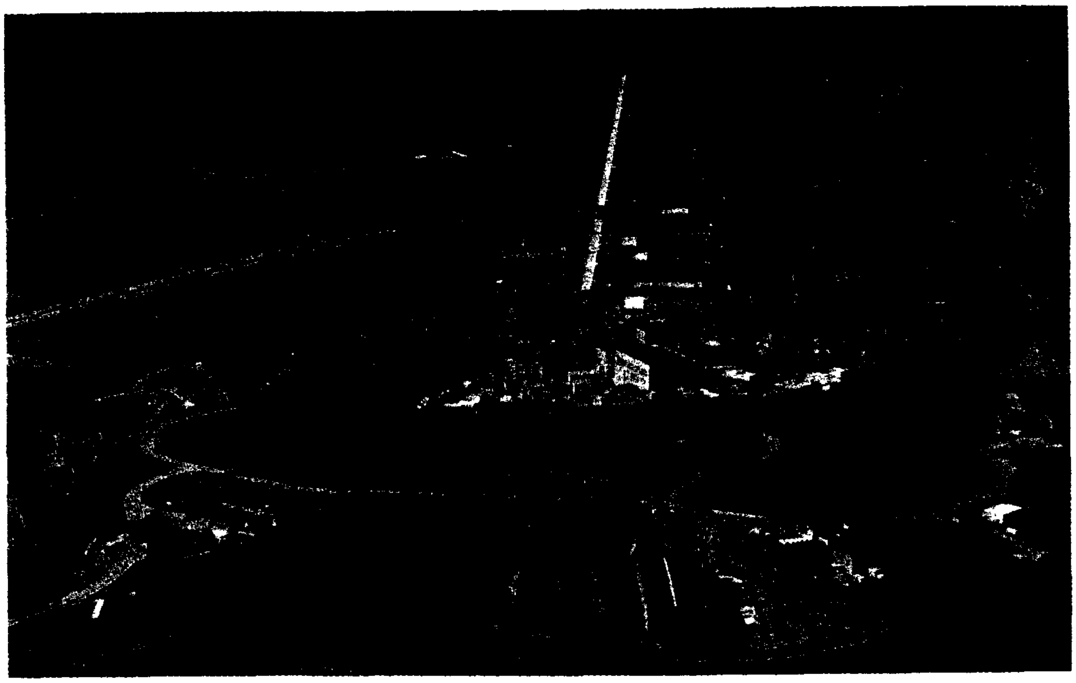
SLAC-327

Department of Energy

Health Physics Manual of Good Practices for Accelerator Facilities



R.C. McCall
W.R. Casey
L.V. Coulson
J.B. McCaslin
A.J. Miller
K.F. Crook
T.N. Simmons

SLAC - Report - 327
April 1988

Prepared for the U.S. Department of Energy
Assistant Secretary for Environment, Safety, and Health
under contract DE-AC03-76SF00515

Stanford Linear Accelerator Center
Operated for the U.S. Department of Energy
by Stanford University

2/80

SLAC–327
UC–41
(A)

HEALTH PHYSICS MANUAL OF GOOD PRACTICES FOR ACCELERATOR FACILITIES

W. R. CASEY, BNL
A. J. MILLER, LANL
J. B. MCCASLIN, LBL
L. V. COULSON, FNAL

Advisors:
K. F. CROOK, SLAC
T. N. SIMMON, SNL

R. C. MCCALL, SLAC, CHAIRMAN

E. J. VALLARIO, DOE PROJECT MANAGER

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

April 1988

Prepared for the U.S. Department of Energy Assistant Secretary for Environment, Safety, and Health under Contract DE–AC03–76SF00515.

Printed in the United States of America. Available from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161. Price: Printed Copy A07, Microfiche A01.

ACKNOWLEDGEMENTS

Important contributions to the text were made by W. Freeman, T. Jenkins, W. Swanson, and M. Howe. Technical editing was performed by Roberta Friedman. Assistance in computer processing the text was obtained from W. Nelson, D. Gelphman, and B. Kempton. Many days of patient and skillful secretarial work were done by D. Lacey. The Committee gratefully acknowledges the help of all of the people listed above.

FOREWORD

The Department of Energy's (DOE) Office of Nuclear Safety (ONS), Health Physics Branch, has, in coordination with principals at many of the DOE laboratories, identified the need to develop four priority facility guides of good practice. These include radiological safety guidance for accelerator, plutonium, tritium, and uranium facilities.

This manual presents guidance to be used to develop and conduct radiation protection programs at DOE accelerator facilities. The guidance was prepared by a carefully selected cadre of expert accelerator health physicists representing the experience of six major accelerator sites, i.e., (1) Stanford Linear Accelerator Center (SLAC), (2) Brookhaven National Laboratory (BNL), (3) Fermi National Accelerator Laboratory (Fermilab), (4) Lawrence Berkeley Laboratory (LBL), (5) Los Alamos National Laboratory (LANL), and (6) Sandia National Laboratories (SNL). The manual was subsequently reviewed by a peer review group of accelerator health physicists throughout the Department's program preparatory of finalization and publication.

Unlike other facility categories, such as plutonium facilities, the diversity of accelerator types, their size, design, and beam properties require varying strategies for radiation safety. For example, proton accelerators, in contrast to electron accelerators, exhibit different radiation characteristics, and hence measurement control processes. The authors of this guide provided greater emphasis on the unique characteristics from the radiological safety viewpoint of the various accelerators and less stress on those radiation safety aspects which are common to all accelerators. It is hoped that this manual will serve both as a teaching aid as well as a useful adjunct for program development. In the context of application, this manual addresses good practices that should be observed by management, staff, and designers since the achievement of a good radiation program indeed involves a combined effort. Ultimately, radiation safety and good work practices become the personal responsibility of the individual.

The practices presented in this manual are not to be construed as mandatory rather they are to be used as appropriate for the specific case in the interest of radiation safety. As experience is accrued and new data obtained in the application of this document, ONS will update the guidance to assure that at any given time the guidance reflects optimum performance consistent with current technology and practice.

Edward J. Vallario
Acting Director
Radiological Controls Division
Office of Nuclear Safety

TABLE OF CONTENTS

1. INTRODUCTION 1
   1.1 Applicability of this Report 3
   1.2 Small versus Large Facilities 4

2 ACCELERATOR FACILITY DESIGN 5
   2.1 Criteria for Siting Accelerator Facilities 5
   2.2 High Energy Interactions (Source Terms) 9
   2.3 Other Radiation Sources 15
   2.4 Shielding Design 17
   2.5 Interlock and Warning Devices 21
   2.6 Beam Containment 28

3. OPERATIONAL CONSIDERATIONS FOR HEALTH PHYSICS 32
   3.1 Control of Radioactivation and Contamination 32
   3.2 Radioactive Waste Management 42
   3.3 Radiation Damage to Components 44
   3.4 Instruments and Measurements 47
   3.5 Personnel Dosimetry 61
   3.6 Experimenter Access to Secondary Beams 64

4. ADMINISTRATION OF A HEALTH PHYSICS PROGRAM 65
   4.1 Records 65
   4.2 Audits 69
   4.3 Written Procedures and Administrative Controls 71
   4.4 Radiation Safety Staff 76

5. DISMANTLING, DECONTAMINATION, AND DECOMMISSIONING 79
   5.1 Facility Design 79
   5.2 Facility Operations 80
   5.3 Planning Dismantling and Decommissioning 81
   5.4 Dismantling and Decommissioning Operations 82
   5.5 Operations After Dismantling and Decomissioning 84

APPENDICES 86

REFERENCES 111

INDEX 133

1. INTRODUCTION

Particle accelerators pose unique problems for health physics. The primary particle beam can produce enormous dose rates of radiation over small areas. Moreover, the secondary radiation (bremsstrahlung, neutrons, scattered electrons, and so forth) can create very high dose rates over large areas of the accelerator workplace. Some of the secondary radiation is quite penetrating. If the primary energy is high enough, residual radioactivity can be produced.

Accelerators vary, and strategies for radiation safety must be tailored to the beam properties of each. Prompt radiation, both primary and secondary, is often produced in pulses. For some accelerators, the pulses may be a small fraction of a second long and come at several hundred pulses per second. In other machines, pulses a few seconds long are produced several times per minute. Great diversity also exists in the kind of particle accelerated, the energy range, and method of acceleration. Table I gives a partial list of DOE accelerators; it does not include a number of smaller accelerators.

Radiation doses for personnel working at DOE accelerators have been rather small and have decreased over the years (see Appendix A). The nature of accelerator radiation fields is such that while the potential for very high accidental exposures exists, routine doses are small. This will become apparent in later sections of this guide.

The amount of literature on the health physics of a given type of accelerator is, in general, proportional to how many of that type are in use. The electron linacs used in radiation therapy (about 1100 in the United States) have been well characterized, and the NCRP has published several guides to their radiation safety problems (NCRP76, NCRP77, NCRP84). While therapy electron linacs and conventional x-ray machines are not discussed in the present manual, some aspects covered in the NCRP reports may nevertheless apply to the health physics of other accelerators. Then there are half a dozen or so

TABLE I. DOE SELECTED LIST OF ACCELERATORS

Accelerator	Laboratory Field Office	Energy (GeV)	Year of Initial Operation	Interaction Type
BNL AGS	BNL/CH	33	1961	Proton Synchrotron
LLNL Linac	LLNL/SAN	0.05	1970	Electron Linac
Super Hilac	LBL/SAN	0.0085**	1971	Positive Ion Linac
Fermi Main Ring	FNAL/CH	400	1972	Proton Synchrotron
Los Alamos Meson Physics Facility (LAMPF)	LANL/AL	0.8	1972	Positive Ion Linac
Bates	MIT/CH	1.0	1972	Electron Linac
SPEAR	SLAC/SAN	3.5×3.5	1972	(e^+e^-) Colliding Beam
Intense Pulsed Neutron Source	ANL/CH	0.5	1976	Proton Synchrotron
BEVALAC	LBL/SAN	2.1**	1977	Positive Ion Synchrotron
PEP	SLAC/SAN	15×15	1981	(e^+e^-) Colliding Beam
Holifield Heavy Ion Facility	ORNL/OR	0.025	1982	Heavy Ion/Tandem Van de Graaff
Advanced Test Accelerator (ATA)	LLNL/SAN	0.05	1982	Electron Linac
Flash X-Ray Accelerator (FXR)	LLNL/SAN	0.02	1982	Electron Linac
National Synchrotron Light Source	BNL/CH	0.75 VUV 2.5	1983 1983	VUV Ring x-Ray Ring
ATLAS	ANL/CH	0.025	1986	Positive Ion Linac
Stanford Linear Collider (SLC)	SLAC/SAN	50×50	1986	(e^+e^-) Colliding Beam
Tevatron I	FNAL/CH	1000×1000	1987	(pp) Colliding Beam
Tevatron II	FNAL/CH	1000	1986	Proton Synchrotron
Particle Beam Fusion Accelerator (PBFA II)	SNLA/AL	30	1986	Lithium Ion Linac Array
Hermes III	SNLA/AL	0.02	1986	Electron Linac x-Ray
CEBAF	SURA/CH	4	1990***	Electron Linac
Superconducting Super Collider	Not Selected	20,000×20,000	1990***	(pp) Colliding Beam

*Not including lower energy van de Graffs, dynamitrons, neutron generators, and university operated accelerators.
**Per nucleon.
***In planning or construction stage.

high energy accelerators that operate above 1 GeV. A greater range of physics comes into play in the health physics of these machines, which are more likely to be modified and used for different purposes than are small accelerators. Except for one book (Pa73), and two book size IAEA reports (IAEA79, IAEA89) most of the literature for the health physics of these large machines is in the form of journal articles or reports.

The intent of this guide therefore is to:

- Define common health physics problems at accelerators.
- Recommend suitable methods of identifying, evaluating, and managing accelerator health physics problems.
- Set out the established safety practices at DOE accelerators that have been arrived at by consensus and, where consensus has not yet been reached, give examples of safe practices.
- Introduce the technical literature in the accelerator health physics field.
- Supplement the regulatory documents listed in Appendix D.

Many accelerator health physics problems are no different than those at other kinds of facilities, e.g., ALARA philosophy (DOE80, ICRP82, NCRP87), instrument calibration, etc. These problems are touched on very lightly or not at all. Similarly, this document does not cover other hazards such as electrical shock, toxic materials, etc. This does not in any way imply that these problems are not serious.

1.1 Applicability of this Report

Some portions of this report are less broadly applicable than others; such sections will be indicated. Moreover, safety solutions and suggestions given here are not necessarily unique. The responsible health physicist must be alert to other options offering equal or better safety under particular circumstances of management, hardware, or staffing. This document should thus be viewed as a guide to selecting safety measures that will give adequate radiation protection. There will always be exceptions, and the responsible health physicist will sometimes have to decide that certain recommendations made here cannot be applied at his or her facility. Any exceptions and the reasons for them be must be carefully considered. Such exceptions should be reviewed periodically, and when the accelerator or its mode of operation are changed, to check that the reasons for the exceptions are still valid.

1.2 Small Versus Large Facilities

Many different kinds of accelerator facilities exist within programs sponsored by the DOE. The tasks performed vary considerably, ranging from studies performed in a simple, one-room setting to those conducted in multiple buildings spread over many square miles.

Keeping size differences in mind, certain points should be made about the safety guidelines set forth here. Most important is to understand that any accelerator creates a substantial hazard. A small accelerator operating at 3 MeV can produce levels of radiation just as dangerous as those from the highest energy machines. Thus, even for small accelerators, access control and many other safety features should be as well designed and maintained as at bigger facilities.

Usually, though, smaller facilities mean simpler control systems. With less staff to coordinate, smaller areas to monitor, and fewer points of access to control, the radiation safety program will be simpler. As an example, a small accelerator may have a single health physicist who is also responsible for other areas. The health physicist periodically visits each facility to monitor activities in progress, review records, discuss coming activities, and provide other services that may be needed. In such cases, it is important to set approved limits to the operation of the accelerator. To operate beyond these limits would then require prior review with the health physicist, to determine whether additional safeguards or monitoring are necessary.

Another potential pitfall of the simpler organization at small facilities is when someone is designated as Radiation Safety Officer (RSO) who may have no formal training in health physics. Frequently this person may be a scientist or operator at the facility who is assigned the duties of RSO in addition to his or her other responsibilities. This arrangement can work safely if the RSO is chosen to have minimum conflicts of interest. However, there must be a periodic, professional overview of the health physics program and a clear definition of the approved bounds within which the accelerator has been shown to operate safely. In addition, when the RSO carries multiple responsibilities, management must be particularly vigilant that safety not be compromised by operating pressures. In all cases, internal audits should be performed (see Section 4.2).

In contrast to smaller facilities, a large accelerator will usually employ several professional health physicists and technicians whose only duties concern the safety at that accelerator. Still, the distinction between small and large facilities is gradual, not sharp. Smaller size may permit a reduced scale for the radiation safety program, but it never justifies poorly-defined or carelessly-implemented safety measures.

2. ACCELERATOR FACILITY DESIGNS

2.1 CRITERIA FOR SITING ACCELERATOR FACILITIES

Setting criteria for radiation protection in advance of site selection can simplify finding and selecting a satisfactory site for an accelerator. If a site is chosen which closely matches well-thought-out design criteria, delays for redesign and costly retrofits can be avoided.

Although one can develop siting criteria after the accelerator and its facilities are designed, it is often more efficient and economical, especially for large projects, to develop the criteria in parallel with the design. This can provide prompt feedback to designers on the safety impact of design features.

Once the primary accelerator parameters such as energy, kinds of particles, and power are decided, determining the siting criteria requires cooperation among personnel. Participants should be familiar with the facility's design, and with radiation physics and safety regulations. It is invaluable to have persons on the team, or at least available for consultation, who have had working experience in all these areas.

Knowing the magnitude of the radiation source and the allowable radiation levels makes it possible to design appropriate protection into the facility. The starting point is to list design parameters for the accelerator. Design parameters can then be combined with assumptions about the expected operation and be used to estimate radiation levels. Restrictions on radiation levels, set from appropriate standards, can then be used to develop the facility's design. The resulting criteria would thus specify shielding walls, berms, distances, and other features of the site required to accommodate the measures necessary for radiation protection.

Recommendations for Setting Site Criteria

The larger or more complicated the accelerator design, the more effort will be needed to decide siting criteria. The general procedures recommended here can be scaled up or down to fit the need.

The accelerator's design parameters completely determine the nature and magnitude of the radiation source. The most important parameters are: kind of particle accelerated, particle energy, beam power, target material, and work load.

A wide variety of techniques are available to estimate radiation levels. These techniques range from very sophisticated Monte Carlo computer programs or direct analytic expressions, to "rules of thumb" and published and unpublished experimental measurements. Details of these methods will be discussed below. In addition, guidance is available from radiation physics personnel at any of the major DOE accelerator laboratories.

A full listing of all potential radiation problems which should be analyzed is not attempted here. Following are some of the most important and less obvious ones.

Prompt-Direct Radiation: Numerous computer codes and mathematical models have been developed which can predict the amount of direct, prompt radiation (neutrons, photons, muons, and so forth) which will contribute to off-site dose. Both normal operating conditions and conditions of abnormal beam loss should be considered. Section 2.2 of this guide introduces the most common, relevant techniques to calculate prompt radiation.

Skyshine: Historically, a common weak point in accelerator design has been thin "roof" shielding. As a result, skyshine (air scattered) neutrons commonly contribute significantly to the radiation dose in uncontrolled areas. Measurements (Co85, Ri75, St84) have verified that mathematical models (Je74, Pa73, Ri75) are adequate to calculate doses of neutron skyshine out to about 1200 feet. However, at distances of half a mile or more, the various models may disagree by at least an order of magnitude. At large distances, dose rates are simply too low to measure with any degree of accuracy. Deliberately increasing the source strength to allow such measurements is probably not justified, in view of the dose that would result to the general population and the trivial level of the normal skyshine dose (Je74).

It is required to report the annual general population dose (person-rem within a 50-mile radius). Here the choice of model can affect calculated results considerably. For consistency, the methods and constants given in St84 should be used to calculate annual population dose.

Photon skyshine is usually less of a problem but should be considered, especially for areas where radioactive material is stored. Again, there are models for calculating this component of the environmental radiation dose (Bi69; Bo75).

Activation: Estimates of the off-site dose from airborne radioactivity should be made. Air activation is most significant in areas of routine, high intensity beam losses such as near beam dumps, targets, or collimators.

Radioactive Water: Routine discharges and spills of radioactive water should also be considered. Common sources of radioactive water are the closed loops containing water used to cool magnets, targets, and beam dumps. However, one should also consider the water that is collected in sumps and then discharged to the environment.

For some accelerators, activation of soil and ground water outside the shielding may also be relevant. Ground water that is either directly exposed to the prompt radiation, or passes through soil that has been activated, may transport radionuclides to an underground aquifer or to surface water.

Information from state or local hydrologists and geologists on annual rainfall, the nature of the site's geology, and velocity of the area's subsurface water can be used to predict the concentrations at which isotopes would begin to leach into drinking water (CEBAF87, Go78).

Storage and Transportation: Storage and transportation of activated accelerator components can contribute significantly to the annual site boundary dose. By estimating the amount and nature of radioactive material to be stored, one can estimate the site boundary dose due to both direct radiation and photon skyshine. Other contributions to site boundary dose are the shops or labs where radioactive items are repaired or maintained. Judicious locations of storage areas, shops, and labs will help minimize the site boundary dose.

Radiation Protection Standards: DOE Orders define minimum standards for radiation protection. However, state and local requirements for environmental protection are often more restrictive than federal ones, and may prevail off-site. It is recommended that, early in design, concurrence of the DOE be sought on all applicable radiation limits. (See Appendix D.)

Facility Design: Once the radiation source terms and applicable radiation limits have been determined, the necessary radiation protection measures can be designed. For accelerators, this most often means shielding the sources with concrete, steel, or earth. However, the use of distance, interlocks, barriers, and even restriction of operations should be considered.

Accident Considerations: Rarely do thoughts of possible accidents affect siting designs for accelerators. Yet accidents should be considered (El86).

2.2 HIGH ENERGY INTERACTIONS (Source Terms)

Particle accelerators are designed for a variety of purposes, such as research into the nature of matter, production of radioisotopes, generation of bremsstrahlung for radiography, induction of fusion, pumping of lasers, and production of synchrotron radiation. Each purpose dictates a particular energy range and choice of particle to be accelerated—electrons, protons, or nuclei of heavier elements. For a particular primary beam, then, the health physicist has to understand the radiation fields produced as the beam is absorbed, since the resultant dose rates can be quite high.

Proton Accelerators

If the accelerated particle is a proton, the physics of the interaction can be discussed in the following energy domains.

- Elastic Interaction Region: In this energy domain, the proton interacts only by elastic scattering. For most target materials, proton energies in excess of 6 to 8 MeV will be required to exceed the inelastic threshold, though in certain materials (for example, protons on tritium) reactions can take place at very low energies. The range of protons with energies less than 8 MeV is quite limited; it is less than 1 mm in most solid materials and less than 1 m in air.

For the most part, the Radiation Safety Officer for proton machines operating in this low energy range will need only to prevent direct exposure to the primary beam.

- Inelastic Interaction Region: If the incident particle has enough energy to penetrate the coulomb barrier, that energy can be transferred to the nuclei of the target, which will emit neutrons and other nuclear fragments. This transfer is classified as an inelastic process. For energies up to about 100 MeV, the dominant inelastic process is the isotropic emission of neutrons from the target nucleus. These evaporation neutrons have energies up to about 20 MeV, depending on the energy of the primary particle.

  The dose rates produced by evaporation neutrons can be quite high. The need to attenuate them dominates shielding requirements for this energy range.

- Particle Production Region: In addition to evaporation neutrons, neutrons and protons will also be emitted in the forward direction, at energies which can be a significant fraction of the incident particles' energy. These are called cascade neutrons and protons since they are part of the cascade started by an incident particle. In the cascade, energy is transferred or lost to the target materials if the incident particle's energy is high enough. And as the energy of the incident particle increases, the emission angle of the cascade particles becomes more and more peaked in the forward direction. When the energy of the incident proton exceeds about 140 MeV, pions and other particles can be produced, which must also be managed.

  Because so many particles are produced in the forward direction, shielding must be much more extensive along the beam direction. For example, muons produced by the decay of pions in flight are very penetrating, especially at energies greater than a few GeV. Yet these muons are quite forward peaked, so they do not enter into considerations for the shielding needed at wide angles. As accelerator energies increase, muons become important at increasingly wide angles, however.

Electron Accelerators

If the incident particle is an electron, the physics of the interactions can be discussed in the following energy domains.

- Low Energy (<6 MeV): Below 6 to 10 MeV, electrons lose energy only by ionization and bremsstrahlung (x-rays) production in most target materials (beryllium and deuterium are exceptions). For electron machines that operate in this energy region, the primary electron beam and the photons it produces must be shielded. The bremsstrahlung becomes forward peaked in intensity when the electron energy is more than about 2 MeV. Backscattered electrons can also produce significant doses of radiation within shielded enclosures.

- Giant Resonance Region (6 to 50 MeV): In the energy region between 6 and about 50 MeV, energy can be transferred to the nucleus by photons produced along the electron's track, leaving the nucleus in an excited state with the subsequent boil-off of a neutron. Bremsstrahlung is still the predominant source of radiation that shielding must deal with, but the presence of neutrons usually dictates use of a hydrogenous shielding material such as concrete.

  The bremsstrahlung is increasingly forward peaked as the electron energy increases, whereas giant resonance neutrons are produced nearly isotropically. For exposures inside the shield, electrons may be a major factor, depending upon the primary electrons' energy, and the target configuration.

- Intermediate Energy Region (30 to 150 MeV): In this energy region, neutrons are produced by the pseudodeuteron process. The production cross section for this process is lower than that for giant resonance and bremsstrahlung still dominates shielding considerations. However, the energy of the neutrons is increasing, and their removal cross section is smaller. For exposures inside the shield, electrons, and bremsstrahlung will be the major components of the dose.

- High Energy Region (above 150 MeV): Above the threshold for pion production, neutrons can be produced with energies up to nearly the energy of the primary particle. These neutrons are very penetrating, and in fact determine the required thickness of concrete shields greater than about 120 cm. While these high energy neutrons are forward peaked, they still are the most important consideration for thick transverse shields. For exposures inside the shield, bremsstrahlung will usually be the major source of radiation dose. However, the exact nature of the radiation field becomes increasingly dependent on particle energy, the target's configuration and material, and the relative position of the target and the subject.

