>
<td>LEP</td>
<td>CM</td>
<td>100</td>
<td>716</td>
<td>3</td>
<td>2 × 10⁴</td>
</tr>
<tr>
<td>LEP</td>
<td>CM</td>
<td>100</td>
<td>716</td>
<td>8</td>
<td>9 × 10³</td>
</tr>
</tbody>
</table>

a) M = measurement, CE = calculation with EGS, CM = calculation with MORSE.
b) Incomplete shielding simulated in the calculation by adding 3% of non-shielded dose to 97% of the shielded case.
Table 19

Doses inside the air pocket of the magnet yoke as measured and calculated for PETRA and calculated for LEP

<table>
<thead>
<tr>
<th>Machine</th>
<th>Measurement or calculation</th>
<th>Beam energy (GeV)</th>
<th>Critical energy (keV)</th>
<th>Shielding of the air pocket (mm of lead)</th>
<th>Dose (Gy·A⁻¹·h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETRA</td>
<td>M</td>
<td>17</td>
<td>57</td>
<td>None</td>
<td>5 × 10⁶</td>
</tr>
<tr>
<td>PETRA</td>
<td>CE</td>
<td>17</td>
<td>57</td>
<td>None</td>
<td>2 × 10⁶</td>
</tr>
<tr>
<td>PETRA</td>
<td>M</td>
<td>17</td>
<td>57</td>
<td>4.5</td>
<td>8 × 10²</td>
</tr>
<tr>
<td>PETRA</td>
<td>CE</td>
<td>17</td>
<td>57</td>
<td>4.5</td>
<td>2 × 10³</td>
</tr>
<tr>
<td>LEP</td>
<td>CE</td>
<td>86</td>
<td>455</td>
<td>8</td>
<td>1 × 10⁷</td>
</tr>
<tr>
<td>LEP</td>
<td>CM</td>
<td>86</td>
<td>455</td>
<td>8</td>
<td>2 × 10⁴</td>
</tr>
<tr>
<td>LEP</td>
<td>CE</td>
<td>100</td>
<td>716</td>
<td>8</td>
<td>3 × 10⁴</td>
</tr>
<tr>
<td>LEP</td>
<td>CM</td>
<td>100</td>
<td>716</td>
<td>8</td>
<td>5 × 10⁴</td>
</tr>
</tbody>
</table>

a) M = measurement, CE = calculation with EGS, CM = calculation with MORSE.
b) Incomplete shielding simulated in the calculation by adding 3% of non-shielded dose to 97% of the shielded case.

Fig. 21 Dose measurements and calculations for the PETRA storage ring (DESY, Hamburg) as a function of lateral distance from a bending magnet, showing a 1/r dependence on distance (solid curve).

Yam81, Bur82a and Fas82b. The first important information can be found in the figure, namely that near the open shielded gap of the magnet, the decrease in dose rate with distance can be described by a 1/r dependence expected for a line source. At higher photon energies as in LEP and in regions near the tunnel wall, this dependence breaks down. This deviation from the 1/r behaviour is due to the increased contribution to dose from scattered photons, as has been shown in calculations with the program MORSE.

Tables 18 and 19 show the problem of extrapolation, i.e. the extension of measured PETRA data to LEP energies, where, at an operation at 86 GeV, the critical energy is higher by one order of magnitude.

At PETRA, measured and calculated values agree within a factor of 2. For LEP, the results of two independent calculations with EGS and MORSE can also be compared; for these the agreement is also within a factor of 2.

Since no clear trend is visible with respect to an under- or over-estimation by one particular calculation method, nor are clear discrepancies observed between measurements and calculations, it is expected that the calculations performed for LEP will give a reasonable estimate of the real radiation situation.

7. ATMOSPHERIC DISPERSION OF GASEOUS RELEASES

7.1 Dispersion and atmospheric conditions

In order to evaluate the possible effects of gaseous releases on the environment, it is necessary to determine the concentrations at ground level after dilution in the atmosphere (Fas82c). These concentrations vary as functions of the rate of release, the wind speed, the height of the axis of the plume, and also on the type of plume. The type of plume is determined by the distribution of atmospheric temperature.
The trajectory of the plume depends principally on the speed of release of the air, as well as on the wind speed. At a distance \( x \) from the release point, the height of the trajectory stabilizes and may produce a variety of plumes. These types depend, in large measure, on the vertical gradient of the temperature (see Fig. 22).

7.1.1 Condition of inversion (fanning)
Under stable conditions, when the temperature decreases by an amount less than 1°C for each 100 m of height, or if the temperature gradient is zero or increases with height to form an inversion, vertical dispersion of the plume is prevented. This leads to a plume which is wide, flat, and fan-shaped. This condition occurs frequently at night and dispersion is enhanced.

7.1.2 Condition of mild turbulence (coning)
The conical plume is formed when the temperature decreases approximately 1°C per 100 m of height. This generally occurs on days when there is a strong wind. In this case, the vertical and horizontal diffusion rates are approximately equal. Diffusion calculations are generally the most reliable for this type of plume.

7.1.3 Condition of strong turbulence (looping)
Under unstable conditions, when the temperature decreases more than 1°C per 100 m of height, vertical diffusion is enhanced in the atmosphere but the form of the plume is perturbed by turbulent ascending and descending eddies, leading to a plume having a wavy form.

7.1.4 Condition of turbulence near the ground with inversion above (fumigation)
Under these conditions, in which an unstable layer of air is established beneath a stable layer, the dispersion of gas towards the ground is larger than if both layers were unstable. This condition occurs most often in the morning after a very stable night, when the ground becomes warmed by the sun, producing an unstable layer close to the ground.
Even if this condition never persists for very long (about 30 min), three-minute averages of concentration may be twice as high as with a conical plume.

7.1.5 Condition of inversion near the ground with turbulence above (lofting)

These conditions are the reverse of those just described (fumigation). That is, a stable layer of air forms beneath an unstable layer, and there is only upward dispersion of the plume. This condition occurs most often towards the end of the afternoon, when a stable layer develops near the ground as solar radiation decreases. During this period, concentrations of release gases will be very low near to the ground.

7.2 Concentration at ground level

The maximum concentration at ground level \( C_{\text{max}} \) is proportional to the rate of release \( Q_m \), and inversely proportional to the square of the total effective height \( h_e \):

\[
C_{\text{max}} \propto \frac{Q_m}{h_e^2}.
\]  

As it is limited by the wind speed, the rise of the plume depends on its speed of emission and on its thermal capacity. The point of maximum concentration at ground level is located downwind from the release point.

Atmospheric mechanisms are very complex, and a satisfying simple form does not exist for calculating the rise of the plume and the ground-level concentrations. Nevertheless, the equation of Sutton (Ste62, Lon63) has generally been employed and is judged to be adequate. In this equation the gaseous concentration at ground level at a distance \( x \) from the chimney stack and within the axis of the plume is given by

\[
\bar{c}_x = (2Q_m/\pi C_z u x^{2-n}) \exp (-h_e^2/C_z x^{2-n}),
\]  

where \( \bar{c}_x \) = concentration (in mg/m\(^3\)), corresponding to a sampling time of three minutes, at a distance \( x \) (in m) from the release point;

\( u \) = wind speed (in m/s);

\( h_e \) = effective height of the stack;

\( Q_m \) = rate of gaseous release (in mg/s);

\( C_z, C_y \) = coefficient of vertical and lateral dispersion, respectively (for a height \( h_e > 20 \) m, these coefficients become equal, according to Sutton);

\( n \) = turbulence index determined by temperature gradient.

The maximum concentration at ground level \( \bar{c}_{\text{max}} \) is given as

\[
\bar{c}_{\text{max}} = (2Q_m/\pi e u h_e^2) (C_z/C_y),
\]  

where \( e \) is the base of the natural logarithms. The distance \( x_{\text{max}} \) at which the maximum concentration occurs is given by

\[
x_{\text{max}} = (h_e/C_z)^{2/(2-n)}.
\]  

Values of \( x_{\text{max}} \) are calculated from values of \( C_z \) and \( n \) estimated by Sutton for neutral conditions (Ste62, Lon63). These values are given here in Table 20. Instantaneous concentrations can be higher than the mean calculated for a three-minute sampling time; but on the axis of the plume, experience has shown that they do not exceed twice this mean. Results given in Table 21 are averages corresponding to sampling periods of three minutes. Because of changing wind

<table>
<thead>
<tr>
<th>Table 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values of the dispersion parameter ( C_y ) (equal to ( C_z ) for stack heights greater than 10 m) for neutral conditions (( n = 0.25 ))</td>
</tr>
<tr>
<td>Stack height (m)</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>150</td>
</tr>
</tbody>
</table>


Table 21

Maximum concentrations of ozone produced by LEP operation at 85 GeV and at 125 GeV assuming different exhaust and wind speeds (averaged over three-minute intervals)

<table>
<thead>
<tr>
<th>Speed of exhaust (m/s)</th>
<th>Wind speed (m/s)</th>
<th>Δh</th>
<th>hc</th>
<th>Max. conc. Cmax (ppm)</th>
<th>smax</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>85 GeV</td>
<td>125 GeV</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>48</td>
<td>58</td>
<td>0.002</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>24</td>
<td>34</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>22</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2</td>
<td>12</td>
<td>0.002</td>
<td>0.009</td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
<td>68</td>
<td>78</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>34</td>
<td>44</td>
<td>0.002</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17</td>
<td>27</td>
<td>0.002</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>7</td>
<td>17</td>
<td>0.002</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3</td>
<td>13</td>
<td>0.002</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 22

Estimated average concentration at ground level, as a function of sampling time

<table>
<thead>
<tr>
<th>Sampling time</th>
<th>3 min</th>
<th>1 h</th>
<th>1 day</th>
<th>1 y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative concentration at ground level</td>
<td>1/2</td>
<td>1/10</td>
<td>1/100</td>
<td></td>
</tr>
</tbody>
</table>

velocity, the point of maximum concentration as well as the concentration itself is constantly varying. Sutton (Sut75) has suggested that, in the absence of detailed local meteorological data, an estimation can be made based on general observations. Table 22, from Sut75, gives factors which may be used to estimate concentrations at a point when averaged over longer periods of time.

7.3 Effective height of release

The effective height of release depends on the physical chimney stack height, exhaust speed, atmospheric pressure, and wind speed. In the case of LEP, the physical height is limited by esthetic considerations to about 10 m. The temperature of the exhaust air is always higher than the ambient air while LEP is in operation, but the difference is too small to be considered in the calculation. (This will lead to a slight underestimation of the effective height.) The only parameter remaining under our control is the exhaust speed in the vertical direction. A high speed of release will ensure a large effective height, but at the same time 20 m/s should not be exceeded, as this might lead to noise problems. The effective height of the stack in the case of LEP was calculated as follows: \( h_e = h + \Delta h \), where \( h \) is the physical height of the stack and the increment \( \Delta h \) arising from the exhaust speed is given by the Oak Ridge formula (Ste62):

\[
\Delta h = (1.5 V_s d + k Q_h)/u, \tag{7.5}
\]

where \( \Delta h \) = effective height increment (m);
\( V_s \) = exhaust speed at stack exit (m/s);
\( d \) = internal diameter of the stack (m);
\( u \) = wind speed (m/s);
\( Q_h \) = thermal emission of the stack;
\( k \) = a constant.

Given that the release temperature is only slightly above that of the ambient air, the term \( Q_h \) is negligible compared to the term arising from atmospheric pressure. Therefore we have:

\[
\Delta h = 1.5 V_s d/u. \tag{7.6}
\]

Calculations for LEP emissions are based on this equation, using the additional assumptions:

i) the physical stack height is 10 m above ground level;
ii) the exhaust speed lies between 10 and 20 m/s;
iii) the rate of release of air is 10 m³/s per octant, or 20 m³/s at each release point.
7.4 Natural concentrations of ozone

There are no available long-term measurements of ozone in the Pays de Gex. The set of measurements nearest to CERN are those made at Anières (in the Geneva countryside) by the Institut d’Hygiène du Canton de Genève. These are shown in Table 23. One could assume that natural concentrations of ozone near CERN would be similar to these. Concentrations at ground level calculated for LEP were given above in Table 21. Comparison shows that the natural concentrations measured at Anières are at least 10 times as large.

Table 23
Average monthly concentrations of ozone for the first 10 months of 1980
(Institut d’Hygiène, Anières, Geneva).

<table>
<thead>
<tr>
<th>Month</th>
<th>Average concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.012</td>
</tr>
<tr>
<td>February</td>
<td>0.022</td>
</tr>
<tr>
<td>March</td>
<td>0.034</td>
</tr>
<tr>
<td>April</td>
<td>0.052</td>
</tr>
<tr>
<td>May</td>
<td>0.056</td>
</tr>
<tr>
<td>June</td>
<td>0.036</td>
</tr>
<tr>
<td>July</td>
<td>0.035</td>
</tr>
<tr>
<td>August</td>
<td>0.036</td>
</tr>
<tr>
<td>September</td>
<td>0.032</td>
</tr>
<tr>
<td>October</td>
<td>0.017</td>
</tr>
</tbody>
</table>

8. RADIATION DAMAGE STUDIES

8.1 Introduction

Radiation damage studies have been performed on organic and inorganic materials and on electronic components and metals used in the construction and operation of high-energy accelerators such as LEP. Apart from electronics components and devices, the organic materials are the ones that are most sensitive to radiation. As a consequence of this, a large number of radiation tests have been made on these materials and the results extensively documented (Bil61, Kir64, Van70, Van72, Sch75, Phi81, Sch77, Sch79a, McG75, McG76, Bat76, Wul81). Design engineers are, however, often faced with the problem of finding the desired information quickly in the available literature. CERN has therefore published its radiation damage results on organic materials in the form of a three-volume catalogue (Sch79b, Sch79c, Bey82).

Part I of the catalogue contains data on commercially available cable-insulating materials. The samples were supplied by some 30 European cable manufacturers in the form of moulded plates, from which tensile samples were cut. Tests on degradation of the mechanical properties and Shore hardness are reported as a function of the absorbed dose in the range $5 \times 10^5$ – $5 \times 10^6$ Gy. The end-point criterion of an elastic cable-insulating material is considered to be the dose at which the elongation at break is 100%.

Part II contains information on thermosetting and thermoplastic resins, except for cable-insulating materials which are given in Part I. Most of the data were obtained from epoxy resins used as insulation for large high-energy accelerator magnet coils. Again, mechanical properties were recorded as a function of the absorbed dose in the range $5 \times 10^6$ – $1 \times 10^8$ Gy but, in the case of rigid plastics, flexion tests were carried out. As an end-point criterion it was required that at a given dose D the ultimate flexural strength of the material be 50% or more of the initial value at zero dose. The electrical properties were not tested, since usually the permanent effects only become important at doses where the mechanical damage is already severe.

Part III contains all items which did not fit into the categories of the two previous reports, e.g. cable ties, glasses, hoses, motors, oils, paints, relays, scintillators, seals, etc. The items for the tests were either supplied by firms from whom CERN was intending to procure certain items containing materials that were particularly sensitive to radiation, or they were simply taken from the CERN stock without particular choice of material and supplier.

The tests for Parts I and II were performed in accordance with the International Electrotechnical Commission (IEC) Standard 544 (IEC79) for insulating materials. For Part III, the variety of materials and components presented had to be irradiated and tested in a specific non-standard way, depending on size, composition, and function. Also, critical parameters were only vaguely defined, and in some cases only operational tests or visual inspections could be performed.

The entries in this series of data compilations cover a large spectrum of materials and components used in high-energy accelerator engineering; however, this list is still far from complete. Because of the extended period of
about 10 years during which the data were collected, several items may have become obsolete or are no longer available on the market.

For the LEP project, we should make it clear that all information contained in the three-part report on organic materials is valid for the radiation environment around this new installation. This is partly due to the fact that, for organic materials, the damage is to a large extent related to the absorbed dose irrespective of the type of radiation (\Phi_{78}). For inorganic substances, e.g. semiconductors and metals, this is not true, and great care must be taken if the radiation field in an application is different from the one during the radiation test. It is stressed that electronics components are amongst the most radiation-sensitive items used in accelerator engineering. Although electromagnetic radiation, which will be the main contribution to the absorbed dose at LEP, may cause up to 100 times less damage to semiconductors than would particle radiation from proton accelerators or neutrons from a nuclear reactor, this has to be seriously considered.

8.2 Irradiation conditions

The irradiation conditions depend on the size, composition, and function of the item to be tested. Basically, three radiation sources were used for this series of investigations:

i) the 7 MW ASTRA pool reactor at Seibersdorf, Austria;
ii) \(^{60}\)Co irradiators or spent-fuel elements;
iii) dump and target areas of the CERN accelerators.

Table 24 gives a summary of the characteristics of the various radiation sources and their positions, and indicates which items have been irradiated there. Most of the materials were irradiated in the ASTRA reactor. This source has the advantage of having a well-defined radiation field, reliable dosimetry, and sufficiently high dose rates and therefore short irradiation times (Sch75).

Spent-fuel elements (or switched-off reactor) and \(^{60}\)Co irradiations were preferred for items with metallic parts, as these would have become too radioactive after irradiation in a reactor or high-energy accelerator field. The radiation-sensitive parts within these items were, of course, the organic materials.

Irradiations around the CERN accelerators were carried out in only a very limited number of cases, because of high dose gradients, imprecise knowledge of the particles and their energy spectra, and difficult dosimetry. Some parasitic irradiations were carried out on electronics components and on insulating materials, near dumps and at target stations, in order to study the effects of the radiation field and the dose rate.

The aim of the tests was to predict the lifetime of the materials and components used in a radiation environment, such as within the LEP tunnel, prior to their installation. Therefore these types of tests were accelerated ones, where the integrated total dose was collected over a period ranging from hours up to three weeks, whereas the same dose would be accumulated after periods of the order of 10 years in LEP operation.

It is known that radiation damage to organic materials may depend not only on the absorbed dose but also on the irradiation time and dose rate (Wil76, Clo81, Kur79). The amount of oxygen available by diffusion into the sample, in relation to the number of radiation-produced chemically reactive radicals, or chain scission sites, may strongly influence the amount of permanent damage to the material. Therefore the damage caused by irradiation over a long period of time may be more important than damage from irradiation to the same total dose, at high dose rates for a short time. The dose rate effect is, in addition, dependent on the chemical structure of the material itself. The amount of oxygen available is a function of the sample thickness and of its permeability for gases, and of the amount of stabilizers added to the polymer to control oxidation damage under normal ageing conditions. For example, it is known that the effect is more pronounced in polyolefins, but is usually not of great importance for polyvinyl chloride (PVC) and ethylene-propylene rubber (EPR).

8.3 Presentation of results

The information tabulated in Sch79b, Sch79c, and Bey82 has to be used with caution and in many cases must be considered only as a guideline. Nevertheless it is felt that, from the experience gained over the past 10 years, the expected lifetime of materials in a high-energy accelerator environment can confidently be predicted to within the right order of magnitude. If results for different items made of the same base material are found to differ, this may be due to a specific composition or condition. Furthermore, the function of the items may require different degrees of performance from the base material, and therefore different evaluations of the radiation resistance may result.

Data for specific materials, components, or devices are presented in alphabetical order in Sch79b, Sch79c, and Bey82. In addition, a review of general relative radiation effects, is given in the form of tables, under the following entries:

- cable insulations,
- elastomers,
- G-values (radiochemical yield),
- hoses,
- oils,
- paints,
<table>
<thead>
<tr>
<th>Radiation source</th>
<th>Irradiation position</th>
<th>Characteristics of radiation field</th>
<th>Irradiation medium</th>
<th>Irradiation temperature (°C)</th>
<th>Dose rate (Gy/h)</th>
<th>Dosimetry method</th>
<th>Items irradiated</th>
</tr>
</thead>
</table>
| 7 MW ASTR Astra research pool reactor | Pos. 11 | $5 \times 10^{10} n_{n}/m^2 s$  
$3 \times 10^{10} n_{p}(E > 1 \text{ MeV})/m^2 s$ | Water | 40–50 | $2 \times 10^4$ | Calorimeter Activation detector | Thermosetting resins |
| | Ebene 1 (E1) | $4 \times 10^{10} n_{n}/m^2 s$  
$3 \times 10^{10} n_{p}(E > 1 \text{ MeV})/m^2 s$ | Air | 32–45 | $2 \times 10^5$ | Ionization chamber | Cable-insulating materials;  
other organic materials |
| | SNIF | $2 \times 10^{10} n_{n}/m^2 s$  
$5 \times 10^{10} n_{p}(E > 1 \text{ MeV})/m^2 s$ | Air | 35–45 | $\geq 2 \times 10^3$ | Activation detector Activation chamber | Electronics components, optical  
glasses |
| | Core | $1 \times 10^{10} n_{n}/m^2 s$  
$8 \times 10^{10} n_{p}(E > 1 \text{ MeV})/m^2 s$ | Water or N$_2$ or He | 50–100 | $3 \times 10^8$ | Activation detectors | Magnetic materials, copper wires |
| Fuel elements Astra | Pos. 35 | Gamma radiation field characteristic for reactor fuel elements (0.5–3 MeV) | Air | 25–35 | $1 \times 10^4$ | Ionization chamber | Insulating materials containing metal;  
hoses with metal connectors |
| $^{60}$Co source | Various | Gamma rays 1.2 MeV | Air | $\approx 25$ | $1 \times 10^4$ | Fricke dosimeter | Insulating materials containing metal;  
motors |
| CERN accelerators | ISR beam dump | Hadron cascade and secondary gamma rays. Primary proton energy ~ 30 GeV | Air | $\approx 22$ | 4 | RPL and PDG glass dosimeters | Electronics components and items containing metal, up to $10^3$ Gy |
| | SPS neutrino target area | Hadron cascade and secondary gamma rays. Primary proton energy ~ 400 GeV | Air | $\approx 23$ | $3 \times 10^2$ | RPL and glass dosimeters | Cable and magnet insulations; items containing metal, up to $5 \times 10^6$ Gy |
| | PS or SPS ring | Primaries (losses) and secondaries up to 30 GeV (PS) or 250 GeV and 400 GeV (SPS) | Air | $\approx 22$ | 1–10 | RPL and glass dosimeter, ionization chambers | Cable and magnet insulation; paints;  
operational life-tests |
The main materials and entries contained in the study are grouped under the following categories:
- not recommended, or to be used with caution,
- usable up to $1 \times 10^7$ Gy,
- usable above $1 \times 10^8$ Gy.