  In this energy range, muons also can be produced by direct pair production as well as by pion decay. These muons are important contributors to radiation in the forward direction (IAEA79).

Heavy Ion Accelerators

Experience has shown that neutrons dominate the radiation field outside of the shielding of heavy ion accelerators at energies above the coulomb barrier. With light ions of several hundred MeV per nucleon and thin shields or at forward angles to the beam direction the dose equivalent outside the shield may be dominated by neutrons of energy greater than 20 MeV. Unlike protons, there does not exist a large body of experimental source term data. Hubbard et al. (Hu60) measured global neutron yields from carbon, and nitrogen and neon beams at 10.4 MeV·A (MeV per ion, A is the atomic mass number) on several target elements. Ohnesorge et al. (Oh80) measured neutron dose equivalent rates at 90^{o} near medium-mass targets for carbon, nitrogen, oxygen, and neon beams of 3

MeV·A to 16 MeV·A. Greenhouse et al. (Gr87) used a Bonner sphere neutron spectrometer to measure the energy spectrum of neutrons outside of a concrete shield for 8.5 MeV·A argon ions on a thick copper target.

Other experimental data are cited and briefly summarized by Clapier and Zoidins (Cl83) who present analytical expressions for the unscattered neutron fluence and dose equivalent rates from unshielded thick targets. The fit to the sparse experimental data as a function of incident nucleon energy and atomic number is within a factor of two for beam ion energies of less than 15 MeV·A.

Measurements of neutron yields and angular distributions were made by McCaslin et al. (Mc85) with 670 MeV·A neon and silicon ions on a thick copper target. A rough measure of neutron spectra was obtained by using activation detectors with energy thresholds from thermal energies to 50 MeV. Fluence attenuation profiles through concrete were also determined.

For shielding design, the energy spectra of the reaction products are needed in addition to particle yields and angular distribution. Also, fluence or dose equivalent attenuation profiles through the shielding are very useful. For example, although the average nucleon energy was 10.4 MeV for the ion beams in Hubbard's measurements, the presence of neutrons of energy greater than 20 MeV has been observed outside of the concrete shield by carbon activation measurements, although at a significantly lower fluence rate than for the predominant neutron energy group of about 1–3 MeV. In order to shield a low intensity beam it may be acceptable, in absence of the full source term, to base the calculation on neutrons of the average nucleon energy of the beam ion. However, for a high intensity beam which will require a much thicker shield, the neutrons of lower energy will be attenuated in the first layers of the shield so that it will be the high energy component which ultimately determines the overall shield thickness.

Initially, for low energy heavy ion beams, one must determine whether the incident ion has sufficient energy to penetrate the coulomb barrier of the target atom and consequently to produce neutrons. For ions of mass greater than that of protons, the energy below which only coulomb interactions can occur is given by (Al72)

$$(E_B)_{MEV} = \frac{Z_1 Z_2 \left(1 + \frac{A_1}{A_2}\right)}{A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}} + 2}$$

where Z_1 and Z_2 are the charge numbers of the beam particle and target nucleus, respectively, and A_1 and A_2 are their respective mass numbers.

The approximate relationship between charge and mass number for stable nuclei is given by (Al72)

$$Z = 0.487 \frac{A}{1 + \left(\frac{A^{\frac{2}{3}}}{166}\right)}$$

Radiation Field Calculations

The calculation of numerical values for the radiation fields discussed above is a topic too large for this manual, and the reader is referred to the literature (IAEA79, IAEA89, ICRU78, Je79, NCRP77, NCRP84, Ne76, Ne80, Pa73, Ri73, Te79). This list is a representative sampling but is by no means exhaustive. Some useful computer codes for calculating source terms are EGS4, FLUKA82, HETC, CASIM, and ITS (see Appendix E).

Residual Radioactivity

While not properly a source term, residual radioactivity may make up an important part of the radiation field inside the shield. Whenever the electron energy is greater than the binding energy of a nucleon, or when a proton can penetrate the coulomb barrier, a residually radioactive nucleus may form. Residual radioactivity is not as great in electron machines as in proton machines, since in the former, most of the primary energy goes into ionization and production of photons and electron-positron pairs.

Accelerators used to produce isotopes present special problems because of the wide variety of target materials used, and because the parameters of machine and target are deliberately optimized to produce radioactive isotopes.

2.3 OTHER RADIATION SOURCES

While the accelerator is the most obvious source of radiation at a facility, there can be others, such as klystrons, experimental devices in other buildings, or RF tests. These other sources can be much harder to control because the health physicist may not know they exist, the way that the radiation is produced may not be understood, or, the experimenter or user may not recognize that a device produces radiation.

In general, whenever there is high voltage or RF power in a vacuum, x-rays can be produced. This is true even though there is no heated filament or some other obvious source of electrons. Since the physics is not well understood, some anecdotal examples will show the severity of these radiation problems.

- The RF cavity for a storage ring was being tested. At 200 kW of RF power, the x-ray dose at 1 meter was 500 mrad/hour (1.4 μGy/s). The dose was found to increase with the 5th power of the RF power. The highest planned power level was 350 kW which would have produced about 8 rad/hr (22 μGy/s).
- A secondary emission test device being operated at 110 kV dc produced 160 rad/hour (440 μGy/s) at 10 cm from a glass viewing post.
- A doubler RF cavity, with 65 kW of RF applied, produced about 5 rad/hr 14 μGy/s) at 1 foot (30 cm).
- In a test for a high gradient accelerator, high RF power was applied to a 10 inch (25 cm) section of a standing wave accelerator that had no gun. With 35 MW of RF power and 120 pps (Hz), at a position 140 cm from the center line of the accelerator section, the dose rate was 6100 rad/hr(17 mGy/s).

These x-rays were quite high energy and at 2 meters, through 4 inches (10 cm) of lead and 4 feet (122 cm) of concrete, the dose rate was 10 mrad/hour (28 nGy/s). On the axis of the accelerator section, the dose rate was much higher. At high RF fields (greater than 20 MV/meter), stray electrons at rest can be captured and continuously accelerated. In this experiment, sufficient beam was accelerated to melt a hole in the stainless steel plate at the end of the accelerator section.

- Measurements were made on three klystrons running at 50 MW with the end cap shield removed. At 8 cm from the end cap, the dose rates ranged from 1700 to 3600 rads/hour (4.7 to 10 mGy/s).

- At a resonating microwave waveguide driven by a klystron at 17.5 MW, an x-ray field of 300 rad/hr (830 μGy/s) was measured 6 cm from the waveguide (Gi81).

- A particle beam separator containing a pair of 400 kV, 1 mA high voltage units was having high voltage difficulties. The separator is normally interlocked to exclude personnel, but because of the need to troubleshoot, the interlock was temporarily jumpered. With a troubleshooting high voltage of about 50 kV, a radiation survey showed no evidence of x-ray production. A subsequent wiring error caused the separator's high voltage stack (Cockcroft Walton) to operate at about 400 kV instead of the indicated 50 kV, an event identified by the sound of sparking from the separator. A follow-up radiation survey showed dose rates of about 100 rad/spark (1 Gy/spark) or 1500 rad/hr, (4.2 mGy/s) about 30 cm from the separator's surface center line.

- A 20 kJ KrF UV laser, pumped by a 1.7 MeV, 40 kA, 20 ns pulsed electron source, emits x-rays that produce 300 mrad (3 mGy) per pulse at 15 feet (4.6 m). Electron-pumped KrF lasers, including a 40 kJ model, are available from at least two commerical vendors. Vendors often expect users to provide their own shielding.

The only way to control such radiation sources is by alerting experimenters to potential hazards. Experimenters must learn to inform the health physicist when an apparatus that could generate radiation is being assembled. The health physicist on his part must show the experimenter that he can be a useful partner in helping the experiment run safely and expeditiously. Periodic "all hands" reminders of these types of hazards are recommended.

2.4 SHIELDING DESIGN

Shielding or equivalent protection by adequate distance is needed to guard employees and the general public against unnecessary radiation exposure. The degree to which the radiation must be attenuated will be determined by several factors, such as the time that radiation workers or the public spend near sources, and potential environmental factors such as soil or air activation.

In most cases, the applicable dose limits provide a starting point for determining shielding requirements. However, it is inappropriate to design shielding that allows an individual to receive a significant fraction of the exposure limit. DOE now recommends that shielding for new installations keep facility workers from being exposed to doses of leakage radiation greater than one-fifth of the limit or 1 rem/year (10 mSv/year) (DOE Order 5480.1, dated 4/29/81). The facility's boundary dose must not exceed 100 mrem/year (1 mSv/year) (DOE Memorandum from William A. Vaughan dated Aug. 5, 1985). Further information on regulatory dose limits is given in Appendix D.

Several difficult questions must be considered when specifying the shielding requirements. An accelerator's beam capability is often far greater than its desired operating level. The designer is faced with the dilemma of choosing to shield for either the desired operating level or for the accelerator's maximum capability. ANSI78 clearly states that the maximum should be the determinant. Yet this may be prohibitively expensive. Alternatives might include the following:

- Pulsed magnets deflecting the beam into the area might be rendered incapable of pulsing at more than the desired repetition rate.
- Radiation monitors around the area might be interlocked with the accelerator to shut it off, should radiation levels exceed a preset value.
- Beam current-monitoring toroids might similarly be interlocked with the accelerator.
- The beam transport might be made inefficient by, for example, a beam-dispersing foil followed by a small collimator, so that the full intensity cannot be transported to the area.

Such measures lack the inherent reliability of adequate shields and must be carefully analyzed to see if the proper degree of safety will be achieved.

Another situation that might force compromise is when limitations of cost or space prohibit adequate shielding for expected beam losses at all spots. In such cases, it is sometimes possible to keep beam losses to certain points by use of collimators, beam scrapers, and so forth. These points can then be heavily shielded and the rest of the machine can be more lightly shielded. This technique requires close control of the location and alignment of the beam-defining devices.

Shielding problems also arise when beam loss becomes uncontrolled, that is, in an accident. Accident situations as well as normal operation should be considered to see which should set the shielding limits. An evaluation must be made as to whether radiation levels on- or off-site determine the required shielding levels for accidents. If the site boundary is close, the off-site radiation level may be limiting. It has been customary to assume a "worst case" scenario where the full power of the beam is lost at one spot. Inherent in such a scenario is the assumption that the beam loss will be terminated in some finite time. This may be from operator intervention, beam loss detection devices, or burn-through of the vacuum tank walls. Therefore, the worst case scenario may actually be where a smaller loss, e.g., 10–20%, occurs undetected and continues for a long time. Each possible scenario must be carefully considered. Again, however, the cost of providing such protection with some accelerators is quite substantial and in some cases has forced a more realistic appraisal. For example, a "point" loss of a high energy proton beam in a circular accelerator is not a realistic assumption. When an accelerator is shielded in a tunnel, the depth to which the tunnel is dug may not make a cost difference.

Resolution of these questions is not simple. It requires considerable cooperation by the shielding designer and the machine physicists to decide realistic operating and accident scenarios. In particular, it is very important for the machine operators to understand what consequences follow if shielding is not adequate for all possible situations. For normal operating conditions, shielding can be specified by consideration of usual occupancy and work loads, but work loads should not then be increased beyond the design limits.

Shielding design is a complex problem. The geometry of cells and tunnels includes labyrinths, ducts, and other penetrations. Evaluating potential doses from radiation scatter through penetrations can be more difficult than determining wall thicknesses. Three-dimensional transport codes may be required. Skyshine is similarly difficult to determine. Besides accounting for attenuation by shielding, one must consider activation of the shield and perhaps of soil, air, and water.

For additional information, refer to De68, IAEA89, Je79, NCRP76, NCRP77, NCRP84, Ne76, Pa73, Ri73, Ri75, Sc73, Sw85, and Te79. The codes EGS4, CASIM, FLUKA86, HETC, and ITS can be applied to many accelerator shielding problems. Codes used in other shielding problems, such as ANISN, DOT, MORSE, ONEDANT TWODANT, and XSDRN (see Appendix E), may also help in design of shields for $<$ 20 MeV photon or neutron sources. The Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory maintains a large collection of computer codes useful for shielding accelerators.

A method of calculating shielding needs for high energy proton accelerators is the "Moyer Model," described in Chapter 6 of Pa73, St82, and Mc87. An adaptation of this method for high energy electron accelerators can be found in Je86.

No matter how thick the shield at high energy proton accelerators, neutrons will dominate the radiation field at large angles. At high energy electron accelerators, photons will dominate for thin to moderately thick shields. Only in the case of very thick shields will neutrons dominate at electron accelerators.

Neutron energy loss by elastic scattering requires a hydrogenous shield to maximize energy transfer as the particles slow down. For higher energy, above about 10 MeV, inelastic processes are effective. Iron will shield against these high energy neutrons, but it must be followed by a hydrogenous material that will remove the lower energy neutrons formed by the inelastic interactions. There is no effective mechanism in iron to remove neutrons with energies less then a few hundred kilovolts, so that an iron shield alone will be nearly transparent to these neutrons of low and intermediate energies.

Outside of very thick shields muons will dominate the shielding requirements in the forward direction, for both proton and electron high energy accelerators. The relevant source terms are discussed in ICRU78.

For most accelerators, concrete is the shielding material of choice because it offers a reasonable compromise on density, hydrogen content, cost, and flexibility of construction; it is also self-supporting. Ordinarily, concrete has a density of about 2.4 g/cm^3 (2.4×10^3 kg/m^3). However, note that some aggregates can lower the density to a bout 2.2 g/cm^3 (2.2×10^3 kg/m^3), which will still be considered "normal" concrete. The reader is also advised that over long periods of time the water content (hydrogen) in hydrogenous shielding materials may be reduced through evaporation.

A rule of thumb used in shielding assessments is that after one or two attenuation lengths of shield material, neutron energy equilibrium is reached and thereafter will remain constant. For concrete, then, the dose equivalent outside of the shielding will be attenuated with an attenuation length of 120 g/cm^2

(1200 kg/m^2). For iron, an attenuation length of 145 g/cm^2 (1450 kg/m^2) is appropriate.

Heavy concrete can be made for special applications by using aggregate of limonite, ilmenite, barite, magnetite, or iron. Densities have been obtained as high as 6.5 g/cm^3 (6500 kg/m^3). Note that heavy concretes give increased linear attenuation for photons, charged particles, and high energy neutrons. However, these concretes usually contain less hydrogen and give decreased linear attenuation for neutrons with energies below a few MeV. The heavy concretes are often quite expensive because contractors are unfamiliar with their properties and quote higher prices for contingencies. Pumps designed for ordinary concrete often cannot handle the increased weight of high density concrete.

Some sources of information on the use of concrete for radiation shielding are ACI62, Wa61, Sc71, and Ja68.

2.5 INTERLOCKS AND WARNING DEVICES

This section describes the general guidelines for designing interlocks to protect accelerator personnel. The guidelines apply in particular to accelerators that produce life-threatening levels of radiation. Guidelines to set the degree of interlock protection for radiation areas might be based on the NRC proposed rules (CFR86). Further guidance can be found in NCRP86. For installations with a lower radiation hazard, less stringent design guidelines are acceptable, but only on advice of an expert.

A personnel protection system can be considered to have two main parts, an access control system and a radiation alarm system.

The access control system is intended to prevent unauthorized or accidental entry into radiation areas. Elements of this system include physical barriers, signs, closed circuit TV, flashing lights, audible warning devices including the associated interlock system, and a body of administrative procedures that define conditions where entry is safe.

The radiation alarm system can include radiation sensors which monitor the radiation field directly, or indirect methods which use beam current detectors, magnet current interlocks, or high voltage measurements.

This section guides design of interlocks which make decisions for an access control system. Recommendations are also made on aspects of operating the access control system.

Interlock Design

The objective of a safety interlock system is to prevent injury or damage from radiation. To achieve this end, the interlock must operate with a high degree of reliability. Components and materials should be of high grade for dependability and long life. Materials that resist radiation should be selected for those components located in areas where the radiation levels are high enough to cause radiation damage.

Fail-safe circuits and components should be used whenever practicable. Fail-safe design takes into consideration the failure of primary ac power to the area, dc power to logic circuits or beam-line components, or of the pressurized air that feeds air-actuated solenoids in safety devices. In each case, the safety interlock system should react to render the area safe in the event that a key safety component fails or the power source is lost.

Duplicate (parallel) circuits or redundant components should always be used in critical applications where the single failure of a circuit or device could lead to a hazard. In design of redundant circuits, parallel chains should be used. The chains should remain independent, and not neck down to a single connection or component. Independence should be carried all the way from duplicate sensors through to the devices or mechanisms that shut off the radiation source. Wherever possible, at least two different methods should be in place to remove the beam or radiation source. Examples of mechanisms appropriate to many accelerators are: removing high voltage to the radiation source, inserting beam stoppers, and turning off a magnet bend string.

Conditions or circumstances may exist where the magnitude of a radiation hazard may not justify the requirements for duplicate or redundant interlock circuits or components. Specific guidelines to deal with questions of when redundancy is appropriate are generaly impractical since the issues that initiate redundancy questions will usually vary from case to case. Whether or not interlock redundancy is required must, therefore, be evaluated and decided by risk analysis processes. In performing a risk analysis, the consequences of unacceptably high personnel radiation exposure, severe personnel injury, and potential legal actions must be weighed against facility operating schedules and redundancy implementation costs. A few elements entering into such an analysis include: examination of accelerator and/or beam line failure modes, and the probability for such failures to occur, the number and reliability of "built-in" safety devices to guard against or mitigate the occurrence of undesirable events, occupancy, and the maximum radiation exposure or personnel injury that could occur from the failure of a nonredundant interlock circuit or component. If the risk of an unacceptable event occurring is sufficiently small, then redundancy in interlock circuits and components is clearly unneccessary. Facility management, acting in consultation with the health physicist, must, however, understand the risks and consequences, and based on this information establish levels of risk acceptable to the operation and the facility.

To reduce the likelihood of accidental damage or deliberate tampering, all cables should be protected. Preferred methods are to use armor-covered cable or to run the cable in conduit. It is acceptable to lay cable in metal trays, particularly where long runs are involved, providing that the cable is run in conduit between the tray and the junction box or cabinet. When using conduit or armored cable, the covering should be continuous, with solid elbows and no inspection plates. For installations in high radiation areas, particular attention should be given to selecting radiation-resistant cable.

Logic equipment should be mounted in locked racks, cabinets or boxes. When using racks that are part of a tray of racks used for other systems, solid partitions should be installed between the racks housing the safety equipment and the adjacent racks.

The equipment design should include ways to manually test the system. One way is to introduce fault signals and then check the system for proper response. This is normally done off-line, when the accelerator is not operating. Or it may be possible to incorporate self-check features that operate automatically at regular intervals, to continuously check that the system is functioning properly.

Radiation detectors should be designed for very high reliability. One should consider use of small, built-in radioactive sources to provide signals that show the detector is operating within specifications.

The use of computers in safety interlock systems has been studied by a subcommittee. Their report is included as Appendix B.

Features of an Interlock System

- Emergency-off (Scram) buttons should be clearly visible, labeled, and readily accessible. Large, red, mushroom-head buttons are recommended.
- Run/safe switches are sometimes used to prevent start-up of an accelerator or radiation source when a radiation area is occupied. They are set to the safe position on entering the area, and must be manually reset to the run position to allow start-up. Run/safe switches serve as a valuable back-up to other interlock devices that break the security chain (door microswitches, keybank interlocks, and so forth). They also provide a clear and positive indication to personnel in the exclusion area that the interlock chain is broken.
- Emergency exit mechanisms must be provided at all doors and man-ways. Emergency entry features are not precluded.

- Warning lights or annunciator signs should be located outside entrances to accelerator enclosures. Inside radiation areas, clear visual warning should be given that the accelerators is about to come on. This may be done with rotating beacons or by dimming or flashing the main lights for the area.
- Audible warning should be given inside accelerator enclosures before the accelerator is turned on. This may be in the form of sirens with a distinctive sound (2500 Hz or lower, with 1 Hz pulse modulation, for example) or by a recorded voice warning system that alerts those in the area that the accelerator is about to come on.
- Search of a radiation area should be initiated by activating a "Search Start" switch. "Search Confirmation" switches, mounted at appropriate locations along the search path, should also be provided. At the conclusion of the area search, a "Search Complete" switch at the exit point should also be set. Run/safe switches can double as "search" switches, if desired. Means should be provided to prevent people from entering behind the search team.
- The interlock system should prevent beams from being turned on until after the search has been completed and acknowledged and the audible and visual warning light cycle has ended.
- Any violation of the area, such as a door being opened, or an emergency-off switch being tripped, should cause the interlock system to immediately render the area safe. Restarting the accelerator should not be possible until the area has again been searched, as described above.
- A "Controlled Entry" mode may be desirable for some larger accelerators. Under this mode, a small number of workers (up to eight, for example) are permitted to enter an already searched area to carry out specific tasks. Each person is issued a key which must be kept in his or her possession during the entry period. Release of the key and records of name, date, and time should be carefully supervised by an operations or health physics group.

Removal of a key from its keybank automatically breaks the interlock chain and prevents beams from being turned on. Return of all keys to the keybank permits beams to restart without needing a complete search. However, beams are to be held off until the visual and audible warning system has completed its cycle.

Posting guards at radiation gates may be an acceptable alternative to key control under some circumstances. The guards should be responsible personnel other than those working on the experiment. All entries and exits must be carefully logged.

Other procedures to control and keep account of access to accelerator vaults or tunnels have been worked out and successfully employed at DOE facilities. At Brookhaven National Laboratory, for example, entry into the primary area of the Alternating Gradient Synchrotron (AGS) is allowed under two different modes. In "Restricted Access" any individual who has authorized work and who possesses a "film-badge" key (issued to AGS personnel who have been instructed on apppropriate radiation safety) can unlock the personnel gates for access. Following a period of restricted access, prior to accelerator start-up, a complete search of the area must be completed.

The second mode used at Brookhaven is called "Controlled Access" and can be used when the machine is in a beam-ready status. It is intended to maintain the ready status without requiring a search of the entire enclosure. In this mode, a Control Room Operator is dispatched to the gate of entry. The operator is responsible to sign in all personnel entering the tunnel or cave, and is also responsible to sign them out when they exit. The operator takes a gate key from the Control Room which will open a primary gate if a simultaneous release from the Control Room is provided. Following the completion of the activity, the operator, after checking that everybody who was signed in has signed out, resets the gate using the gate key and returns the key to the Control Room. The accelerator can then be restarted.

- The interlock system should permit a key release or a door opening only when an area is safe to enter.

  Interlocks are not to be used to shut off beams for routine entries.

Interlock systems should be carefully documented. The documentation package should include schematics, wiring diagrams, parts lists, instructions, and a written description of the functional behavior.

There should be a clear chain of responsibility for interlock design, installation, and check-out. Only authorized personnel should be permitted to install or modify safety interlocks. The system should be certified by the authorized personnel before it is put into routine use. Certification should be repeated after any modifications, maintenance, repair, or additions.

Bypass of a radiation interlock may be done only with written approval of a specific person designated by the manager. Bypassed interlocks should be carefully logged including the time, date, reason, and the signature of the responsible operator. If the condition persists into the next operating shift, the responsible operator on that shift should also sign off on the bypass. He should also review whether the bypass is still necessary.

Interlocks should be tested periodically, according to written procedures, and the results of the tests should be carefully recorded. Two types of testing are appropriate. Detailed, rigorous testing of the entire system should be done at the start of each running cycle. If the machine is operating continuously, a detailed test should take place at least every six months. These tests should demonstrate correct operation of all devices at entrances, all emergency-off switches, the interlock logic itself, and all redundant paths to the shutdown mechanisms.

In addition to the rigorous testing, overall operation of the system should be tested more frequently—once a week to once a month may be appropriate. Tests might typically involve violating security at a different entrance point each time and checking that the beam is shut off.

2.6 Beam Containment

Radiation safety around an accelerator usually depends on the beam going to preselected places and depositing its power there. If the beam power is deposited elsewhere, very high radiation levels in unprotected areas may result. Some examples follow.

- A lightly shielded experimental hall contains a thin target which will absorb about 1% of the beam power while the rest of the beam passes through into a heavily shielded beam dump. Due to an alignment error, the beam instead strikes the target's thick housing, increasing radiation by one to two orders of magnitude.
- In an experiment, the beam strikes a target, producing secondary particles or photons, and then is bent by a magnet into a dump. The magnet fails (entirely or partly) allowing the full beam to pass out of the secondary beam line to occupied areas.
- By operator error, the beam strikes an inadequate beam stopper, melts through it, and passes into an occupied area.

Such scenarios, which have actually happened, have produced radiation levels ranging from minor to potentially lethal. As a specific example, on initial check of a new beam line, a magnet was connected backwards. As a result, a 30-watt beam struck the outer shielding wall (1.8 m of concrete). The error was discovered when a dose rate of 360 rad/hr (1 mGy/s) was read outside, on a survey meter known to underrespond. The accelerator was capable of generating hundreds of kilowatts (Wa73). Preventing such accidents is the subject of this section.

Not many publications are available on beam containment. One (Je70) is for a 500 kW electron linear accelerator in the GeV range. Another (Ne76) touches on the topic and points out some of the similarities and differences between electron and proton machines.

Beam containment is not exclusively a concern for health physics. In fact, it has traditionally been assigned to the accelerator operations group, except for the testing done by radiation measurements outside of the radiation shield. More properly, it should be a joint concern among health physics, accelerator operations, and beam line designers. The line dividing responsibilities between health physics and operations is often blurred, and friendly cooperation is essential. This issue is discussed in Je70, which also details one laboratory's solution. At other laboratories, beam containment is handled by decentralizing the health physics group and assigning people to each operations group.

Beam containment is usually accomplished by a combination of mechanical devices (slits, collimators, magnets, beam stoppers, dumps) and electronic devices, including interlocks, which are considered separately below.

Mechanical Devices

Design of a beam line includes a precise calculation of where to locate mechanical containment devices, and lists of their specifications. Design will usually include ray traces, consequences of missteering, shielding calculations for beam loss at various points, and necessary power ratings for slits, collimators, and beam stoppers.

Possibile melting or burn-through must be considered, which, however, is more of a problem for electron accelerators than for proton accelerators. For electrons, the inherent lateral spread and electromagnetic shower length are much smaller than the angular spread and hadronic cascade length for protons (Je70). In addition, more energy is carried off by neutrons in the hadronic cascade. As a result, the energy deposition density is lower for proton machines than for electron machines of similar power levels.

Some tests of burn-through for 13 different devices are described in (Wa73). The devices were irradiated with various beam powers and the time for burn-through recorded. As an example, a copper cylinder 15 cm in diameter and 38 cm long, when struck by a 360 kW electron beam, spewed molten copper out radially and burned through its length in about 22 seconds.

When the device under consideration is critical to beam containment, one or more of the following preventive measures should be taken.

- The device can be designed to absorb the maximum beam power available.
- It can be designed to fail in a safe manner. For example, a plug with a low melting point can be installed near shower maximum that destroys the accelerator vacuum when excessive power is deposited.
- The device can be protected by electronic devices that turn off the beam when they sense high power absorption, such as ionization chambers or temperature sensors.

As the position of mechanical devices is usually critical, an initial check of a new or rebuilt beam line should be carefully planned to confirm placement. Ideally, this should be a joint test by accelerator operations and health physics. Such a check-out might include steering the beam to confirm its appearance and disappearance at various points downstream of each device, at the expected magnet currents and radiation levels. These tests would, of course, be done at low currents or repetition rates. The tests would also confirm proper polarity of magnet connections which might ultimately be locked in place.

Electronic Devices

Some electronic devices to contain the beam have already been discussed above as those intended to prevent burn-through. Others might include circuits that use microswitches to position moveable devices, or circuits that limit or test current in magnet power supplies. In addition, there are often devices to measure beam current, such as toroids or secondary emission monitors. Beam current measuring devices might be used in an accounting mode where, for example, the signal from a toroid at the beam's final destination is compared with that from a toroid at the beginning of the area being protected. If comparison on a pulse to pulse basis shows a beam loss greater than some specified amount, the beam is automatically turned off.

One additional type of electronic device for beam containment is a radiation detector or system of detectors set outside the shielding in occupiable areas. (Ba68, Aw71). If the dose rate rises above a preselected level, various actions result. Actions may range from providing warning signals to turning off the accelerator. The output of such devices should be available to the accelerator operator. Administrative procedures should require that if such a radiation detector trips, the operator must turn the machine back on at reduced current until he determines the cause of increased radiation, and corrects it.

With such electronic systems there are always concerns about improper circuit operation, unauthorized gain adjustments, tampering, inadvertent cable switching, and so on. Some techniques can give increased reliability:

- A wire passing through the toroid can give a test pulse that checks the system between machine pulses.
- Critical electronics can be locked in cabinets.
- Cable runs for critical devices can be isolated and/or labeled.
- Administrative controls can limit the persons permitted to adjust the circuitry.

As with mechanical devices, the electronic devices to contain beam should be tested and their operation confirmed during initial check. This test too might be interdisciplinary, depending on who is responsible for the installation and maintenance of the electronic devices.

3. OPERATIONAL CONSIDERATIONS FOR HEALTH PHYSICS

3.1 CONTROL OF RADIOACTIVATION AND CONTAMINATION

The general approach at any accelerator facility should be to increase controls as the hazard of contamination or activation increases. Each facility should develop guidelines for controlling contamination and activation, and set limits that are appropriate for the facility and consistent with applicable DOE Orders as well as state and local regulations (see Appendix D). In developing these guidelines, the facility should consider the potential hazards for environment, personnel, equipment, and area contamination or activation. A program of routine sampling and monitoring should ensure that both on- and off-site releases of radioactivity do not exceed acceptable limits.

Zones of activation or contamination should be clearly marked with appropriate signs or labels indicating the nature and degree of the hazard. When necessary, proper survey, and decontamination techniques should be applied to reduce contamination to acceptable levels.

Removable activity (contamination) in the workplace should be limited. Unrestricted areas should be essentially free of removable contamination. Acceptable limits for general use are not given in current DOE Orders but might be taken from NRC regulatory guide 1.86. The list from this regulatory guide is reproduced here as Table II.

DOE has not yet set its own limits for unrestricted release of activated materials. There are applicable DOT regulations (49 CFR83b) for off-site shipments of contaminated or activated materials, which discuss external dose rate limits, contamination limits, bulk specific activity, and so forth.

TABLE II. ACCEPTABLE SURFACE CONTAMINATION LEVELS

Reference: U. S. NRC Regulatory Guide 1.86; *Termination of Operating Licenses for Nuclear Reactors*

Nuclide[a]	Average[b,c]	Maximum[b,d]	Removable[b,e]
U (nat.), ^{235}U, ^{238}U, and associated decay products	5,000 dpm/100 cm^2	15,000 dpm/100 cm^2	1,000 dpm/100 cm^2
Transuranics, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{230}Th, ^{231}Pa, ^{227}Ac, ^{125}I, ^{129}I	100 dpm/100 cm^2	300 dpm/100 cm^2	20 dpm/100 cm^2
Th (nat.), ^{232}Th, ^{90}Sr, ^{223}Ra, ^{224}Ra, ^{232}U ^{126}I, ^{131}I, ^{133}I	1,000 dpm/100 cm^2	3,000 dpm/100 cm^2	200 dpm/100 cm^2
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except ^{90}Sr and others noted above.	5,000 dpm/100 cm^2	15,000 dpm/100 cm^2	1,000 dpm/100 cm^2

[a] Where surface contamination by both alpha- and beta-gamma-emitting nuclides exists, the limits established for alpha- and beta-gamma-emitting nuclides should apply independently.

[b] As used in the table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[c] Measurements of average contaminant should not be averaged over more than 1 square meter. For objects of less surface area, the average should be derived for each such object.

[d] The maximum contamination level applies to an area of not more than 100 cm^2.

[e] The amount of removable radioactive material per 100 cm of surface area should be determined by wiping that area with dry filter or soft absorbent paper, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removable contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally and the entire surface should be wiped.

Note: The appropriate SI units are Bq/m^2. To convert the values in the table to SI units multiply by 167.

Contamination Control

The potential for radioactivation and contamination at an accelerator facility can vary widely. Factors such as beam type (protons, electrons, or heavy ions), energy, intensity, pulse repetition rate, and target and shielding materials can affect the extent to which radioactivation and contamination become important concerns. The presence of intrinsically radioactive materials such as sources, targets (for example, tritium), or detector components such as depleted uranium, all create potential problems.

Most radioactive contamination from accelerators is created when the beam activates dispersable materials. Thus, if liquids, small particles, dust, gas, or grease are present, and beam losses are large enough, contamination will be a potential problem. The magnitude of the problem is strongly affected by the composition and amount of the material, as well as by how easily it is dispersed. Reducing the amount of material has obvious benefits. Simple things like good housekeeping to reduce dust and debris within accelerator enclosures can significantly control contamination.

Careful selection of materials used around accelerators can also have dramatic effects. At high energy proton accelerators, it is a rule of thumb that material with higher atomic numbers have greater contamination potential, since spallation reactions in those materials produce a wider variety of nuclides, some of which may be long-lived. Materials which are both radioactive and hazardous present special problems and will be discussed later.

New construction or remodeling can also produce contamination. Drilling or sawing of the concrete of accelerator enclosures can produce contamination due to the dust. Excavating earth around beam dumps or enclosures can be a source of contamination by the inadvertent spread of activated soil. The principal long-lived nuclides that can be leached in these cases are ^{22}Na and ^{3}H. Many other nuclides can also be present, however, depending on time since irradiation.

Other typical sources for contamination include flaking or peeling paint; rust on beam-line components; spilled cooling water from magnets; flakes, chips, dust or liquids created when activated material or equipment is machined or refurbished; damaged or broken radioactive check sources; and naturally occurring radioactive material, such as uranium, that is found in some high energy calorimeters. A few illustrative examples follow.

- Grinding of welds and repair of magnet coils are two examples of activities that produce contamination when magnets are reworked. In the iron or steel magnet yokes of hadron machines, ^{54}Mn is often the primary isotope of concern. For certain alloys, other isotopes may also need to be considered (e.g., ^{60}Co). In activated copper coils, ^{65}Zn, and ^{57,58,60}Co are often present. In contrast to hadron accelerators, ^{55}Fe may be significantly present in iron at electron accelerators due to (γ,n) reactions.

- Magnet coils are often wrapped with fiberglass tape and impregnated with epoxy. The remnants of such wrappings (epoxy and fiberglass dust and flakes) can be sources of contamination during repair, as is the residue of sandblasting used to remove old material from the coils. ^{22}Na can often be found in the coil remnants. When heated in ovens to cure or remove the epoxy, ^{3}H can also be driven off.

- Fine wire septa are often used to extract beam from high energy machines. The wires occasionally break and the septa must be repaired. The very fine wires are difficult to see and might be considered a contamination problem since they are quite small and easily transported, for example, on the sole of a shoe.

- Pumps that are used within accelerator enclosures or that are used outside but are connected to the enclosures through vacuum lines also can be contaminated, either by direct activation of lubricating oils within the pump or by pumping on radioactive material, such as targets. One should be aware that ^{3}H, which is not detectable with typical survey instruments, can be present in activated pump oil. Care should be used to avoid contaminating personnel or the area when taking apart or repairing such pumps.

- To prevent surface oxidation, bare metal surfaces are often protected by applying some type of coating such as paint, grease, or epoxy. Materials of low atomic number generally are preferable. For example, substituting a Li-based grease for a Mo-based one minimizes the number of long-lived isotopes that could be produced.
- At many high energy accelerators, depleted uranium plates are finding increasing use in calorimeters. The plates are a potential contamination problem due to their surface oxide, which comes off easily. The amount of oxidation can vary widely depending on how the surface is treated. When bare, uncoated plates are in cryostats, the cryogenic liquids they contact can also become contaminated. Machining and welding of such plates is an additional problem due to the waste chips (which are also pyrophoric) or contaminated welding fumes.
- Equipment used in areas where activation is likely are sometimes removed for disassembly and repair, elsewhere, e.g., in a machine shop. The contamination can then occur at that location.

Target Problems

Numerous problems can be created by target activation. In addition to the intense residual radiation fields that can be produced by the interaction of the high energy particles in the target material, physical degradation of the target produced by heating can create significant contamination problems. A number of severe contamination incidents have occurred at several high energy accelerators. The Brookhaven AGS experience has been reviewed in the literature (La86). As reported, particularly bad experience has been encountered with tungsten alloy and iridium targets. An observable growth of whiskers or snow as well as swelling of the targets occurred at machine intensities of 2×10^{12} protons/sec, even in a beam spill as long as one second. The use of platinum, or lower Z materials such as beryllium or copper has resulted in relatively trouble-free operation over periods of time when used in beam spills of hundreds of milliseconds or longer.

Very short pulses of beam can create much more severe target problems. For example, fast extraction at the AGS can produce 12 bunches, each 30 ns long, over a time of 2.5μs. Severe target degradation has occurred with such beams in sapphire ($A\ell_2O_3$) and tungsten-rhenium targets. A platinum target disintegrated with a single 30 ns bunch delivered every 2.5 seconds. The most successful materials for these short pulses of beam have been titanium or copper targets. It is prudent practice in such targeting situations to perform frequent contamination monitoring to avoid incidents involving contamination of workers entering these target caves.

Heating of targets by energy deposition can be calculated by the use of appropriate computer codes (see Appendix E).

Radioactivation Control

Activated material can be created when high energy particles or photons strike accelerator components. To plan adequate control of this activated material, it is useful to have:

- a definition of "radioactive." Many facilities treat any material that exceeds two times the natural background as radioactive.
- a labeling scheme that clearly identifies the hazard level (external dose rate, for example) of an activated object.
- designated locations for storing radioactive materials.
- appropriate procedures for radioactive waste disposal.
- appropriate procedures for transporting radioactive materials on- and off-site.

- a program to ensure that activated material is not removed from the place where it became activated without proper surveying and labeling. It is especially important to ensure that radioactive material is not inadvertently introduced into nonradioactive material or equipment stockpiles or waste streams. Particular attention should be paid to surroundings known to become activated, such as water in closed loop cooling systems; the earth and concrete shielding surrounding beam enclosures; air in target vaults; and magnets, beam pipes, electrostatic septa, or other beam-line components.

The amount of radioactivity generated in unprotected water and soil, or in air or cooling water may be calculated using the techniques noted in Section 2.2.

Radioactivation of Water

Water exposed to high energy radiation will become radioactive. The major sources of activated water will be the water used to cool beam dumps, collimators, targets, magnets, and so forth. Since cooling water is normally undergoing continuous purification by filters and ion exchange resin beds, the only significant element available for activation is the oxygen in the water. Commonly produced radionuclides that can cause problems are ^{15}O, ^{13}N, ^{11}C, ^{3}H and ^{7}Be. These same radionuclides are produced by both electron and proton accelerators.

The nuclides ^{15}O, ^{13}N and ^{11}C are all positron emitters with no accompanying gamma rays. They are rather short-lived; the hazard is due to their annihilation radiation which can produce high radiation levels around cooling water systems. Shorter-lived isotopes are produced of all three of these elements but do not contribute significantly to the total radiation dose levels. If released to the air, these three nuclides are not an inhalation hazard, only an external dose hazard. (Wa69). Since they will be present in water in gaseous form, as O_2 or CO_2, they might escape to the atmosphere if the surge tanks are vented. In some cases, it has been decided to catalytically recombine the hydrogen and oxygen that result from radiolysis. This enables the water system to be sealed and avoids problems from venting the radioactive gases.

^{7}Be is long-lived and is efficiently trapped from cooling water by the ion exchange resin beds. Concentrations of ^{7}Be in the resin can easily be high enough to make the resin beds be considered radioactive material. In extreme cases, the beds may become local radiation sources that require shielding.

In special circumstances where water is rapidly sent to the heat exchangers and the exchangers' only shielding is lead, ^{17}N may present a problem. ^{17}N is a neutron emitter with a half life of 4.17 seconds (In84).

^{3}H is the only long-lived radionuclide produced in water that cannot be removed by ion exchange resins. Hence, it may continue to build up in a water system at a rate determined by the intensity of radiation producing ^{3}H, and the natural decay and water leakage which remove it. There should be sumps large enough to contain the water in case of a spill. Cooling water systems should also be sampled periodically for ^{3}H concentrations.

It may be desirable to dispose of the water before the ^{3}H concentration becomes too high. Since cooling system capacities range from less than ten gallons to tens of thousands of gallons, it is difficult to give any general guidelines for disposal. Some possibilities are as follows:

- Disposal through the sanitary sewer. This may be regulated by several agencies, such as DOE, NRC, EPA, and state and local water pollution control boards. Their regulations will set concentration limits and, perhaps, annual limits.
- The water can be evaporated in engineered evaporation systems.
- The water can be used to make concrete for solidifying other liquid wastes for disposal.
- Water from a small volume, high ^{3}H concentration system could be transferred to a large volume, low ^{3}H concentration system where it can decay safely.

Radioactivation in the Soil

The two radionuclides with long half-lives that are produced in soil by high energy (> 10 MeV) particles and can be leached by water percolating through the soil are ^{3}H and ^{22}Na. Since tritiated water behaves chemically the same way as ordinary water, it travels with ordinary water.

Some ^{22}Na can be picked up by the passage of water through soil. The ^{22}Na-laden water will then continue to percolate and eventually meet nonirradiated soil and a portion of the ^{22}Na previously picked up will now go back into the soil. This pick-up and exchange process reduces the concentration of ^{22}Na in the originally-irradiated soil, relative to ^{3}H, which has replaced atoms of hydrogen in water molecules.

Liquid scintillation counting is used for detecting the ^{3}H beta particle. ^{22}Na can be detected by several techniques. A good one is gamma-ray detection using a Ge(Li) semiconductor detector.

One can calculate the expected concentrations of radionuclides produced in soil using computer programs. Several are available which can follow the cascade of secondary particles produced by action of the primary particle coming from the accelerator. CASIM, FLUKA82, and HETC are the principal programs applicable for high energy accelerators.

Transport of any leached radionuclides from soil to an aquifer can take years, so it is important to monitor the activated soil, and the water percolating through this soil, to provide an early warning. Samples should also be collected from the aquifer. If possible, targets and dumps should be adequately shielded with steel and concrete to prevent activating the surrounding soil in the first place.

Normally, shield enclosures are fitted with drains around their footings to collect water. These drains go to sump pits which can be sampled periodically for radionuclides.

It is desirable to drill occasionally into the activated soil to collect soil samples. These can be assayed for radionuclides and leached with water to search for ^{3}H and ^{22}Na. Commercial drilling companies have hollow stem augers for obtaining samples far below the surface, if necessary.

For further reading on the subject of soil and groundwater activation, the reader is referred to (Ba75, Ba85, Ba86, Bo72, CFR85, Co82, Go78, St72, Th79, and Va75).

Radioactivation of Air

Spallation reactions from high energy beams passing through air produce radionuclides similar to those created in water. ^{15}O, ^{13}N and ^{11}C are the principal short-lived ones to be concerned about. The pure beta emitter ^{11}C is of primary interest here due to its relatively long half-life (20.4 minutes). However, ^{13}N (half-life 10 minutes) and ^{15}O (half-life 2 minutes) cannot be neglected if enclosures are entered soon after the beam is turned off. Where air activation is a concern, it is therefore good practice to delay entry after beam shut-off for a time appropriate to the half-lives and relative airborne concentrations of the radionuclides. These nuclides are all positron emitters, so the hazard is primarily an external one, due to the 511 keV annihilation radiation.

Real-time, continuous monitoring of gaseous effluent from some enclosures may be needed to ensure that releases to the environment remain below legal limits. In some cases, concentrations at the exit point may be so high that personnel should be prevented from entering by appropriate barriers or by increasing the height of a stack. To estimate doses to the public when actual off-site concentrations of radionuclides are too low to measure directly, airborne concentrations at the release point can be monitored. Assumptions must then be made about transport off site. A preferred model is one of gaussian plume diffusion (Is68, Mo79, Pa76, Tu70*).

⋆ A draft version of DOE Order 5480.XX Dated 8/15/6 mandates the use of the computer code AIRDOS-EPA as described in Mo79.

3.2 RADIOACTIVE WASTE MANAGEMENT

The radioactive waste from an accelerator facility tends to be mostly machine components or experimental equipment used in or near the particle beam. These components are usually of copper, iron (steel), and aluminum. Other items contributing to radioactive waste are:

- shielding blocks (iron, lead or concrete)
- water
- ion exchange resins.

For planning purposes, it is necessary to know what radioisotopes will be produced in waste and to estimate their quantities. Useful data for making estimates can be found in IAEA79 for electron accelerators and Pa73 for proton machines. Further data is available in Ba69a.

During decommissioning, structural materials such as concrete walls and building support structures make significant contribution to radioactive waste. Yet many of these components can be reused. An accelerator site should have sufficient radioactive storage space so that such large items can be safely kept for long periods until they can be reused. At least part of the storage space should be protected to avoid weathering and, in a few cases, to avoid dispersal of contamination by rain and wind.

Sometimes trace elements may pose more of an induced activity problem than the main material. Some common materials, and their minor constituents that may be present in a concentration of 1% or more, are as follows:

- Standard steels — (primarily iron) — manganese, nickel, chromium, molybdenum.
- Stainless steels — (iron with nickel and chromium) — cobalt, manganese, molybdenum, tungsten.
- Aluminum alloys — (primarily aluminum) — magnesium, zinc.

- Copper alloys — (basically copper but may have large fractions of zinc or nickel) — lead, iron, aluminum, silicon, beryllium, chromium.
- Tungsten — usually sintered with a few percent copper and/or nickel added. It also can be alloyed with tantalum or rhenium.

Shielding blocks are quite large and their highest specific activity is usually below the surface. Thus, shielding blocks showing several R/hr at the surface may have no removable (wipable) surface contamination and can easily be stored without contamination problems. An exception is when activation was mainly by thermalized neutrons from the surroundings. Whenever possible, shielding blocks should be kept and reused where surface dose rate is not a problem.

Water contaminated with radioactive materials is most apt to come from leaks in cooling water systems, or from having to drain a cooling system for repairs. Pumping the water through a mixed-bed ion exchange column will remove all radionuclides except tritium. There can be surprises, however. For example, tungsten in contact with water has been known (Bu72) to form an insoluble material. Because this material is so heavy, it may collect in low places in the water system and will not circulate through filters.

If possible, cooling water should be cleaned and reused. No release of contaminated water should be permitted without thorough check of DOE, state, and local regulations. If tritium is the only contaminant, the water can be disposed of through the sanitary sewer, provided the concentration is less than 0.1 microcurie per cubic centimeter (DOE 5480, Chap. XI). Some states, however, may have other restrictions. California, for example, will allow no more than one curie per year.

Mixed-bed ion exchange resins are usually used to purify water in the accelerator's cooling systems. In water systems that are kept clean, high energy accelerators may contribute only ^{7}Be to the resin bed. However, a system that is corroding may have other radionuclides in the water containment system. Regenerating spent resin beds in-house can be economical—the beryllium can be concentrated on a much smaller amount of resin for storage or disposal.

Mixed waste is defined as waste material which is both radioactive and hazardous. Hazardous means ignitable (flashpoint $<$ 140deg F (60deg C)), corrosive (pH $<$ 2 or $>$ 12.5), reactive (undergoes violent change without detonating and normally is unstable, or reacts violently with water, or is explosive), or toxic (as defined in 40CFR261). There is presently no approved method to dispose of mixed wastes, and long term storage is required. Common examples of mixed waste materials at accelerators are: lead (shielding, batteries, etc.), PCBs, cadmium, acids, bases, solvents, and degreasers which have become radioactive.

Protective clothing may be needed to protect workers from contamination and to keep them from inadvertently spreading contamination. If radioactive waste is handled only rarely, it is probably better to use disposable coveralls, gloves, and shoe covers. An alternative to costly disposable (paper) anticontamination clothing is to purchase reusable, washable clothing such as coveralls, lab coats, and booties, and have them cleaned by a licensed commercial laundry.

Most large metropolitan areas will have at least one commercial laundry that has been licensed by the state or NRC to handle, or have on their premises, a modest amount of radioactive material. A convenient way to find such a laundry is to contact local hospitals or research laboratories, which probably use radioisotopes, and ask who launders their lab coats and linens.