An example of such a classification is given in Table 25. It should, however, be stressed that the limits are specific to the item tested and to the end-point criteria applied, and that it may be possible to obtain higher or lower dose tolerances for differently designed applications of the same type of material. Nevertheless, experience has shown that the mechanical damage to a base material is consistent in relation to the dose, and that radiation-sensitive materials, such as Teflon, must not be employed after they have reached their dose limit. Table 25 contains, in abbreviated form, a classification of materials and components studied.

### Table 25

Classification of materials and components according to the dose range up to which they may typically be used

<table>
<thead>
<tr>
<th>Materials</th>
<th>Upper dose limit in Gy = 100 rad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic scintillator</td>
<td>$10^2 - 10^4$</td>
</tr>
<tr>
<td>Butyl rubber</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>Electronics components (active)</td>
<td>$10^2 - 10^4$</td>
</tr>
<tr>
<td>Optical fibre</td>
<td>$10 - 10^2$</td>
</tr>
<tr>
<td>Perfluoro ethylene-propylene (FEP)</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>Phenolic resin, unfilled</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Polyacryl (Plexiglas)</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Polyamide (Nylon)</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>Polyester resin, unfilled</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>Silicone oil</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>Silicone rubber</td>
<td>$5 \times 10^5$</td>
</tr>
<tr>
<td>Teflon (PTFE)</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>Viton</td>
<td>$1 - 2 \times 10^6$</td>
</tr>
</tbody>
</table>

* Use of these materials in radiation areas is not recommended, or must be used with precaution.

9. HAZARDS DUE TO NON-IONIZING RADIATION AND MAGNETIC FIELDS

9.1 General

The subject of protection against non-ionizing radiation (NIR) has been under consideration since 1974 by the International Radiation Protection Association (IRPA). Consequently, in many countries protection against hazards arising from the use of NIRs has been added to the task of the radiation protection authorities, who had previously considered only those problems related to ionizing radiation. At CERN, the Site Section of the Radiation Protection Group has been given the responsibility of determining potential hazards from NIR devices. This group performs
radiation measurements as necessary and proposes regulatory actions. Control of NIR is divided into the following general areas:

i) microwaves, radiofrequency and electromagnetic fields,
ii) ultrasound and noise,
iii) lasers, ultraviolet, and other electro-optical radiations,
iv) magnetic fields.

Although magnetic fields are not actually forms of radiation, control of exposure to them is administered by the same group. Of particular concern for LEP are items (i), (iii) and (iv). They are elaborated on in this section.

9.2 Biological effects of NIR

9.2.1 Radiofrequency and microwave radiation

Radiofrequency and microwave radiation is absorbed by body tissue, which causes a temperature increase of the tissue exposed. This may lead to thermal effects (depending on frequency and intensity of the radiation). Well-known thermal effects caused by microwave radiation are cataract induction and effects due to thermal sensitivity of the testes. The threshold for lens opacities is generally assumed to be at least 100 mW/cm², which is well above the limits in use at CERN.

One matter of concern is the conflict between specialists working in the field of microwave bioeffects, some of whom claim that low-level microwave exposure (less than 1 mW/cm²) will cause reversible disturbances of the central nervous system, such as headaches, emotional instability, changes in the EEG pattern, and alterations in blood chemistry. Most of these claims of non-thermal effects are made by scientists working in East European countries. Other specialists do not accept that these phenomena have been proven. This is the basis of the wide divergence of opinion regarding exposure limits in, for example, the USSR and the USA.

Interference with the function of cardiac pacemakers has also been a matter of concern. However, modern devices use shielded wires between pacemaker and heart to eliminate this problem.

9.2.2 Lasers

The main hazard arising from the use of lasers is damage to the eye, since the lens of the eye focuses visible radiation onto the retina and consequently increases the power density of the incident radiation by many orders of magnitude. Damage to the retina is due to thermal effects, and the burns resulting from laser exposures could lead to serious and permanent damage to vision. High-power lasers (above about 100 mW) may present an additional risk of skin burns. However, it is clear that damage to the eyes, which could well be irreparable, must be considered to be the main hazard of all lasers.

9.2.3 Static magnetic fields

In spite of a large amount of experimental work in the field of biomagnetics, our understanding of the effects of magnetic fields on the human body is still rudimentary. At the time of exposure to strong fields, some mild taste sensations and tooth "pain" associated with metal fillings have been reported. However, on the basis of past experience, it has generally been concluded that these biological effects are fully reversible and no cumulative effects seem to remain, even following repeated exposures to magnetic fields without adequate recovery times between them.

9.3 Sources of non-ionizing radiation in LEP

9.3.1 Radiofrequency and microwave equipment

The acceleration of particles at CERN implies the use of very powerful radiofrequency systems. High-power sources of radiofrequency in the LEP system are the klystrons, which will operate at 352 MHz. Since the klystrons are linked by a closed system to the RF cavities via waveguides, only leakage radiation is of concern. Measurements in the vicinity of a full-sized LEP prototype klystron connected to a LEP cavity have shown no power density levels exceeding 1 mW/cm² at 5 cm distance from the equipment. Therefore it can be concluded that exposure to RF and microwave radiation will not present any hazard of importance. This also applies to the LEP injection system (LIL, PS, SPS).

Nevertheless, it is planned to carefully monitor RF power levels in the initial phase of LEP operation. Past measurements at the SPS, near the RF system operating at 800 MHz, have only revealed minor power density levels. It should be mentioned that experience has shown that the main radiation hazard associated with RF systems arises from X-ray exposures rather than from microwaves.

9.3.2 Lasers

The use of powerful lasers for the calibration of parts of the experimental equipment (e.g. drift chambers) may have to be assessed. Ultraviolet lasers produce narrow ionization tracks in commonly used chamber gases, which can be used as straight reference lines. Nitrogen (N₂) and KrF lasers have been or will be tested for this purpose at CERN. The extent of the use of such lasers will only be known at a later stage of the LEP project. However, they are likely to belong to the Class 4 (highest) potential hazard (see below). For example, a KrF laser at present being installed has an output of 220 mJ per pulse at a pulse repetition frequency of 2 Hz; even the reflected beam from such lasers may be hazardous.
9.3.3 Magnets in experimental areas

The detectors needed for experiments at LEP will contain large solenoids producing fields of the order of 1 T. The strengths of stray fields in accessible areas are not yet known, but are likely to be similar to those of existing experiments at CERN or DESY.

9.4 Rules and regulations for NIR

9.4.1 Microwave and radiofrequency equipment

CERN is developing a set of rules for the use of microwave and RF equipment, and the CERN Safety Note No. 9 defines the limits for personnel exposures shown in Table 26.

9.4.2 Lasers

Rules for the safe use of lasers at CERN are set down in CERN Safety Instruction No. 22 (Tuy82). Lasers are classified according to their relative exposure hazard in four classes, as described in Table 27.

The classification is made according to the Accessible Emission Limit (AEL). The AEL for a given classification would be the maximum accessible emission level permitted within a particular class compatible as a function of emission duration, and time- and wavelength-dependent factors.

9.4.3 Magnetic fields

No formal limits of exposure to magnetic fields exist at CERN. However, in the past, it has been proposed to follow the same standards as have been developed at SLAC (StL77). These are repeated in Table 28, and should be considered as recommended values, not to be exceeded if possible.

<table>
<thead>
<tr>
<th>Power density limit (mW/cm²)</th>
<th>Frequency range (MHz)</th>
<th>Standard applies to</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>10 – 30000</td>
<td>Maximum level for continuous exposure</td>
</tr>
<tr>
<td>10.0</td>
<td>10 – 30000</td>
<td>Limit for occasional exposure of 1 hour maximum</td>
</tr>
</tbody>
</table>

Table 27
Classification of lasers

<table>
<thead>
<tr>
<th>Class and description</th>
<th>Reason for classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1 Exempt</td>
<td>Output is so low that they are inherently safe.</td>
</tr>
<tr>
<td>Class 2 Low power, low risk visible continuous-wave and pulsed lasers</td>
<td>In the case of continuous-wave lasers, some protection is afforded by natural aversion response of the eye (blink reflex). Hazard can be controlled by relatively simple procedures.</td>
</tr>
<tr>
<td>Class 3A Medium-power lasers</td>
<td>Some protection still provided by blink reflex, but direct intra-beam viewing with optical aids hazardous. Hazard from direct beam viewing and from specular reflections. More detailed control measures are necessary.</td>
</tr>
<tr>
<td>Class 3B High-power lasers</td>
<td>Not only hazard from direct beam viewing and from specular reflections, but possible from diffuse reflections also. Their use requires extreme caution.</td>
</tr>
<tr>
<td>Class 4</td>
<td></td>
</tr>
</tbody>
</table>

Table 28
Standards for exposure to steady magnetic fields in milliteslas

<table>
<thead>
<tr>
<th>Members exposed</th>
<th>Extended periods (hours)</th>
<th>Short periods (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole body or head</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Arms and hands</td>
<td>200</td>
<td>2000</td>
</tr>
</tbody>
</table>
10. ELEMENTS OF THE LEP RADIATION PROTECTION SYSTEM

10.1 Definitions

The CERN Radiation Protection System (RPS), broadly defined, consists of a number of very different elements. Some of these elements are independent systems designed to respond to particular requirements, such as, for example, the personnel safety system which ensures that no person can enter the primary beam area during operation. Other examples are the radiation-monitor instrumentation which measures the release of radioactivity, and the warning monitor system which indicates unusual dose rates in occupied areas. The RPS also contains elements which impose design conditions, such as on the choice of materials or on the siting of the LEP main ring and the arrangement of the experimental and service areas. Included in the system are intangible elements such as rules, regulations, and procedures, which impose conditions on LEP operation. Last but not least is a group of competent Radiation Protection Staff whose task it is to assess radiation risks and to ensure that the rules are followed. They are responsible for operational radiation protection, and must be trained and familiarized with the facility before beams are first accelerated within LEP. As we define it here, the LEP RPS system should be understood to comprise at least the following elements:

- the ensemble of all design parameters and their implications and requirements;
- all physical subsystems and instruments dedicated to radiation protection;
- all rules and procedures for radiation protection, which ensure that the dose limitations of the ICRP, the laws of the host countries, and the CERN Radiation Protection Manual (CER83) are complied with;
- the collective judgement of the CERN RP staff (and in the design phase, members of the LEP Radiation Working Group RAWOG) in interpreting and implementing appropriate and effective radiation-safety procedures.

In this section we describe some of the most important elements of the LEP RPS. The elements of the system which are specific to the different LEP installations are discussed in more detail in Sections 11 to 13; here, we restrict our discussion to a more general review.

10.2 RPS implications for the LEP design

Radiation protection considerations affect, to varying degrees, the design of many major features of LEP. As examples, we discuss the impact of RP requirements on the following principal elements:

- shielding of the LIL and the EPA;
- shielding of the LEP-MR;
- design of access points for the LEP-MR;
- LEP-MR ventilation system;
- protection of sensitive equipment from radiation damage;
- drainage of the LEP-MR;
- shielding of experimental areas.

The two existing accelerators which will be used in the LEP injection system (the PS and SPS) have operated as proton accelerators for several years. There is virtually no reason to make any changes in the design of these accelerators because of new RP requirements arising from the operation as part of the LEP injection system. On the other hand, for the LIL and the EPA, which will be new facilities expressly built for LEP, the RP consequences for the design are:

- need for main concrete and/or steel shielding walls and roof;
- adequate shielding or baffling of RF waveguide routings;
- choice of a "closed" air-conditioning system to contain radioactive air and radiogenic gases; and
- selection of radiation-resistant organic materials for some areas of the LIL.

The LIL and EPA shielding must be constructed of concrete (and/or steel) as there is not sufficient space for an earth cover similar to that of the PS ring. Also, because of occupied areas in the vicinity of these installations, there must be very low radiation levels outside the shielding. The cost of this design requirement cannot therefore be entirely ascribed to the LEP RPS; the need for the more expensive compact shielding arises from the requirements of pre-existing facilities.

The shielding above the LEP-MR requires only about 2-3 m of earth when LEP is operated with electrons. Construction of the main ring within a relatively shallow covered trench would therefore be fully acceptable from a radiation protection point of view. However, there is no site with a diameter of 9 km close to CERN, and which is flat enough to allow an open-trench construction (cut-and-cover). Moreover, the main ring would occupy too much valuable agricultural land if built close to the surface. Because of these factors, the cost of tunnelling, as compared to shallower cut-and-cover trench construction, should not be considered as arising from an RP requirement.

Machine access shafts and shafts serving the experimental areas are all positioned to the side of the LEP-MR, rather than penetrating directly into the LEP tunnel. This is certainly a technical necessity, but the particular layout of the LEP klystron galleries, for example, is determined by RP considerations; a minimum of shielding between the galleries and the main tunnel is needed if access to the galleries is permitted during operation. Radiation-protection requirements have the same implications for the design of the RF feedthrough penetrations and the connections of the
galleries to the main tunnel. The civil engineering design must also allow for suitable location of the safety and interlock doors, whilst permitting easy transit through the whole ring. In the critical area near the service shafts, space must also be found to bring the ducting of the ring ventilation system, through occupied areas, to the surface, as persons working in the service areas and klystron galleries must not be exposed to air from the main ring.

Because the release of air to the environment must be governed by certain standards, RP requirements influence the design of the main-ring ventilation system. Adequate dispersion into the outside atmosphere must be provided in order to avoid undesired concentrations of radioactive or noxious gases. However, the ventilation system must be designed to fulfill further safety requirements (e.g. those related to fire protection), and therefore the entire cost cannot be ascribed to the RPS alone.

One of the most important ways in which RP requirements affect the LEP design is in the need for radiation-resistant materials and for the protection of sensitive components from synchrotron radiation. The choice of each component installed in the tunnel must be guided by consideration of its radiation resistance. A substantial effort has been made to study the materials and classify them by their suitability in this respect (see Section 8).

In addition, 16 deep alcoves will be built, connecting onto the main-ring tunnel. Most equipment employing solid-state electronics will be located in these alcoves, shielded from direct view of the circulating beams. The provision of these alcoves results partly from an RP requirement, and partly from the simple need for adequate underground space to house the equipment.

Because the main ring is inclined, water (from possible leaks in cooling-water circuits or from ground-water) will mainly collect at the deepest point of the tunnel. Before it can be released, this water must be checked and its residual activity found to be acceptably low.

At the request of the LEP experimental support group, it was decided that the detector areas should not be separated from the experimental control rooms by a shielding wall. Therefore it became clear that each LEP detector must provide at least a minimum amount of radiation shielding for the safety of experimenters; the detector itself would then constitute the entire radiation barrier between the beam and the experimenter. This obviously has implications for the design of these detectors as well as for the interaction of experimenters and RP personnel. A procedure is being established which will require a review of the detector design, from the shielding point of view, by the RP Group. A further consequence of this shielding concept is the necessity for an area monitoring and warning system similar to the present PAX Radiation Monitor System.

Therefore, instead of having just a shielding wall as in the SPS underground area LSS5, the RPS for the LEP experimental areas will consist of three elements:

- radiation shielding incorporated into the detector design;
- procedures for review and assessment of the detector shielding (and shielding modifications); and
- a radiation monitor and warning system in all experimental areas.

This enumeration of major design features influenced by RP requirements is far from complete; it is only meant to demonstrate that the planning of many elements of LEP subsystems and also of major civil engineering projects is largely determined by RP considerations. Although not immediately obvious as such, these design consequences should be considered as part of the over-all RPS, as we have broadly defined it for this report.

10.3 Assessment of radiation parameters

A description of the LEP RP Section would be incomplete if the assessment of stray radiation, radioactivity, and releases were not mentioned as being part of the system. By assessment we mean a two-step process:

- gathering of information (by measurement or calculation);
- subsequent interpretation of the information.

The LEP RP Section will be equipped to measure all forms of radiation and radioactivity produced by LEP. In addition, the Group will monitor levels of non-ionizing radiation and of concentrations of noxious chemical substances produced by radiation.

Both active and passive radiation monitor systems will be installed and connected to a computerized data-acquisition system. Data from the active system will be immediately available both locally and remotely, and all data will be logged for reference. Readings from monitor systems installed in occupied underground areas will also be used to give immediate warning to persons in the area if exposure rates rise above predetermined levels. It is the task of the RP Group to set warning levels after due assessment of the use of the area and the risks involved.

Most of the radiation measurements are used for long-term assessments and as the basis for eventual improvements. Data from release monitors are also periodically communicated to the host countries' radiation protection authorities.

The assessment of many radiation parameters involves the use of models. The RP Group has developed many computer codes, in particular to simulate hadronic and electromagnetic cascades for shielding calculations and for estimating the production of radioactivity and noxious chemical substances.

In the field of environmental protection, the expected ground-level concentrations from releases are so small that measurements will not reveal any increase above existing background concentrations. Extensive calculations have been made to predict the production of these substances. Certain amounts of these noxious products must be released
from the LEP-MR in order to avoid unacceptable accumulations. The subsequent dispersion into the environment has again been calculated, using well-established models. In the design stage — but also during operation — calculations, simulations, and extrapolations are important tools for assessing these risks. Therefore the development, maintenance, and improvement of these computational tools constitutes an important part of RP Group activities. Measurements and calculations based on reliable models are both important elements of the LEP RPS. Calculations and estimates are legally accepted as a means of establishing the exposure by different pathways in the human environment. Owing to the very low levels of radiation expected from LEP, measurements with even the most sensitive equipment will not be able to detect a change from the natural background levels. Therefore estimates by calculation will be the only useful tool for establishing upper limits of radiological risk.

10.4 Rules, access and operational conditions, and operational radiation protection

The elements described in this section can be characterized as the "software" of the RPS. General rules for CERN are set forth in the CERN Radiation Protection Manual (RPM) and in the CERN Radiation Protection Policy Statement (CER81). More detailed rules will be developed for LEP, in particular for the transport of radioactive materials between different sites of the laboratory. It is foreseen that such transport will be made either by the CERN RP Group or by the CERN Transport Service Group following consultation with the RP Group.

The existing CERN rules give sufficient guidance to make LEP activities safe from the radiological point of view. After a complete revision, the RPM was re-issued in 1983 (CER83). The needs of LEP have been taken into account for this new edition, and the RPM is now an integral part of the LEP RPS.

Design and installation of the access and interlock system will be accomplished by members of the SPS/LEP Controls Group. Access control consoles for the SPS and LEP will be combined and operated in common from the same location.

The access control system also requires a complementary search and patrol system. Provision of hardware for, and organization of, the search control system is the task of the SPS/LEP Controls Group. The system will provide a sufficient number of check points and tunnel subdivisions to facilitate a thorough and efficient search operation. The LEP RP Section does not anticipate being actively involved in the search and patrol procedures.

Operational radiation protection is a future task of the LEP RP Section. After the LEP tunnel has been searched and closed, the klystron galleries and experimental areas will require regular surveillance in order to assess radiation levels. During shutdowns, efforts will be made to prevent unsuitable (radio-sensitive) materials from being installed in the high-radiation areas, particularly in the curved sections of LEP. In an ongoing program, the LEP RP Section also will monitor the doses received by ring components, using an extensive system of passive dosimeters. Beam loss measurements will also be made with passive dosimeters in locations close to occupied areas. Islands at the head of the access shafts will be treated as individual laboratories in so far as monitoring of stray radiation or release of radioactive or noxious substances is concerned.

Apart from the routine activities mentioned, it is planned that operational RP services will be mainly "on demand", and that all LEP RP technicians will have fully equipped vehicles at their disposal for quick and effective response to operators' and experimenters' requests. However, an RP team will be based at Access Point No. 6 as this is the farthest from the main CERN facilities and it combines both RF and experimental facilities at one location.