3.3 RADIATION DAMAGE TO COMPONENTS

High radiation levels inside accelerator shielding can damage the facility's components, including electronic devices, cables and wiring, water hoses, motors, or loudspeakers and alarms. Normally, damage will occur only near points of high beam loss. The damaging radiation for proton accelerators will be mostly neutrons and charged particles. For electron accelerators, the main cause will be bremsstrahlung, secondary electrons, synchrotron radiation, and perhaps neutrons. While radiation damage is not a traditional health physics concern, it should be, for the following reasons:

- The devices that fail, such as audible alarms, may be crucial to radiation safety.
- Failures will require work in areas that often have the highest residual radiation levels, thus increasing the total dose for the workers.
- Predicting radiation damage requires knowing radiation dose rates and the tolerance of the device. The health physicist probably knows dose rates better than anyone else and may therefore become the *de facto* expert.

Radiation damage should be considered during the design phase of the accelerator. When calculations indicate that radiation damage will be a problem in a given area, it may be possible to improve the situation by design changes.

- Sometimes magnets can be turned around to take advantage of shielding provided by the magnet's iron.
- Sensitive devices can be moved to areas with lower radiation levels.
- Radiation-hardened electronic devices are available in some cases. Cables, wiring, and water hoses can be chosen for best radiation resistance.
- Alcoves can be provided to partially shield electronics.
- Shielding can be installed at critical points.
- Scrapers or collimators can sometimes be installed to force losses to occur where they are less of a problem.

To minimize potential radiation damage, there should be close collaboration during design among the health physicist, the accelerator designer, and designers of the auxiliary systems—electronics, vacuum pumps, motors, and so forth.

Radiation can also do secondary damage from the chemicals it produces. For example, nitric acid formed in moist air can cause corrosion. In one instance, acid condensed on a window of a water dump, and ate through the window. Radiation-produced ozone can also corrode. Moreover, chemical reactions that would not normally take place may do so, under influence of the ionization caused by radiation.

Metals and ceramics are not usually damaged by radiation. Instead, the worst problems will be with semiconductors and organic materials. Every use of organic and halogenated organic material should be evaluated, including electrical insulation, o-rings and gaskets, lubricants, and optics. The radiation resistance of these materials varies widely. Teflon is probably the least resistant material of interest and should always be avoided in high radiation areas.

The literature on radiation damage is extensive, but scattered. This report will attempt only to present some review articles, which in turn will give many more references.

Sandia Report SAND85-0776 (Go85) is a good introduction to radiation effects on semiconductors and electronic circuits. It describes general effects and gives some specific information on failure. It has 150 references. An earlier report (Ha83) is similar, but covers some different materials. Bo85 summarizes the radiation damage to synthetic organic materials and covers insulators, elastomers, lubricants, adhesives, and coatings. It gives threshold dose and 25% change dose for many materials, and has 80 references. There are a series of CERN reports which have been issued since 1970. These reports (Be82, Li85, Ph81, Sc75, Sc79a, Sc79b, and Va70) deal with materials of interest at accelerators. An older reference that covers some materials not included in the previous ones is Ki64.

The present committee knows of only one published report (Sw85) that describes calculations of radiation dose with application to radiation damage from an accelerator, even though such work has frequently been done.

3.4 INSTRUMENTS AND MEASUREMENTS

To completely characterize the radiation field of a high energy accelerator is a formidable task, one not routinely attempted. However, once the field's components and energy distribution are precisely determined, less complicated surveys are possible. For instance, the total dose equivalent (DE) can be related to that fraction of the total DE measured by fewer, less sophisticated detectors. In a similar manner, the response of personnel dosimeters can be calibrated.

No single type of detector can satisfy all measurement needs at a high energy accelerator. In practice, both physical and dose-tailored detectors have important advantages and disadvantages.

The current lack of consensus on preferred instruments and techniques is due in part to the diversity of their tasks. But it is also due to the fact that there have not been extensive comparisons among well characterized and reproducible radiation fields at high energy accelerators (Pa73, Th85).

Criteria for Instrument Selection

Measurements of prompt radiation fields (Mc81) are required for occupational and enviromental monitoring, for accident dosimetry and calibration of the dosimeters, as well as for health physics research. In selecting measurement techniques and instruments, one should consider the purpose of the measurement and the radiation field's parameters. Practical factors should also be taken into account when making selections.

One can define two types of measurement effort, limited and extended. Limited survey efforts are those tasks which are limited in time, effort, and scope. They can be performed with minimal instrumentation that responds to only a limited portion of the energy spectrum. Prior knowledge of the radiation field will then be needed to interpret the results. (See Table III.)

TABLE III. METHODS FOR LIMITED SURVEYS

Technique	Description	Advantages	Disadvantages	Reference
Moderated and DE–moderated thermal neutral detectors; BF_3, ^3He, LiI (ACTIVE) IN and Au foils, TLD (PASSIVE)	*a*) Andersson–Braun: boron-loaded, plastic-layered, DE–moderated with BF_3 gas proportional counter; *b*) Leake: spherical DE–moderated ^3He gas proportional counter; *c*): other: cylindrical or spherical moderators with thermal detectors to measure neutron fluence; *d*) as in *c*) but with DE–moderators.	(*a,b,c*) portable, good noise and photon pileup immunity, stable; (*a,b*) Gives DE estimate for neutrons $<$ 10 MeV to within a factor of 2; (*c*) Immune to beam structure, noise and rate when activation foils are used.	Active portable counters sometimes respond to r. f. sources; (*a,b*) Rate meters may not respond correctly in pulsed fields; (*c*) Prior knowledge of energy spectrum is needed to assess DE; (*d*) As in (*c*) when energy range exceeds instrument cutoff.	*a*) An63a,b *b*) Le68 *c*) St58
Moderated or DE–moderated thermal neutron detectors as in first technique plus a high energy detector such as (^{12}C (n, 2n)^{11}C) or 18-inch spherical moderator	DE's are additive except when prior spectral knowledge suggests otherwise.	Simplicity.	Activation detectors needs time versus intensity information to calculate saturated activity.	*b*) Gi68 *b*) Mc60 *c*) Te70
a) Tissue-equivalent I. C. *b*) Paired ion chambers	*a)* Reading multiplied by 5 to 10 to estimate DE; *b*) One IC is tissue equivalent, the other has nonhydrogenous walls and gas of low atomic number.	*a*) Allows rapid estimate of DE, conservative; *b*) Separates neutron and gamma components.		*a*) Co53 *b*) Go68
Scintillation Method	Response of organic scintillator is dependent on LET, used with T. E., I. C.		Caution when used near magnetic fields.	Ps71,77
AIR and TE IC's used with first two techniques.	Allows photon and charged particle estimate to be included in the total DE estimate. Yields an effective quality factor.			Ho72

Extended survey efforts require the use of major techniques to assess the major components of the radiation field. They may involve direct DE assessment of accelerator-produced neutrons or some form of neutron spectroscopy, as well as methods for assessing the other components, especially photons (Tables IV and V).

Monitoring environmental radiation at laboratory boundaries involves measuring direct and air-scattered prompt neutrons when the accelerator is running, and the natural radiation background when it is not. The neutron energy spectrum is usually assumed to be such that rem-moderated neutron detectors are suitable.

The contribution of DE from accelerator laboratories to the general public is often a small fraction of the natural background. This may make it difficult to determine the accelerator's contribution to the total DE. For new installations, prestartup measurements of the natural radiation background are recommended. Once an accelerator is operating, one set of detectors at the site boundary may be gated on only when the accelerator is on; another set can monitor during periods between accelerator beam pulses.

The primary photon contribution to the total DE diminishes more quickly with distance from the accelerator than does the primary neutron component. For accelerators whose energy exceeds about 10 GeV, muons may dominate at small angles to the beam direction wherever the beam strikes. This is because the muons are highly penetrating. Ionization chambers of suitable sensitivity can be used as monitors, as can charged particle scintillation and solid state detectors.

Limited surveys to measure accelerator radiation are appropriate if time and effort must be conserved. If the purpose is, for example, to allow someone to enter for quick repairs, the measurements taken may be of little subsequent value. However, it is good practice to record, in a log book, such details as the beam species, energy, and intensity, target material and thickness, shielding type and thickness, detector position, and measurement geometry.

TABLE IV. MAJOR TECHNIQUES FOR DIRECT DOSE EQUIVALENT ASSESSMENT OF ACCELERATOR–PRODUCED NEUTRONS

Technique	Description	Principal Use	Reference
Paired ion chambers	One chamber is tissue equivalent; the other is made with non-hydrogenous walls and gas of low atomic number.	Indicates maximum DE ($\pm 15\%$) for neutrons $\leq$ 10 MeV	Go68
Moderated LiI, ^{3}He; BF_3 detectors	Moderator tailored to give response similar to DE response (En) curves.	< 20 MeV	
Recombination-type TE ion chambers	Characteristics of columnar recombination are used to determine the LET of charged particles. Q is inferred from comparison of ioniziation currents collected with two different voltage gradients in tissue-equivalent ion chambers whose gas pressure is 3 kg cm^{-2} (294 kPa).	High energy mixed radiation fields	Zi62 Su63 Su64 Zi64 Su84
LET spectrometer	Spherical TE ion chamber at a pressure equivalent to one micron chamber diameter. Response proportional to product of LET and track length. Data computer-processed to yield differential LET spectrum. The total dose equivalent is obtained by folding the associated Q over the entire LET spectrum to get the DE spectrum and then summing over the DE spectrum.	High energy mixed radiation fields	Ro55
BNL DE meter	Modification of Rossi LET spectrometer (more rugged, improved ion chamber field shape and leakage, and reduced need for frequent gas re-filling). Two signals are extracted: one is proportional to dose rate independent of LET; the other is processed by nonlinear amplifiers to produce an amplitude dependence which varies as does Q with LET.	High energy mixed radiation fields	Ba69a Ku73a Ku73b
Scintillation	TE ion chamber, with organic scintillator which has a response dependent on LET	High energy mixed radiation fields	Ps71 Ps77
Moderated BF_3 + NE 213 proton recoil detector	DE determined by sum of two instrument readings: (1) Andersson–Braun or Leake rem meters, and (2) NE–213 organic scintillator biased at 8.5 MeV		Te70

TABLE V. MAJOR TECHNIQUES FOR NEUTRON SPECTROSCOPY

Technique	Description	Principal Use	Reference
Threshold detectors	Active (e.g., Bi fission counter) and passive [e.g., ^{12}C (n,2n) ^{11}C] detectors may be used separately or combined along with an appropriate spectrum unfolding code. Low resolution technique but can be reliable for accelerator produced neutron spectra which is devoid of sharp structure. Activation detectors have the advantage of immunity to counting losses at high fluence rates.	High energy mixed radiation fields	Sm65 Th79 Ro69
Nuclear emulsion	*a*) Proton recoil spectrum measurements can give +/-20% accuracy for 2–20 MeV neutrons for 10^7 n/cm^2 in 600μ emulsion. *b*) Star prong production, 20-300 MeV. Both techniques yield reliable results; both are relatively insensitive, tedious, and time-consuming, using techniques and equipment no longer in readiness at many laboratories.	High energy mixed radiation fields	Le64 Ak63 Re65 Pa69
Spark chamber	Large array approximately 1 m $\times$ 1 m with alternating converters and spark counters, has anticoincidence shield for external charged particle. Track length and angle are measured and input to unfolding code. Useful range: 30 MeV at 15% efficiency to 300 MeV at 0.5% efficiency.	High energy mixed radiation fields	Ri69 Ri74 Ma74 Li73
Multisphere	Hydrogenous spheres up to 18 inches diameter house thermal neutron detectors. Possiblity of photon interference during high instantaneous fluence rates when LiI is used. This problem is lessened with ^3He detectors. Activation and track detectors may also be used. Response is from thermal to 50 MeV or higher. Response functions depend largely on calculation.	High energy mixed radiation fields	Na72
Proton–recoil telescope	Requires point source, lacks sensitivity required for personnel monitoring. High resolution method. Invaluable for research efforts.		Ma73

For accident dosimetry, a simulated scenario, real or suspected, would be appropriate. The scenario could involve in-beam or other high dose exposures to personnel. Measurements are then made with appropriate dosimeters. These measurements may help determine if a suspected exposure was real, and to estimate the magnitude of the DE.

Calibrating and interpreting dosimeters can involve appreciable effort. Simple dosimeters such as those used in personal dosimetry, and simple survey instruments, should be calibrated when possible in radiation fields that are similar to those in which they will be used. Conversely, to interpret measurements made with these instruments, one should know as much as possible about the radiation field which was measured.

Research efforts in health physics may involve measurements of particle yield and angular distribution as the beam hits the target (source term measurements), absolute primary beam intensity or reaction cross sections. Shielding and particle transport studies are also in this category.

For all determinations, choice of instrument and technique is often strongly influenced by the characteristics of the radiation field. Types of fields encountered include mixed radiation fields and pulsed fields. The energy distribution of the field is also of interest for instrument selection.

At high energy particle accelerators it may be necessary to measure muons at small angles to the beam direction. A simple measurement using an ionization chamber with and without a suitable thickness of lead between the source and the detector may suggest the presence of muons, and may provide a rough indication of its magnitude. A more sophisticated method involves the use of a pair of scintillators in coincidence in the form of a telescope such that the scintillator size and distance between them defines the solid angle. Lead may be interposed as a diagnostic tool to determine the presence of electron or hadrons. This method has the advantage of greater sensitivity because it detects discrete events with the reduced background afforded by its directional response. Its directionality may also be of value in determining the source of the muons.

Detectors for Mixed Radiation Fields

The complexity of the radiation field, and therefore of radiation measurements, increases with the energy of the accelerator. For electron accelerators of energies below the threshold for neutron production, one is concerned only with bremsstrahlung from beam-target interactions and x-rays from high voltage generators and accelerator structures. To measure these, an ionization chamber would be appropriate.

Neutrons are produced at electron accelerators when the electron energy exceeds the threshold for photoneutron production (1.7 MeV for Be, 2.2 MeV for D, and 6–10 MeV for most other nuclei). At both proton and heavier ion accelerators, neutrons are produced when the energy of the beam particles exceeds the coulomb barrier of the target nuclei. However, even at low energies, heavy ions can produce copious neutrons through various exoergic reactions. As long as the neutron energy does not exceed a few MeV, a moderator with a thermal neutron detector will suffice for readings meant to guide worker protection. The moderator should be one that responds proportionally to neutron DE. Examples of such moderators are the Andersson-Braun (An63a, An63b) or Leake (Le68) instruments.

Nonhydrogenous ionization chambers are useful to determine the contribution of photons and charged particles to the total absorbed dose. When used with a tissue equivalent ionization chamber, one can determine the absorbed dose due to neutrons. A conservative value of quality factor (Q, usually 10)* can then be used to estimate the total DE.

At some accelerators of intermediate energy, neutrons with energies in excess of several MeV are produced, but the primary beam energy is less than that

* At the time of this writing, the NCRP has recommended that Q be increased by a factor of 2 so that a conservative value would be 20. Regulatory bodies have taken no action yet.

required to produce large numbers of pions (threshold of about 140 MeV). For these machines, one must take into account the limited energy response of DE-moderated neutron detectors. Significant numbers of neutrons may be produced whose energies are too high to be detected adequately by moderated thermal neutron detectors. This does not mean that DE-moderated or fluence-moderated detectors (whose fluence response is approximately independent of energy within its applicable range) would be useless. However, the degree of underresponse must be previously established so that an appropriate correction can be applied. The radiation field can be characterized beforehand through one of the more extensive neutron spectroscopy techniques or by DE assessment. Examples of neutron spectroscopy methods are given in Table V.

High energy accelerators produce abundant neutrons with energy greater than 100 MeV (ICRU78), as well as muons from beam-target interactions at forward angles. The high energy component of the neutron field becomes more important when shielding is greater than about 2 meters of concrete, because of the longer attenuation length of neutrons above 100 MeV. Photons and neutrons are likely to be comparable contributors to the DE at electron accelerators, while at proton and heavier ion accelerators, neutrons will dominate the field. In thinly shielded areas, a significant fraction of the neutron DE is likely to be delivered by neutrons whose energy exceeds 20 MeV.

Detectors based on ionization recombination can exhibit a nearly ideal response as a function of LET, and can therefore be very useful in determining DE and Q (Su84). But, as discussed in Su84, these detectors have several disadvantages. Only about 3% of the ion pairs recombine when the field is composed of photons or other low LET radiations. Consequently, large chamber volumes are needed to attain adequate sensitivity. Even then, it is difficult to measure DE rates below 10 mrem/hr (28 nSv s^{-1}).

Unfortunately, having large chamber volumes under high pressure introduces or enhances other problems, such as microphonics and noise. Also, the thick metal containers needed to contain high pressures absorb the low energy part of the spectrum. These detectors, because of their large size, tend to be impractical for depth dose distribution studies. Similar problems exist for the sensitivity of LET spectrometers, due to the saturation that can be encountered in pulsed fields of high peak intensity. Consequently, few are used routinely at high energy accelerator laboratories. In addition, an important theoretical concern currently questions the issue of the Q/L relationship itself (De85, ICRU86).

Pulsed Radiation Fields

Measurments of pulsed fields will be influenced by the field's instantaneous intensity, its duration and cycle time, and by the characteristics of the detector and its circuitry. The amount by which the instantaneous or peak intensity of the radiation field exceeds its average value depends on the accelerator's repetition rate or cycle time, and the length of time that the beam interacts with the target. The peak or instantaneous radiation intensity, Ip, during the beam spill, is related to the average value, I, by:

$$Ip = I/DF$$

where DF is the duty factor of the accelerator.

An instrument which accurately records the average dose rate of events spread evenly in time might not be able to contend with high instantaneous dose rates delivered in one or more short bursts. Yet a pulsed field which causes problems with one detector may not with another.

The term "pulse" has two different meanings in the dosimetry of accelerator radiation. The time that the accelerated beam interacts with the target is variously called "spill," "burst," or "pulse." When instruments are used to detect discrete events and electronically process them, each event is also called a "pulse." To avoid confusion, the terms "beam pulse" and "detector pulse" will be used.

Instruments which use count-rate meters are affected by the problem associated with pulsed fields, that of beam targeting repetition rate. If the beam continues to interact with the target for the few seconds necessary for a full response by count-rate meters, there is no problem. But if the duration of the beam spill is much shorter than the meter's response time, and the time between beam bursts is much longer, then the meter response is meaningless.

The following sections will discuss various types of detectors in terms of how they are affected by pulsed radiation fields.

Ionization Chambers

Recombination is most pronounced in ionization chambers dominated by ionic conduction. The air-filled ion chamber is an example. Most of the electrons produced in the chamber attach themselves to the gas molecules within. As a result, efficiency of charge collection at high dose rates is limited, as is collection at large charge densities produced by intense beam pulses. The more quickly the charges can be collected, the smaller will be the recombination.

Transit time in air-filled ionization chambers at normal temperature and pressure will depend on ion mobility (about 1.3 cm/sec per V/cm for the slower positive ion), chamber dimensions, the collection voltage gradient, and gas pressure.

For chamber-filling gases which do not attach to free electrons to form negative ions (argon, nitrogen, and others), the mechanism which limits collection efficiency at high charge concentration is positive ion space charge, rather than general recombination.

Within limits, steps can be taken to mitigate these ionization chamber problems. Keeping the volume constant, the charge separation potential can be increased up to the point beyond which there is excessive leakage, breakdown, or ionization by collision of accelerated ions. Or the chamber volume may be decreased, assuming that, in the process, a closer electrode spacing and the resulting increased voltage gradient is achieved. However, a smaller volume will decrease sensitivity.

As an example of a pulsed field situation, consider the case of an electron linear accelerator which delivers evenly spaced, one-microsecond beam pulses at a repetition rate of 360 Hz. Assuming that the dose associated with each beam pulse is one nanorad (10 pGy), the dose per hour would be 1.3 mrad (13 μGy). These are both relatively low values. The instantaneous dose rate, however, is 3.6 rads/hour (10 μGy/s). Many instruments can handle such dose rates; others cannot. An instrument which can handle large dose rates for an extended period of time will certainly perform well for shorter time periods.

If recombination is suspected, it may be possible to assess and compensate for decreased collection efficiency. Two sets of measurements can be made in the same field at different collection voltages. This two-point technique for assessing collection efficiency is described in ICRU-82.

Another approach is to compare the ion chamber's integrated dose values with that of LiF TLDs which do not show limiting effects at high dose rates.

When the charge is deposited in a time that is shorter than the charge collection time, the important factor is the total charge density that is deposited, rather than the deposition rate. The problem of recombination at high charge concentrations is compounded when the beam cycle time is less than the charge collection time for the ionization chamber. Each beam pulse's contribution to charges in the chamber will then overlap. The result will be a larger recombination than would be the case for a single isolated beam pulse. In our example above, however, the interval between beam pulses is 2.8 ms, which is long compared to the time necessary to clear most ionization chambers of charges from the previous pulse.

Appendix C gives a case in which successive beam pulses arrive at the ion chamber in a time which is short compared to the time necessary to sweep charges out of the ion chamber (Bo66, ICRU82).

Proportional Counters

Pulse pair resolution time is a measure of the ability of electronic circuitry to resolve closely spaced events. The circuitry's performance sets a limit on the ability of gas proportional counters to count each event when dose or event rates are high. The pulse durations can be electronically reduced. However, the mechanism that determines the rise time of the event (ion multiplication and collection) limits how short the pulse can be. Further differentiation of the pulse will result in a decreased pulse height which lowers the signal-to-noise ratio and makes the detector system more susceptible to interference from photon pileup. Proportional counters do not exhibit dead time as do Geiger-Muller counters. Instead, the collection voltage typically drops less than one volt during multiplication and charge collection, which does not appreciably lower the electronic gain of the detector. Also, the region of the anode over which the multiplication takes place is very small, leaving the rest of the anode wire undisturbed.

Gas proportional counters with reduced volume may be used to lessen counting losses, provided one can accept a corresponding loss in sensitivity. Also, substitution of less sensitive counters of the same volume may be possible, such as BF_3 tubes depleted in ^{10}B.

Geiger-Muller Counters

Geiger-Muller (G-M) pulse counters exhibit long dead time, on the order of 1 microminute, and can become temporarily incapacitated by a rapid rate of events (NCRP85a). However, some G-M counters are designed to switch from pulse to current mode when event rates become excessively high.

Obviously, for accelerators with beam pulses of a few microseconds or less, one can never detect more than 1 G-M detector pulse per beam pulse.

Scintillator/Photomultiplier Detectors

The count rate capability of scintillator/photomultiplier detectors depends critically on whether the photomultiplier high voltage supply can stay regulated during the high current drain associated with high count rates. Given sufficiently high count rate, temporary failure of linearity is assured.

The size of the detector in scintillator/photomultiplier systems can be decreased to reduce the current drain of the photomultiplier. However, this may not be practical in situations where the scintillator must be large to contain the energy of the photon in the photopeak. Some improvement can be made by increasing the power available to the last dynodes of the photomultiplier.

Photomultipliers are very sensitive to magnetic fields (even to that of the earth), and they should be used with caution near the stray fields of particle accelerators and their associated magnets. The effects of magnetic fields depend on the field strength and the orientation of the photomultiplier tube in the field, and can range from slight to complete loss of signal, or a change in position of the photopeak in a multi-channel analyzer. An indication that poor response may be due to a magnetic field is to rotate the detector about the point of measurement and see if there is an unwarranted change in response.

Some commercial suppliers of detectors either neglect to enclose them in magnetic shields or do not extend the shield beyond the face of the photomultiplier. A rule of thumb is that the magnetic shield should extend beyond the photomultiplier's face by a distance equal to the photomultiplier's diameter. In addition, all magnetic shields are only partially effective. It is quite difficult to shield a photomultiplier tube well enough to operate in a 100 gauss (0.01 T) field.

The amplitude of signals from scintillator/photomultiplier combinations will vary with temperature. Both scintillators and photomultipliers exhibit temperature-related gain variations. Field instruments, because of the uncontrolled temperatures where they are generally used, may be particularly prone to such problems when used with narrow-window, single-channel analyzers. Instruments of the same type must be individually checked prior to their first use, because differences may exist. Although these temperature effects are not large, they should be evaluated, as should temperature effects on the auxiliary electronics (HV supply, amplifier, discriminator, and so forth).

Fine Structure on the Beam Pulse

A simplifying assumption made thus far is that the intensity of events during beam spill is uniform. This is not always the case. Fine structure on the beam spill can be found by observing detector events on an oscilloscope. If the oscilloscope's horizontal time sweep is triggered by a timing marker coincident with the start of beam targeting, and beam spill duration is presented on the x-axis, fine structure will be seen as one or more spikes or peaks on the y-axis.

If the observation is made with a scintillator/photomultiplier system, high intensity fine structure may exceed the capability of the photomultiplier's high voltage power supply. If so, the oscilloscope display will indicate few or no events during the period of highest beam loss—a dropout will result rather than a spike. Usually, radiation measurements taken at some distance from the target and outside of thick shielding will not be adversely affected. The potential remains, however, and should be considered.

Often, research groups will have detectors in the beam which can indicate the amount of fine structure on the beam spill, which can help the health physicist tell if a potential for counting loss exists. Scattering and degradation of neutron energy in both nearby shielding and moderators of neutron detectors will spread the arrival time of the events. For BF_3 moderators that are 6 cm thick, half of the events from an instantaneous burst will not be captured until about 100 microseconds or more have elapsed. See Fig. 1 (Je64).

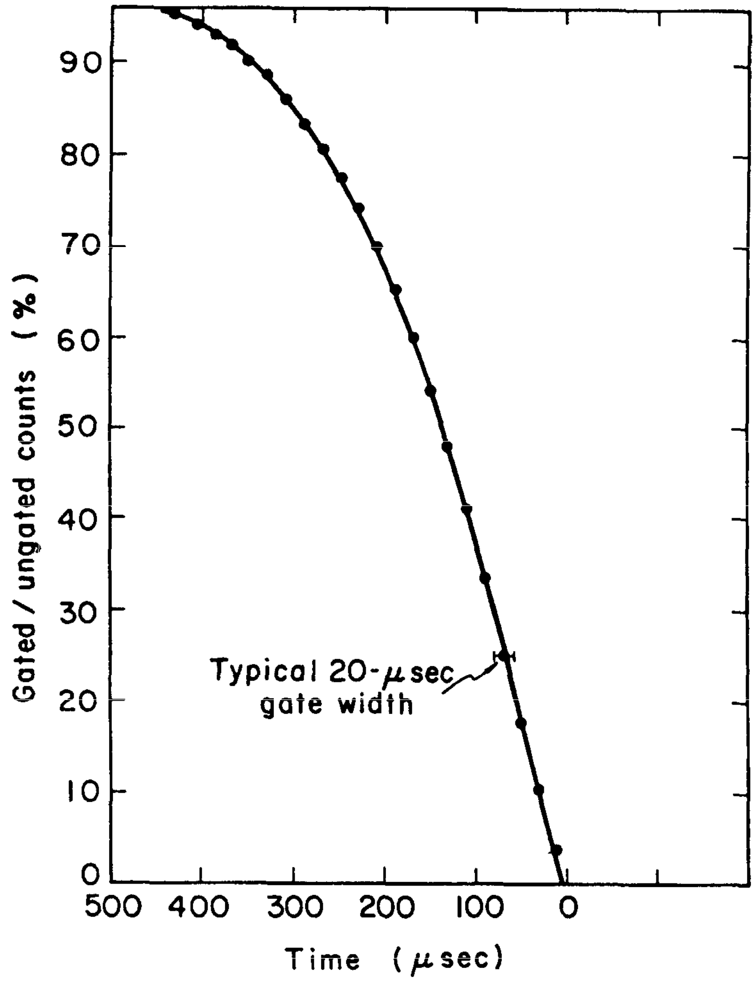


Fig. 1

3.5 PERSONNEL DOSIMETRY

Beta-gamma Dosimetry: The problems involved with beta-gamma dosimetry at an accelerator are by no means unique. The radioisotopes ^{64}Cu, ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, ^{59}Fe, ^{54}Mn, ^{56}Mn, ^{22}Na, and ^{24}Na are those that produce most of the dose to personnel, regardless of whether the source is a proton or electron accelerator. And these isotopes, aside from being primarily neutron-deficient ones, might be encountered in any other radiation environment. Finally, at an accelerator facility, almost all of the radiation dose to personnel comes from radioactivity induced in the accelerator's components rather than prompt radiation during accelerator operation. Personnel dosimeters therefore can be those acceptable elsewhere, such as film badge or TLDs. DOE requires that beta-gamma dosimeters are accepted under the DOELAP program (DOE86).

Since the activation at an accelerator is more of a volume process than a surface one, it is rare for the beta dose to be important. However, the prudent Radiation Safety Officer should keep the possibility of beta exposures in mind.

In the rare case where prompt ionizing radiation is important, it would always be either photons (bremsstrahlung) from an electron accelerator or muons from either a proton or an electron accelerator (Ne76). For these also, a film badge or TLD would be adequate.

Neutron Dosimetry: The situation for neutron fields is much more complicated at accelerators than other facilities. The reason is that the range of neutrons energies is greater—from thermal to several GeV. The fraction of the DE due to the different neutron contributors can vary markedly from one spot to another at the same accelerator. An example is measurements on the CERN Proton Synchrotron shown in Table VI (reproduced from Ri73). Both points would be considered to be behind thick shields. In such a situation, it is clearly necessary to measure all of the components.

Measurements such as those in Table VI are difficult to do, even with large equipment that is only semi-portable. As another example, in Ho84, three different measurement systems were compared at seven locations around CERN. The ratio of the highest response to the lowest response was as high as 1.8. Measurements at the Serpukhov proton synchrotron comparing six different systems are also reported in Ho84. Here the ratio of the highest response to the lowest response was as high as 3.6. Measurement systems used included multiple ionization chambers, remmeters, moderated detectors, recombination ionization chambers, and LET spectrometers. While the above measurements were all on proton accelerators behind thick shields, the results are probably also valid for

TABLE VI.

COMPOSITION OF RADIATION FIELDS ABOVE THICK SHIELDS AT THE CPS

Radiation	Percentage of Dose Equivalent	
	Above concrete shield bridge	Above target through earth shield
Thermal neutrons	11–12	< 1–3
Fast neutrons (0.1 MeV < E < 20 MeV)	50–70	10–37
High energy particles (E > 20 MeV)	2–25	52–89
γ-rays and ionization from charged particles	2–19	1–13

thick shields and electron accelerators. Obviously, if agreement between complex measurement systems is so poor, it will be worse for personal dosimeters.

A quick survey of some DOE accelerator laboratories showed three laboratories using NTA film and two using quasi-albedo dosimeters with TLDs. One facility found that the ratio of thermal neutron fluence to total neutron DE varied only about an order of magnitude, so this lab measures thermal neutron fluence with TLDs. The neutron DE is then calculated using a ratio that may overestimate the true DE by a factor of 6 or underestimate it by a factor of 2. One facility intends to switch to CR-39 track-etch detectors, one is considering it, and one has tried CR-39 and is abandoning it. At this time it is not possible to recommend any personnel neutron dosimeter as being very satisfactory. Fortunately, neutrons probably contribute less than 10% of the total person-rem at any high energy accelerator. Neutrons may be significant at the entrances to lower energy accelerators, however (NCRP84).

Consideration should be given to accident dosimetry. In an accelerator environment, the only accident that involves special dosimetry problem is when a person is exposed near a point of high beam loss without the interposition of customary shielding. This might occur when someone is inside the accelerator housing with the beam on or when a primary beam escapes to an occupied area. In such cases, the nature of the radiation field may be quite different than that normally encountered and interpretation of personnel dosimeter data correspondingly difficult. In a few cases, health physicists have evaluated the induced radioactivity of the body as a method of estimating the accident dose (Ba66, Di73, Je68, Ko65, Le65, Mi72).

3.6 Experimenter Access to Beams

Experimenters often must have access to beam areas when the particle beams are on, to make adjustments or to investigate equipment problems. Such work can be carried out without radiation danger if beams are well-defined and the operator does not have to place his or her body into the beam. On the other hand, it is easy to conceive of situations wherethe experimenter inadvertently places part of his or her body in the beam; the experimenter thinks the beam is off when in fact the beam is on; or, the experimenter intentionally works in the beam, failing to appreciate the radiation doses that can result. Any program which permits experimenter access should address the following criteria.

- Training. Any individual with access to secondary beams should be specifically instructed on what activities are acceptable around the beam. This information should also include biological effects of radiation and dose rate information. Only individuals who have had these instructions should be authorized to work under beam-on conditions.

- Limits According to Beam Intensity. Access to beams should be decided based upon the beams' dose rates. Some beam intensities will be so low that no controls are needed. Conversely, some intensities are so high that no access should be permitted. An example of such a system used at Brookhaven National Laboratory is shown in Table VII.
- Beam Barriers. Barriers around the beam serve as important safeguards against accidental exposures. These barriers should be substantial enough to prevent easy removal (a beam pipe rather than simply marking the path with tape) and should enclose the beam specifically, not identify a beam area.
- Beam-On Indicators. Visual and audible indicators which are activated by the beam serve as important reminders to people working in the area that the beam is on.

4. ADMINISTRATION OF A HEALTH PHYSICS PROGRAM

4.1 RECORDS

Recordkeeping is a necessary part of all health physics operations, including those at accelerators. Records will help to show that the health physics program is adequate, and can help analyze and solve future safety problems. Records are needed for legal purposes, to protect the facility in case of a lawsuit, or to assist in investigating contested, unusual, or accidental personnel exposures. Keeping records, moreover, is mandated by DOE, and the data so produced will provide, for audits, a trail of compliance with DOE requirements.

TABLE VII. GENERAL GUIDELINES FOR AGS RADIATION SECURITY SYSTEM CLASSIFICATION AND APPLICATION

Allowable Radiation Area R/hr	Allowable Radiation Beam p/sec/cm²	Allowable Radiation Small Source Residual @ 3" R/hr	Access	Enclosure Barrier	Enclosure Gate	Potential Radiation under Abnormal Conditions Area R/hr	Potential Radiation under Abnormal Conditions Beam p/sec/cm²	Minimum Security System	Purpose of Security System
> 300	$> 3 \times 10^7$	> 3000	Absolute Prohibition	Impregnable	Primary			Hardwire, Failsafe Dual	Preventing Access or Beam
< 300	$< 3 \times 10^7$	< 3000	Special Procedure	Fully Enclosed	Primary	> 300	$> 3 \times 10^7$	*a*) Hardwire, Failsafe, Dual *b*) Not Specified	*a*) Controlling Access or Beam
< 30	$< 3 \times 10^6$	< 300	HP Supervision	Walls/ Fixed Fences	Secondary	< 300 > 300	$> 3 \times 10^7$ $> 3 \times 10^7$	*a*) Hardwire, Failsafe *b*) Active, Failsafe c) Hardwire, Failsafe Dual	*a*) Controlling Access or Beam *b,c*) Preventing rise to these levels
< 3	$< 10^5$	< 30	Authorized Individuals	Fences/ Barriers	Locks	< 30 < 300 > 300	$< 30 \times 10^6$ $< 3 \times 10^7$ $> 3 \times 10^7$	*a*) Active, Failsafe *b*) Active, Failsafe, Hardwire, Failsafe, Dual	*a*) Controlling Access and/or Beam, Warning *b*) Preventing rise to these levels
$> .1$	< 3000	$< .3$	Radiation Warning Signs	Noticeable	None	< 3 < 30 > 30	$< 10^5$ $< 3 \times 10^6$ $> 3 \times 10^6$	*a*) Active *b*) Dual, Active *c*) Active, Failsafe, Dual *d*) Hardwire, Failsafe	*a*) Alarm on Excessive Radiation *b,c,d*) Preventing rise to these levels
$< .005$	< 50	$< .005$	No Control	None	None	$< .1$ < 3 > 3	< 3000 $< 10^5$ $> 10^5$	*a*) None *b*) Active *c*) Active, Failsafe, Dual *d*) Hardwire, Failsafe, Dual	*b,c,d*) Preventing rise to these levels

The principal guide for retention periods is DOE Order 1324.2—Records Disposition, Chapter V—Retention of Contractor Records, dated 5/28/80. Other recordkeeping requirements are scattered throughout the DOE Orders. Table VIII is a compilation of records that are needed and the required retention periods. The health physicist will probably find that other records are necessary for his own purposes. At this time, DOE Order 1324.7 has placed a temporary freeze on destroying any records related to health and safety.

Log books may be used to record information which must be available to rotating shifts of the accelerator's operators. Logged information which needs to be associated with a particular activity or facility location can be kept in separate files. At a large facility, it is often easier to retrieve information if it is filed in the log book by subject, instead of in chronological order. The ability to retrieve historical data about radiation patterns, shielding, and so forth is useful when a new operating condition arises. While this is true for either large or small facilities, retrieval is usually easier at smaller sites because of the more limited possibilities and closer proximity of the physical areas.

Control of access to the records should be consistent with requirements of the Privacy Act.

Systems for recording radiation exposure are covered in ANSI66.

Storage of records for the required retention periods is difficult. Government repositories require very specific instruction to retain stored records for more than five years. Storage of records in computer format is a compact way of doing it but it is necessary to review the system whenever there is a change in computer equipment. For example, one laboratory had been using magnetic tape storage. They found there had been a change from 7-track to 9-track tape and they were no longer able to read their tape archives. Future changes in computers over a

TABLE VIII. RECORD RETENTION

Item	Filing Unit Title and Description	Retention Period
1	Individual Radiation Dose Records	75 years
2	Radioactive Waste Disposal Records	Permanent
3	Radiation Detection Instrument Calibration Records	75 years
4	Inspection Surveys	Permanent
5	Nuclear Counting Lab Analysis Reports and Quality Assurance Records	Permanent
6	Interlock Review and Test Notification Records	Permanent
7	Radioactive Sources Inventory and Records	Permanent
8	ALARA Committee Minutes	Permanent
9	On–Site Radiation Monitoring Records	Permanent
10	Radiological Facilities Records	Permanent
11	General Correspondence Files	Permanent
12	Site Environmental Reports	Permanent
13	Environmental Contamination Records	Permanent
14	Environmental Protection Program Procedures (includes Environmental Evaluations, Nonradioactive and Radioactive Pollution, Decommissioning and Environmental Reviews	Permanent
15	Radiation and Contamination Surveys, Air Sampling Logs	75 years
16	DOE Reports — Annual, Semi–annual, Quarterly, Monthly	Permanent
17	Significant Occurrence Reports	Permanent
18	Appraisals, Audits, Inspections (includes those conducted by DOE and internal)	10 years
19	Procedural Manuals/Handbooks, e.g., Radiation Guide or Safety Manual	Permanent
20	Laboratory Safety Committee/ Subcommittee Files	Permanent
21	Budget and Cost Files	2 years
22	Experiment Review Files	Permanent

period as long as 75 years could make all present memory methods unreadable. In addition, magnetic recording media of today are sufficiently stable that storage of only 10–20 years is practical (NRC86). This same reference contains valuable information concerning record storage in many other formats including paper.

4.2 AUDITS

Internal audits of a radiation safety program are required by DOE Order 5480.1A. If properly implemented, internal audits will assure the top levels of management that radiation safety is kept consistent with DOE orders and laboratory policy.

Recommendations for Audits

The audit program should fit the size and nature of the facility. It is intended as an addition to, not a replacement of, an inspection program. An inspection is usually a rather informal "walk through" by a safety person, to list discrepancies and check if there has been follow-up on action items. However, an audit should be more thorough, better documented and involve management.

Following are suggested audit procedures.

- Determine the elements of the program to be audited.
- Determine how often each element should be audited.
- Develop and announce the schedule each year.
- Leave the schedule flexible so that unscheduled but timely subjects can be substituted.

The audit format should be as follows:

- Select the time to minimize impact on laboratory operation.
- Select the appropriate audit team.
- Develop the detailed subjects to be addressed.

- Formally announce the details—time, subjects, and audit team—to both line and top management. The announcement should strongly encourage participation by the line organization.
- Conduct the audit.
- Draft a report.
- Obtain concurrence from top management and the line organizations on action items and dates of completion.
- Issue the final report. The report should be signed by top management, line management, and the Radiation Safety Officer.
- Follow-up should document completion of action items.

The audit team should use the following approach:

- Review relevant external standards, such as DOE orders.
- Compare the Laboratory Policy and Program to the external requirements.
- Review the line organization files which document compliance and implementation of their program.
- Conduct spot inspections to compare actual practice with records.

Frequency of internal audits should be based on changes in the program or facilities. Major program elements should be reviewed every three to five years, or if a significant change occurs. Other elements may need review only when significant changes occur.

The members of the audit team should be selected for their expertise in the subject being audited, yet should have no conflict of interest. The charge to the audit team should be well thought out and specific. Adequate time should be given for the team to fulfill their charge.

Experts from outside the facility can be a useful way to either supplement expertise or obtain a more independent review. Smaller facilities may have to rely more heavily on outside experts.

4.3 WRITTEN PROCEDURES AND ADMINISTRATIVE CONTROLS

For clarity, written procedures and administrative controls are treated separately within this section. Written procedures are addressed first and in detail, since administrative controls frequently refer back to written procedures that need to be modified.

Definition of Written Procedure

A written procedure is a document that details or describes an operation by breaking it down into specific steps. Generically known as Written Procedures, the document may be also be called Standard Operating Procedure, Program Statement, Radiation Rules, Radiation Safety Notes, or Operating Instructions. Regardless of title, a written procedure is a document that addresses a single issue or a spectrum of health physics issues dealing with accelerator operation or radiation safety.

Written procedures serve a number of important functions, three of which are especially significant. First, they provide personnel in management, operations, and safety with spelled-out statements of understanding about important aspects of a facility or operation. Second, the document that is properly drafted and followed can significantly mitigate potential for serious incidents. And third, a written procedure serves as a valuable training aid for the health physics staff, personnel in facility operations, and experimenters.

Situations that Call for Written Procedures

Any high risk operation, routine or not, repetitive or occuring only once, should be considered to see if a written procedure would be appropriate. As a minimum, written procedures are needed for operations that are not obvious to trained personnel, that involve unique equipment, could adversely affect people or the environment, or which require a sequence of steps.

Specific instances where written procedures are appropriate and recommended include:

- searches of secured high radiation areas
- bringing new beam lines or experimental caves into operation
- interlock checks
- calibration of area radiation monitors
- monitoring equipment or materials for release to public domain
- intra-site transfer of radioactive or contaminated materials
- off-site shipment of radioactive or other hazardous materials
- handling and disposal of radioactive wastes, liquid or solid
- decontamination of facilities or equipment.

Besides a written procedure, a risk assessment or safety analysis may be appropriate for those operations which could endanger personnel, the environment or the public in an accident or could significantly disrupt facility operations. Specific operations which fall into this category may include:

- unusually hazardous in-beam targets, such as kilocurie tritium targets or uranic and transuranic targets
- high pressure gas targets where catastrophic rupture could disperse radioactive material
- any operation or experiment that poses special concerns of either fire or explosion in areas of radioactive contamination or high radiation.

Elements of a Written Procedure

A written procedure is usually a formalized document that addresses critical issues and is made readily available or posted at locations appropriate to the operation, such as the work area, control room, health physics office, beam channel or shielded enclosure entrance, or experimental cave entrance. A written procedure may include the following suggested elements:

- an appropriate title with current date and expiration date
- an introduction that states the objective(s) of the document
- clearly defined statements of the steps necessary to achieve the objective(s)
- a statement identifying responsibility and qualified operators or individuals
- a safety assessment or accident analysis if applicable
- samples of forms, checklists, tags, or other auditable documentation that are appropriate to or referenced in the written procedure
- an approval sheet for reviewer(s).

An exception to the above format for written procedures is what is sometimes called a "temporary procedures book." This book is a method of establishing short-term or temporary procedures for radiation safety where a need arises out of unanticipated, limited, or emergency operations. Rules or procedures entered in the book are readily revised or cancelled depending upon the circumstances that dictated their need. Alternatively, these procedures may be developed into formalized written procedures as operating experience is gained and variable operating parameters stabilize.

The nature of an operation or issue influences the comprehensiveness of a written procedure. High risk operations, for example, should be evaluated from standpoints of accident and risk probability. In an accident or failure scenario, the procedures should evaluate the potential for radiation exposure of the facility's personnel and the general public. Procedures written for low risk and minimum impact operations need only address operation basics and be brief.

<u>Review and Approval of Written Procedures</u>

A written procedure should have provision for review, approval, and, if appropriate, periodic recertification.

Review and Approval: The issues or operations addressed in a written procedure will largely dictate which scientific disciplines and management levels, besides health physics and safety, need to be involved in the review and approval process. High risk operations such as high pressure tritium gas targets should be reviewed and approved by experts in the fields of metallurgy and high pressure physics, along with upper level management of the facility and health physics. Conversely, the review and approval process for personnel searches, for example, may only need approval from local operations, safety, and health physics management. Regardless of reviewer or management level, a signed approval shows that the reviewer is satisfied with the procedure, and accepts a share of the responsibility.

Recertification Review and Approval: Periodic recertification reviews of written procedures are recommended. A one-year time frame is reasonable, but depends on the particular procedure or operation. A recertification review is always required, regardless of time since the last review, if the scope or nature of an operation significantly changes. The more hazardous the operation covered by the procedure, the smaller the operational change required to prompt a recertification review. The approval chain for review should track changes in the procedure. If an operation has become more hazardous, the rewritten procedure should reflect this, and the corresponding approval levels reviewed and adjusted. Conversely, if an operation has become less significant, the approval levels can be relaxed.

Administrative Controls

Written procedures that address issues of accelerator health physics may also specify some level of control to assure safety of the facility and its personnel. The controls may be physical barriers such as a locked door, or they can be administrative, or a combination of both. Administrative controls may be permanent or temporary. However, in operations where an accident could have major impact on personnel, the facility, or the environment, administrative controls are not recommended for long-term use, because human error can occur.

Administrative controls are generally a flexible form of safety assurance. Many times they are implemented where physical barriers do not exist, are inappropriate, or are temporarily deactivated. Administrative controls usually involve a situation where a responsible operator, experimenter, or safety official controls access to or surveillance of an operation that is potentially hazardous. Again, the danger is that administrative controls leave more room for human error.

Operations that Require Administrative Controls

Administrative controls are likely to be most effective at accelerator facilities where operation areas are small enough to see or hear anyone in them, and where elaborate electrical, mechanical or electromechanical controls are not found or necessary. Working from specific written procedures and simple physical control mechanisms, the operator (and/or safety person) controls access to and provides surveillance over the hazard area.

At large, complex facilities, administrative controls are more likely to be implemented for only brief periods. Such controls are, for example, put in place during times of simultaneous facility construction and operation, while the facility is being operated with safety or interlock systems under repair, or when experimental demands require short-term occupancy of an area normally controlled by barriers. Operator, safety, or other authorized personnel will then provide the control, operating from specific written procedures which either have been formalized or are in "Radiation Rule Book" form.

Elements of Administrative Control

Implementing administrative control requires a standardized record system and a clearly delineated chain of command. Controls such as temporary physical barriers, controlled key issues for controlled locks, and/or guard or watch personnel are also effective in leaving as little room for human error as possible. Administrative controls should be reviewed frequently to assess their adequacy and continuing need. Frequency of review depends on the degree of hazard. Finally, a condition that continually requires administrative control suggests that a physical control system should be put in place. Administrative control should not be continued for the sake of convenience or easy access.

4.4 RADIATION SAFETY STAFF

An accelerator health physicist should be involved as soon as design of an accelerator begins. The health physicist should give guidance to ensure the facility will meet applicable federal, state, and local requirements for radiation protection. Prior to the start of operations, the facility management should appoint a Radiation Safety Officer (sometimes referred to as Principal Health Physicist) and insure that sufficient radiation safety personnel are hired and trained to provide an effective safety program.

The Radiation Safety Officer should:

- Report to the top level of management. Advise top management on all matters concerning radiation.
- Define, with the concurrence of top management, the radiation safety requirements and assure compliance with DOE Orders.
- Monitor, and report to top management, the effectiveness of the radiation safety program.
- Have authority to stop activities which appear to present imminent hazard or which violate the facility's safety policy.

The radiation safety staff should have a broad range of expertise. If it is necessary to hire staff without the required expertise, training should be provided, or the needed expertise should be made available either by a radiation safety committee or outside consultants. Required areas of expertise are as follows:

- Physics. Knowledge of the physics of the interactions for the appropriate particle types and energy is essential.

- Radiation Physics. Calculations of shielding and activation are needed in order to predict both prompt and residual radiation levels.
- Operational Health Physics. There should be a good understanding of radiation and protection methods, dosimetry, and regulatory requirements.
- Familiarity is also needed with electronics, accelerator design and operation, beam transport, and experimental techniques.