Routine operational RP activities for LEP will comprise measurements of stray radiation, assessment of risks, control of radioactive materials (including transport), and assistance to the site and environmental RP programs. The number of technicians assigned to LEP operational RP will be determined in part by the large area covered by LEP and also by the need for RP services at other CERN facilities. The LEP RP Section will need five technicians and one physicist full-time. An equivalent amount of work related to LEP will be performed by the RP Group infrastructure, which may have to be reinforced.

11. THE LEP PRE-INJECTOR SYSTEM (LIL, EPA, and PS)

11.1 Introduction

The LEP pre-injector consists of a high-intensity linear accelerator which brings electrons up to 200 MeV before they strike a tungsten target to produce positrons. Electrons and positrons are then accelerated to 600 MeV in a second linac, 74 m long, after which they are injected into the EPA. This storage ring, which has a circumference of 126 m, collects the particles in order to condition them before onward transmission to the PS. The position of the pre-injector in the LEP chain is shown in Fig. 4. The machine will produce radiation by way of bremsstrahlung from lost electrons, which in turn can create neutrons via (y, n) reactions. As the machine is to be built on the surface near existing buildings alongside the PS, the shielding requirements will be severe. Details of the shielding calculations are given in Sul82d.

Estimates of radiation levels in the pre-injector tunnels are also necessary in order to investigate the possibility of radiation damage and to ensure that, where there is an option on materials, the appropriate choice is made. Estimates of the activity in both water and air are also required so as to indicate where precautions may be needed. Details of these estimates and calculations are given in Sul82a.
11.2 Beam losses expected in the pre-injector

The design study for the pre-injector gives the beam currents and transmission efficiencies to be expected in the various parts of the machine (LEP79). The over-all efficiency of the pre-injector is expected to be very low. When accelerating electrons, only 12% of those leaving the gun will be collected and injected into the PS. For positron production, 1800 electrons will be lost for every positron finally used. The expected beam currents and losses in the various sections of the pre-injector are summarized in Table 29. For estimating the shielding thickness, it is assumed that the loss could occur at any point in the section of the machine considered, and under the most unfavourable conditions.

To estimate the dose to components inside the machine tunnel and to predict induced radioactivity, it is the average beam loss conditions over an operating period that are of interest. The relations between maximum beam loss rate and the average will depend on the LEP filling cycle. This is not definitive, but, for the purpose of making calculations, a 22-minute LEP filling time is assumed from which the average beam power losses given in Table 29 are determined (Mad82).

<table>
<thead>
<tr>
<th>Position</th>
<th>Energy (MeV)</th>
<th>Current (nA)</th>
<th>Average energy (MeV)</th>
<th>Average power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun-buncher</td>
<td>10</td>
<td>5500</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>First linac</td>
<td>200</td>
<td>2200</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Converter</td>
<td>200</td>
<td>2200</td>
<td>200</td>
<td>440</td>
</tr>
<tr>
<td>Second linac (e+)</td>
<td>600</td>
<td>18</td>
<td>300</td>
<td>2.2</td>
</tr>
<tr>
<td>Second linac (e-)</td>
<td>600</td>
<td>75</td>
<td>300</td>
<td>2.2</td>
</tr>
<tr>
<td>EPA ring</td>
<td>600</td>
<td>2.1</td>
<td>600</td>
<td>5.4</td>
</tr>
<tr>
<td>PS ring</td>
<td>3500</td>
<td>1.7</td>
<td>3500</td>
<td>1.2</td>
</tr>
</tbody>
</table>

11.3 Shielding of secondary radiation from electron beams

11.3.1 Source-terms and shielding parameters

The shield necessary to reduce the radiation levels from beam losses has to take into account both bremsstrahlung and neutrons that could be produced under optimum conditions. Shielding data for electron accelerators have been reviewed by Swanson (Swa79a). The best available data suggest that the yield of bremsstrahlung at large angles ($\sim 90^\circ$) can be considered proportional to beam power loss independent of electron energy in the range 100–600 MeV. Although a source term of 50 Sv/h at 1 m, from a 1 kW loss, has been suggested for the bremsstrahlung emitted at 90° (or $2.2 \times 10^{-11}$ Sv · cm$^2$ · GeV$^{-1}$ per electron), an effective source term of 100 Sv/h has been taken as a more conservative choice. Attenuation mean free paths of 49 g/cm$^2$ in concrete and 37 g/cm$^2$ in iron have been taken as appropriate values to determine the transmission of the radiation through the shielding. These values are more conservative than those of subsection 6.1.3; this is consistent with CERN policy for areas where protection of persons, rather than equipment, is of primary importance (Section 1).

Neutrons are produced by high-energy electron beams in three types of interactions: Low-energy neutrons are produced in so-called giant-resonance reactions by bremsstrahlung photons and have a spectrum similar to fission neutrons. Their yield has been well studied (Swa79a, Ch. 2.4, p. 52), and a value of $10^{12}$ neutrons per second per kilowatt lost, independent of electron energy, appears to be a reasonable estimate for determining shielding requirements. Taking into account radiation build-up in the shield, the effective source term becomes 100 Sv/h at 1 m from a 1 kW beam loss. The effective mean free path of the neutrons is estimated to be 40 g/cm$^2$ in concrete (Tes79).

Data on the yield of neutrons of energy greater than 25 MeV from electrons of a few hundred MeV are scarce. Over the electron energy range 150–266 MeV, the experimentally measured neutron production cross-section spectra in lead of Von Eyss and Luhrs (Von73) have been used to estimate the yield of neutrons, in the energy ranges 25 to 100 MeV and greater than 100 MeV, from electrons up to 300 MeV. As the yield of high-energy neutrons appears to increase with decreasing atomic weight, the yields have been increased in inverse proportion to atomic weight to determine the neutron production in copper (Swa79a, Ch. 2.4, p. 91). For 400 MeV electrons, the neutron spectra obtained from Monte Carlo calculations of Alsmiller and Barish (Als73) have been used, again to determine the neutrons emitted at 90° in the energy ranges 25 to 100 MeV and greater than 100 MeV.

Neutron flux densities have been converted to dose rate on the basis of 3.3 cm$^{-2}$·s$^{-1}$, equivalent to 10 µSv/h. This conversion factor takes approximately into account the equilibrium secondary radiation spectra that
will accompany neutrons of energy greater than 25 MeV. The resulting source terms for the two energy groups of neutrons are shown in Fig. 23 as a function of electron energy. Also included are source terms that have been derived from the calculations of DeStaebler et al. (Des68) for very high energy electrons. Their formulation shows that at very high electron energies the neutron yield and spectra depend on beam power, independent of energy, and hence may be taken to represent the high-energy electron limit of neutron yield, when expressed per kilowatt of power dissipated. The calculations have been shown to correspond reasonably with measurements of neutron fluxes above 25 MeV at 90° from a thick copper target bombarded with 10 GeV electrons. These data for very high energy electron beams enable a crude extrapolation to be made of neutron yields over the entire electron energy range of interest for the pre-injector shielding.

The effective mean free path of neutrons in the energy range 25–100 MeV was estimated to be 65 g/cm², taking into account the neutron spectra and the dependence of attenuation on neutron energy (Swa79a, Ch. 3.5, p. 189). Neutrons of energy greater than 100 MeV were assumed to be attenuated with the maximum mean-free path of 120 g/cm² in concrete. This conservative choice is at the upper range of values quoted for this parameter (subsec­tion 6.1.3). Information on source terms and attenuation of important radiation components, as adopted for the shielding design, is illustrated in Fig. 19.

11.3.2 Comparison of shielding estimates with measurements

In order to check the validity of the model developed to estimate the shielding, a series of measurements were made on the shielding over the linac and converter target of the Orsay Linear Accelerator Laboratory (Sul81). Measurements were made using various detectors from which the dose equivalent of neutrons and gamma-rays could be estimated separately for five different electron energies in the range 200 to 800 MeV. The results of the measurements at 200 and 800 MeV are shown in Fig. 24. The roof shielding over the target was only 1 m thick concrete, but the target had a massive iron yoke around it, which provided considerable local shielding. This shielding was in the form of a collar 30 cm thick and 20 cm wide; also, the solenoid immediately down-beam from the target was surrounded by a 15 cm thick iron cylinder which extended for 35 cm along the beam line. The position of the maximum dose rate on the shielding coincides with the direction of minimum local shielding. The maximum neutron and gamma dose rates measured on the shielding near the target are shown in Fig. 25 as a function of electron energy. These dose rates are effectively measured at a distance of 2.2 m from the target at 65° to the beam direction, after attenuation by about 15 cm of iron and 105 cm of concrete. As can be seen, the gamma dose rate exceeds the neutron dose rate, as expected from the shielding model, but only in the immediate vicinity of the target. Everywhere else, including over the linac shield, neutron dose rates predominate. This apparent enhancement of neutrons appears to be due to the greater absorption of bremsstrahlung, relative to neutrons, by local iron shielding. In addition, measurements made near cable ducts indicate that neutrons are preferentially escaping through holes in the shielding.

The maximum neutron and gamma dose rates measured over the target do not appear to vary smoothly with electron energy. A non-systematic variation appeared to coincide with a change in pulse width made during the energy change from 600 to 400 MeV. Within the limits of this scatter, the gamma dose rate could be considered energy independent at 3.5 mSv/h, whilst the neutron dose rate appears to increase from 1 mSv at 200 MeV to 3 mSv/h at 800 MeV. The dose rates that would be obtained from the shielding model, taking into account a local shielding of 15 cm of iron and assuming that emission at 65° is the same as at 90°, are 8.8 mSv/h for gammas, and from 5 mSv/h at 200 MeV to 10 mSv/h at 800 MeV for the neutrons. Considering the complicated structure around the target, the gamma over-estimation by a factor of 2.5 is reasonable, as the shielding model assumes secondary radiation
production under optimum conditions. For the same reasons the neutron dose estimate is not excessively high. It should be mentioned that the measurements do not give a direct check on the very high energy neutron component, as these make a relatively small contribution to the dose behind 1 m of shielding.

11.4 The shielding for the pre-injector

11.4.1 Shielding walls

The shielding required at all points on the pre-injector can be determined using the radiation yield and attenuation data, together with the beam loss distribution given in Table 29, provided the degree of access to the areas outside the shielding is also known. A possible scheme is given in Table 30. The shielding thicknesses given are the bulk concrete shields that would be necessary to bring dose rates down to below

a) 2.5 µSv/h for free-access areas;

b) 25 µSv/h for simple-controlled areas;

c) 2 mSv/h for limited-stay areas.

Table 30

A possible shielding layout for the pre-injector

<table>
<thead>
<tr>
<th>Place and conditions</th>
<th>Concrete shield(^a) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun</td>
<td>Side and top — free access</td>
</tr>
<tr>
<td>First linac</td>
<td>Side — free access</td>
</tr>
<tr>
<td></td>
<td>Top — controlled access</td>
</tr>
<tr>
<td>Converter</td>
<td>Side — free access</td>
</tr>
<tr>
<td></td>
<td>Top — controlled access</td>
</tr>
<tr>
<td>Second linac</td>
<td>Side — free access</td>
</tr>
<tr>
<td></td>
<td>Top — controlled access</td>
</tr>
<tr>
<td>Accumulator (EPA)</td>
<td>Side — controlled access</td>
</tr>
<tr>
<td></td>
<td>Top — restricted access</td>
</tr>
</tbody>
</table>

\(^a\) The concrete is assumed to have a density of 2.35 g/cm\(^3\), and is of the thickness necessary to reduce the dose rate to the required level at 5 m from the point of beam loss in the case of side shielding and at 3 m for the top shielding.
Fig. 26 Plan of LEP pre-injector showing location of the LIL and the EPA, and injection into the PS.

Fig. 27 Cross-section of the LIL building at the position of the converter (cut at A–A of previous figure). The shielding at this point consists of ordinary concrete, steel, and baryte concrete.
In the actual shielding design, other factors (such as cost) are also taken into account. The layout of the shielding is shown in Fig. 26. This side shielding is everywhere 30 cm of cast concrete, to which standard shielding blocks are added. As the unit of thickness of these blocks is 80 cm, the side shield will tend to be somewhat thicker than the values given in Table 30. The roof shielding of the two linacs and converter will be everywhere 2 m thick. This uniform thickness is necessary not only for ease of construction but also to avoid a step in the klystron gallery on top of the shielding. A composite shielding of concrete, heavy concrete, and iron has been designed to ensure adequate shielding over the converter target in the space available. The tunnel cross-section near the converter is shown in Fig. 27 (cut at A–A in Fig. 26).

11.4.2 Roof of the EPA

The estimate of an optimum shielding around the EPA ring requires detailed knowledge of the distribution of beam loss as well as the effects of local shielding by beam elements. These parameters are more difficult to estimate than those relating to the transmission of radiation through the shielding. Only very simple assumptions can be made but these should be sufficient to ensure that the shielding will be adequate but not excessive. The criterion for the side walls is to limit the dose rate to 25 µSv/h outside the shielding. The criterion adopted for the roof shielding is that the dose rate at ground level, due to air-scattered radiation coming through the roof (skyshine), shall not exceed 10 µSv/h at 20 m from the point of beam loss. A beam loss of 10 W (averaged over the LEP filling cycle) is assumed (Mad82).

The roof-shielding thickness can then be calculated using previously determined secondary radiation emission and attenuation data (Sul82c), together with relations connecting direct radiation to skyshine doses for both neutrons (Nak81) and photons (NCR77). To simulate possible self-shielding (by beam elements) or added local shielding, different thicknesses of iron have been assumed between the radiation source and the roof. The result of these calculations, which gives the roof thickness necessary to reduce neutrons and gamma-rays to 10 µSv/h at 20 m, is given in Table 31. For the calculations the attenuation parameters assumed were: for photons in iron and concrete, 37 and 49 g/cm², respectively; for giant-resonance neutrons in concrete, 40 g/cm², and in iron (if followed by a reasonable concrete absorbing layer), 48 g/cm².

Table 31
Required EPA concrete roof thicknesses, assuming various amounts of local iron shielding

<table>
<thead>
<tr>
<th>Local shielding (cm of iron)</th>
<th>Roof thickness (cm of concrete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>Photons</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>16</td>
<td>12</td>
</tr>
</tbody>
</table>

49
From this table it can be seen that it should always be the photon radiation field that will determine the roof shielding thickness. As a compromise, 80 cm of concrete would appear to be reasonable for the roof shielding, provided the main-beam loss points can be protected by at least the equivalent of 5 cm of iron. With such a shield, the dose-rate on the surface of the shielding would be about 1 mSv/h at a point just above a beam loss of 10 W.

In the actual design, the roof over the accumulator is only 80 cm thick concrete. Beam losses in the accumulator are expected to occur at limited localized positions. The roof of the accumulator is to be made such that it can support a further 80 cm of concrete in the form of concrete blocks that will be used to reinforce the shielding where necessary. The cross-section of the EPA and linac tunnel is shown in Fig. 28 (cut B–B in Fig. 26). The shielding towards the enclosed areas on the inside of the accumulator ring will be 1.1 m of concrete.

### 11.5 Radiation levels expected outside the shielding

The shielding will be adequate to ensure that radiation dose rates will be less than 2.5 μSv/h at all freely accessible places outside the shielding. Dose rates in the klystron gallery on top of the shield, which will be a controlled radiation area, may rise to 25 μSv/h in places owing to radiation penetrating the shield, radiation scattering up the waveguides, as well as to a possible small contribution by X-rays from the klystrons themselves. Dose rates higher than 25 μSv/h could occur on the roof of the accumulator tunnel. It is proposed to make this area inaccessible during machine operation. Similarly, the areas enclosed by the EPA ring are planned to be used for storage of radioactive materials and will also be inaccessible during operation.

The total radiation escaping from the pre-injector is expected to make only a very small contribution to the annual dose at the border of the site.

### 11.6 Radiation levels inside the machine tunnel

For the radiation levels near the machine it is the bremsstrahlung X-rays which constitute, by far, the major component of the radiation pervading the machine tunnel. The emission of these X-rays depends on a number of factors in addition to beam power loss, such as electron energy, thickness and material of the target, and angle of emission. The resulting dose rate to an object in the tunnel will depend on its position relative to the point of beam loss and on the influence of local shielding, particularly that of machine elements in which the beam loss may have occurred.

Measurements have been made of the dose rate at different angles from a beam striking a thick target. Three sets of data, using 33 MeV electrons (Tor80), 100 MeV electrons (Wyc71), and 5 GeV electrons (Din77), have been combined to determine an empirical law relating the parameters involved. The ‘best’ obtainable relation is:

\[
\dot{D} = 2.7 P R^{-2} E^{1/2} \theta^{-3/2},
\]

where \(\dot{D}\) is the dose rate in Gy/h, \(E\) is the electron energy in MeV, \(P\) is the electron beam power loss in watts, and \(R\) is the distance in metres at an angle \(\theta\) (degrees) to the beam direction. The validity of this relationship is demonstrated in Fig. 29 using the three independent sets of data, where \(\dot{D}/E\) has been plotted against \(\theta\), with all data normalized to a 1 W power loss at a distance of 1 m. The dose rate at small emission angles depends strongly on target dimensions. In all cases the target was thick; for the 33 MeV data it was a copper sector target 29 g/cm² long and 8 cm in diameter. The 100 MeV data were for a 68 g/cm² long, and 2.5 cm diameter tantalum target. The dose rate from the tantalum target has been reduced by a factor of 1.3 to make it comparable to that from a copper target. The 5 GeV data were for a 10 cm thick steel target of about 2 cm diameter. The effect of adding material between the source and detector is to cause a dose build-up in the radiation emitted at small angles where the electromagnetic cascade continues to develop, whereas perpendicular to the beam the radiation appears to contain a soft component that is readily attenuated. This component accounts for about 50% of the dose at 100 MeV, and at 5 GeV the dose rate appears to be reduced by nearly two orders of magnitude in the first 2 g/cm² of intervening material (Din77).

#### 11.6.1 The dose to machine components inside the tunnel

To determine a reasonable value for the dose to which a component in the machine could be exposed, it is necessary to know the distribution of beam losses along the machine, both as a function of position and time, as well as the effects of local shielding. These quantities have to be assumed and involve a considerable uncertainty. The assumptions that have been made are as follows:

1) 25% of the losses listed in Table 29 can occur at any one point in the LIL and the EPA.
2) The loss occurs at the most critical position relative to the object being irradiated. For a given distance from the beam line, the critical angle of emission for maximum dose rate from a point loss will be at about 50°.
3) Self shielding by the machine is equivalent to about 3 cm of copper. (This is also about the effective local shielding of the targets used to determine the dose rates given in Fig. 29.)
4) The dose rate around the converter can be considered to originate from a point source, and the dose rate will be twice that predicted from Eq. (11.1) because of the target being tungsten.
5) The beam loss can occur for 4000 h/y. Although operation of the pre-injector is not thought to require more than about 400 h/y for filling LEP, it is not unreasonable to assume that the machine might be working at least half the year on experiments and improvement projects between LEP fills.
Using these assumptions together with beam loss data from Table 29, the dose rates inside the pre-injector tunnel can be calculated. These are given in Table 32 as the hourly dose rate at 1 m from the different parts of the machine, and as the yearly dose expected at 20 cm from the beam line (corresponding to roughly the position of cable and hose connections to the beam elements).

The dose rate from electron beams in the PS machine tunnel has also been estimated. The values obtained are less than 10% of those measured during normal proton operation.

### 11.6.2 Monte Carlo studies of dose rates around the converter

The design for the LIL positron converter provides for a tungsten target disk approximately two radiation lengths (1 \( \times \) 0 = 6.763 g/cm\(^2\) = 0.35 cm) thick in the beam direction and of 1 cm diameter, enclosed in a copper vacuum chamber. An average current of 2.2 µA at 200 MeV (440 W) is incident on the converter. These data indicate that the most severe radiation problems associated with the pre-injector would occur in the vicinity of the converter. The RP considerations are the following:

i) confirmation of source term for personnel shielding;

ii) protection of equipment against ionizing radiation:
   (a) target mechanism,
   (b) second electron injector and its electronics,
   (c) other electronics and auxiliary equipment;

iii) reduction of induced radioactivity and noxious gas production;

iv) heat deposition and removal in the target and collimators.

To accomplish these objectives simultaneously it is necessary to know the distribution of bremsstrahlung X-ray doses around the converter. The EGS Monte Carlo program (For78) was set up in cylindrical geometry, and doses in appropriately positioned annuli made of 5 cm thick polyethylene (CH\(_2\)), were determined. Runs were repeated with 2, 3, 4, 6, and 10 \( \times \) 0 tungsten targets.

### Table 32

Dose rates inside the pre-injector tunnel during machine operation

<table>
<thead>
<tr>
<th>Position</th>
<th>Dose rate at 1 m (Sv/h)</th>
<th>Dose rate at 20 cm (Sv/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun-buncher</td>
<td>0.05</td>
<td>5 ( \times ) 10(^3)</td>
</tr>
<tr>
<td>First linac</td>
<td>0.3</td>
<td>3 ( \times ) 10(^4)</td>
</tr>
<tr>
<td>Converter</td>
<td>60</td>
<td>6 ( \times ) 10(^6)</td>
</tr>
<tr>
<td>Second linac</td>
<td>0.04</td>
<td>4 ( \times ) 10(^5)</td>
</tr>
<tr>
<td>EPA ring</td>
<td>0.15</td>
<td>1.5 ( \times ) 10(^4)</td>
</tr>
<tr>
<td>PS ring</td>
<td>0.08</td>
<td>8 ( \times ) 10(^3)</td>
</tr>
</tbody>
</table>
Figure 30 shows the partition of energy, as a function of target thickness, amongst three regions: a) the target itself, b) forward transmission (within 45° half-angle), and c) scattering at large angles (45° to 180°). These data show that, for the design target thickness of 2 X₀, about 23% of the beam energy is absorbed in the target, whilst about 73% must be absorbed by components downstream of the target, within a half-angle of 45°. As the target thickness is increased, the fraction of energy absorbed increases but appears to approach a limiting value, for this target diameter, of about 72%. This information may have consequences for heat-removal requirements.

Figure 31 shows the dose to the 5 cm thick polyethylene annuli as a function of angle for converter thicknesses of 2, 4, and 10 X₀. Comparison was made with measurements performed at DESY (Din83) and Frascati (Esp83) at large angles (45° to 135°) and reasonable agreement was found. The dose determinations of Fig. 31 can also be compared with rules-of-thumb frequently used for the dimensioning of shielding (Swa79a, Ch. 2.4, pp. 53, 188). In the forward direction (0°) this source term appears to be reasonable for targets of 2–4 X₀ thickness, and conservative for thicker targets. At 90°, a source term of 100 Sv · m² · kW⁻¹ · h⁻¹, assumed for the shielding design, is confirmed in these calculations.
Besides confirming the source term for computing the bulk shielding walls, the dose distribution of Fig. 31 is useful when positioning lead shielding around the converter in order to protect sensitive equipment, and also to reduce the amount of activation and noxious gas production. Additional details concerning these studies are given in Swa83b.

11.6.3 Comparison with measurements
The assumptions used to estimate the dose in the pre-injector complex have been used in calculating the dose in the Orsay linac tunnel and around the converter target. These estimates can be compared with measured values (Dar81). The ratio of calculated to measured dose along the linac varies between 10 and 0.5, indicating the degree of dependence of dose on actual beam loss patterns and machine self shielding that cannot be estimated. Even so, the calculated dose rates are not unreasonable taking into account all the uncertainties. Around the converter the calculated dose rates agree with those measured to better than a factor of 3 if a mean shielding of 10 cm of iron is assumed around the Orsay converter (Sul81).

11.6.4 Possibility of radiation damage
Details of the radiation resistance of materials are given in Sch79b, Sch79c and Bey82. These data, together with a knowledge of the likely dose rates, should suffice for selecting the most suitable materials for use in radiation areas on a cost effective basis.

It is doubtful that the dose rates estimated for the pre-injector complex will give rise to any serious problems if the use of Teflon is avoided and if active electronics components are kept out of the tunnel. Dose rates near the converter may cause cable and insulation damage in the long term, and the design of equipment in the target area should take possible radiation effects into account. When considering the possibilities of damage to electronics, the duty cycle of the machine should also be considered, as the instantaneous dose rates will be $10^2$ times higher than the average, which could cause spurious transient effects.

11.7 Induced radioactivity in machine components
The radioactivity induced in different parts of the machine will also depend on the beam loss distribution. Barbier (Bar69) has calculated the induced activity that can occur with electron beams, and his data are shown in Fig. 32. The activity is nearly all due to reactions of type $(\gamma, n)$, even for electrons of 3.5 GeV. The distribution of isotopes produced is therefore different from that for high-energy particle reactions where most isotopes result from spallation reactions. This can be seen in the radiation decay curves shown in the figure. Materials such as Al and Pb are to be preferred as the induced isotopes decay rapidly, whereas longer-lived isotopes are produced in iron and other materials. The curves are for the dose rate that would be achieved if it were possible to concentrate activity at one point. In practice this is not possible, as a certain mass is necessary for the bremsstrahlung to interact to produce the activity via the $(\gamma, n)$ reaction. Hence dose rates will be less than those indicated in the figure by at least a factor of 3.

Fig. 32 Radiation fields at 1 m from a point source containing all the radioactive nuclei produced in a target by the electromagnetic cascade from an electron beam incident at 1 electron per MeV and second (after Barbier (Bar69)).
Table 33

Dose rates expected (at 50 cm from pre-injector) from induced activity

<table>
<thead>
<tr>
<th>Location of induced activity</th>
<th>Dose rate in mSv/h at 50 cm</th>
<th>1 h after stop</th>
<th>1 day after stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>0.20</td>
<td>0.07</td>
<td>0.015</td>
</tr>
<tr>
<td>Copper</td>
<td>0.13</td>
<td>0.01</td>
<td>0.002</td>
</tr>
<tr>
<td>First linac</td>
<td>15</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Converter</td>
<td>0.20</td>
<td>0.01</td>
<td>0.09</td>
</tr>
<tr>
<td>Second linac</td>
<td>0.25</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>Second linac (dump)</td>
<td>0.25</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>EPA ring</td>
<td>0.05</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>PS ring</td>
<td>0.01</td>
<td>0.006</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Using the beam-loss data given in Table 29 and assuming that the hottest spot occurs when 25% of the total beam loss occurs at one point, the dose rate at one hour and at one day after beam off can be determined. The maximum dose rates obtained at 50 cm from the various parts of the pre-injector complex are indicated in Table 33. The actual dose rates will be a function of the geometry around the point of beam loss, and depend on self shielding in the machine. In addition, the calculated dose rates are those after a long operation of the machine with the LEP filling cycle. Continuous operation of the second linac and the EPA with electrons could produce four times as much radioactivity, as is indicated in Table 32. Hence the dose rates given should be considered as indicative only.

11.8 Induced activity in pre-injector air and cooling water

Radioactivity will also be induced in air and cooling water in the vicinity of the accelerator structure. These activities require special consideration as they can be transported through the shielding.

Radioactivity in the exhaust air will contribute to the external radiation dose to persons downwind of the venting point (beta–gamma radiation from the activated plume). Owing to the small quantities and short half-lives of the radionuclides produced in air, this is not a significant hazard, even to persons entering the shielded areas immediately after beam shutoff. Although this additional dose is very small, it can be totally avoided at low cost if the air is recirculated. This has the additional advantage that humidity control is less expensive. The ventilation system of the pre-injector tunnel must be separated from other areas, not only because of the radioactivity but also to avoid enhanced corrosion from chemically active radiogenic gases, especially NOx.

The saturation activity per watt in a medium of thickness X (g/cm²) surrounding a point of beam loss is given by

\[ A = \frac{f XY}{\lambda}, \]

where

- \( A \) is the activity in Bq;
- \( f \) is the fraction of the impinging electron energy that converts to bremsstrahlung and escapes from the machine structure and into the air or water. (This factor depends strongly on the location of the beam loss, but a reasonable figure might be \( f = 0.3 \).)
- \( Y \) is the neutron yield per unit of incident electron beam power. [The neutron yield gives directly the total activity production rate as every isotope formed in \((\gamma, n)\) reactions in air or water will be radioactive. We adopt the values \( Y = 3 \times 10^8 \) and \( 2 \times 10^8 \) neutrons per watt and second for air and water, respectively (Swa79a, p. 85).]

The thickness \( X \) of the medium surrounding the target is assumed to be thin compared to the mean-free path \( \lambda \) of the X-rays. At energies above about 1 MeV, the absorption mean-free path is about 50 g/cm² in both air and water. Assuming that the layer of cooling water is 5 mm thick and that the air layer is everywhere equivalent to a path length of 2 m inside the tunnel around the point of loss, the induced radioactivities can be estimated.

The above assumptions lead to a water activity of 0.66 MBq/W and an air activity of 0.44 MBq/W. The total activity produced by the entire pre-injector complex will therefore be about 300 MBq of water activity and 200 MBq of air activity. The main isotopes present will be \(^{14}\text{N}\) for air and \(^{18}\text{O}\) for water, having half-lives of 9.96 and 2.05 min, respectively. Table 34 shows the amounts of activity produced in water and air, as well as noxious gases produced in the pre-injector.

Dose rates in the tunnel from the water and air activity will be negligible compared to the dose rates from the accelerator structure. If the air activity escaped continuously via the ventilation system, the maximum release rate would be about 0.3 MBq/s, which could give a beta dose rate of the order of 1 \( \mu \text{Sv}/\text{h} \) at 10 m downwind from the release.
Table 34
Activity induced in water and air, and noxious gases produced in air by radiation from pre-injector

<table>
<thead>
<tr>
<th>Medium</th>
<th>Isotope or noxious gas</th>
<th>Half-life (min)</th>
<th>Production rate (MBq/s or ml/s)</th>
<th>Equilibrium activity or quantity (MBq or ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>${}^{17}$O</td>
<td>2.05</td>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>Air</td>
<td>${}^{13}$N</td>
<td>9.96</td>
<td>0.3</td>
<td>200</td>
</tr>
<tr>
<td>Air</td>
<td>Ozone</td>
<td>50</td>
<td>0.01</td>
<td>30</td>
</tr>
</tbody>
</table>

point (Sol82b). The gamma dose rate would be less than 10% of this value. If continuously released, the dose due to gaseous radioactivity at the site boundary should be less than 10 µSv/y.

The water activity is circulated through a heat exchanger. The ${}^{17}$O activity in the water-cooling circuits next to the converter target could result in a dose rate of about 60 µSv/h at 1 m from the heat exchanger. This would require shielding if situated in an accessible area.

11.9 Ozone concentration

For the sake of completeness, the ozone production has also been calculated using similar arguments. The rate of production is given in litres of ozone per second per watt of electron beam power by

$$C = 6.25 \times 10^{18} \left[ f \frac{X}{\lambda} N \right] \left[ \frac{G}{100} \right] ,$$  \hspace{1cm} (11.3)

where $f$ is the fraction of electron energy that escapes in air as X-rays (assumed to be 0.3, as before); $X$ is the thickness of the air layer, and $\lambda$ is the photon mean-free path (for a 1 m path length, $X/\lambda = 2.6 \times 10^{-3}$); $G$ is the radiolytic yield for ozone, taken to be 10 molecules per 100 eV; and $N = 2.7 \times 10^{22}$ is the number of molecules per litre of gas at NTP. The numerical coefficient converts watts to electronvolts per second.

With the above data, the ozone production rate becomes

$$C = 1.9 \times 10^{-5} \cdot 1 \cdot s^{-1} \cdot kW^{-1} \cdot m^{-1} ,$$  \hspace{1cm} (11.4)

which compares very well with $1.2 \times 10^{-5} \cdot 1 \cdot s^{-1} \cdot kW^{-1} \cdot m^{-1} \left( \text{Swa79a, p. 155} \right)$. Assuming an electron beam power of 440 W and an average path length of 2 m, the total ozone production in the entire pre-injector becomes about $1.67 \times 10^{-7}$ l/s. Assuming a 3000 s dissociation time, the total amount of ozone in equilibrium becomes about 0.05 l. Considering that the ozone will be predominantly produced in the LIL tunnel (volume about $945 \times 10^3$ l), we estimate the average ozone concentration to be

$$(1.67 \times 10^{-7} l/s) \times (3000 s)/(945 \times 10^3 l) = 0.05 \text{ ppm} .$$  \hspace{1cm} (11.5)

This figure is close to the limit of 0.1 ppm for continuous occupancy and the tunnel will be ventilated prior to personnel entry to ensure compliance. With ventilation turned on for an adequate time beforehand, the legal requirement should be easily met.

Continuous release of the ozone to the outside would give levels of the order of $2 \times 10^{-3}$ ppm at a location 10 m downwind from the point of release. This concentration is small compared to natural levels.

11.10 The LIL klystron gallery

Further sources of low-energy X-rays are the klystrons installed in a special housing above the linac (Fig. 27). The klystron area will be classified as a "Radiation Area" (see Table 2), and during operation it will only be accessible to personnel under administrative control. Such access would require efficient shielding against X-rays produced by the klystrons during formation and routine operation. This shielding is provided by the manufacturer according to CERN specifications, and is routinely checked at the time of installation. During operation at maximum power, dose rates at 10 cm from the outer accessible surface must be less than 2.5 µSv/h.

Final boundaries to Controlled-Radiation Areas will be determined when radiation levels have been measured. In the planning stage, it is envisaged that, besides the pre-injector beam areas, only the klystron gallery will be declared a Controlled-Radiation Area.

11.11 The PS as electron-positron accelerator

The accelerator system of the PS will be modified to permit acceleration of $e^\pm$ from 600 MeV to 3.5 GeV. Radioactivity and stray radiation in the PS will arise whenever electrons are lost from their orbits; these losses are...
assumed to be 20% of the injected beam. The secondary radiation from the $e^\pm$ interacting in the PS is so low that it will not measurably increase the average radiation levels outside the existing PS shielded tunnel. The radioactivity produced in the PS is less than 0.1% of the proton-induced activity.

The synchrotron radiation produced by circulating $e^\pm$ has a critical energy (at 3.5 GeV) of 1.36 keV, and a total power loss of about 1 kW for a 5 mA circulating current (combined $e^+$ and $e^-$). The fraction of synchrotron radiation which can penetrate the PS vacuum chamber (stainless steel) is negligible, and heating of the chamber in the curved sections (~ 440 m long) with about 2.2 W/m is too small to be of any concern.

The Radiation Protection System for the PS in the dedicated LEP-filling mode is entirely covered by the existing system; no additional precautions for $e^\pm$ operation are therefore required.

11.12 Summary
In summary, the essential elements constituting the Pre-Injector Radiation Protection System are: the shielding configuration; the containment of radioactive air; cooling water; an area radiation-monitoring system; and shielding and surveillance of the klystron gallery. Operational radiation protection will be entrusted to the local PS Radiation Survey Section, which is equipped to cope with any problem stemming from ionizing radiation in this area.

Radiation levels will be monitored by 10 PAX radiation monitor systems (Rau81) in accessible areas near the pre-injector. These will be placed where operating personnel are routinely present, and in areas where higher radiation levels are expected. This would be the case near penetrations such as access-ways. These monitors are arranged to give warnings of unusually high radiation levels (if present), and to automatically shut off the beam at pre-determined levels.

12. The SPS as LEP Injector
12.1 Adequacy of the present radiation protection system
Electrons and positrons transferred from the PS to the SPS via the transfer tunnels TT70 and TT10 at 3.5 GeV will be accelerated in the SPS to 20 GeV and then extracted and transported to the LEP main ring. About 20% of the $e^\pm$ are expected to be lost in these operations. These $e^\pm$ interact with accelerator components and produce secondary radiation and some radioactivity. Any prompt radiation is completely absorbed by the massive shielding above the transfer tunnels and the SPS main ring; the intensity is so low that even in adjacent areas the radiation levels will be insignificant. Existing shielding, monitoring systems and access control systems are more than adequate for controlling the prompt radiation.

Furthermore, the total amount of radioactivity produced by $e^\pm$ in any material is orders of magnitude lower than the activity induced by proton operation of the SPS. This statement applies to the radioactivity produced in air and cooling water as well as in metallic or other solid components. Control measures already implemented at the SPS cover all such problems.

12.2 Dose to components from synchrotron radiation
The synchrotron radiation produced in the SPS by 22 GeV $e^\pm$ and its effect on materials have been extensively studied (Bri80); this study has been revised (Ste82) for 20 GeV operation.

The variation of energy loss per orbit path length in a bending magnet of the SPS and the associated critical energy are shown in Fig. 16 as functions of electron energy. Appropriate parameters for assessing the effect of synchrotron radiation in the SPS are listed in Table 35. As the critical energy is a strong function of electron energy, the magnitude of radiation effects will vary greatly within an acceleration cycle. Unless otherwise stated, it is assumed that one complete $e^\pm$ cycle is equivalent to 150 ms of electron operation at 20 GeV.

Whether the $e^\pm$ cycles are interleaved with proton cycles or a dedicated mode is used does not affect the synchrotron radiation provided that the same SPS supercycle is maintained. The normal procedure will be to fill LEP

<table>
<thead>
<tr>
<th>Parameters determining SPS synchrotron radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum energy</td>
</tr>
<tr>
<td>Number of electrons or positrons per SPS pulse</td>
</tr>
<tr>
<td>Mean radius of SPS</td>
</tr>
<tr>
<td>Current of circulating $e^\pm$ (each beam)</td>
</tr>
<tr>
<td>Bending radius of main ring magnets</td>
</tr>
<tr>
<td>Energy loss for one $e^\pm$ turn</td>
</tr>
<tr>
<td>Energy loss per path length in dipole</td>
</tr>
<tr>
<td>Power loss per path length in dipole</td>
</tr>
<tr>
<td>Critical energy of synchrotron radiation</td>
</tr>
<tr>
<td>Superperiod of SPS magnet cycle</td>
</tr>
<tr>
<td>Number of $e^\pm$ cycles per superperiod (2 $e^+$, 2 $e^-$)</td>
</tr>
</tbody>
</table>

56
within about 20 minutes every 2 to 4 hours. For non-rate-dependent effects, it will be assumed that $e^\pm$ acceleration in the SPS takes place during 10% of the entire operating time of LEP, assumed to be 3000 hours. However, it should be realized that $e^\pm$ acceleration for development purposes could take place between LEP fills, and so some rate-dependent effects will be estimated on the basis of continuous operation.

The critical energy at 20 GeV is 24 keV, and the power radiated amounts to about 1.8 W/m for an electron current of 0.45 mA (from Table 35). In particular, the effect of the synchrotron radiation on the vacuum chamber and accelerator components as well as on the production of noxious gases in the SPS tunnel has been assessed.

In a normal SPS period, synchrotron radiation impinges on the vacuum chamber at a grazing angle of approximately 20 mrad. This incident radiation is heavily absorbed by the stainless steel of the vacuum chamber (about 90% of the incident energy) and therefore the dose received by the magnet insulation is due to the component scattered at 90° to the incident radiation (mainly photons of energies close to a few keV). The dose received by the insulation in the horizontal plane close to the vacuum tube depends on the magnet type: the main bending magnet type B (MBB) receives twice the dose received by the type A bending magnet (MBA), since the vacuum chamber wall thickness is different (1.5 mm for the MBB against 2 mm for the MBA). The dose is also a very strong function of electron energy.

Calculations previously reported (Bri80, Ste80, Ste82) assumed a maximum $e^\pm$ energy of 22 GeV. Reducing this to 20 GeV, as is currently proposed, reduces the dose to the bending magnet coils by a factor of 2.8. In addition, the circulating current assumed for this report is a factor of 5 lower than that in Bri80. Thus at the maximum energy, the dose to an MBB coil is now 6.6 mGy/s instead of about 70 mGy/s as estimated previously (Ste80). Using the same assumption as before, that a complete acceleration cycle is equivalent to 150 ms of operation at the maximum energy, and also using the parameters listed in Table 35, the yearly dose to an MBB magnet coil becomes

$$6.6 \text{ mGy/s} \times 150 \times 10^{-3} \text{ seconds per cycle} \times 3600/15 \text{ supercycles per hour} \times 3 \text{ } e^\pm \text{ cycles per supercycle} \times 3000 \text{ h/y} \times 10\% \text{ (time filling)} = 300 \text{ Gy/y}.$$

This is insignificant compared with the radiation dose from normal SPS proton operation.

### 12.3 Particular locations in the SPS

At certain points in the SPS the magnet coil can be irradiated almost directly by the synchrotron radiation. The insulation is protected only by the thickness of the steel bellows and can be irradiated by about 1 m length of the $e^\pm$ orbit. Calculations for a 0.45 mA beam at 20 GeV show that the MBB coil will be exposed to dose rates of 400 Gy/s for each metre of orbit to which the bellows flange is exposed. A protective lead collar of 10 mm thickness would reduce this to 5 mGy $\cdot$ m$^{-1} \cdot$ s$^{-1}$.

At extraction from the SPS, the electrons are deflected out of the normal circular orbit by a relatively sharp bend. The critical energy of the synchrotron radiation coming from this bend could be an order of magnitude higher than that of the main-ring magnets. However, the $e^\pm$ pass this section only once per cycle instead of circulating many times as in the main ring. Calculations for a 22 GeV beam bent by 50 mrad in a magnet of 5 m show that the dose received by an object 20 m downstream would be about 100 $\mu$Gy per pulse from synchrotron radiation passing longitudinally through a 1.5 mm stainless-steel vacuum chamber.

It was found that lead shielding is needed to protect the magnet coils only where the synchrotron radiation is normally incident on components such as vacuum flanges.

### 12.4 Production of noxious compounds

Calculations made using the MORSE (Emm75) and EGS (For78) programs confirm that the dose received by air in the bending magnets between the vacuum chamber and coil insulation is close to the dose received by the superficial layer of the insulation itself. Averaged over the full height of the magnet gap, this leads to an energy deposition in the air of $8.3 \times 10^6$ eV $\cdot$ cm$^{-3} \cdot$ s$^{-1}$ for a beam circulating at 20 GeV, or $3.34 \times 10^8$ eV $\cdot$ cm$^{-3} \cdot$ s$^{-1}$ averaged over an entire LEP fill.