Often it is difficult to hire professionals trained in all the above areas. It is recommended that all radiation safety staff go through training to orient them to the particular accelerator facility. The following elements, as appropriate, should be included in the training:

- Fundamentals of Radiation Protection
- Instrumentation
- Residual Radioactivity/Contamination
- Radiation Emergencies
- Transport of Radioactive Material
- Storage of Radioactive Material
- Radioactive Waste
- Radioactive Sources
- Personnel Dosimetry
- Accelerator Operation
- Beam Transport
- Interlock Systems
- Shielding Calculations
- Review of Operations/Experiments for Radiation Safety
- Regulatory Requirements—DOE, DOT, EPA, etc.

- Environmental Protection.

Elements of the above outline should also be included, in as much detail as the particular facility requires, as part of a technician training program.

Both staff and technical personnel should be encouraged to keep current by reading the literature and attending professional conferences. Seminars and short courses can be invaluable for staying up-to-date with regulatory changes. Outside courses are available, especially at the technical level, which can aid training in fundamentals. Finally, laboratory policy should encourage and support certification by professional societies such as the National Registry of Radiation Protection Technologists (NRRPT) for technicians and the American Board of Health Physicists (ABHP) for staff.

In addition to the full-time health physics staff, it may help to have other persons review new and ongoing health physics problems. These persons can be either reviewers or part of a Radiation Safety Committee.

Reviewers can provide an outside perspective on programs. They may be used as a part of the audit program (see Section 4.2) or as a more informal reviewer. Such reviewers may be recruited from other personnel with an interest in radiation safety; they may also be health physicists from other facilities.

The Radiation Safety Committee should be formed of representatives from such groups as health physics, radiation groups, accelerator physics, operations, and interlock design and maintenance groups. It should meet, as necessary, to review new accelerator or experimental configurations, changes in interlock philosophy, significant staffing changes that affect radiation safety, and so forth. They should report to top management. The committee should also be available to review problems brought to their attention by concerned staff members or visiting experimenters.

5. DISMANTLING, DECONTAMINATION, AND DECOMMISSIONING

The health physics involved in dismantling and decommissioning accelerators should be considered during the facility's design, operation, and expansion or modification. Original plans for decommissioning should be updated to accommodate any modifications to the facilities, or any changes in disposal options. Plans to decommission should also respond to changes in radioactive waste regulations and prevailing attitudes on release or reuse.

5.1 FACILITY DESIGN

The eventual decommissioning of an accelerator should be planned for even as the facility is being designed and built. The goal should be to keep radiation exposure during dismantling at "ALARA" levels—as low as reasonably achievable.

During construction, materials should be chosen that will not be significantly activated by the accelerator, to minimize radiation exposure at decommissioning. Prudent initial design could mean the difference, at decommissioning, between having to discard material or incur additional costs, and being able to recover valuable resources without undue exposure of personnel (ANSI78, Go76, IAEA79, Pa73).

Certain design measures to keep exposure low at decommissioning would clearly add significant cost to initial construction. A cost analysis should be made, comparing the costs added at the time of construction to those of measures which would otherwise be needed at dismantling time. Potential decontamination costs should be added to the cost analysis. Decontamination can add significantly to the cost of some decommissioning projects, whereas taking action during design may be quite cost-effective.

5.2 FACILITY OPERATIONS

Personnel who will be operating an accelerator facility should insist on adequate "as-built" drawings from the construction contractor. During operation of a typical facility, modifications will undoubtedly be made to the accelerator, the experimental areas, and the support facilities. Whenever possible, the same measures for keeping radiation exposure ALARA during decommissioning should be included in the design of any expansions or modifications. Changes should be added to the "as-built" drawings to keep them up-to-date.

The documentation of how systems and structures went together (both original construction and subsequent modifications) should show names of responsible people who understood the construction details. When feasible, these people should be included in the planning for dismantling and decommissioning.

Most large accelerator facilities provide storage space for excess materials. These areas, sometimes referred to as "bone yards," are often outdoors and tend to include both activated ("hot") and nonradioactive ("clean") materials and equipment. Experience has shown these storage yards to be a tremendous detriment to efficient decommissioning if they have not been carefully controlled and the stored materials rigorously segregated according to radioactive content. Adverse effects from sloppy storage can include unnecessary exposure of personnel during cleanup operations, inadvertent release of radioactive material to commercial scrap dealers or public waste sites, or inappropriate routing of clean as well as radioactive material to radioactive burial sites. Strict control of storage is thus recommended and the facility's health physics organization may be the logical choice for maintaining such control. Regardless of who is responsible, adequate control of the storage area requires support from operations management during those times when keeping materials segregated may not seem "convenient."

5.3 PLANNING DISMANTLING AND DECOMMISSIONING

Health physics considerations for decommissioning particle accelerators center around two primary aspects. One is the dose of radiation that decommissioning personnel may receive while dismantling, decontaminating, and preparing radioactive components of the accelerator for shipment. The second aspect is potential radiation hazard to the general population. Public exposure can occur from interim, on-site storage of radioactive components or from transport to other sites, or to retrievable storage or waste disposal. The public may be exposed to radiation when accelerator components or structures containing induced radioactivity are reused (Op79).

Based on these considerations, all radiation exposures should be planned so as to keep radiation exposure ALARA. The collective dose should be minimized for both the decommissioning personnel and the affected general population. Radiation Work Permits would be appropriate for many tasks during the course of the project, to assure adequate consideration of the ALARA goal. Similarly, an environmental assessment may be appropriate to judge and document potential environmental impact from decommissioning operations and the materials released.

Logistics should be carefully thought out. Estimates should be made of the number of personnel required for both dismantling operations and health physics oversight. Availability of the people who were listed as knowledgeable of the original construction or later modifications should also be determined. Need for special equipment for rigging, remote manipulation, shielding, or contamination control should be assessed, as should be the required equipment for monitoring radiation. Such equipment may include exposure rate meters, detectors for smearable contamination, airborne contamination monitors, hand and shoe monitors, and off-site environmental monitors (NCRP85a). Providing portable, or at least transportable, equipment for counting smears can greatly improve efficiency.

Planning for personal radiation dosimetry may require some lead time if decommissioning personnel do not already have badges. Similarly, where needed, fitting and testing of respirators should be done in advance.

An inventory system should be developed to allocate components for reuse as research equipment, or for disposal as scrap or radioactive waste. This inventory would include the radiological status of each item as of the date it is assessed. All identifiable items should be inventoried—no equipment or material should leave the site with its radiological status unknown. Adequate personnel for inventory duties should be included in estimates of personnel requirements, and should be budgeted for.

5.4 DISMANTLING AND DECOMMISSIONING OPERATIONS

Ideally, the decommissioning project would follow plan, the ALARA goal would be achieved, and everything would be carefully documented. Realistically, continual oversight and input from health physics will be required. Daily "game plans" for critical activities which have high risk for radiation exposure should be developed jointly by personnel from operations and health physics.

A brief period of mothballing in place, between the shutdown date and the actual decommissioning, may be advisable for reasons of both safety and economics. A significant reduction in exposure rate occurs during the first several months after the accelerator is turned off. Since the radiation doses received by workers are substantially reduced, work could proceed in many areas with less costly protection measures (Op79, Su65). Certain work will not be practical at all before some time for radioactive decay has elapsed.

The health physicists should keep personnel exposure records as current as is feasible, and evaluate to-date exposures, and trends, with respect to predicted exposures. Results of radiation surveys should be documented and, as much as possible, be related to the inventory of materials and equipment.

A certain amount of interim storage or materials staging is typically necessary. As with the storage areas used during accelerator operation, strict controls should be maintained. Radioactive and nonradioactive materials should be kept segregated, and valuable materials which happen to be radioactive should be protected from theft. In some cases, shielded containers to store or ship highly activated components will be necessary.

For many accelerator facilities, decontamination will not be a significant part of decommissioning. Exceptions would be high current, high energy accelerators; isotope production facilities; areas with special targets such as transuranic targets with cladding failure; and various highly irradiated liquid handling systems.

Yet contamination problems could arise during dismantling operations if precautions are not observed or when imprudent original design precludes a desired approach. Examples include torch cutting of activated materials by inexperienced welders, or oversized, poured-in-place concrete shielding that has to be blasted apart. Proper procedures for dealing with such problems are not specific to either accelerators or their decommissioning, but in many accelerator facilities, health physics technicians may need to be reminded of potential complications if they have not dealt with loose contamination.

One of the largest health physics efforts during decommissioning involves shipping. A recordkeeping system that is consistent with the materials inventory system is essential for handling the large volume of data from a major decommissioning. As part of the materials disposition chain, recorded data should, at minimum, identify the material consistent with the inventory system, list radiation readings as items are loaded, and give an identifying number for the shipping vehicle. Regulations for shipping radioactive materials are covered in DOE Order 5480.3. Other regulations are discussed in Section 5.7 of this manual.

At some point as decommissioning proceeds, the separate data from the interim inventory, proposed disposition, and health physics radiation surveys should be combined to form the core of the final disposition documentation. It should then be possible to determine where each identifiable item ended up and what its radiation level was as it left the site.

A more difficult task arises when it is necessary not only to determine radiation level, but to specify as well the constituent nuclides and their concentrations. Various techniques have been employed to make such estimates, ranging from educated guesses to use of sophisticated spectroscopy equipment and elaborate calculations. The level of effort involved should be consistent with the applicable regulations. For instance, the requirements of a waste burial site might justify a better estimate of nuclides than what DOT requires. For shipping material and equipment that contain only induced radioactivity, external exposure rate is the most significant parameter, whereas regulations for waste burial should be based on exposure pathways to the general public. References Ro56, Mo81, and Mo85 contain information on calculating nuclide content from exposure rate readings. Further developments are needed on this problem, including a more formalized approach.

5.5 OPERATIONS AFTER DISMANTLING AND DECOMMISSIONING

After the accelerator facilities at a given site have been dismantled, the initial decontamination accomplished, and disposition accomplished for all known radioactive material other than permanent structures, a radiological characterization of the site should be conducted. This would include laboratory and office buildings, experimental halls, the building housing the accelerator, and any known storage areas and the roads leading to them. From this assessment would come final decontamination requirements, knowledge of residual radioactive equipment and materials, and need for other remedial action, as well as the necessity of controlling access to certain structures or land areas. Residual radioactive material would then be handled according to previous disposition procedures. Decontamination would be carried out according to the ALARA principle. Decisions on release or for controlled access would then be made according to prevailing DOE Orders and EPA guidance.

Regardless of what final activities might be necessary, a final characterization assessment document would then be published. The document should include an estimate of potential health risks from the radiological status of the decommissioned facility. Health effects should be considered for any personnel who would reuse the site and for members of the general population.

Regulations pertaining to decommissioning are referenced in Appendix D.

Appendix A

DOE ACCELERATOR DOSIMETRY RESULTS

In 1968, the U. S. Atomic Energy Commission (AEC) established a program for reporting certain occupational radiation exposure (dose equivalent) information. Annual summaries (WASH-1350-R1 through WASH-1350-R6) were reported for the years 1968–1978 and included data on AEC contractor employees as well as employees of companies in the private sector licensed by the AEC.

In January 1975, the operational functions of the AEC, including the maintenance of records on the occupational radiation exposure of contractor employees, were transferred to the Energy Research and Development Administration (ERDA) and the AEC's regulatory functions, including the reporting of information on the occupational radiation exposure of licensees, were transferred to the Nuclear Regulatory Commission. Radiation exposure data for AEC/ERDA and AEC/ERDA contractor employees from 1974 to date were reported in the documents as follows:

Year	Document Number
1974	ERDA 76/119
1975	ERDA 77-29
1976	DOE/EV-0011/9
1977	DOE/EV-0066/10
1978	DOE/EV-0066/11
1979	DOE/EP-0039
1980	DOE/EP-0040
1981	DOE/EP-0040/1
1982	DOE/EP-0040/2
1983	DOE/PE-0072
1984	DOE/EH-0011

Monitoring at DOE and DOE contractor facilities is required where the potential exists for an individual to receive a dose or dose commitment in any calendar quarter in excess of ten percent of the quarterly standards as prescribed in DOE 5480.1A, Chapter 11.

Whole body radiation exposure reportings for accelerator facilities for the years are tabulated in Table A-1. These results are compiled from the referenced documents and are subject to some error due to different interpretation of reporting codes. They are approximately right, however, and show the correct trends. The data indicate that as time progresses, the dose equivalents have been reduced. There are multiple reasons for this reduction, e.g., increasing operation in storage ring mode rather than fixed target mode, financial restrictions on operating time, improved design of components subject to failure, etc.

Table A-1. Collective Dose Equivalents for DOE/DOE Contractor Employees and Visitors at Accelerator Facilities

Year	Number of Persons Monitored	Number of Persons with Measurable Exposure	Based on Total Number Man–Rems	Avg. DE (Rem) per Person (all exposures)	Avg. DE (Rem) per Person (measurable exposures)
1974	6674	2357	1131	0.17	0.48
1975	7384	2382	1071	0.15	0.45
1976	1766	1384	670	0.24	0.48
1977	3055	1692	773	0.26	0.47
1978	3178	1579	571	0.18	0.36
1979	3402	1615	492	0.15	0.31
1980	5315	1968	412	0.08	0.21
1981	3591	1525	348	0.10	0.23
1982	3446	1216	254	0.07	0.21
1983	3366	1249	273	0.08	0.22
1984	3875	1266	248	0.10	0.16

Appendix B
SAFETY INTERLOCK REPORT

During the preparation of this manual, DOE requested that a sub-committee be formed to consider the safety aspects of using computers in safety interlock systems. Their report is appended here as Appendix B. The report was written, circulated widely for comments, and revised to its present form. The sub-committee composition is:

K. Crook, Chairman	SLAC
S. Goldsmith	SNL
W. Freeman	FNL
A. McGeary	BNL

COMPUTERS IN PERSONNEL SAFETY SYSTEMS

Computers for Accelerator Control and Monitoring

The use of digital computers in control systems for accelerators is now well established. From the middle sixties, as the cost of computers came down and as the reliability improved, computers were integrated into the control systems of many accelerators. Initially, the primary application was status monitoring and logging, but more recently the computer has become a central element in the control system itself, providing both digital and analog output signals that are used to control beam-line devices along the accelerator. Today, the high reliability of computer hardware, the sharp decrease in costs of computer components and modules, coupled with the increased complexity of the control requirements for modern accelerators, make the choice of computer control highly desirable, if not absolutely essential.

Computers For Personnel Safety Systems

The use of computers in personnel safety systems has been rare in large accelerators built during the past ten years. Those responsible for the design of safety systems tended to favor the conservative and proven technology that grew out of railroad signalling systems, ship safety systems, and conventional power plant technology. Most nuclear power plants designed over the last 30 years have adopted this same safety system design approach—hardwired sensors and alarm devices, coupled with electromechanical relay technology for the logic panels and chassis.

More recently, some designers in both the nuclear and accelerator fields, have replaced the relay logic panels with solid-state logic elements. This has been particularly true in cases where the complexity of the logic requirements would have required hundreds or even thousands of relays, or where the required response time was too fast for relay circuits.

As confidence in the reliability of control computers increases there is mounting interest in the use of computers in accelerator safety systems. By way of comparison, in the normally conservative nuclear industry, digital-based systems are now becoming prevalent even to the point where fully computerized shutdown systems will be installed in certain nuclear power plants starting in 1987 (Ref. 1).

In deciding between the relative merits of conventional relay systems versus a solid-state or computer-based approach, a primary concern of designers is the fail-safe nature of the circuits. When power is lost, when a sensor becomes disconnected, or a wire connection is broken, does the circuit or system fall back to the safe condition?

For relays, an energized coil will deenergize, and its contacts will normally open when coil voltage is lost or when the coil itself shorts or opens. Thus if all relays in the chain are held energized for normal operating conditions, almost all fault conditions such as breaking a wire or removing a connector will cause the circuit to revert to the safe state.

In the case of solid-state or computer systems, the failure mode is much more difficult to predict. Design techniques must be adopted that prevent damage to solid state components from external transient noise sources prevalent in a high energy accelerator environment. High reliability components, self-checking curcuits, and redundancy are also important features in improving overall system security.

It should be noted that there are designers who hold strong views that computer-based systems are not an appropriate choice for safety systems involving life-threatening hazards. The sensitivity of solid state electronics in a hostile electromagnetic environment as well as software reliability are issues that cause concern.

While the committee as a whole is sensitive to these apprehensions, we recognize that computer-based safety systems are already a fact of life in accelerators today.

It is our intent in these recommendations to propose broad guidelines for those designers who believe that computer systems are appropriate for their safety system applications.

RECOMMENDATIONS

General

1. Computer-based systems should only be selected after careful consideration of all the options. Examples of applications when computers might be suitable include:
   (a) If the complexity of the logic would result in an unreasonably large number of conventional relays.
   (b) If speed of response higher than that achievable with relay systems is judged to be an important factor.
   (c) If operational flexibility is an important requirement.

It should be noted that a design approach using hard-wired solid state logic may be a satisfactory alternative to the use of a computer system for some applications.

2. Computer-based systems should be chosen for safety applications only if professional, full-time staff are available for the system implementation. This requirement applies to the design, construction, and maintenance phases of the project, and is important for both the hardware and software aspects of the system. The software design and implementation should only be undertaken by those who are specialists in both software engineering and sensor-based industrial control systems. It is also essential that software designers be familiar with all the operational aspects of the safety system.

Minimum Requirements

The following constitute the minimum requirements for the use of computers in accelerator personnel safety systems.

Hardware

1. Computer-based systems may be used for accelerator personnel safety as long as it can be demonstrated that the use of a computer does not increase the risk of an accident to an unacceptable level. The computer system, including software, must have high reliability. At a minimum, the safety system including the computer and its input/output devices should be designed to have a MTBF of not less than 90,000 hours. Thus, if a monthly service inspection were carried out, the system would be operational 99.2 percent of the time.

   One method of improving reliability is to use completely redundant hardware–two computers and associated I/O. In some instances, triple redundancy may be justified. Consideration may also be given to the use of the class of "ultra-high availability" fault tolerant computers which have internal built-in redundancy in both hardware and software. This latter approach may only be adopted if it can be demonstrated that the reliability and fault tolerance is at least as high as the independent, redundant hardware approach.

2. For applications in typical accelerators, computers used for safety systems must be dedicated to that function alone.

3. Programs written for computers used in safety systems should reside in Read Only Memory (ROM) or Programmable Read Only Memory (PROM) wherever feasible. If volatile memory must be used, it should have error detection and correction features and it should have sufficient battery back-up for long-term retention of the program state.

4. Watchdog timers should be incorporated so that action can be taken if the program fails to reach appropriate checkpoints within a specified time.

Software

1. All programming must be undertaken by designated and authorized professionals using accepted methodology to insure software of the highest quality. High modularity and testability must be incorporated in all software. The emphasis must be directed toward writing fault tolerant programs. Software hazard analysis should be performed wherever feasible. Accepted techniques such as redundancy and checkpointing should be used.

   Some suggested software standards are given in Refs. 2, 3, 4, and 5.

2. Program changes to meet new operational needs must be carefully controlled using strict configuration management techniques. All changes must be thoroughly tested, not only for the specific intended function that the program change was meant to accomplish, but also for other unexpected and unwanted effects in other parts of the program.

3. In the approach where parallel independent computers are used to achieve

reliability, consideration should be given to installing nonidentical but functionally equivalent software to reduce common mode failure.

Testing

A computer-based system must be thoroughly tested before being placed in service, and at regular intervals thereafter. Testing must include all elements of the system—the sensors, the computers, and the shutdown mechanisms, and must be auditable with respect to description of tests, dates, and personnel performing tests.

Operator Override

If computers are chosen for safety interlock applications, there should be, in addition to the computer hardware and its connection to the shutoff equipment, a separate independent operator (crash) override button on the console that permits manual shutdown of the facility.

REFERENCES

1. Control and Safety Computers in CANDU Power Stations, R.S. Gilbert, IAEA Bulletin, Autumn 1985.
2. Standard for Quality Assurance Plans, ANSI/IEEE STD 730-1984.
3. Standard for Requirements Specification, ANSI/IEEE STD 830-1983.
4. Standard for Software Test Documentation, IEEE STD 829-1983.
5. Standard for Software Configuration Plan, IEEE STD 828/1983.

Appendix C
RECOMBINATION CALCULATIONS

The following is an example of recombination calculations for a spherical air ionization chamber at STP.

$a = 10$ cm , $b = 1$ cm (outer and inner electrode radii, respectively)

collection potential (V) = 350 volts

accelerator pulse repetition rate = 100 Hz

average dose rate = 1 rad/h (0.01 Gy/h).

The collection efficiency, f, for a single beam pulse is given by the following expression:

$$f = (1/u)\ ln\ (1 + u)$$

where

$u = \mu r \left(\frac{d^2}{V}\right)$,

$d = (a - b)\, K_{SPH}$

$K_{SPH} = \left(\frac{1}{3}\left(\frac{a}{b} + 1 + \frac{b}{a}\right)\right)^{\frac{1}{2}}$

$r =$ Initial charge density per pulse – esu cm^{-3} (C m^{-3})

$\mu\ = 1.005 \times 10^3\ V\text{cm}\ esu^{-1} (3.02 \times 10^{10}$ V m C^{-1}) ($ICRU82$) .

Then the efficiency, f, is equal to 0.999.

The transit time, T_{SPH} , is compared with the machine pulse repetition rate to determine whether there will be an overlapping of pulses:

$$T_{SPH} = \frac{(dK_{SPH})^2}{Vk} \quad ,$$

where k is the mobility of the slowest ion and is assumed to be 1.3 cm^2 V^{-1} s^{-1} (1.3×10^{-4} m^2 V^{-1} s^{-1}). Then,

$$T_{SPH} = \frac{[(0.09)\,(1.9235)]^2}{(350)\,(0.00013)} \approx 0.66 \text{ seconds} \quad .$$

At 100 Hz, 66 beam pulses arrive during the transit time of the first pulse. Recombination in this case is similar to that for continuous radiation at the average dose rate.

The efficiency, more aptly calculated now for continuous radiation, is given by,

$$f = \left(\frac{1+\xi^2}{6}\right)^{-1}$$

where $\xi = m\ d^2\ q^{\frac{1}{2}}\ V^{-1}$

$m = 36.7$

$q =$ Average charge density.

For this example,

$$\frac{1}{f} = 1 + \frac{1}{6}\left[\frac{36.7\ \ [(10-1)\ \ 1.9235]^2\left(2.778\ \ 10^{-4}\right)^{\frac{1}{2}}}{350}\right]^2$$

$$f = 0.956 \quad .$$

For this case, it is clear that the efficiency, calculated on the basis of a single pulse, would be about 5% too high. Table C-1 shows the expressions to be used to calculate collection efficiency for parallel plate, cylindrical, and spherical ion chambers.

TABLE C-1.

Geometry	Efficiency Continuous Radiation	ξ	K	Transit Time, T
Plane Parallel	$\left(1 + \frac{1}{6}\,\xi_{pl}^2\right)^{-1}$	$\xi_{pl} = md^2\; q^{1/2}\; V^{-1}$		$T_{pl} = d^2/Vk$
Cylindrical	$\left(1 + \frac{1}{6}\,\xi_{cy1}^2\right)^{-1}$	$\xi_{cyl} = m\frac{K_{cyl}^2\;(a-b)^2\;q_{cyl}^{1/2}}{(V/d)\;b\;\ell n(a/b)}$	$K_{cyl} = \left(\frac{a/b+1}{a/b-1}\;\frac{\ell n\;a/b}{2}\right)^{1/2}$	$T_{cyl} = \frac{[(a-b)\;K_{cyl}]^2}{Vk}$
Spherical	$\left(1 + \frac{1}{6}\,\xi_{sph}^2\right)^{-1}$	$\xi_{sph} = m\frac{K_{sph}^2\;(a-b)^2\;q_{sph}^{1/2}}{(V/d)\;(b/a)\;(a-b)}$	$K_{sph} = \left[\frac{1}{3}\left(\frac{a}{b}+1+\frac{b}{a}\right)\right]^{1/2}$	$T_{sph} = \frac{[(a-b)\;K_{sph}]^2}{Vk}$

Appendix D

REGULATORY INFORMATION FOR DOE CONTRACTORS

The Environmental Protection Agency (EPA) has the responsibility to develop radiation protection guidance for Federal agencies. This guidance is normally based on recommendations of the International Commission on Radiation Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP). The EPA guidance, upon approval of the President, is implemented in the regulations of all federal agencies, including the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE).