Ozone formation was considered in detail for the LEP ring itself in Höf81b (also see Section 12.3). Using the same parameters as were applied in that report and assuming that electron acceleration in the SPS continues for longer than the normal dissociation time of the $O_2$ molecules (approx. 50 min), one arrives at an equilibrium concentration of $1.07 \times 10^{14}$ ozone molecules per cubic metre, or $4 \times 10^{-3}$ ppm of $O_3$. For comparison, the limit of concentration for human exposure is 0.1 ppm.

The irradiation of air forms various oxides of nitrogen which combine with water vapour (which is always present in sufficient quantities) to form acids of nitrogen. Using the parameters developed by Perrot (Per80), the nitric acid concentration after one LEP fill of 20 minutes is predicted to be $6.0 \times 10^7$ HNO$_3$ molecules per cubic centimetre, or $2.2 \times 10^{-4}$ ppm of HNO$_3$.

The effect of this acid concentration on the SPS vacuum chamber is not directly known, but since no effects have been observed that are attributable to HNO$_3$ because of the present irradiation of the vacuum chamber by protons in the SPS at a rate several orders of magnitude higher than that calculated for electron operation, it can be assumed that nitric acid produced by electron acceleration will not be of importance.
Apart from the addition of lead shielding in selected places, the existing Radiation-Protection System in the SPS is completely adequate for e⁺ operation.

13. RADIATION PROTECTION SYSTEM FOR THE LEP MAIN RING

13.1 Radiation in accessible areas during operation

13.1.1 Shielding philosophy and assumptions

The areas of the LEP main ring (LEP-MR) accessible to personnel while LEP is in operation include the following:
- klystron galleries,
- experimental areas, and
- access shafts and tunnels serving these areas.

Except for the experimental areas, these are separated from the LEP-MR and intersection areas by a minimum shielding equivalent to 2.0 m of concrete. Shielded doors will be provided for equipment-access penetrations, and either shielded doors or labyrinths for personnel access-ways. Figures 33 and 34 show examples.

In the case of experimental areas a more flexible approach is necessary. With the restriction that, during normal operation and service periods, no person should receive more than 1/5 of the annual dose limit, the installations should be so planned, and shielding and geometrical factors so defined, that an annual area dose of 10 mSv will never be exceeded. The occupancy time will then provide an additional safety factor.

There are two significant sources of radiation that can be transported from the LEP-MR to the accessible areas:

i) high-energy radiation, especially neutrons, produced by beam losses, and
ii) synchrotron radiation streaming through the RF ducts or other penetrations.

Neutron production in LEP has been studied in relation to three different potential problems:

i) activation of the accelerator structure by the produced neutrons (Goe81);
ii) streaming of neutrons into the klystron galleries via ducts housing the RF waveguides (Fas82a); and
iii) shielding requirements for experiments in the intersection regions (Din81).

The first problem can be dismissed as being of secondary importance in comparison with direct activation from (γ, n) processes. At the same time, the (γ, n) reactions are the main source of neutron production from photons of the electromagnetic cascade. These constitute the source of problems (ii) and (iii).

Predictions regarding neutron yields given in the above-mentioned references used a figure of 0.3 neutrons per GeV per electron lost (Swa79a). In order to check this figure, an experiment on neutron yields from electrons up to 100 GeV on medium-Z targets was performed (Ste83b). The measured figure at 20 GeV for an electron beam lost on a thick copper target was 0.19, whilst at 86 GeV a neutron yield of 0.42 per GeV per electron was obtained. These figures were used to determine the source strengths for two hypothetical cases of beam loss:

i) full injection loss of $1.55 \times 10^{10}$ e⁺ or e⁻ per second at 20 GeV; and

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Fig. 33  LEP tunnel at Access Point 1, nearest the injection system (notice injection points at left and right). Tunnels shown are 82 m below surface. One shaft allows access to experimental equipment, the other to the service area.
ii) total loss of $2 \times 10$ mA of beam at 86 GeV owing to beam mis-steering or a hypothetical obstruction in the LEP vacuum chamber. This corresponds to $1.1 \times 10^{13}$ $e^+$ and $e^-$ lost locally.

The production of synchrotron radiation is discussed in Section 4.6. Owing to the intense radiation produced, it is necessary to consider the possibility that synchrotron radiation originating in the bending sections could stream down the long straight sections to the accessible areas. Studies have shown that the penetration into these straight sections, where the accelerating cavities are located, is substantial (Bur82d, Fas82a).

13.1.2 Radiation in the klystron galleries

The radiation situation in the klystron galleries has been discussed in three reports (Höf81a, Höf81c, Fas82a). The radiation risk in those areas could come from two different sources: first, photons and neutrons could stream from the LEP tunnel through RF waveguide ducts of 8 m length and 80 cm diameter. The source stems from either synchrotron radiation streaming from the bending sections and scattered into the ducts, or beam losses giving rise to high-energy radiation. Secondly, possible radiation sources within the galleries are the klystrons themselves—although shielding is provided by the manufacturer.

a) Direct radiation from beam losses

Doses from the high-energy component transported along a straight line directly from the nearest point of the LEP beam line to the opening of the RF duct into the klystron gallery (see Fig. 35) are reviewed in Fas82a. The revised parameters assumed for this report are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam loss</td>
<td>$1.55 \times 10^{10}$ $e^+$ per second at 20 GeV,</td>
</tr>
<tr>
<td>High-energy source term</td>
<td>$1.2 \times 10^{-12}$ Sv$\cdot$cm$^2$$\cdot$GeV$^{-1}$,</td>
</tr>
<tr>
<td>Total distance</td>
<td>1120 cm</td>
</tr>
<tr>
<td>Thickness of rock and concrete</td>
<td>620 g/cm$^2$,</td>
</tr>
<tr>
<td>Attenuation parameter</td>
<td>115 g/cm$^2$.</td>
</tr>
</tbody>
</table>

Using the method described in Section 6.1, a maximum dose rate of $4.9$ $\mu$Sv/h was calculated. This is negligible compared with the doses transported by streaming. At other locations along the axis of the beam, away from the RF ducts, the radiation is entirely negligible owing to the full 8 m of earth and rock shielding available.
b) Streaming of radiation from beam losses

In Fig. 36 the basic layout of the LEP tunnel, the RF waveguide ducts, and the klystron galleries is shown (Fig. 35 shows the simplified geometry used for calculation). Figure 37 shows the photon dose equivalent as a function of distance into the duct, based on this geometry and assuming loss of beam at a point in the ring nearest the duct. Figure 38 shows the neutron dose equivalent as a function of distance into the duct, for the same conditions as calculated by the MORSE transport code, and assuming two different spectra for the giant-resonance neutrons (Als73, DeS68). Table 36 summarizes these results in terms of doses at the point where the duct enters the klystron gallery.

It should be emphasized that the figures quoted are upper limits under extremely unlikely beam-loss conditions. Furthermore, doses and dose rates quoted are those possible on the axis of the RF duct locally, with a strong decrease to the sides. Nevertheless, beam losses in the region of the accelerating cavities will lead to an increase of the general radiation level in the klystron galleries, an effect which could be greatly reduced by blocking, as far as possible, the open space around the waveguides by 50 cm of concrete at the main-ring tunnel.

An interesting lesson resulted from studies of various configurations of the 50 cm concrete lining of the RF duct (Fas82a). It was found that if the same 50 cm lining were located at the opposite end of the RF duct, nearest the klystron...
Photon dose in the Klystron duct
Input spectrum from EGS
MORSE forward calculation

Neutron dose equivalent in Klystron duct
• Alsmiller's spectrum
• DeStaebler's spectrum
MORSE forward calculation

Fig. 37 Dose equivalent of photons as a function of distance into the RF waveguide duct as calculated by EGS and MORSE.

Fig. 38 Dose equivalent of neutrons as a function of distance into the RF waveguide duct assuming two different spectra. References are to Alsmiller (Als73) and DeStaebler (DeS68).

Table 36
Dose rates and doses at the exit of the klystron duct (high-energy radiation due to beam losses)

<table>
<thead>
<tr>
<th>Quantity and beam parameters</th>
<th>Duct arrangement</th>
<th>Photons</th>
<th>Giant-resonance neutrons</th>
<th>High-energy particles (hadrons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum dose rate in µSv/h for an injection loss of $10^{11} \text{s}^{-1}$ at 22 GeV</td>
<td>Unshielded</td>
<td>150</td>
<td>1900</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Shielded*</td>
<td>40</td>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>Dose in µSv for a total beam loss of $1.9 \times 10^{13} \text{e}^\pm$ at 85 GeV</td>
<td>Unshielded</td>
<td>&lt; 10</td>
<td>45</td>
<td>&lt; 10</td>
</tr>
<tr>
<td></td>
<td>Shielded*</td>
<td>&lt; 10</td>
<td>12</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

* Space within the duct around the waveguide packed with 50 cm of concrete at the end nearest the main ring (see Fig. 35).

Since these calculations were completed, the LEP injection parameters have been revised. The new assumptions are: a full injection loss would occur with only $1.55 \times 10^{10} \text{e}^+ \text{or e}^-$ per second at 20 GeV. Hence the corresponding dose rates in the klystron galleries are also reduced: 0.17 and 0.05 mSv/h for the open duct and the partially shielded one, respectively. The dose figures for a beam loss at 86 GeV are now based on a total loss of $2 \times 10$ mA of beam at 86 GeV, corresponding to $1.1 \times 10^{13} \text{e}^+ \text{and e}^-$ lost locally. The revised values, for a beam loss of $1.1 \times 10^{13} \text{e}^+ \text{and e}^-$ at 86 GeV are calculated to be 37 and 99 µSv, respectively. These figures, although nearly a factor of 4 higher than the earlier estimates, are still fully acceptable from the radiation protection point of view.
c) Streaming of synchrotron radiation

Dose rates in the klystron galleries from synchrotron radiation in the main ring depend strongly on the distance of the duct from the nearest bending magnet. For LEP operating at 85 GeV with a circulating beam of 2 x 3.3 mA, a dose rate of 1.3 Sv/h will exist in front of the first RF duct, situated 240 m from the interaction region. Other ducts are at 230, 216, and 206 m, for which dose rates are reduced. Assuming a nearest distance of 240 m, with a circulating beam of 2 x 3.3 mA at 85 GeV, local dose rates of 400 µSv/h have been estimated for the klystron galleries. These decrease by a factor of four if shielding (50 cm of concrete) is provided around the waveguide at the side of the LEP tunnel (Fas82a).

d) Klystrons as X-ray sources

The klystrons in the klystron galleries are also sources of low-energy X-rays. Radiation levels in these areas could be higher than the radiation from the main ring if shielding is missing from any of them. The shielding of each individual klystron is the responsibility of the manufacturer, and the requirements specify a maximum dose rate of 2.5 µSv/h or less, at 40 cm from the accessible surface. However, during testing or routine operation, shielding of the klystrons may be inadvertently removed. To prevent doses to personnel under these circumstances, a shielding interlock will be provided on each unit, as well as a radiation monitor for each gallery. Thus by these means it is expected that doses accumulated by the service staff will be less than 1 mSv/y for all these areas. These zones will be regarded as Controlled-Radiation Areas and personal dosimeters must be worn at all times during access.

13.1.3 Radiation in experimental areas

With the shielding philosophy set forth above (subsection 13.1.1), it has been determined that a minimum shielding of 1.20 m of concrete (or the equivalent) is needed in all azimuths around the interaction point (Din81, Höf81a, Bur82c). This thickness corresponds to about 280 g/cm². Behind this thickness it is the high-energy hadron component which dominates the radiation field. To estimate doses in the experimental areas, we take the source term for high-energy particles of $1.2 \times 10^{-12}$ Sv $\cdot$ cm² $\cdot$ GeV⁻¹ previously assumed for a point beam loss (Section 6.1) and an attenuation length of $\lambda = 115$ g/cm² for concrete. This results in a dose rate of 720 µSv/h for the injected beam current of $1.55 \times 10^{10}$ e⁺ or e⁻ per second at 20 GeV at a minimum distance of 4 m from the intersection point. This figure is reduced from the earlier calculation by about a factor of 10. Again, this arises because the magnitude of an injection beam loss has been reduced by about this amount. However, the estimated dose rate is still high enough to fully justify the monitoring of radiation levels in experimental areas.

Doses for a total beam loss of $1.1 \times 10^{13}$ e⁺ and e⁻ at 86 GeV at an intersection point are calculated to be 620 µSv for the same shielding thickness as mentioned above and at a distance of 4 m.

Owing to the massive size of the detectors and to the requirement of keeping cable connections short between the detector and the electronics, such a shielding could be realized by means of the detector components themselves. In Fig. 39, an example of an experimental arrangement shows how the shielding is achieved and what radiation levels could be expected for a situation in which the beams are completely lost within or near the detector. Here, as in the shielding calculations for the service areas, only high-energy radiation from the e⁺ interactions need be considered. It is evident that, because of design limitations, dose rates in excess of 10 µSv/h are possible in accessible areas under conditions of beam mis-steering.

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1.2 x 10⁻¹² Sv $\cdot$ cm² $\cdot$ GeV⁻¹

280 g/cm²

115 g/cm²

720 µSv/h

620 µSv

1.1 x 10¹³ e⁺ and e⁻
The philosophy of incorporating the shielding in the detector implies a more elaborate system of co-ordination and review between the Radiation Protection Group and the experimenters than would a simple fixed-shielding concept. Each detector concept must be carefully designed and studied before approval for installation can be granted.

Before installation, each experiment must provide shielding as specified by the RP Group. In addition, radiation surveys will be required both in the checkout stage and for routine operation. A permanent radiation monitoring system will also be employed, consisting of both passive (thermoluminescence dosimeters (TLDs)) and active monitors. The active monitors (a minimum of three for each experimental area) will be connected on-line to an expanded RP data-acquisition system and to the LEP control centre. The monitors are of conventional design and have already been proved in use at the existing CERN accelerators. The data-acquisition system (already in use at CERN) provides for continuous readout of instantaneous dose rates, and also develops a "history" of the radiation levels of each instrument, which can be recalled later if necessary. This system retains the history of dose readings for a period of one year.

With the exception of limited areas very close to the detector, it is expected that dose rates will be well below 10 $\mu$Sv/h in most parts of the experimental areas (typical values will probably seldom exceed 2.5 $\mu$Sv/h). Experimenters are likely to receive doses of the order of 0.5 to 5 mSv/y in the underground LEP areas. Although such doses are in the range that would be acceptable, even to members of the general public, many experimenters also handle radioactive sources and work around test beams at other accelerators. Therefore each member of an experimental team will be given medical clearance to work with radiation and will carry a personal dosimeter. The large, sensitive LEP detectors require that the background radiation be kept extremely low, and it can be expected that special care will be taken to keep the number of interactions of beam particles with the walls of the vacuum chamber and other components as low as possible. As the experiments are located in the straight sections, synchrotron radiation will be at a minimum. Therefore the amount of remnant induced activity will also be very low, and we do not anticipate the need for any special precautions for protecting personnel from these potential radioactive sources.

In order to restrict access to experimental areas to personnel familiar with the risks, or to visitors escorted by such personnel, the experimental areas will be designated Controlled-Radiation Areas (see discussion in Section 2). Access rules are those described in the CERN Radiation Safety Manual (CER83).

A team of RP technicians and professional RP experts will oversee the experimental areas, and will be on call at all times to assist experimenters and operators.

### 13.2 Induced radioactivity in the LEP main ring

#### 13.2.1 Induced radioactivity from beam losses

The mode of operation of LEP provides for the injection of $2.34 \times 10^{11}$ electrons and positrons at 20 GeV in a supercycle of 15.12 s (Bac80). The loss figure assumed will be $1.07 \times 10^{10}$ (total of $e^+$ and $e^-$) per second (mostly at injection), which corresponds to a beam power loss of 34.4 W. It will take about 22 minutes to fill the LEP machine in order to reach currents of 5.5 mA for each of the beams.

Circulating beams will be subject to continuous losses, probably at a rather low rate. It will, however, be assumed that stored beams of $2 \times 9.6$ mA at 86 GeV will be lost over a period of three hours, corresponding to an average power loss of 13.6 W. This is an over-estimation with respect to intensities but a reasonable assumption for radiation protection, as complete loss of the stored beams around the machine must be considered in case no special beam dumps are envisaged. For an estimation of total radioactivity it is actually not necessary to specify locations of beam losses although we expect most of the radioactivity will be found near the injection point.

In order to get a reasonable estimate of induced radioactivity it will be assumed that the beam power of 13.6 W is lost uniformly around the LEP ring. Calculation with EGS for a grazing incidence of 86 GeV electrons into the vacuum chamber inside a LEP dipole gave the distribution of energy deposition shown in Table 37. Tables on saturation

<table>
<thead>
<tr>
<th>Component and material</th>
<th>Fraction of energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum chamber (Al)</td>
<td>8</td>
</tr>
<tr>
<td>Cooling water (H$_2$O)</td>
<td>6</td>
</tr>
<tr>
<td>Lead shielding (Pb)</td>
<td>25</td>
</tr>
<tr>
<td>Dipole magnet (Fe)</td>
<td>10</td>
</tr>
<tr>
<td>(Concrete)</td>
<td>30</td>
</tr>
<tr>
<td>Surrounding air (for infinite medium)</td>
<td>21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 37

Energy deposition for grazing incidence at 86 GeV
Table 38
Radioactivity calculated for components assuming dipole configuration and local power absorption of 13.3 W from circulating beams

<table>
<thead>
<tr>
<th>Material</th>
<th>Power absorbed (W)</th>
<th>Radio-</th>
<th>Activity (MBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>nuclide</td>
<td>At saturation</td>
</tr>
<tr>
<td>Al</td>
<td>1.1</td>
<td>(^7\text{Be})</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(22\text{Na})</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(24\text{Na})</td>
<td>10.1</td>
</tr>
<tr>
<td>Pb</td>
<td>3.4</td>
<td>(^{204}\text{Tl})</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{205}\text{Pb})</td>
<td>105</td>
</tr>
<tr>
<td>Fe</td>
<td>1.4</td>
<td>(^{40}\text{Sc})</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{48}\text{Y})</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{51}\text{Cr})</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{55}\text{Mn})</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{54}\text{Mn})</td>
<td>29.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{55}\text{Fe})</td>
<td>666.4</td>
</tr>
<tr>
<td>Concrete</td>
<td>4.1</td>
<td>(22\text{Na})</td>
<td>15.1</td>
</tr>
<tr>
<td>Total</td>
<td>10.0(^a)</td>
<td></td>
<td>886.5(^c)</td>
</tr>
</tbody>
</table>

\(a\) No gamma emitter; lead shows very low activation.
\(b\) Plus 3.3 W deposited in water or streaming into the air of the tunnel gives 13.3 W total.
\(c\) Mostly \(^{55}\text{Fe}\).

activity, as published by Swanson (Swa79a), are used to estimate activities in LEP, as at electron energies above 1 GeV the activation will scale with the power deposited. Assuming a beam power of 13.6 W as a continuous loss will lead to an over-estimate with respect to long-lived activity. On the other hand, it is unlikely that components could be removed from the ring in less than 24 hours time. For disposal of machine components, only remanent activities with half-lives of the order of one year are generally important. The global results for the LEP machine are given in Table 38. If these beam losses occur uniformly around the ring, specific activities will be so low that there will not be any danger of external radiation from induced radioactivity in the machine structure. However, this may not be true in the injection region, where most of the e\(^+\) at 20 GeV will be lost rather locally.

Before this case is examined, an estimate of induced radioactivity in water and air will be given. Since cooling water is transported to areas outside the LEP tunnel, short-lived isotopes such as \(^{13}\text{N}\) and \(^{11}\text{C}\) will be considered. In case the water is released, \(^7\text{Be}\) and \(^3\text{H}\) concentrations must also be taken into account. Results are given in Table 39. As can be seen, concentrations of \(^7\text{Be}\) and \(^3\text{H}\) likely to be accumulated in the cooling water remain well below the concentration limits. Further dilution will occur as the cooling channel contains only about \(5 \times 10^6\) cm\(^3\) of water; this will mix with water of the same cooling circuit not directly irradiated by the beam losses.

In the case of air activation, only radioisotopes having medium half-lives must be considered, as nuclides with half-lives less than three minutes will have decayed before they reach the exhaust of the ventilation system or before

Table 39
Radioactivity in the LEP vacuum chamber cooling water, assuming dipole configuration and local power absorption of 0.8 W from circulating beams

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity (MBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At saturation</td>
</tr>
<tr>
<td>(^{13}\text{N})</td>
<td>3.0</td>
</tr>
<tr>
<td>(^{11}\text{C})</td>
<td>12.2</td>
</tr>
<tr>
<td>(^7\text{Be})</td>
<td>1.2</td>
</tr>
<tr>
<td>(^3\text{H})</td>
<td>6.0(^b)</td>
</tr>
</tbody>
</table>

\(a\) Unlikely to reach saturation.
\(b\) Concentration stays well below the limits of 740 Bq/cm\(^3\) for \(^3\text{H}\), as the cooling channel volume is about \(5 \times 10^6\) cm\(^3\).
Radioactivity in air around the LEP dipole, due to beam losses from circulating beams with 2.6 W streaming into the tunnel.

<table>
<thead>
<tr>
<th>Radio-nuclide</th>
<th>Saturation activity (MBq)</th>
<th>Concentration (Bq/cm³)</th>
<th>Concentration limit (Bq/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$C</td>
<td>$2.9 \times 10^5$</td>
<td>$1 \times 10^{-4}$</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>$3.0 \times 10^6$</td>
<td>$1 \times 10^{-5}$</td>
<td>$7 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

a) Tunnel volume assumed to be $3 \times 10^{11}$ cm³ and average path length in air 10 m.

entrance to the LEP tunnel becomes possible after beam off. Entrance procedures will probably require a delay of several tens of minutes. Radioisotopes of half-lives longer than 25 minutes will have no time to reach saturation because of constant renewal of the air by ventilation. Hence only $^{13}$N and $^{11}$C need be considered. As shown in Table 40, their concentration is well below the limits set for radiation workers.

Higher levels of induced radioactivity are only expected near the injection region. In simulating beam losses inside the copper cavities with EGS, it was found that 55% of the beam power was absorbed in the copper and 10% in the cooling water, with 35% escaping into the air. Even when considering the higher beam loss of 34.4 W during limited injection periods, the locally expected higher concentrations of radioisotopes in air and water will be diluted over the LEP tunnel and will not significantly increase the values above those in Tables 39 and 40.

Local dose rates are estimated around the copper cavities for an injection loss of 13.6 W. Although it is not expected that radioactivities will reach their saturation values because of the limited time of injection, estimates were made for such a case assuming decay times of one hour and of one day. Most of the dose rate is expected to come from $^{64}$Cu, giving rise to a hypothetical dose rate of 1.3 mSv/h at 1 m distance after one hour of decay (Table 41).

<table>
<thead>
<tr>
<th>Radio-nuclide</th>
<th>Activity (MBq)</th>
<th>Dose rate at 1 m distance after 1 h decay (mSv/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At saturation</td>
<td>After 1 hour</td>
</tr>
<tr>
<td>$^{58}$Co</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>$^{63}$Ni</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>$^{64}$Cu</td>
<td>610</td>
<td>500</td>
</tr>
<tr>
<td>$^{64}$Cu</td>
<td>3500</td>
<td>3300</td>
</tr>
</tbody>
</table>

13.2.2 Activation and neutron production by synchrotron radiation

Although the synchrotron radiation spectrum at LEP energies peaks below 1 MeV (subsection 4.6), photons in the high-energy tail are in principle still capable of inducing radioactivity in nuclei via giant-resonance photoneutron reactions. It is difficult to make exact predictions concerning this effect, because cross-sections have been measured for only a limited number of nuclides, and even for these the accuracy close to threshold is very poor. Owing to the extremely fast decline with energy of the synchrotron radiation spectrum (typically a factor of 10 for every 1 MeV at LEP energies), even small uncertainties in threshold energy, threshold cross-section, or photon attenuation are likely to affect the results drastically. Under these conditions, it is clear that only orders of magnitude can be established with confidence. Fortunately, however, all calculations point to such low photoneutron yields and activity levels, even under the most conservative assumptions, that errors of about one or two orders of magnitude can be safely accepted without imposing any constraint on the project or on the future operation of the machine.

a) Radioactivation by synchrotron radiation

As a first step, then, upper limits for activation were established in the most straightforward way, by assuming that the unattenuated synchrotron radiation interacts directly with the materials of interest, the interaction rate being simply proportional to the activation cross-section and the length of medium traversed. Traversal was assumed to take place in a plane perpendicular to the electron beam, without taking into account the small angle of incidence (about
7 mrad), because only scattered radiation can reach materials other than aluminium (or the length traversed in aluminium would be more than 40 m, which is obviously very unlikely).

These preliminary results, summarized in Goe81, showed no activation at all at 50 GeV, a small contribution at 85 GeV, and a possible measurable effect at 125 GeV — at that time the highest LEP energy envisaged. Since then, it has seemed advisable to perform more accurate calculations, taking into account the new LEP parameters (especially the revised maximum expected energy — 100 GeV) and at the same time using a more realistic model for photon attenuation and transport. It was hoped that new calculated values would be further reduced to such a low level that the whole problem of activation by synchrotron radiation could henceforth be neglected.

For this purpose, the program MORSE (Emm75) as set up for energy deposition calculations (see subsection 6.3) was used, despite the fact that such a code does not extend above 14 MeV photon energy. It was possible to treat the problem in this manner, because it had been shown in previous EGS runs that the attenuated synchrotron radiation spectrum keeps the original exponential shape for all energies above 2 MeV, although with a different slope, depending on the material. Track length and collision densities were scored as a function of photon energy, in order to establish the spectrum slope in each material of interest. Induced activities were then calculated by exponentially extrapolating each spectrum into higher-energy regions. Photon boundary crossings were also scored to obtain an idea of activity gradients and maximum specific activities.

As anticipated, the new calculated activity values lay several orders of magnitude below the previous estimates, the improvement being especially large for those materials for which the radiation is substantially attenuated, such as the dipole yoke and tunnel air. The only exception is the aluminium vacuum chamber, where the calculated production of $^{26}$Al is (at 86 GeV) about a factor of 30 larger than previous estimates owing to the longer average photon path when grazing incidence is taken into account. However, the half-life of this nuclide is so long that even after eight years of LEP operation at 86 GeV the total $^{26}$Al activity in LEP would only be about 11 kBq. At 100 GeV, the corresponding total activity would be about 600 MBq. The average specific activities would be about 0.04 and 3 Bq/g at 86 and 100 GeV, respectively. Maximum specific activities (at the point of impact on the vacuum chamber) are three and seven times the average, respectively.

The only other nuclide produced that is of comparable importance is $^{203}$Pb. Unfortunately, no experimental $(\gamma, n)$ cross-section is available for the parent nuclide $^{204}$Pb, so it was assumed to be the same as for $^{206}$Pb. (This assumption is likely to lead to an over-estimation, $^{206}$Pb being more neutron-rich than $^{204}$Pb.) The estimated total production of $^{203}$Pb is (at saturation) 2.7 and 700 Bq for 86 and 100 GeV operation, respectively. Corresponding specific activities are 0.008 and 3 Bq/g. All other radionuclides having specific activities smaller than 50 mBq/g will be hardly detectable, especially in the 86 GeV phase.

Table 42 includes those radionuclides whose total saturation activity is larger than 1 kBq. These data refer to 100 GeV operation. Most of the photonuclear cross-sections used were taken from Ber75. However, the only available cross-section data for iron were found in Cos67.

b) Neutron production by synchrotron radiation

Neutron production was calculated in the same way as that described above for activation. Two materials contribute the most — lead and water (the latter because of its deuterium content). Early calculations had been made (Nel79) using the program EGS in slab geometry with several different synchrotron radiation spectra. The new results show a slightly higher neutron yield at 86 GeV ($8 \times 10^6$ neutrons per second and metre of bend) and an increase by more than a factor of 100 ($4.1 \times 10^8$ neutrons per second and metre of bend) at 100 GeV. The reasons for the higher yield at 100 GeV are, in part, the revised machine parameters and the more accurate geometry. The most important reason, however, is to be found in the use of measured cross-section values (Ber75) rather than the analytical Lorentz description of the excitation curve, the latter giving lower values around the theoretical threshold. The cross-section for deuterium photodisintegration was taken from Bre73.

### Table 42

<table>
<thead>
<tr>
<th>Nuclide produced</th>
<th>Component</th>
<th>Saturation activity (kBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{15}$O</td>
<td>Cooling water</td>
<td>120</td>
</tr>
<tr>
<td>$^{53}$Fe</td>
<td>Magnet yoke</td>
<td>60</td>
</tr>
<tr>
<td>$^{55}$Fe</td>
<td>Magnet yoke</td>
<td>900</td>
</tr>
<tr>
<td>$^{57}$Mn</td>
<td>Magnet yoke</td>
<td>70</td>
</tr>
<tr>
<td>$^{206}$Pb</td>
<td>Lead shielding</td>
<td>5</td>
</tr>
<tr>
<td>$^{207}$Pb</td>
<td>Lead shielding</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{1}$N</td>
<td>Tunnel air</td>
<td>20</td>
</tr>
</tbody>
</table>

66
Table 43

Ozone concentrations in ppm at saturation assuming no ventilation in the LEP tunnel

<table>
<thead>
<tr>
<th>Air volume affected</th>
<th>Operating parameters and concentrations (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>86 GeV (2 × 3.3 mA)</td>
</tr>
<tr>
<td>Air in tunnel, 3 mm lead shielding at dipole magnet</td>
<td>0.52</td>
</tr>
<tr>
<td>Air in tunnel, 8 mm lead shielding at dipole magnet</td>
<td>0.23</td>
</tr>
<tr>
<td>Inside dipole magnet yoke</td>
<td>9.2</td>
</tr>
<tr>
<td>Between bellows and lead shielding</td>
<td>11</td>
</tr>
</tbody>
</table>

13.3 Noxious compounds

13.3.1 Calculations for the LEP ring

As outlined in Section 5, ozone and nitrogen-oxide production by synchrotron radiation is one of the major problems for the operation of LEP. Table 43 gives the result of ozone concentrations in the LEP tunnel, based on the most recent machine configuration; this incorporates the lead shielding described in the following section and takes anticipated operating parameters into account (Fas82c). Because of the ventilation of the LEP tunnel, concentrations indicated for saturation conditions will actually be halved inside the tunnel. However, for poorly ventilated air pockets inside the magnet yokes, or for spaces within the bellows shielding, the highest concentrations are expected. The radiolytic-yield values (G-values) found in the literature for the formation of nitrogen oxides are smaller than those for ozone. In addition, rapid chemical reactions with humidity in the air remove these compounds to form nitric acid. In the presence of water vapour, a G-value of 1.5 molecules of nitric acid per 100 eV will lead to a steady production in the poorly ventilated air pockets mentioned. A production rate of 5.3 ppm/h for a stored current of 2 × 3.3 mA at 86 GeV is estimated. This estimate increases to 24 ppm/h for 2 × 5.5 mA at 100 GeV.

13.3.2 Maximum acceptable concentrations (MAC)

Maximum acceptable concentrations in air for working areas (MAC values), as given in the literature, are given in Table 44 (Kel79).

Table 44

<table>
<thead>
<tr>
<th>Radiolytic product</th>
<th>MAC (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>0.1</td>
</tr>
<tr>
<td>NOₓ</td>
<td>25</td>
</tr>
<tr>
<td>HNO₃</td>
<td>2</td>
</tr>
</tbody>
</table>

Comparison shows that problems may arise with regard to adequate ventilation before entry is allowed, since the expected concentrations of ozone are higher than the corresponding MAC values. On the other hand, hazards due to NOₓ can be completely excluded. Concentrations of nitric acid exceeding the MAC values are expected only in small air pockets near and around the machine. These do not constitute a health hazard, but are of some concern because of the potential for corrosion.

Production of O₃ and NOₓ in air is reduced by means of the Pb shielding and a minimum ventilation speed ensures that no pockets containing high concentrations of NOₓ are formed near the vacuum chamber. Where the air exchange rate is low, protective paints will be applied to reduce corrosion.

Although the predicted concentrations of O₃ and NOₓ are completely acceptable for accelerator protection, they are in excess of the exposure limits for workers. As explained above, the LEP ring is a Prohibited Radiation Area and will not be occupied during operation. Experience will show whether waiting times before allowing access have to be imposed because of concentrations of noxious gases. In order to prevent accumulations in the experimental areas, which will be occupied by experimenters, exhaust air from the main tunnel will be channelled directly to the release point (see below).
13.4 Doses near the main ring and protection of materials

High dose rates are expected inside the main LEP tunnel, particularly in the curved sections. As described in Section 4, these doses arise from two different fundamental mechanisms: synchrotron radiation (SR) and high-energy particle (HEP) radiation. In the primary beam tunnel, which is inaccessible during operation, all equipment is exposed to SR and HEP radiation. The latter, averaged over longer periods, is very low compared to the radiation resistance of most components, but the synchrotron radiation in curved sections and near quadrupoles produces high dose levels.

a) Doses from synchrotron radiation

Figure 40 illustrates the dose levels to be expected from SR in the LEP-MR tunnel. Table 45 shows doses imparted to various LEP systems or components for 200 A·h of beam at 86 GeV, with the lead shielding described below.

The dose limitations cited in the table are for standard, commercially available materials, which have been selected because of their known radiation resistance. This selection is partly determined by experience gained during operation of existing CERN accelerators, and partly based on radiation damage tests performed during the design and construction period of the SPS (see subsection 13.4.1). In some cases, and especially for electronics components, further shielding will be required.

The LEP management has decided on criteria for judging the acceptability of various materials, in respect to their radiation resistance. According to these criteria, the components must remain fully operational after having been

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**Fig. 40** Dose-distributions (in Gy) produced by synchrotron radiation in LEP tunnel. Solid circles indicate average doses within the volume shown. Arrows indicate a surface dose in the area shown. Values are calculated with the program MORSE. Portions (a), (b), and (c) are for nominal operating lifetime at 86 GeV (200 A·h).

- a) Distribution in the LEP tunnel at the location of an intermagnet gap, shielded by 1 cm of Pb in all directions.
- b) Distribution at the location of a bending magnet, shielded by 8 mm of Pb towards the walk-way (at right).
- c) Distribution within the dipole magnet for the above conditions. The vacuum chamber is shielded by 8 mm towards the inside, 3 mm on the top and bottom, and 8 mm towards the walk-way.

Portions (d), (e), and (f) are similar to (a), (b), and (c), respectively, but are for maximum operation (330 A·h) at 100 GeV.
Table 45
Synchrotron-radiation doses in the LEP tunnel (in the vicinity of the dipole magnets) produced by 200 A · h of beam at 86 GeV with the Pb shielding arrangement described in text a)

<table>
<thead>
<tr>
<th>System or component</th>
<th>Basic radiation-sensitive component</th>
<th>Dose limitation assumed (Gy)</th>
<th>Calculated dose (Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole magnet:</td>
<td>Glass-fibre-reinforced epoxy resin</td>
<td>$5 \times 10^7$</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>outer coil</td>
<td>$5 \times 10^7$</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>Quadrupole magnet:</td>
<td>Ditto</td>
<td>$5 \times 10^7$</td>
<td>$1 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td>coils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet connections,</td>
<td>Various thermoplastics</td>
<td>$1 \times 10^6$</td>
<td>$2.5 \times 10^4$</td>
</tr>
<tr>
<td>such as bus-bars,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hoses, etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable trays:</td>
<td>EPR, polyolefins</td>
<td>$1 \times 10^6$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>top, side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronic equipment under magnets</td>
<td>Various</td>
<td>$10^2 - 10^4$</td>
<td>$1 \times 10^4$</td>
</tr>
<tr>
<td>Aux. equipment</td>
<td>Telephone, crane</td>
<td>$1 \times 10^6$</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>in passageway</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunnel lighting</td>
<td>Fluorescent tubes</td>
<td>$1 \times 10^6$</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>Air in tunnel</td>
<td>(Noxious gas production; see text)</td>
<td>–</td>
<td>$2.5 \times 10^7$</td>
</tr>
<tr>
<td>(average)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) Doses at 100 GeV will be 2 to 3 times higher.

Fig. 41 Vacuum chamber, showing lead shielding provided to attenuate synchrotron radiation. The principal material is aluminium, with cooling-water channels provided to remove heat deposited by the SR.

(a) Design used within dipole magnets. (The object in separate chamber at the right is a getter pump.) Lead thicknesses are 3 mm (top, bottom) and 8 mm (sides).

(b) Chamber designed to fit between poles of quadrupole magnets. Lead thickness varies between 6 and 8 mm.

Exposed in the ring to radiation produced during the course of operation equivalent to 200 A · h at a beam energy of 86 GeV. The dose values in critical locations within the LEP main ring for such an irradiation are given in Table 45. The corresponding values for 100 GeV beam energy are 2–3 times higher.

The doses predicted in Table 45 are achieved by shielding the entire aluminium vacuum chamber with a continuous sheath of lead — within the bending magnets, in the inter-magnet gaps, and along the straight sections and most of the long straight sections (see Fig. 41). The Pb thickness ranges from 3 to 8 mm, depending on its location, and attenuates the radiated power by 98–99%. This shielding is one of the primary measures of the Radiation
Protection System, as it limits not only the doses to components but also the production of noxious gases and radioactivity in the air. This protection measure reduces the radiation to less than the highest levels found in the proximity of the already existing accelerators. The solution presented is a reasonable compromise taking available space, weight, and fabrication requirements into account.

b) Doses from high-energy radiation

High-energy radiation is produced only when the injected or stored e± beams “hit something”, such as the walls of the vacuum chamber. Such an event can occur accidentally, for example, when a magnet power supply fails or if the beams are mis-steered for any other reason. In this case the momentary dose rates will be very high in the immediate vicinity of the beam-loss point. The integrated dose of such beam loss will be in the range 0.01-1.0 Gy, depending on how the beam is actually stopped. It is also possible that the beam is slowly lost over a period of time; Table 46 shows the dose rate in the tunnel passageway during a period of beam loss extended over 160 minutes.

### Table 46

Dose in main LEP tunnel from high-energy interactions of e+, e− at 86 GeV, assuming currents of 5.5 mA (3 × 10^{12} particles) for each beam

<table>
<thead>
<tr>
<th>Beam loss condition (no shielding assumed)</th>
<th>Dose or dose rate at 1 m due only to e± interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>All beam lost at 1 point</td>
<td>2.4 Sv</td>
</tr>
<tr>
<td>All beam lost at 1 point within 160 min</td>
<td>0.9 Sv/h</td>
</tr>
<tr>
<td>Half of total beam lost at 8 points over 160 min</td>
<td>0.06 Sv/h</td>
</tr>
<tr>
<td>All beam lost over 160 min, uniformly around circumference</td>
<td>25 µSv/h</td>
</tr>
</tbody>
</table>

a) 160 minutes is the expected lifetime of beams.

### 13.4.1 Selection of materials and components

It is essential that, already in the design stage of LEP, all materials which could be subject to radiation damage are carefully selected. In the following, a brief review of some typical materials and their possible restrictions in use is given. This is based on the experience gained from tests performed for the existing CERN accelerators and storage rings (see Section 8).

a) Magnet coil insulation

For the magnet insulation, glass-fibre reinforced epoxy resins are envisaged. These composites will not withstand doses exceeding 10^{8} Gy (Phi81). Therefore damage may occur at 100 GeV operation. Careful material selection and further radiation tests to higher doses are essential.

b) Cable insulation

According to recent CERN policy, materials that produce corrosive gases when burned, such as polyvinyl chloride (PVC), Hypalon, or Neoprene, are to be excluded from the LEP system (Bad82). Instead, ethylene-propylene rubber (EPR) and polyolefins (polyethylene, polypropylene and copolymers) are to be used in their place. Cables will be installed along the LEP tunnel near the ceiling and the outer side-wall. In these locations, cables of the approved types, if carefully selected, could resist radiation damage up to the stage of 100 GeV in the short straight sections for several years, assuming a limiting dose of 10^{6} Gy. Connections from the cable trench to the magnets should be short jumpers, easily exchangeable or of special radiation-resistant materials (up to 10^{8} Gy) that are available for both control and power cables (Bad82, Grü80).

c) Electronics components

Electronics components are amongst the most radiation-sensitive items (Bat76) in the LEP tunnel. Near the short straight sections, where most beam monitoring equipment is located, but also beneath the magnets, doses are expected which could cause radiation damage even at the lowest energy stage. This means that most electronic devices would be damaged in a short time. Although one may expect that, for the same absorbed dose, damage by low-energy X-ray radiation is less than that by radiation from present CERN proton accelerators (Lam75), it will be essential to house electronics components in shielded boxes underneath the bending magnets or deep within the alcoves.
d) General installation materials

From our studies of synchrotron radiation in the LEP tunnel, it is evident that dose gradients are less pronounced than along a proton beam line. In the 86 GeV phase, dose rates in the tunnel are nearly everywhere of the order of 10^6 Gy/y, and 10 to 100 times higher close to the vacuum chamber. All materials for general installations in the main ring must therefore be justified and carefully selected.

Water hoses on an EPR base, reinforced with glass tape or Kevlar, should be able to operate under nominal pressures up to 5 × 10^7 Gy.

Seals and O-rings of an organic type should be avoided wherever possible. Specially selected joints for nuclear applications, fabricated from EPR or nitrile rubber, may be operational up to 5 × 10^6 to 10^7 Gy.