NRC does not license accelerator facilities. Some State agencies do; however, if an accelerator facility is DOE-controlled (i.e., the buildings or grounds are owned or leased by DOE), then an exemption from all radiological licensing exists. DOE will then exercise statutory authority for radiological safety matters by way of contractual requirements. Depending on other factors, DOE may even have authority for the entire spectrum of safety at a given facility; this is the case at most DOE national laboratories. In cases where DOE does not control the facility (in the above sense) and the local State agency has an adequate capability for accelerator radiation protection matters, that agency will exercise authority.

DOE authority (and responsibility) for safety at its contractor facilities is of an overview nature. DOE conducts on-site appraisals and enforces compliance with Federal guidance, DOE Orders, and specific consensus standards. The contractor is responsible for day-to-day operational matters and normally resolves safety-related problems. However, employees may also approach DOE, and eventually the Occupational Safety and Health Administration (OSHA), if their concerns are not satisfied.

DOE radiation dose limit for individual members of the general public due to the operation of a DOE facility is 500 mrem (5 mSv) in any year (DOE 5480.1A, Chapter XI). For larger populations the radiation dose limit has been 170 mrem/year (1.7 mSv). However, the draft revision of this chapter would change this value to 100 mrem/year (1 mSv). In the interim, a memo from William A. Vaughan, Asst. Secretary for Environment, Safety and Health, dated August 5, 1985 has established the dose limit for any member of the public as 100 mrem/year (effective July 1, 1985). An occasional annual exposure of 500 mrem/year (5 Smv) is still allowed. This same memo establishes a DOE administrative action level of 25 mrem/year (250 μSv/year) which would require an investigation by the responsible DOE field office. Most of the DOE accelerators try to hold the site boundary doses below about 10 mrem/year (100 μSv/year).

At present the occupational dose limits, as set by DOE 5480.1A Chapter XI, are 5 rem/year (50 mSv/year). Planned revisions to the Order would establish the limit as 5 rem effective dose equivalent consistent with the EPA Radiation Protection Guidance to Federal Agencies for Occupational Exposures published January 1987. For the purpose of keeping radiation exposures ALARA, the design objective for new or modified facilities must be 20 percent of these limits.

The Federal Water Pollution Control Act, the Clean Air Act, and the Safe Drinking Water Act authorizes the EPA to set standards for the control of radioactivity in liquid effluent discharges, air emissions, and public drinking water supplies, respectively. A maximum of 4 mrem/year (40 μSv/year) is the limit due to radioactivity in community drinking water supplies. Similarly, 25 mrem/year (250 μSv/year) is the limit due to radioactivity released into the air. This limit of 25 mrem/year (250 μSv/year), with a reporting level at 12.5 mrem/year (125 μSv/year), for exposures to the general public from radioactivity released in the air was promulgated to DOE contractors in the earlier referenced William A. Vaughan memo. In most cases, state environmental protection agencies have enforcement powers. However, the Federal EPA has authority to enforce the regulations if a state fails to act.

The following is a list of DOE Orders applicable to radiation safety at accelerators. Specific requirements will in each case be promulgated by the DOE Contracting Officer.

DOE ORDER	TITLE
1540.2	Hazardous Material Packaging for Transport-Administrative Procedures
5480.1A	Environmental Protection, Safety, and Health Protection Program for DOE Operations
5480.2	Hazardous and Radioactive Mixed Waste Management
5480.3	Safety Requirements for the Packaging and Transportation of Hazardous Materials, Hazardous Substances, and Hazardous Wastes
5480.4	Environmental, Safety, and Health Protection standards
5480.11	Radiation Protection
5481.1B	Safety Analysis and Review System
5482.1A	Environmental Protection, Safety and Health Protection Appraisal Program
5483.1A	Occupational Safety and Health Program for DOE Contractor Employees at Government Owned Contractor Operated Facilities

5484.1	Environmental Protection, Safety and Health Protection Information Reporting Requirements
5500.2	Emergency Planning, Preparedness, and Response for Operations
5820.2	Radioactive Waste Management
6430.1A	General Design Criteria

Appendix E

SOME USEFUL COMPUTER CODES

Code: FLUKA86

Author: J. Ranft, G. R. Stevenson, and P. Aarnio

Location of code in USA: SLAC (contact W. R. Nelson)

Description: Monte Carlo for high energy primary hadrons. Tracks cascade of particles down to 50 MeV through materials.

Output: Star density, energy deposition density, and secondary particle distribution.

Advantage: Comprehensive production model including production of resonances which should be valid up to 20 TeV and above.

Code: HETC

Author: R. C. Alsmiller, Jr., T. W. Armstrong, and T. A. Gabriel

Location of code in USA: ORNL

Description: Monte Carlo for primary protons pions and muons up to 30 GeV. Tracks cascade of particles down to 20 MeV neutrons through materials.

Output: Particle flux distributions and activation product distributions.

Advantage: Lower energy neutron transport possible with coupling to MORSE.

Code: CASIM

Author: A. Van Ginneken

Location of code in USA: Fermilab

Description: Monte Carlo for high energy primary protons. Tracks cascade of particles down to 50 MeV through geometries of arbitrary composition and magnetic fields. CASIMU Version tracks muon generated by the cascade. AEGIS subroutine follows electromagnetic showers.

Output: Star and energy density contours.

Advantage: Interaction processes during transport permit tracking of 20 TeV and primaries weighting techniques greatly reduce computer running times.

Code: MORSE

Author: M. B. Emmett

Location of code in USA: RSIC (ORNL)

Description: Monte Carlo for transport of neutrons with energies from thermal to 20 MeV up to 400 MeV with available cross sections), and photons to 14 MeV.

Output: Fluences, dose for any given response.

Advantage: Three-dimensional.

Code: EGS4

Author: W. R. Nelson, H. Hirayama, and David W. O. Rogers

Location of code in USA: SLAC

Description: Monte Carlo for electrons-photons in the range of 10 TeV down to few tens of KeV.

Output: Particle flux distributions, energy deposition, etc.

Advantage: Very well-understood QED processes. Numerous benchmark examples.

Code: ITS (Integrated Tiger Series)

Author: J. A. Halbleib and T. A. Melhorn

Location of Code in USA: R.S.I.C. or Sandia National Laboratories

Description: Time-independent Monte Carlo for coupled electron/photon radiation transport from 1.0 keV to 1.0 GeV with or without the presence of macroscopic electric or magnetic fields. Slab, spherical, cylindrical, or combinatorial geometries.

Output: Electron and photon fluences, energy and charge deposition.

Advantages: User friendly but rigorous. Runs on Cray, IBM, Vax, and CDC.

Code: ANISN-W

Author: Westinghouse

Location of Code in USA: R.S.I.C.

Description: An old, but useful multigroup one-dimensional time-independent discrete ordinates transport code for neutrons and photons less than 20 MeV.

Output: Neutron and photon fluences, fission rate, dose rates, and activation through "activities."

Advantages: Well-proven and widely implemented. Runs fast.

Code: DOT4

Author: ORNL

Location of Code in the USA: R.S.I.C.

Description: Multigroup two-dimensional time-independent discrete-ordinates transport code for neutrons and photons less than 20 MeV.

Output: Neutron and photon fluences.

Advantages: May converge sooner than Monte Carlo for two-dimensional problems.

Code: OneDant

Author: LANL

Location of Code in the USA: R.S.I.C.

Description: Multigroup one-dimensional time-independent discrete-ordinates transport code for neutrons and photons less than 20 MeV.

Output: Neutron and photon fluences.

Advantages: May converge sooner than Monte Carlo for one-dimensional problems.

Code: TwoDant

Author: LANL

Location of Code in the USA: R.S.I.C.

Description: Multigroup two-dimensional time-independent discrete-ordinates transport code for neutrons and photons less than 20 MeV.

Output: Neutron and photon fluences.

Advantages: May converge sooner than Monte Carlo for two-dimensional problems.

Appendix F

TREATMENT OF COUNTING LOSSES

1. Paralyzable Counters

Assuming that the dead time, ρ , of a Geiger-Muller counter is the parameter which is determining the extent of the counting losses rather than, for example, a mechanical register, the true counting rate, N, can be approximated by the following expression:

$$N = n\,(1 + n\rho) \quad , \quad \text{at low counting rates}$$

where n is the observed counting rate, and $N\rho << 1$. It is further assumed that ρ is independent of count rate; however, this assumption must be examined when high count rates are likely to be encountered.

A maximum in the counting rate is observed when $N\rho = 1$ as shown in Fig. F1 (Ev55). A maximum in the counting rate is reached when $N\rho = 1$ at which condition the counting system registers only 0.368 of the true count rate. The observed count rate decreases when $N\rho > 1$ because of the diminishing number of intervals whose time greater is than the dead time of the detector.

2. Nonparalyzable Counters

Such systems (the BF_3 gas-filled proportional counter is an example) never exhibit complete paralysis; its observed count rate, n approaches $1/\rho$ as the true count rate, N, approaches infinity. The true count rate is then given by the expression

$$N = \frac{n}{1 - n\rho}$$

where ρ is the pulse pair resolution time of the counting system.

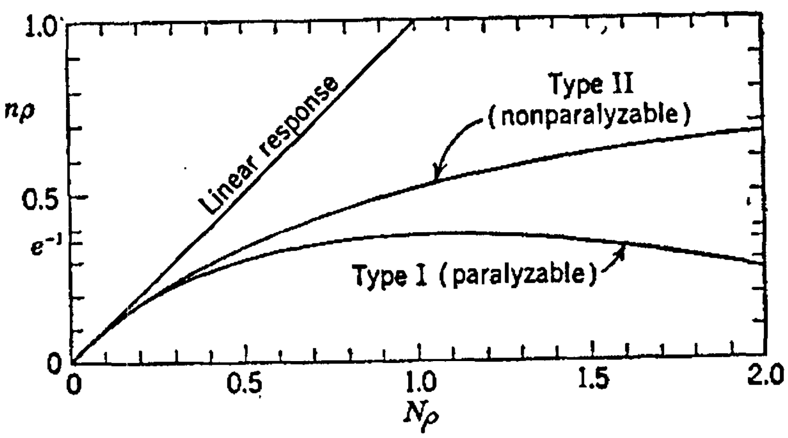


Fig. F1. (*This figure is reproduced from EV55 by permission of McGraw-Hill Book Co.*)

3. Dead Time Losses for Pulsed Sources (Kn87)

Assumed Source:

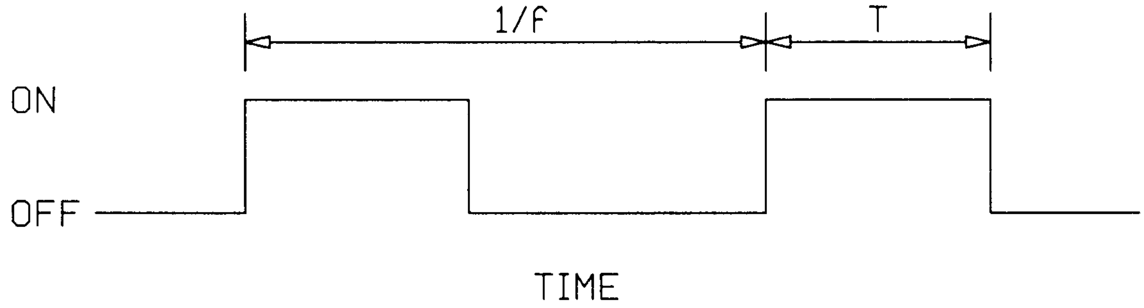


Fig. F2

Let:

T = Source pulse length

f = Source pulse frequency

τ = Resolving time of detector system

m = Observed counting rate

n = True counting rate (if τ were 0)

We will only address the case when:

$$T < \tau < (1/f - T) \quad .$$

(Then one can have a maximum of one count per source pulse, or $m < f$, always. Also, the detector will be fully recovered at the start of each source pulse.)

Then:

Probability of observed count per source pulse = $\frac{m}{f}$.

Average number of true events per source pulse = $\frac{n}{f}$

(can be > 1)

From Poisson distribution:

$$P(>0) = 1 - P(0)$$

$$= 1 - e^{-\overline{x}} \quad .$$

Thus:

$$\frac{m}{f} = 1 - e^{\frac{-n}{f}}$$

or

$$m = f(1 - e^{\frac{-n}{f}}) \quad .$$

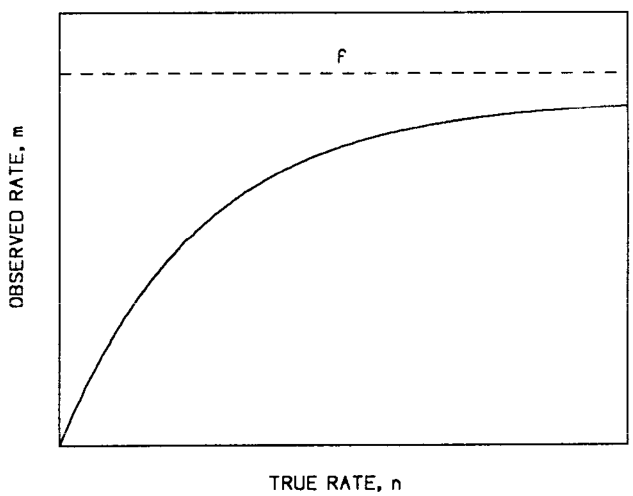


Fig. F3

We are more often interested in solving for n to provide a correction formula:

$$n = f \; ln\left(\frac{f}{f - m}\right) \quad .$$

Note that under these conditions, neither the length of the resolving time τ nor the detailed dead-time behavior of the system (e.g., whether it is paralyzable) have any effect on the correction.

References

ACI62 American Concrete Institute, 1962, Concrete for Radiation Shielding, Compilation No. 1 (Detroit MI: American Concrete Institute).

Ak63 Akagi H. and Lehman R., 1963, "Neutron dosimetry in and around human phantoms by the use of nuclear track emulsion," Health Phys. 9, 207.

Al72 Alder K., 1972, "Coulomb interactions with heavy ions," in Proc. Heavy Ion Summer Study ORNL, Conf.-720669, Distribution Category UC-34 (Springfield, VA: National Technical Information Services).

An63a Andersson I. O. and Braun J., 1963, "A neutron rem counter," Nukleonik 6, 237.

An63b Andersson I. O. and Braun J., 1963, "A neutron rem counter with uniform sensitivity from 0.025 MeV to 10 MeV," in: Proc. Symp. on Neutron Detection, Dosimetry and Standardization, STI/PUB/69 (Vienna: International Atomic Energy Agency)> Harwell, England.

ANSI66 American National Standard Institute, 1966, Practice for Occupational Radiation Exposure Records Systems, ANSI N13.6-1966(R 1972) (New York ANSI).

ANSI72 American National Standards Institute, 1972, Specification for Accident Prevention Signs, ANSI Z35.1-1972 (New York ANSI).

ANSI78 American National Standards Institute, 1978, Radiological Safety in the Design and Operation of Particle Accelerators, ANSI 43.1 (Washington, DC: U.S. Government Printing Office).

Aw71 Awschalom M., Howe H., Schamber F., and Shafer R., 1971, "Radiation monitoring at NAL: instruments and systems," Proc. of Int. Congress on Protection Against Accelerator and Space Radiation, Volume II p 1035, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 71-16.

Ba66 Barbier M., Hutton A. and Pasinetti A., 1966, Radioactivity Induced in Tissues by 600 MeV Protons, CERN, Geneva, Switzerland, CERN 66-34.

Ba68 Babcock G., Breymayer K. E., Busick D. D., Crook K., Jenkins T. M., Mallory K. B., McCall R. C., Reagan D. D., and Warren G., 1968, "Protection systems," in: The Stanford Two-Mile Accelerator, (edited by R. B. Neal), 775-819 (New York: W. A. Benjamin, Inc.)

Ba69a Barbier M., 1969, Induced Radioactivity (Amsterdam: North Holland Publishing Company).

Ba69b Baum J. W., Woodcock R. C. and Kuehner A. V., 1969, "Factors affecting pulse size in sealed tissue equivalent counters," in: Proc. 2nd Int. Conf. on Accelerator Dosimetry and Experience, USAEC CONF-691101 p 648 (Stanford, CA: United States Atomic Energy Commission).

Ba75 Baker S. I., 1975, "Soil activation measurements at Fermilab," in: Proc. Third Environmental Protection

Conference, Volume I, p 329, ERDA-92 (Washington, D. C.: U. S. Energy Research and Development Administration).

Ba76 Batisti R., Bossart S., Schonbacher H. and Van de Voorde M., 1976, "Radiation damage to electronic components," Nucl. Instrum. Methods 136, 451.

Ba85 Baker S. I., 1985, "Fermilab soil activation experience," in: Proc. Fifth DOE Environmental Protection Information Meeting, Vol. 2 p 673 CONF-841187 (Washington, D. C.: U. S. Department of Energy).

Ba86 Baker S. I., 1986, Site Environmental Report for Calendar Year 1985, Fermi National Accelerator Laboratory, Batavia, IL 60510, Fermilab Report 86/37.

Be82 Beynel P., Maier P. and Schonbacher H., 1982, "Materials used around high-energy accelerators," in: Compilation of Radiation Damage Test Data, Part III, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 82 - 10.

Bi69 Birchall I., 1969, "Gamma scatter from open top cells," Health Phys. 16, 47.

Bo66 Boag J. W., 1966, "Ionization chambers," in: Radiation Dosimetry Volume II (edited by Frank H. Attix and William C. Roesch), pp. 2-72 (New York: Academic Press).

Bo72 Borak T. B., Awschalom M., Fairman W., Iwami F., and Sedlet J., 1972, "The underground migration of radionuclides produced in soil near high energy proton accelerators," Health Phys. 23, 679.

Bo75 Borak T., 1975, "A simple approach to calculating gamma ray SKYSHINE for reduced shielding applications," Health Phys., 29, 423.

Bo85 Bouquet F. and Winslow J., 1985, Radiation Data for Design and Qualification of Nuclear Plant Equipment, Electric Power Research Institute, EPRI NP-4172 (Palo Alto, CA: EPRI).

Br81 Bruce M. B. and Davis M. V., 1981, Radiation Effects on Organic Materials in Nuclear Plants, Electric Power Research Institute, EPRI NP-2129 (Palo Alto, CA: EPRI)

Bu72 Busick D. and Warren G., 1972, "Tungsten-181 contamination incident," in Health Physics Operational Monitoring, Vol. 2 (edited by C. A. Willis and J. S. Handloser) pp. 1281 - 1289 (New York: Gordon & Bresch).

Ce83 Cember H., 1983, Introduction to Health Physics (Second Edition) (New York: Pergamon Press).

CEBAF87 Continuous Electron Beam Accelerator Facility, 1987, TN-0061 (Virginia: CEBAF).

CFR83a Code of Federal Regulations, 1983, "Standards for Protection Against Radiation", 10 CFR 20 (Washington, D. C: Office of the Federal Register).

CFR83b Code of Federal Regulations, 1983 "Transportation", 49CFR (Washington, D. C: Office of the Federal Register).

CFR85 Code of Federal Regulations, 1985, "Environmental Protection Agency," 40 CFR 141 (Washington, D. C.: Office of The Federal Register).

CFR86 Code of Federal Regulations, 1986, "Nuclear Regulatory Commission," 10 CFR 20 Draft, Federal Register 51, Jan 9, 1986 (Washington, D.C.: Office of the Federal Register).

Cl83 Clapier F. and Zoidins C. S., 1983, "Neutron dose equivalent rates due to heavy ion beams," Nucl. Instrum. Methods 217, 489-494.

Co53 Cowan F. P. and Handloser J. S., 1953, <u>Health Physics Program for the Brookhaven Cosmotron,</u> Brookhaven National Laboratory, Upton, NY 11973, BNL 264 (T-43).

Co82 Cossairt J. D., Mokhov N. V., and Murphy C. T., 1982, "Absorbed dose measurements external to thick shielding at a high energy proton accelerator: Comparison with Monte-Carlo calculations," <u>Nucl. Instrum. Methods.</u> 197, 465.

Co85 Cossairt J. D. and Coulson L. V., 1985, "Neutron skyshine measurements at Fermilab," <u>Health Phys.</u> 48, 175.

De68 De Staebler H., Jenkins T. M., and Nelson W. R., 1968, "Shielding and Radiation," in <u>The Stanford Two-Mile Accelerator,</u> (edited by R. B. Neal), pp 1029-1064 (New York: W. A. Benjamin Inc.).

De85 Denis J. A. and Dunster H. J., 1985, "Radiation quality and radiation protection: Implications of changes in quality factors," <u>Rad. Prot. Dosim.</u> 13, 327.

Di73 Distenfeld C. H., Colvett R. D. and Ash J. A., 1973, <u>Evaluation of Accidental Exposure to Accelerator Personnel,</u> Brookhaven National Laboratory, Upton, N. Y. BNL 17796.

DOE80 Department of Energy, 1980, A Guide to Reducing Radiation Exposure to as low as Reasonably Achievable (ALARA), DOE/EV/1830-T5 (Springfield, VA: National Technical Iformation Service).

DOE86 Department of Energy, 1986, DOE Standard for the Performance Testing of Personnel Dosimeters, DOE/EH-0027 (Washington, D. C.)

EL86 Elder J. C., Graf J. M., Dewart J. M., Buhl T. E., Wenzel W. J., Walker L. J. and Stoker A. K., 1986, A Guide to Radiological Accident Considerations for Siting and Design of DOE Nonreactor Nuclear Facilities, Los Alamos National Laboratory, LA-10294-MS (Los Alamos, NM).

ERDA76 U. S. Energy Research & Development Administration, 1976, Nuclear Air Cleaning Handbook, ERDA Publication 76-21 (Springfield, Va: National Technical Information Service).

Ev55 Evans R. D., 1955, The Atomic Nucleus (New York: McGraw Hill).

Gi68 Gilbert W. S., Keefe D., McCaslin J. B., Patterson H. W., Smith A. R., Stephens L. D., shaw K. B., Stevenson G. R., Thomas R. H., Fortune R. D., and Goebel K., 1968, CERN-LRL-RHEL Shielding Experiment at the CERN Proton Synchrotron, Lawrence Berkeley Laboratory, Berkeley, CA 94720, UCRL-17941.

Gi81 Gibson T. A., Ozaki C. B., and Becker J. F., 1981, "The health physics hazards of x-rays produced by evacuated micro-wave waveguides," Health Physics 40, 893.

Go68 Goodman L. J. and Rossi M. N., 1968, "The measurement of dose equivalent using paired ionization chambers," Health Phys. 14, 168.

Go76 Gollon P. J., 1976, "The production of radioactiviy by accelerators," IEEE Trans. Nucl. Sci. NS-23(4), 1395.

Go78 Gollon P. J., 1978, Soil Activation Calculations for the Anti-Proton Target Area, Fermi National Accelerator Laboratory, Batavia, IL. 60510, TM-816.

Go85 Gover James E. and Srour Joseph R., 1985, Basic Radiation Effects in Nuclear Power Electronics Technology, Sandia National Laboratories, Albuquerque, NM 87185, SAND85-0776.

Gr87 Greenhouse N. A., deCastro T. M., Hankins D. E., McCaslin J. B., Smith A. R., and Sun R. K., "An evaluation of NTA film in an accelerator environment and comparison with CR-39," submitted to Radiat. Prot. Dosim.

Ha83 Harrell J. A., Manke P. L. and Gover J. E., 1983, The Application of Remote Electronics in a Nuclear Fuel Reprocessing Environment: Radiation Effects and Design Guidelines, Sandia National Laboratories, Albuquerque, NM 87185, SAND82-2151.

Ho72 Hofert M., 1972, "Dose equivalent and quality factor of radiation from high-energy accelerators," in: Proc. 1st Symp. on Neutron Dosimetry in Biology and Medicine, EUR 4896 d-f-e (Munchen: EURATOM).

Ho75 Hofert M., 1975, A Comparison of Dose Equivalent Measurements Around a GeV Proton Accelerator, European Organization for Nuclear Research, CERN, Geneva, Switzerland, Internal Rep. DI/HP/187.

Ho84 Hofert M. and Stevenson G. R., 1984, "Dose equivalent measurement around GeV accelerators," Radiat. Prot. Dosim. 9, 235.

Hu60 Hubbard E. L., Main R. M., and Pyle R. V., 1960, "Neutron production by heavy ion bombardments," Phys. Rev. 118, 507.

IAEA79 International Atomic Energy Agency, 1979, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Tech. Report Series No. 188 (written by W. P. Swanson) (Vienna: IAEA).

IAEA89 International Atomic Energy Agency, 1989, Radiological Safety Aspects of the Operation of Proton Accelerators, Tech. Report Series No. XXX (written by R. H. Thomas and G. R. Stevenson) (Vienna: IAEA).