All organic components in auxiliary equipment, such as vacuum pumps, motors, tunnel lighting, emergency lighting, telephones, etc., must be carefully chosen, well positioned, and shielded wherever necessary.

e) Experimental equipment in long straight sections

Owing to the absence of bends, doses in long straight sections where experimental equipment is installed will be considerably lower than in the remaining part of the LEP ring. On the other hand, the devices installed there, such as electronics, scintillators, photomultipliers, glass-fibre optics, films, etc., are much more sensitive than common engineering materials. The expected yearly doses may well be of the order of 100 to 1000 Gy, even if losses are assumed to occur only during injection, which is about 10 to 20% of the operating time. These levels indicate that experimental equipment also has to be chosen with regard to radiation sensitivity. It must be stressed that use of halogen-free cables and other insulating materials is also required for the experimental areas (no PVC).

f) Dose-rate effects and corrosion

The particular radiation field in the LEP tunnel may give rise to effects which have so far not been encountered in existing CERN installations. For example, extremely fast bursts of electron bunches of about 150 ps may give rise to instantaneous dose rates of the order of 10^8 Gy/s if no beam divergence is assumed. This may cause transient effects in pick-up electrodes close to the beam or may induce perturbing signals in coaxial cables. Perturbation in high-voltage cables may occur, since radiation-induced ionization may lead to sparking (Bur82b).

An additional hazard to many materials is the production of chemically reactive substances. It is estimated that in the open tunnel, where the air is exchanged every hour, corrosive effects will be of minor importance. Where necessary, an effective measure for protecting inorganic surfaces is to coat them with paints, available on the market, having radiation resistance up to 10^3 to 10^4 Gy (Bey82).

Table 25 in Section 8 gives a general review of the radiation resistance of materials that are frequently used in high-energy accelerator engineering.

13.4.2 High-level dosimetry (HLD) for LEP

It is proposed to carry out dose measurements inside the LEP tunnel by means of passive dosimeters, as an extension of the routine programme currently in use at the existing CERN accelerators (Con81, Iły80). The purpose of these measurements is to verify the dose predictions made during the design of the project (Fas82b), but even more important is a mapping of the doses received by radiation-sensitive components during operation. This enables us to follow up the dose-history within the ring in order to anticipate changes in critical components before damage occurs or to provide additional shielding where it is necessary and possible.

Two types of glass dosimeters are intended for routine HLD:

- Silver-doped radiophotoluminescent (RPL) glass: the emission of luminescent orange light, following excitation by UV light, is measured, and from this the radiation dose is determined.
- Phosphate dosimeter glass (PDG): absorption of light at a wavelength of 510 nm is measured by means of a spectrophotometer.

The main characteristics of these dosimeters are summarized in Table 47. Other types of dosimeters, such as hydrogen-pressure, alanine, or LiF crystals, may be utilized for special applications or experimental purposes.

Unlike the existing CERN installations, the radiation pattern throughout the LEP tunnel is expected to be rather uniform. Therefore, a distribution of dosimeters all around the ring is not necessary and one can restrict the measurements to one representative octant, in addition to the injection area. Nevertheless, a few hundred measurement points are proposed, situated near radiation-sensitive items such as magnet coils, cables, hoses, electronics, experimental equipment, etc. A detailed programme will be established in due course, and it is essential that all dosimeters are installed before operation begins. The dosimeters will be read and re-installed once a year during the long annual shutdown of the machine.

In addition to this HLD programme, a number of samples of cable and magnet-coil insulation will be installed in the LEP tunnel. Passive dosimeters of the type described above will be exposed with these samples. After several years, at regular intervals, samples will be removed to be examined for changes in mechanical and electrical properties. This allows us to follow the course of ageing of these materials in a realistic radiation environment, and permits a
comparison with results obtained from accelerated radiation tests carried out during the design and construction period (Sch79b, Sch79c, Bey82).

13.5 LEP access system

Access to the LEP areas is governed by CERN access rules. Primary beam areas will be completely inaccessible during operation. During shutdowns, access control (control of interlocked doors and personnel logging) will be maintained, either by the LEP Central Access Control Station or by local access control. The latter provision would be implemented by means of stand-alone local access control equipment, or, in some cases, simply by a guard who operates the door and performs the logging function. The central LEP access system will be part of the access system used at the SPS accelerator, but will be expanded to accommodate LEP. However, the LEP system differs in that "free-access" will not be permitted at any time. The access conditions for the underground experimental areas stipulate that the names and identification numbers of all persons who enter must be known and recorded, so that in case of accident everyone is accounted for. There will normally be no provision for access to experimental areas from the main ring — but the main ring will provide an escape route from those areas in case of emergency.

The access-control system prevents accidental access and shuts off the accelerator in case doors are forced (Fig. 42). The interlock system provides a high degree of safety; failures and malfunctions of the system are extremely unlikely (< 10^{-6} per year of operation). The degree of safety is enhanced by the fact that access to the areas adjacent to primary beam areas is also controlled; therefore only informed persons would have occasion to approach primary-beam access doors. Areas within the experimental apparatus are also inaccessible during operation; an elaborate interlock system will ensure safety in this region inside and outside the detectors.

13.5.1 Access to main ring during shutdown

For operation at 86 GeV, the total inventory of remanent radioactivity is so low in the LEP ring that dose rates will be below 2.5 µSv/h in most areas of the tunnel. Induced activity will be significant only at 100 GeV operation and only for those components most directly exposed to synchrotron radiation. Even in this worst case, the dose rates will be of the order of tens of µSv/h at a working distance of 40 cm, and special precautions will be required only for dismantling and maintenance operations on these items. Table 48 summarizes the information on predicted activity and contact dose rates at 86 and 100 GeV.

Even though the potential radiation exposure to personnel entering the LEP tunnel is small, some rigorous form of access control must be provided because of the difficulty entailed in searching such enormous zones at the time of beam start-up. As for all the LEP underground areas, access control will include registration of name, time, and door location. Prior to beam start-up, trained search teams will inspect the zones that have been entered, and announcements of turn-on will be made in the underground areas to warn persons who may still be below. Emergency shut-off switches that can be activated if anyone still remains in the tunnel will be conveniently located in all beam areas.

13.5.2 Access to underground service areas

The service areas (including the access shafts and tunnels) and klystron galleries are all separated from the main ring and intersection areas by a minimum shielding, equivalent to 2.0 m of concrete. Shielded doors will be provided for equipment access penetrations, and either shielded doors or labyrinths for personnel access-ways. Figures 33 and 34
Fig. 42 Entrance to a high-radiation area (at present in use at SPS). Person wishing to enter inserts his radiation "badge" (containing dosimeter) for positive identification. When conditions for safe entry are met, door keys are released by operator, one per person. Operation cannot resume until all persons have left radiation area and returned their keys. Any violation of the system will automatically shut off the beams.

Table 48

<table>
<thead>
<tr>
<th>Component (material)</th>
<th>Units</th>
<th>20 GeV</th>
<th>86 GeV</th>
<th>100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity in entire machine</td>
<td>GBq</td>
<td>-</td>
<td>4</td>
<td>1100</td>
</tr>
<tr>
<td>Activity in magnets (Fe)</td>
<td>GBq</td>
<td>-</td>
<td>3</td>
<td>900</td>
</tr>
<tr>
<td>Vacuum chamber (Al)</td>
<td>GBq</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Pb shielding</td>
<td>GBq</td>
<td>0.15</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Dose rate in contact with Pb shielding</td>
<td>mSv/h</td>
<td>-</td>
<td>&lt; 10^{-2}</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Activity in Cu from continuous beam loss of 1 W</td>
<td>GBq</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dose rate in contact with tank of the cavity</td>
<td>$\mu$Sv/h</td>
<td>10–100</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

show examples. Detailed calculations have been made for the klystron galleries and access-ways to the main ring (see subsection 13.5.1). The efficacy of the shielding is such that dose rates in excess of 10 $\mu$Sv/h are predicted in only very localized regions (a few square metres); for normal operation the dose rates are likely to be below 2.5 $\mu$Sv/h.

In order to monitor possible accidental situations that might arise from beam mis-steering during injection, a monitor system will be installed in areas adjacent to the primary beam areas. A total of 30 monitors will be positioned, including two for the klystron galleries and two for each of the service areas. These monitors are linked both to the RP data-acquisition and LEP control systems.

The access control facility for the underground areas is installed at the top of the access shafts. All persons entering (including accompanied visitors) must register at the door and indicate their destination by means of an "Area Code". Name, time, and location are logged in. Personal dosimeters (film badges) will be required during periods of LEP operation.
13.6 Operational radiation protection

Operational radiation protection is an essential element of the LEP Radiation Protection System (RPS) (see Section 10). The responsibility for operational radiation protection will be entrusted to the LEP RP Section, which will deal with all related aspects for the LEP MR. The most important tasks are:

- to assist those responsible for access control to the primary beam areas in order to ensure that no person is present during operation;
- to assess radiation risks and to survey radiation conditions in underground areas accessible during LEP-MR operation;
- to ensure radiation protection for those working with, or in the presence of, radioactive sources and materials;
- to ensure that all persons working regularly in the underground areas are provided with individual dosimeters;
- to check that adequate protection is provided against X-rays and non-ionizing electromagnetic radiation produced by auxiliary equipment, such as RF-generating equipment and test installations for detectors (lasers, X-ray equipment, betatrons, etc.);
- to survey all release of radioactivity and radiation to the environment.

For all these tasks the procedures and internal rules must be adapted to the requirements of the LEP-MR. In particular, the access conditions to the main ring must be specified and, in collaboration with the Control Group, procedures for access established. The LEP RP Section will collaborate in developing search procedures for the main ring, and in ensuring that tests on the interlock system and search procedure are properly made.

Access to underground areas will generally be controlled by an automatic system based on personal access cards. Under special circumstances, access may also be controlled by a guard.

Radiation levels in occupied underground areas must be continuously monitored. This will be done by a permanently installed monitor system. Spot checks by RP personnel will supplement these measurements. The operational RP team will also ensure the proper functioning of all installed monitors, including those for release control. It is also the responsibility of the RP staff to perform evaluations of these readings and take the necessary measures.

Direct interventions of the RP technicians are required for controlling radioactive sources and supervising work involving radioactive items, as well as for assessing radiation from auxiliary equipment. Activation of the machine components is insignificant for $e^\pm$ energies up to 86 GeV; however, some activity will be produced in the cooling water and the tunnel air. Before water is released from the LEP-MR drainage system, checks for radioactivity must be made. However, it should be pointed out that in case of an emergency such as flooding, when the volume of water is much above the capacities of the drainage system, the activity will be low enough for the water to be pumped out without delay.

Operational duties also include checks of all radiation from auxiliary equipment in the surface buildings. All work involving radiation or radioactivity must be planned and assessed in collaboration with the RP Group. The transport of radioactive items and sources between the LEP-MR islands on the surface will be performed under the supervision or direct control of the LEP RP Section.

All these operational activities of the RP Group require the presence of RP technicians (and physicists) during, but especially prior to, operation of the LEP-MR. The installed monitor systems require checks, maintenance, and calibration. Samples of all sorts must be taken and analysed, and on-the-spot radiation measurements with mobile instruments are required regularly in all LEP-MR premises. Radiation protection responsibilities for the main ring will be entrusted to the LEP RP Section, whereas environmental monitoring, instrumentation, data acquisition, and calibration will be the responsibility of the Technical Support Section of the RP Group. In addition to a somewhat augmented RP infrastructure, it is estimated that radiation protection activities will require five persons fully occupied with the LEP main ring.

13.7 Instrumentation

An important element of the Radiation Protection System is the complement of instruments provided and maintained by the RP Group for monitoring and measuring radiation and for warning those exposed to unexpected levels. The monitoring system also provides a record of the release of radiation, radioactivity, and noxious products to the environment. Levels at the fence and at critical locations outside the fence are continuously monitored.

The radiation protection instrumentation for LEP includes the following systems:
- waste-water monitoring
- air (stack) monitoring
- environmental monitoring (including collecting and surveying of samples);
- experimental area monitoring
- monitoring of underground areas
- survey and intervention instrumentation.

13.7.1 The monitoring system for underground areas

Monitors in the LEP underground areas will provide protection for service teams in service areas adjacent to the main ring. Because neutrons may be present, along with high-energy electromagnetic radiation, plastic-walled
ionization chambers will be installed as detectors in the klystron galleries and service tunnels. (Because of their hydrogen content, the plastic walls provide good neutron sensitivity.) The chambers are equipped with charge digitizers and linked to the RP control units, where alarms are generated and where the transfer of data to the control system is provided for. The control units also receive signals from the experimental-area monitoring system.

Displays for radiation warnings will be installed in the klystron galleries and at the bottom of the service shafts. They will be triggered by the underground monitors.

13.7.2 Data-acquisition system

The RP data-acquisition system (DAS) has been in operation since the start-up of the SPS in 1976. This system, in operation at all times, gathers data on current radiation levels from several hundred monitors at sensitive locations near the accelerators and at the site boundary. These data are accumulated so that a radiation “history” for any location, extending over more than one year, is immediately accessible via a computer terminal. In addition, the DAS controls the radiation warning system and automatically determines when a warning signal should be turned on (klaxon or illuminated signs).

All monitors to be installed for LEP are compatible with the standard RP DAS control and transmission interfaces. The RP control units will transmit the information from the detectors to the RP DAS. From the RP data base the instantaneous and accumulated information will be accessible to the RP Group, the operations team, and the LEP experimenters. The DAS, linked to the RP alarm- and instrument-surveillance system, provides the relevant information to those who should take action. The present system hardware, with improvements already being implemented, is capable of handling all information on radiation generated throughout CERN, including LEP. However, the implementation of new software and the extension of the acquisition system will require additional resources.

13.7.3 Survey and intervention instrumentation

The types of instruments at present being used by the RP survey technicians are quite suitable for LEP requirements also. However, additional units must be acquired so that the most frequently used instruments are available at each access point. A Radiation Protection Station is needed at each access point in the access buildings to house survey instruments and other radiation protection equipment, such as ropes, signs, and materials for taking samples. In addition, two mobile laboratories equipped with instruments and radiation protection materials should be provided. Ten additional sets of portable survey instruments, including those for the mobile stations, would be adequate to cover the needs of LEP.

14. ENVIRONMENTAL IMPACT

The main ring of LEP will be situated in the Pays de Gex (Département de l’Ain) and in the Canton of Geneva, outside the present CERN domain. “Islands” will be established at eight “access points” to house the access and service buildings for the main ring, which will be 50 to 150 m underground (Figs. 1 and 2). Except for the eight access points, the surface area will be freely accessible to members of the public, and customary activities, such as agricultural and residential uses, will continue. In assessing the environmental impact, it is primarily the release of radiation and radioactivity to areas not under the control of CERN, which is of concern.

The impact due to any such release, including radiation-produced noxious gases, was studied extensively for an earlier LEP design. In that design the main ring was located further under the Jura, and a maximum beam energy of 125 GeV was envisaged (Goe81). For the same design the radiological impact was shown to be insignificant, and no nuisance from stray radiation nor release of noxious gases was expected. The following data are based on a scaling of the former values to the now-approved design, the LEP-12 Version. The reader is also referred to previous sections, where the sources of radiation inside the main ring are discussed.

14.1 The release of stray radiation

The ring will be situated at such a great depth that direct penetration of significant amounts of high-energy radiation to areas above is impossible. Furthermore, a muon of the maximum possible energy (51.5 to 100 GeV) would be easily stopped (“ranged out”) by the natural earth shielding of earth and rock, which is more than adequate in all directions within the median plane. The production mechanism of muons is such that they will follow, almost exactly, the path of the primary $e^+$ that produced them. Therefore the paths of all muons produced must remain very close to the plane of the ring (see Section 4.5). An imaginary “radiation cone” of 100 mrad half-angle about any axis tangential to the ring would not penetrate the natural terrain for at least 6 km, whereas the maximum range of muons produced by LEP is about 200 m.

On the other hand, scattered radiation might reach the surface through access shafts or tunnels, and these penetrations must be carefully located and shielded from radiation sources if necessary. Except for Access Point 3, all are found in straight sections of the main ring, where only weak synchrotron-radiation sources, such as quadrupole magnets, are located. In addition, shielding is provided between these radiation sources and the access shafts. An
estimate of the radiation levels at the top of an experimental equipment shaft has been made. When scaled to the current LEP-12 Version, the annual dose due to scattered radiation would be well below 10 µSv (Ste81a). This is not detectable in the presence of the natural radiation level, which is about 100 times as large. It is to be emphasized that such a dose rate is anticipated only directly above the opening, and at a distance of only a few metres it decreases to an insignificant amount. This situation is the same for all access points.

The LEP RPS will provide for radiation monitors in the underground areas (Moy80b, Rau81); control in those areas will automatically limit the amount of stray radiation released, because levels in the different areas follow one another proportionally.

14.2 Release of radioactivity with water

Radioactivity is produced in the cooling water circuits by high-energy radiation and by the high-energy tail of the synchrotron-radiation spectrum. Radioactivity may also be produced in ground water outside the main-ring tunnel, or be leached out from activated rock or soil by the ground water. Table 49 shows amounts produced and comparisons with naturally occurring amounts.

<table>
<thead>
<tr>
<th>Medium considered</th>
<th>Natural activity</th>
<th>Activity produced by LEP at 100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock around main ring (1-m thick layer)</td>
<td>200 GBq</td>
<td>0.4 GBq</td>
</tr>
<tr>
<td>Water around main ring</td>
<td>–</td>
<td>0.2 GBq (1H)</td>
</tr>
<tr>
<td>Annual rainfall over 10 km²</td>
<td>200 GBq (3H)</td>
<td>–</td>
</tr>
<tr>
<td>Cooling-water circuits</td>
<td>0.2 MBq (3H)</td>
<td>0.2 GBq</td>
</tr>
</tbody>
</table>

Ground-water activation can occur only when the water comes in close proximity to the concrete main-ring tunnel. This situation may only be expected where the rock is not waterproof. However, most of the ring is drilled in molasse (Fig. 2), which is waterproof and dry, as extensive experience with the construction of the SPS has shown. In the Jura formation (about 5 km of the ring), water could penetrate near to the tunnel. However, the total activity production expected in the rock and water is so small that even a 100% leaching of this activity would be an insignificant increase of the natural water activity (see Table 49). Because of the small amount of activity induced, the dilution by other sources, and the time delay, the possible migration and ultimate use of this water does not have any impact on the environment nor constitute any risk to persons.

The cooling circuits will be closed circuits and no release is expected during normal operation. When the circuits are drained (during repair or by accident) the cooling water will be accumulated in the general ring-drainage system, from which it will be pumped and collected. The values in Table 49 show that even a total loss of beam in one ring-octant will not contaminate the large amount of water released from LEP. Water will be periodically sampled at the deepest point in the ring (near Access Point 8; see Fig. 1) and monitored for activity before release. If needed, release from the ring drains can be postponed for a considerable time, as the capacity of the drains is large — more than 200 m³ per octant. In case of flooding, water can be pumped out immediately, as dilution will reduce activity concentrations to negligible levels.

Because of the low levels of activity, direct radiation from pipes and vessels containing activated water is also not a radiological hazard to persons entering the LEP main ring, even immediately following beam turn-off.

14.3 Radioactivity and noxious gases released with air

This subject has been extensively treated in Goe81 and more recently in Fas82c. Although the radionuclides in the exhaust air may lead to external exposure of persons in the most unfavourable location, this risk has been shown to be insignificant. At 100 GeV operation, the production of radionuclides, such as 13N, by synchrotron radiation sets in (the production threshold is 10 MeV), and adds to the very small production by high-energy particles. Table 50 shows predictions assuming that all e± of the beam interact in unshielded regions of the ring, giving the greatest possible exposure to the air.

Note that the two principal radionuclides produced in air, 15N and 15O, have half-lives of 9.96 and 2.03 min, respectively. Thus the effect of average residence time amounting to 60 min is that only a small fraction of the produced radionuclides is finally released to the environment; most of it decays harmlessly below ground. With very pessimistic assumptions concerning the distribution and diffusion of this activity, we arrive at “dilution factors” of 10% for the yearly average at a given location which is 200 to 500 m from any release point, or at a maximum ground concentration of 4 Bq/m² for operation at 100 GeV. During an annual operating time of 3000 hours, and adopting a conversion factor of 4 kBq/m² = 1 µSv/h for the submersion dose (from the radionuclides 13N, 15O, 11C and 41Ar,
combined), we arrive at 3 mSv/y as the maximum possible dose to a member of the public living in the most critical location (a distance of 200 to 500 m) near a release point (Access Points 1, 3, 5, 7; see Fig. 1). The radioactivity is so low that only these yearly dose averages are of interest.

The concentrations of noxious gases, such as O₃ and NOₓ, are also the highest where the maxima for radioactivity are expected. For noxious gases, the instantaneous and the long-term averages are both important. In Fas82c it is shown that all LEP-produced concentrations will remain well below existing natural concentrations, using the release system envisioned. Table 51 outlines the maximum concentrations of O₃ and NO₂ that might be found in the vicinity of a release point. Of the various oxides of nitrogen, NO₂ is most copiously produced and has the lowest value of acceptable concentration. As it is the dominant component of NOₓ, only its concentration is given in Table 51.

The Radiation Protection System provides, firstly, for adequate shielding of the vacuum chamber in order to reduce the amount of synchrotron radiation escaping into the air. This provision reduces the production of both radioactive and noxious gases. Secondly, the system provides for a minimum height of the release point (10 m) and a vertical release velocity of at least 10 m/s for the exhausted air. A vertical exhaust velocity is equivalent to an increased stack height. In addition, filters will be provided at the release points to retain aerosols and reduce the O₃ concentration.

Besides these protective measures, the RPS will provide for monitoring (Rau82a, Rau82b), both in the stacks and at ground level at the critical distance (200 to 500 m, in the prevailing wind directions).

---

**Table 50**

Radioactivity released by air (per year)

<table>
<thead>
<tr>
<th>LEP energy (GeV)</th>
<th>Specific activity (Bq/m³)</th>
<th>Relative production of isotopes (%)</th>
<th>Annual release (GBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchrotron radiation</td>
<td>High-energy radiation</td>
<td>Total</td>
<td>¹⁵N</td>
</tr>
<tr>
<td>51.5</td>
<td>900</td>
<td>900</td>
<td>85</td>
</tr>
<tr>
<td>86</td>
<td>40</td>
<td>1400</td>
<td>1440</td>
</tr>
<tr>
<td>100</td>
<td>1800</td>
<td>1800</td>
<td>3600</td>
</tr>
</tbody>
</table>

---

**Table 51**

Maximum concentrations of O₃ and NOₓ near LEP release points (ppm) a)

<table>
<thead>
<tr>
<th>LEP energy</th>
<th>Ozone (O₃)</th>
<th>Oxides of nitrogen (NOₓ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.5 GeV</td>
<td>0.0015</td>
<td>0.0007</td>
</tr>
<tr>
<td>86 GeV</td>
<td>0.30</td>
<td>0.15</td>
</tr>
<tr>
<td>100 GeV</td>
<td>1.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>In air at release point</th>
<th>At ground level 3 min after release</th>
<th>Naturally occurring concentration</th>
<th>Maximum permissible levels for workers and members of the general public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naturally occurring concentration</td>
<td>7 × 10⁻⁶</td>
<td>0.0013</td>
<td>0.0047</td>
<td></td>
</tr>
<tr>
<td>Maximum permissible levels for workers and members of the general public</td>
<td>0.1 (short exposure)</td>
<td>0.015 (long exposure)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| | NO₂ | | |
|------------------|--------------------------|--------------------------|
| Naturally occurring concentration: NO | 0.01 – 0.06 b) | 0.004 – 0.02 b) |
| MAXIMUM PERMISSIBLE LEVELS FOR WORKERS AND MEMBERS OF THE GENERAL PUBLIC: NO₂ | 0.5 (short exposure) | 0.06 (long exposure) |
| | 0.15 (short exposure) | 0.03 (long exposure) |

a) Distance at which maximum ground-level concentration is likely to occur is 200 to 500 m from release point.

b) Natural concentrations measured at Anières, Geneva, in 1980 (Section 7.4).
Table 52
Elements of the environmental monitoring programme

<table>
<thead>
<tr>
<th>Monitored subject</th>
<th>Kind of radiation, radioactivity</th>
<th>Measuring instruments</th>
<th>Locations</th>
<th>No. of points</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ambient radiation doses</td>
<td>Total $\gamma$</td>
<td>Argon-filled ionization chamber and moderated BF$_3$ counter</td>
<td>Near shaft No. 5 (France)</td>
<td>1</td>
<td>Continuously</td>
</tr>
<tr>
<td></td>
<td>Total $n$</td>
<td></td>
<td>Near shaft No. 1 (Switzerland)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total $\gamma$</td>
<td>TLDs ($^{4}$LiF/$^{7}$LiF)</td>
<td>Near shaft No. 5 (France)</td>
<td>5</td>
<td>$1 \times$ per year (LiF)</td>
</tr>
<tr>
<td></td>
<td>Total $n$</td>
<td>+ ($^{1}$CaF$_2$:Dy)</td>
<td>Near shaft No. 1 (Switzerland)</td>
<td>5</td>
<td>$4 \times$ per year (CaF$_2$)</td>
</tr>
<tr>
<td></td>
<td>Soft and hard components of cosmic radiation, radioactivity in air and soil</td>
<td>Argon-filled ionization chamber</td>
<td>Near shaft No. 5 (France)</td>
<td>1</td>
<td>($\sim 4 \times$ per year)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Near shaft No. 1 (Switzerland)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Other places of interest for special studies</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\gamma$-emitting isotopes in air and soil (in situ measurements)</td>
<td>Ge(Li) diode</td>
<td>Near shaft No. 5 (France)</td>
<td>1</td>
<td>($\sim 2 \times$ per year)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Near shaft No. 1 (Switzerland)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Other places of interest for special studies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Aerosols</td>
<td>Total $\beta$</td>
<td>Large-area prop. counter</td>
<td>Near shaft No. 5 (France)</td>
<td>1</td>
<td>Continuous sampling, filter change $2 \times$ per year</td>
</tr>
<tr>
<td></td>
<td>$\gamma$-spectrometry</td>
<td>Ge(Li) diode</td>
<td>Near shaft No. 1 (Switzerland)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3. Surface water</td>
<td>Total $\beta$</td>
<td>Large-area prop. counter</td>
<td>La Versoix</td>
<td>2</td>
<td>$4 \times$ per year</td>
</tr>
<tr>
<td></td>
<td>$\gamma$-spectrometry</td>
<td>Ge(Li) diode</td>
<td>L’Allondon</td>
<td>1</td>
<td>$4 \times$ per year</td>
</tr>
<tr>
<td></td>
<td>$^{40}$K</td>
<td>Flame photometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{3}$H</td>
<td>Liquid scintillation counter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Tap and underground water</td>
<td>Total $\beta$</td>
<td>Large-area prop. counter</td>
<td>Commune of Versonnex</td>
<td>1(2)</td>
<td>$4 \times$ per year</td>
</tr>
<tr>
<td></td>
<td>$\gamma$-spectrometry</td>
<td>Ge(Li) diode</td>
<td>In LEP tunnel</td>
<td>If water is found</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{40}$K</td>
<td>Flame photometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{3}$H</td>
<td>Liquid scintillation counter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Soil</td>
<td>Total $\beta$</td>
<td>Large-area prop. counter</td>
<td>Near shaft No. 5 (France)</td>
<td>1</td>
<td>$2 \times$ per year</td>
</tr>
<tr>
<td></td>
<td>$\gamma$-spectrometry</td>
<td>Ge(Li) diode</td>
<td>Near shaft No. 1 (Switzerland)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{40}$K</td>
<td>Flame photometer</td>
<td>Other places of interest for special studies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Grass and vegetation</td>
<td>Total $\beta$</td>
<td>Large-area prop. counter</td>
<td>Near shaft No. 5 (France)</td>
<td>1</td>
<td>$1-2 \times$ per year</td>
</tr>
<tr>
<td></td>
<td>$\gamma$-spectrometry</td>
<td>Ge(Li) diode</td>
<td>Near shaft No. 1 (Switzerland)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{40}$K</td>
<td>Flame photometer</td>
<td>Other places of interest for special studies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Fish</td>
<td>Total $\beta$</td>
<td>Large-area prop. counter</td>
<td>La Versoix</td>
<td>1</td>
<td>$1-2 \times$ per year</td>
</tr>
<tr>
<td></td>
<td>$\gamma$-spectrometry</td>
<td>Ge(Li) diode</td>
<td>Le Lion</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
15. ENVIRONMENTAL MONITORING PROGRAM

A programme of ground-level measurements at two locations will begin in 1984, in order to obtain well-established pre-operational natural background values for both radioactivity and noxious gases. Although all studies of the environmental impact consistently predict unmeasurably low radiation, radioactivity, and noxious gas levels, the RPS nevertheless must provide for environmental measurements, essentially to demonstrate that the impact is zero. The programme, outlined in Table 52, is designed to monitor all possible environmental contaminants. Detectors are required to be sensitive enough to measure natural background radiation levels to within ±25% precision. It is expected that none of the levels outside the boundary fences will change significantly from the initial background levels, even when LEP is operating at its full design intensity at 100 GeV.

Stray radiation and doses from exhaust plumes will be measured by ionization chambers and Andersson–Braun neutron counters, and by gamma- and neutron-sensitive TLD monitors (Rau82c, Moy80a). Air activity is also measured in the exhaust stacks—the gaseous beta–gamma activity by in situ GM counters and TLDs, and the aerosol activity by analysing exhaust filters in the laboratory. Aerosol samples will also be taken at locations where the maximum ground-level concentrations are expected. Concentrations of O3 and NO−NO2 are monitored in the stacks and also at ground level.

Activity in the water will be monitored by two continuous stations for both incoming and outgoing water. In addition, water samples taken at the ring and the heat exchangers will be regularly analysed.

15.1 Release-water monitoring system

Water monitoring for LEP is provided by the existing system in SPS Auxiliary Building 6. Here the water released from the SPS and, in the future, from LEP (LEP Access Point 1), passes through a continuously operating water monitor consisting of a NaI(Tl) 7.5 cm × 7.5 cm diameter detector immersed in a 0.8 m³ normal water tank. The total gamma activity (gamma-energy range: 0.1–2.0 MeV) and photons near the positron annihilation energy (0.511 MeV) are recorded. This provides high sensitivity for the measurements of all positron emitters. The limit of sensitivity is about 10⁴ Bq/m³.

In parallel with the continuous monitor, an automatic sampler takes water samples every 2.3 min for separate beta and gamma analysis in the low-level laboratory located in CERN Building 24. Special samples will also be taken for analysis prior to release when water from the main-ring cooling system is drained. Existing instrumentation in the low-level laboratory is well suited for this type of monitoring, but additional units must be acquired to handle the higher total number of routine and special measurements.

15.2 Release-air monitoring system

Air from the LEP-MR ventilation system is released through four stacks located at Access Points 1, 3, 5, and 7 (see Fig. 1). Continuous monitoring of the air for beta activity will be performed in a bypass to the main release duct in Access Points 1 and 5. Owing to the symmetry of the LEP ring, the concentrations of activity and radiogenic noxious compounds are assumed to be the same for the release at Access Points 3 and 7.

The initial monitoring programme is planned to begin as soon as possible, with stations installed near Access Point 1 (on Swiss territory) and near Access Point 5 (in France, far from other CERN installations). In the release system, the air first passes through a filter in which aerosols are retained for later analysis in the low-level laboratory. The released air is routed through a short bypass in which two Geiger–Müller counters (separate thin- and thick-walled tubes) measure the beta and gamma activity in a volume of about 1 m³. The air flow rate will average 16 m³/h through each bypass. An O3 and an NO−NO2 detector are installed in the same bypass. The volume of air released through the bypass and the total air exhausted through all the access points are measured. With these values, the total volume of air and concentrations of possible contaminants can be determined.

As far as airborne radioactivity alone is concerned, the proposed LEP system is identical to the existing system at the SPS; however, the noxious gas monitors added to the LEP system are of a new design. When operational, this air monitoring system will permit estimation of environmental contaminants at the site boundary. As the calculations have shown, these contaminants are unlikely to be detected directly by the environmental monitoring system, described next, because they are so small.

15.3 Environmental monitoring and sampling

The monitoring programme described above requires the laboratory analysis of various samples taken from the CERN sites and in surrounding areas. Samples are typically of vegetation, water, and fish from neighbouring rivers. The instrumentation is identical to that already in use for CERN environmental measurements. Continuous monitoring equipment (Figs. 43–45) will be installed at suitable locations near LEP facilities. Stations for measuring radioactivity and noxious gases at locations beyond the site boundary will be provided near Access Points 1 and 5 (see map, Fig. 1).

Calculations have shown that under present average release conditions (see Section 7), the maximum ground-level concentrations are expected at a distance of 200 to 500 m downwind from a 10 m high release point. In the Pays de Gex the two prevailing wind directions (wind from the SW and NE; see Fig. 46) are nearly equally probable. We
Fig. 43  Photograph of an environmental monitoring station. At the left is a radiation monitoring system, consisting of an ionization chamber and a moderated BF$_3$ counter, contained in weather-proof housing. The chart recorder records atmospheric temperature, pressure, and humidity. The radiation monitors are hard-wired to the computerized central data-acquisition system. Housing at right contains an aerosol-sampling system. Particulates are collected on filter papers, which are periodically removed for laboratory analysis. Eight additional such stations will be installed for LEP.

Fig. 44  Schematic of standard radiation detector electronics for radiation monitors based on ionization chambers. Current from ion chamber (at left) is digitized and the output is conditioned to match transmission requirements over long distances.
Fig. 45 Monitor control and data-acquisition and handling system. Radiation monitors are connected via cables or high-level data-link control (HDLC) to an intelligent monitor controller. A multidrop highway links the monitor controllers via a process control assembly (PCA) to the LEP control network.

Fig. 46 Winds in the Geneva area

a) Average wind velocity as a function of the direction for the four seasons

b) Relative frequency of wind direction.
therefore plan to have one station 300 to 400 m from Access Point 1, and the second station 300 to 400 m from Access Point 5 in the prevailing wind directions.

These stations will contain a stray radiation monitor (site station) consisting of a highly sensitive ionization chamber and an Andersson–Braun neutron counter. There will be an air sampler of the same type as in the release monitors, and O₂ and NO–NO₂ detectors for continuous monitoring. The O₂ and NO–NO₂ monitors will be conventional detectors based on chemical luminescence or absorption in the ultraviolet, and will contain in situ calibration facilities.

Two meteorological stations are combined with the radiation monitoring stations for measuring wind direction, wind speed, temperature, rainfall, and solar radiation (Fig. 43). It is intended that the meteorological parameters be continuously recorded in order to provide the Radiation Protection Group with a complete history of environmental conditions with which to evaluate the consequences of releases from LEP.

16. COSTS OF RADIATION PROTECTION

In Section 10 the major elements of the radiation protection system for LEP were discussed. It was shown there that many major design consequences derive from a combination of technical requirements and radiation protection considerations. In addition to shielding, the design of many components and systems is influenced by radiation sensitivity of materials and potential for induction of radioactivity. It is therefore difficult to give a financial accounting of all aspects of the LEP radiation protection system as it is broadly defined and developed throughout this report. For budgetary planning, the financial estimates given in this section cover only those elements of the system provided directly by the CERN Radiation Protection Group.

We therefore consider only the costs of LEP-related activities and installations which are the direct responsibility of the RP Group. At the same time, we estimate the number of RP personnel partly or fully occupied with the LEP project (Table 53). Most of the radiation protection effort for LEP is an extension of RP Group programmes already established for the other CERN facilities and projects. As research priorities change with time, part of the present RP programme might be somewhat reduced, and RP personnel might be released for reassignment to LEP. However, the staff estimate of Table 53 gives the number of RP personnel who will be working for the LEP project in 1988, assuming that the PS and SPS will also then operate for fixed-target physics with protons, and that pp colliding experiments in the SPS and low-energy antiproton physics in the PS will also continue.

It is anticipated that, with the advent of LEP, the SC will operate for medium-energy physics with a reduced programme compared to that of 1983. CERN will have about 20% more users than in 1983 and 40 to 50% of these will work at LEP (about 1000 persons). The amount of work with or in the presence of radiation is projected to continue at about the present level.

With these assumptions, estimates for personnel and budget for LEP are shown in Table 53. It should be noted that these estimates are less than they would be for a newly-built independent LEP laboratory, because a considerable share of RP overhead and general tasks is presently ascribed to other RP activities.

<table>
<thead>
<tr>
<th>Function</th>
<th>Requirement (man-years/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational radiation protection</td>
<td>5</td>
</tr>
<tr>
<td>LEP Main Ring</td>
<td></td>
</tr>
<tr>
<td>High-level dosimetry and endurance tests</td>
<td>1</td>
</tr>
<tr>
<td>LEP Main-Ring components</td>
<td></td>
</tr>
<tr>
<td>Operational radiation protection</td>
<td>1/2</td>
</tr>
<tr>
<td>LIL + EPA</td>
<td></td>
</tr>
<tr>
<td>LEP monitor systems and instrumentation</td>
<td>2</td>
</tr>
<tr>
<td>LEP environmental protection</td>
<td>1</td>
</tr>
<tr>
<td>General site survey, source and activity control</td>
<td>1</td>
</tr>
<tr>
<td>Additional technician for personnel monitoring</td>
<td>1</td>
</tr>
<tr>
<td>Data acquisition, data base software</td>
<td>1/2</td>
</tr>
<tr>
<td>Overhead for planning, collaboration in development projects, secretariat</td>
<td>1</td>
</tr>
<tr>
<td>Total personnel required for LEP</td>
<td>13</td>
</tr>
</tbody>
</table>
The yearly personnel costs from 1988 onwards are approximately SF 1000000 per year (at 1982 prices). Costs of development work and installations performed by the RP group are shown in Table 54. Making no allowance for unexpected new developments, an annual operating budget of MSF 0.45 (1982 prices) is anticipated for 1988 and the following years. Of the total RP costs for all CERN facilities this will represent about one-third of the total material costs after 1988 (1982 prices) and one-quarter of the personnel costs (1982 prices).

Integrated personnel costs of MSF 5, projected for LEP radiation protection until the end of 1988, are estimated on the basis of a linear increase from 5 man-years in 1982 to 13 man-years in 1988. The total cost for the LEP RPS of MSF 7.5 should be viewed in relation to the full cost of the LEP project. The CERN Council has approved a total budget of MSF 980 for capital investment for LEP. In addition to this, personnel costs are estimated to be MSF 300–350 during the seven years of construction (1982–1988). Radiation protection would represent about 0.6% of the total estimated costs for the LEP project. This is in line with the RP costs for similar facilities, such as at DESY, SLAC, or Fermilab.

### 17. SUMMARY AND CONCLUSIONS

This report, together with the many background references cited, shows that the contemplated Radiation Protection System is completely adequate for controlling all radiation problems related to LEP. In particular, the environmental effects are extremely small, and the environmental measurement programme will demonstrate the absence of any risk outside the confines of CERN. Those who have access to underground areas will be sufficiently protected against any direct radiation or radioactivity produced in LEP. Compared to experience at the proton accelerators, personnel doses will be considerably reduced, as remanent radioactivity is minimal.

The CERN collective dose (or population dose, defined as the total dose received by all persons associated with CERN) is currently of the order of about 3 Sv/y. The contribution to the CERN collective dose predicted for LEP operation would be about 1/10 of this, or 0.3 Sv/y. Yet this is not likely to represent a net increase; as the research priorities of the laboratory change, personnel and other resources, such as available electrical power, will be transferred to LEP activities and this is likely to occur at the expense of programs involving the existing proton accelerators. As this report documents, LEP operation presents significantly less radiological risk than the existing proton machines.

As concerns the collective dose to members of the general public, the following can be said: the deep-underground siting of LEP, the inaccessibility of LEP radiation areas, and the low concentrations of radioactive releases indicate an exceedingly small collective dose to the general population. This is estimated to be of the order of only 1 mSv/y.

It is not obvious where, and by what means, dose commitments could be further reduced below levels estimated in this report. One proposal would be to separate the detectors from the occupied experimental areas by complete shielding walls. This would reduce exposures in some limited areas and for some running conditions. The costs would be high because of increased construction costs and longer cable runs to the detectors. However, the benefits would be minimal; the reduction in radiation dose would at most be of the order of 10 mSv/y in each area.

In the klystron galleries, the dose could be reduced by reducing the personnel occupancy time. This measure will be reconsidered as soon as a radiation survey of the operating klystron area has been made and evaluated together with the need for personnel access. Because of the depth of the LEP tunnel, doses in the surface areas are completely insignificant and further optimization would be pointless.

In general it can be stated that the LEP Radiation Protection System limits radiation doses and exposure to noxious gases to levels that satisfy all applicable legal requirements and are as low as reasonably achievable, taking all factors into account. The system therefore provides satisfactory radiation protection for those working with LEP and for those who live or work in its vicinity.
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APPENDIX

Composition of the LEP Radiation Working Group (RAWOG) (end of 1982):

O. Bayard  SPS
A. Boker  SB
J. Borer  ISR
P. Bramham  ISR
K.W. Burn  ISR
L. Burnod  SPS
G. Dardenne  Orsay
H. Dinter  DESY
J. Dutrannois  TIS
A. Fassó  TIS
K. Goebel  TIS
O. Gröbner  ISR
M. Höfert  TIS
H. Hoffmann  EF
J.H.B. Madsen  PS
B. Milman  SPS
C.W. Nuttall  TIS
M. Pelliccioni  Frascati
A. Perrot  ISR
K.M. Potter  ISR
G. Rau  TIS
W. Richter  PS
H. Schönbacher  TIS
P. Sievers  SPS
G.R. Stevenson  TIS
A.H. Sullivan  TIS
W.P. Swanson  SLAC and TIS
J.W.N. Tuyn  TIS

Divisions within CERN:

EF  Experimental Physics Facilities
ISR  Intersecting Storage Rings
PS  Proton Synchrotron
SB  Technical Services and Buildings
SPS  Super Proton Synchrotron
TIS  Technical Inspection and Safety (formerly HS)

Other organizations represented on RAWOG:

DESY  Hamburg, Federal Republic of Germany
INFN–LNF  Frascati, Rome, Italy
IPN–LAL  Orsay, France
SLAC  Stanford, CA, USA