ICRP82 International Commission on Radiation Protection, 1982, "Cost-Benefit Analysis in the Optimization of Radiation Protection," ICRP Publication 37 (Oxford: Pergamon Press).

ICRU78 International Commission on Radiation Units and Measurements, 1978, "Basic Aspects of High Energy Particle Interactions and Radiation Dosimetry," ICRU Report 28 (Washington, D. C.: ICRU).

ICRU82 International Commission on Radiation Units and Measurements, 1982, "The Dosimetry of Pulsed Radiation," ICRU Report 34 (Washington, D. C.: ICRU).

ICRU85 International Commission on Radiation Units and Measurements, 1985, "Determination of Dose Equivalent Resulting from External Radiation Sources," ICRU Report 39 (Washington, D. C.: ICRU).

ICRU86 International Commission on Radiation Units and Measurements, 1986, "The Quality Factor in Radiation Protection," ICRU Report 40 (Washington, D. C.: ICRU).

In84 Ing H., McCall R. C., Jenkins T. M. and Warren G. J., 1984, "Identification of neutrons from the cooling water of a GeV electron accelerator," Nucl. Instrum. Methods 219, 41.

Is68 Islitzer N.F. and Slade D.H., "Diffusion and transport experiments," in: Meteorology and Atomic Energy-1968, (edited by D.H. Slade), U.S. Atomic Energy Commission, TID-24190 (Springfield, VA: Clearinghouse for Federal Scientific and Technical Information).

Ja68 Jaeger R. G., Editor-in-Chief, 1968-1970, Engineering Compendium on Radiation Shielding, Vols. 1-3, (New York: Springer-Verlag).

Je64 Jenkins T. M., 1964, Private communications.

Je68 Jenkins T. M. and McCall R. C., 1968, Emergency Determination of Dose Equivalent in High Energy Accelerator Accidents, Stanford Linear Accelerator Center, Stanford, CA 94309 SLAC-PUB-447.

Je70 Jenkins T. M., Busick D. D., McCall R. C., Nelson W. R., Svensson G. K., Warren G. J., Baumgarten A., Harris J. L., Murray J. J., Seppi E. J., and Vetterlein R. J., 1970, "Beam-safety considerations at the Stanford Linear Accelerator Center," Nuclear Safety 11, 435.

Je74 Jenkins T. M., 1974, "Accelerator boundary doses and skyshine," Health Physics 27, 251.

Je79 Jenkins T. M., 1979, "Neutron and photon measurements through concrete from a 15 GeV electron beam in a target- comparison with models and calculations," Nucl. Instrum. Methods 159, 265.

Je86 Jenkins T.M., 1986, in CEBAF Workshop on Radiation Safety, Newport News, VA April 7-9 (to be published).

Jo67 Joffre H. and Vialettes H., 1967, "Review of accidental irradiations with accelerators and protective measures against radiation," in: Proc. Symp. on Accidental Irradiation at Place of Work, EUR-3666, CONF-660412, (Nice, France: EURATOM).

Ki64 Kircher J. F. and Bowman R. E., 1964, Effects of Radiation on Materials and Components (New York: Reinhold Publishing Corporation).

Kn87 Knoll G. F., private communication.

Ko65 Komochkov M. M., 1965, Estimation of the Dose from Accidental Irradiation by a Large Amount of High-Energy Particles CERN, Geneva, Switzerland, CERN-Trans. 66-5, Original JINR Report P2008.

Ku73a Kuehner A. V., Chester J. D., and Baum J. W., 1973, "Portable mixed radiation dose-equivalent meter," in: Proc. Symp. on Neutron Monitoring for Radiation Protection Purposes, Vol. 1 (Vienna: International Atomic Energy Agency).

Ku73b Kuehner A. V. and Chester J. D., 1973, Dose Equivalent Meter Operating Instructions, Brookhaven National Laboratory, Upton, NY 11973, BNL, Health and Safety Division, Informal Report.

Kr79 Kraner H. W., 1979, Fast Neutron Damage in Germanium Detectors, Brookhaven National Laboratory, Upton, NY 11973, BNL-26850.

Kr81 Kraner H. W., 1981, Radiation Damage in Semiconductor Detectors, Brookhaven National Laboratory, Upton, NY 11973, BNL-30616.

La65 Lanzl Lawrence H., Rozenfeld Martin L., and Tarlov Alvin R., 1965, "High-dose human exposure from a 10 MeV linear accelerator," in: Proc. 1st Symp. on Accelerator Radiation Dosimetry and Experience, USAEC CONF-651109 (Brookhaven National Laboratory , N. Y: United States Atomic Energy Commission).

La75 Lambert K. P., Schonbacher H. and Van de Voorde M., 1975, "A comparison of the radiation damage of electronic components irradiated in different radiation fields," Nucl. Instrum. Methods 130, 291.

La86 Lazarus D.M., 1986, Particle production and targeting experience, Brookhaven National Laboratory, Upton, New York 11973, BNL 38307.

Le64 Lehman R., and Fekula O. M. 1964, "Energy spectrum of stray neutrons from the bevatron," Nucleonics 22 (11), 35.

Le65 Legeay G., Court L., Prat L., Jeanmaire L., Daburon M. L., De Kerviler H., and Tardy-Joubert P., 1965, "Dosimetrie des protons de haute energie par measure de beryllium-7 forme dans les tissus," in Proc. of Conf. Personnel Dosimetry for Radiation Accidents, IAEA, Vienna.

Le68 Leake J. W., 1968, "An improved spherical dose equivalent neutron detector," Nucl. Instrum. Methods 63, 329.

Li73 Lim C. B., 1973, The Development of a Neutron Spectrometer using Multi-wire Spark Chambers, Ph.D. Thesis, Nuclear Engineering Department, University of California, Lawrence Berkeley Laboratory, Internal Report LBL-1719.

Li85 Liptak G. and Schuler R., 1985, Radiation Tests on Selected Electrical Insulating Materials for High-Power and High Voltage Application, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 85-02.

Lo86 Loew G. A., 1986, Some Issues Involved in Designing a 1 TeV (c.m.) e+/- Linear Collider Using Conventional Technology, Stanford Linear Accelerator Center, Stanford, CA 94305, SLAC-3892

Ma73 Madey R. and Waterman F. M., 1973, "Neutron spectroscopy from 1 MeV to 1 GeV," in: Symp. on Neutron Monitoring for Radiation Protection Purposes, Vol. 1 (Vienna: International Atomic Energy Agency).

Ma74 Mamont-Ciesla K. and Rindi A., 1970, Spark Chamber Neutron and Proton Spectrometer - First Report on Performance, Lawrence Berkeley Laboratory, Berkeley, CA 94720, LBL-3343.

Mc60 McCaslin J. B., 1960, "A high energy neutron flux detector," Health Phys. 2, 399.

Mc81 McCaslin J. B. and Thomas R. H., 1981. "Practical neutron dosimetry at high-energies," in: Proc. Seminar on Radiation Protection Quantities for External Exposure, EUR-7101-EN (Harwood Academic Press).

Mc85 McCaslin J. B., LaPlant P. R., Smith A. R., Swanson W. P., and Thomas R. H., 1985, "Neutron production by Ne and Si ions on a thick Cu target at 670 MeV.A with application to radiation protection," IEEE Trans. Nucl. Sci. NS-32(5).

Mc87 McCaslin J. B., Swanson W. P., and Thomas R. H., 1987, "Moyer model approximations for point and extended beam losses," Nucl. Instrum. Methods A256, 418.

Mi72 Miller A. J. and Patterson H. W., 1972, "Measurement of induced activity to estimate personnel radiation exposures received from accelerator beams," Health Phys. 23, 671.

Mo79 Moore R. E., Baes III C. F., McDowell-Boyer L. M., Watson A. P., Hoffman F. O., Pleasant J. C., and Miller C. W., 1979, AIRDOS-EPA: A Computerized Methodology for Estimating environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides, Oak Ridge National Laboratory, Oak Ridge, TN 37830 ORNL-5532.

Mo81 Moe H. J., 1981, "Contact or near contact external dose estimates," presented as Continuing Education at Health Physics Society Annual Meeting, Louisville, KY.

Mo85 Moe H. J., 1985, "Radiation fields from extended sources," presented in Professional Enrichment Program at Health Physics Society Annual Meeting, Chicago, Il.

Na72 Nachtigall D. and Burger G., 1972, "Dose equivalent determination in neutron fields by means of moderator techniques," in: Topics in Radiation Dosimetry, Supplement 1 (edited by F. H. Attix) (New York: Academic Press).

NCRP76 National Council on Radiation Protection and Measurements, 1976, "Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies up to 10 MeV", NCRP Report No. 49 (Bethesda, MD: NCRP).

NCRP77 National Council on Radiation Protection and Measurements, 1977, "Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities", NCRP Report No. 51 (Bethesda, MD: NCRP).

NCRP84 National Council on Radiation Protection and Measurements, 1984, "Neutron Contamination from Medical

Electron Accelerators", NCRP Report No. 79 (Bethesda, MD: NCRP).

NCRP85a National Council on Radiation Protection and Measurements, 1985, "A Handbook on Radioactivity Measurements Procedures," NCRP Report No. 58 2nd Edition (Bethesda, MD: NCRP).

NCRP85b National Council on Radiation Protection and Measurements, 1985, "Management of Persons Accidentally Contaminated with Radionuclides", NCRP Report No. 65 (Bethesda, MD: NCRP).

NCRP86 National Council on Radiation Protection and Measurements, 1986, "Radiation Alarms and Access Control Systems," NCRP Report No. 88 (Bethesda, MD: NCRP).

NCRP87 National Council on Radiation Protection and Measurements, 1987, "Recommendations on Limits for Exposure to Ionizing Radiation," NCRP Report No. 91 (Bethesda, MD: NCRP).

Ne76 Nelson W. R. and Jenkins T. M., "Similarities among the radiation fields at different types of high energy accelerators," 1976, IEEE Trans. Nucl. Sci. NS-23, 1351.

Ne80 Nelson W. R. and Jenkins T. M., Editors, 1980 Computer Techniques on Radiation Transport and Dosimetry, (New York: Plenum Press).

NRC74 U. S. Nuclear Regulatory Commission, 1974, "Termination of Operating Licences for Nuclear Reactors," U.S. NRC Regulatory Guide 1.86 (Washington, D.C.: U.S. NRC).

NRC86 National Research Council, 1986, Preservation of Historical Records, National Academy Press, Washington D. C.

Oh80 Ohnesorge W. F., Butler H. M., Fulmer C. M., and Mosku S. W., 1980, "Heavy ion target area fast neutron dose equivalent rates," Health Phys., 39, 633-636.

Op79 Opelka J. H., Mundis R. L., Marmer G. J., Peterson J. M., Siskind B., and Kikta M. J., 1979, Particle Accelerator Decommissioning Argonne National Laboratory, Argonne, IL 60510 ANL/ES-82.

Pa69 Patterson H. W., Heckman H. H. and Routti J. T., 1969, "New measurement of star production in nuclear emulsions and applications to high-energy neutron spectroscopy," in: 2nd Int. Conference on Accelerator Dosimetry and Experience, Conf. 691101 (Stanford, CA: United States Atomic Energy Commission).

Pa73 Patterson H. W. and Thomas R. H., 1973, Accelerator Health Physics (New York: Academic Press).

Pa76 Pasquill F., 1976, Atmospheric Dispersion Parameters in Graussian Plume modeling part II. Possible requirements for change in the Turner Workbook Values, U. S. Environmental Protection Agency EPA-600/4-76-030b. (Springfield, VA: National Technical Information service).

Ph81 Phillips D. C., Scott J. M., Goebel K., Schonbacher H., Dieterle W., Eichenberger W., and Maurer J., 1981, The Selection and Properties of Epoxide Resins Used for the

Insulation of Magnet Systems in Radiation Environments, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 81-05.

Ps71 Pszona S., 1971, "The NE 102A organic scintillation detector as an acceptable LET dependent detector for quality factor and dose equivalent determination in mixed radiation field," in: Proc. Int. Congress on Protection Against Accelerator and Space Radiation CERN 71-16, Vol. 1 (Geneva, Switzerland: CERN).

Ps77 Pszona S. and Hofert M., 1977, "A rapid method for the determination of dose equivalent in mixed radiation fields," Nucl. Instrum. Methods 146, 509.

RCRA76 The Resource Conservation and Recovery Act, 1976, Public Law 94-580.

Re65 Remy R., Neutron Spectroscopy by the Use of Nuclear Stars from 20-300 MeV, M.S. Thesis, Lawrence Berkeley Laboratory, Berkeley, CA 94720, UCRL-16325.

Ri69 Rindi A., 1979, "Present and projected uses of multiwire spark chambers in health physics," in: 2nd Int. Conf. on Accelerator Dosimetry and Experiments, USAEC CONF-691101 (Stanford, CA: United States Atomic Energy Commission).

Ri73 Rindi A. and Thomas R. H., 1973, "The radiation environment of high-energy accelerators," Annual Review of Nuclear Physics 23, 315.

Ri74 Rindi A., 1974, "A spectrometer for measuring charged particles and neutrons," Nucl. Instrum. Methods 116, 471.

Ri75 Rindi A. and Thomas R. H., 1975, "Skyshine-a paper tiger?", Particle Accelerators 7, 23.

Ro55 Rossi H. H. and Rosenzweig W., 1955, "A device for the measurement of dose as a function of specific ionization," Radiology 64, 404.

Ro56 Rockwell Theodore III, Editor, 1956, "Reactor Shielding Design Manual," U. S. AEC Report TID-7004 (Washington, D. C.: United States Atomic Energy Commission).

Ro69 Routti J. T., "Mathematical consideration of determining neutron spectra from activation measurements," in: 2nd Int. Conf. on Accelerator Dosimetry and Experience, USAEC CONF-691101 (Stanford, CA: United States Atomic Energy Commission).

Sc71 Schmidt F. A. R., 1971, The Attenuation Properties of Concrete for Shielding of Neutrons of Energy Less Than 15 MeV, Oak Ridge National Laboratory, Oak Ridge, TN 37830, ORNL-RSIC-26.

Sc73 Schaeffer N. M., Editor, 1973, Reactor Shielding for Nuclear Engineers, TID-25951 (Springfield, VA: United States Atomic Energy Commission).

Sc75 Schonbacher H. and Van de Voorde M. H., 1975, Radiation and Fire Resistance of Cable-Insulating Materials Used in Accelerator Engineering, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 75-3.

Sc79a Schonbacher H. and Stolarz-Izycka A., 1979, "Cable insulating materials," in: Compilation of Radiation Damage Test Data, Part I, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 79-04.

Sc79b Schonbacher H. and Stolarz-Izycka A., 1979, "Thermosetting and thermoplastic resins," in: Compilation of Radiation Damage Test Data, Part II, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 79-08.

Sh81 Shapiro J. 1981, Radiation Protection- A Guide for Scientists and Physicians (Cambridge, MA: Harvard University Press).

Sm65 Smith A. R., "Threshold detector applications to neutron spectroscopy at the Berkeley accelerators," in: Proc. USAEC 1st Symp. on Accelerator Radiation Dosimetry and Experience, CONF-651109 (Brookhaven National Laboratory, NY: United States Atomic Energy Commission).

SSC86 1986, "SSC Workshop on Environmental Radiation," SSC Central Design Group, Lawrence Berkeley Laboratory, Berkeley, CA 94720, SSC-SR-1016.

St58 Stephens L. D. and Smith A. R., 1958, Fast Neutron Surveys Using Indium Foil Activation, Lawrence Berkeley Laboratory, Berkeley, CA 94720, UCRL-8418.

St72 Stapleton G. B. and Thomas R. H., 1972, "Estimation of the induced radioactivity of the groundwater system in the neighborhood of a proposed 300 GeV high energy accelerator situated on a chalk site," Health Physics 23, 689.

ST82 Stevenson G. R., Kuei-Lin L., and Thomas R. H., 1982, "Determination of transverse shielding for proton accelerators using the Moyer model," Health Physics 43, 13.

St84 Stevenson G. R. and Thomas R. H., 1984, "A simple procedure for the estimation of neutron skyshine from proton accelerators," Health Phys. 46, 115.

Su63 Sullivan A. H. and Baarli J., 1963, An Ionization Chamber for the Estimation of the Biological Effectiveness of Radiation, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 63-17.

Su64 Sullivan A. H., 1964, An Approach to a Rem Dosimeter Using Ionization Chambers, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN DI/HP/29.

Su65 Sullivan A. H. and Overton T. R., 1965, "Time variation of the dose rate for radioactivity induced in high energy particle accelerators," Health Physics 11, 1101.

Su84 Sullivan A. H., 1984, "The use of detectors based on ionization recombination in radiation protection," Paper presented at the Workshop for Practical Implementation of Microdosimetric Counters in Radiation Protection, 15-17 May, Hamburg/Saar, Germany).

Sw85 Sweeney M. A. and Olsen J. N., 1985, "Monte Carlo calculations of the bremsstrahlung radiation environment expected in the future particle beam fusion accelerator facility PBFA II," Nuc. Sci. Eng. 89, 233.

Te70 Tesch K., 1970, "Neutron dosimetry in the energy range between 10 and 100 MeV," Nucl. Instrum. Methods 83, 295-299.

Te79 Tesch K., 1979, "Data for simple estimates of shielding against neutrons at electron accelerators," Part. Accel. 9, 201.

Th79a Thomas R. H. , 1979, "Passive detectors," in: Radiation Protection and Dosimetry in Medicine, Inter. School for Radiation Damage and Protection, Etorre Majorana Center for Scientific Culture, Erice, Italy. Also LBL-9813.

Th79b Thomas R. H. and Rindi A., 1979, "Radiological environmental impact of high energy accelerators," Crit. Rev. Environ. Control 9(1), 51.

Th85 Thomas R. H. and Stevenson G. R., 1985, "Radiation protection around high energy accelerators," Radiat. Prot. Dosim. 10, 283.

Tu70 Turner B. D., 1970, Workbook of Atmospheric Dispersion Estimates, U. S. Department of Health, Education and Welfare Public Health Service Publications No. 999-AP-26 (Springfield, VA: National Technical Information Service).

Va70 Van de Voorde M. H., 1970, Effects of Radiation on Materials and Components, European Organization for Nuclear Research, CERN, Geneva, Switzerland, CERN 70-5.

Va75 Van Ginneken A. and Awschalom M., 1975, High Energy Particle Interactions in Large Targets. Fermi National Accelerator Laboratory, Batavia, IL. 60510.

Wa61 Walker R. L. and Grotenhuis M., 1961, A Summary of Shielding Constants for Concrete, Argonne National Laboratory, Argonne, IL 60439, ANL-6443.

Wa69 Warren G. J., Busick D. D., and McCall R. C., 1969, "Radioactivity produced and released from water at high energies," in: Proc. 2nd International Conf. on Accelerator Dosimetry and Experience, USAEC CONF-691101 (Stanford, CA: United States Atomic Energy Commission).

Wa73 Walz D., Busick D., Constant T., Crook K., Fryberger D., Gilbert G., Jasberg J., Keller L., Murray J., Seppi E., and Vetterlein R., 1973, "Tests and description of beam containment devices and instrumentation - A new dimension in safety problems," IEEE Trans. Nucl. Sci., NS-20, 465.

Zi62 Zielczynski M., 1962, "Use of columnar recombination for determination of relative biological efficiency of radiation," Nukleonika 7, 175.

Zi64 Zielczynski M., 1964, "Instrument for determination of recommended relative biological effectiveness of radiation," Instrum. Exp. Tech. USSR 6, 1217.

INDEX

accelerators
    DOE, 2, 63
    small, 4
access control, 21, 64, 89
accidents, 9, 18
accident dosimetry, 52
activation, 34
administrative controls, 74
air activation, 8
ALARA, 3, 79-85
audible warning, 25, 26, 65
audits, 69

beam containment, 28-31
    electronic devices, 30
    mechanical devices, 29
beam loss, 18
beams, 64
beta-gamma dosimetry, 61
bremsstrahlung, 11, 62
burn-through, 29
bypass, interlock, 27

calibration,
    dosimeters, 52
    radiation monitors, 72
cascade neutrons, 10
certification, 78
computer codes, 14, 19, 41, 102
computers in safety interlock systems, 89
concrete, 20
contamination, 32-37, 82
contamination control, 32-37
controlled access, 25, 26
coulomb barrier, 10, 13
criteria, siting, 5
circuits, redundant, 22-23

decommissioning, 79, 81-85
decontamination, 72,79
detectors
    activation, 48, 51
    ionization chambers, 48, 50, 53, 54, 56
    moderated, 48, 50, 53
    neutron, 48, 50, 51, 53, 60-61
    scintillation, 48, 50, 52
    thermoluminescent, 48, 57
    threshold, 48, 51
dismantling, 79, 81-84
disposal, radioactive waste, 32, 37, 42-44, 82
documentation, 65-69, 71-76
dose limits, 17, 98
dosimetry,
    mixed field, 53
    personnel, 61-64

elastic scattering, 20
electron accelerators source term, 11
environmental monitoring, 49
emergency exit, 25
evaporation neutrons, 10

facility design, 5-9, 79
fail-safe circuits, 22, 89-94
film badges, 62, 63
foil, beam dispersing, 18

Geiger-Muller counters, 58, 106
giant resonance region, 11
ground water, 8

health physicist, 76-78
heavy concrete, 21
high energy interactions, 10, 12

inelastic interaction, 10
instruments, 47-60, 95, 106
interlocks, 21-26, 72, 75, 89
ion exchange resins, 38, 39, 42, 43
ionization chambers, 48, 50, 53, 56, 62, 95
    paired, 48, 50, 53
    recombination, 50, 54, 62
ionization recombination, 56, 95

keybanks, 25
klystrons, 15-16

lasers, 16
LET spectrometers, 50, 55, 62

mixed waste, 44
moderated detectors, 48, 50, 51, 53, 54, 60-61
monitoring radiation, 31, 47-64
"Moyer Model", 20
muons, 10, 12, 20, 52, 62

neutron detectors, 47-61
  neutron dosimetry, 62
neutrons,
  electron accelerators, 11, 12
  heavy ion accelerators, 12-14
  giant resonance, 11
  proton accelerators, 10, 11
  spectroscopy, 49, 51

particle beam separators, 16
particle production, 10-12
personnel dosimetry, 61-64
personnel protection system, 21-31, 89-94
pions, 10, 12, 54
prompt-direct radiation, 7, 9-14, 60
proportional counters, 48, 50, 51, 58
protective clothing, 44
proton accelerators source terms, 9-11
pseudodeuteron process, 11
pulsed radiation, 55-61, 95-97, 106-110
pumps, vacuum, 35

radiation alarm, 21, 22, 24, 31,
radiation damage, 22, 23, 44-46
radiation detectors, 18, 24, 30, 47-64, 95-97, 106-110
radiation rules, 70-76
Radiation Safety Officer, 76
radiation safety committee, 78
  radiation safety staff, 76-78
radioactivation,
  air, 8, 41
  soil, 8, 40-41
  water, 8, 38-40
radioactivation control, 34-44
radioactive materials,
  disposal, 39, 42-44, 82-84
  storage and transportation, 8, 42-44, 72, 80-84
radioactivity residual, 14, 42-44
recombination in ion chambers, 56, 95-97
recombination ionization chambers, 50, 54, 62
records, 65-69, 82, 83
regulations, 65-69, 98-101
remmeters, 48-50, 53, 62
restricted access, 26
RF cavity, 15, 16
"roof" shielding, 7, 19

scattering, elastic, 20
scattering, inelastic, 20
scintillator detectors, 48, 50, 59
searches, 25, 72
shielding, 17-21
shielding materials, 20, 21
shipping, 8, 83
site criteria, 5-9
skyshine, 7, 19
soil, 8, 40, 41
source terms, 9-14
sources, (other than accelerators), 15-17
spallation, 34
spectroscopy neutron, 49, 51
storage
  radioactive material (and transportation), 8, 42-44, 72, 80-84
  records, 67-69
surveys, radiation, 47-61

targets, 14, 15, 36-37, 72
TLDs, 62, 63
toroids, 18, 30, 31
track-etch detectors, 63, 64
training, 64, 77
tritium, 34, 35, 38-41

uncontrolled beam loss, 18
uranium, 35, 36

warning lights, 25
waste management, 42-44, 80-84

waste disposal, 42-44
water, contaminated, 38, 39, 43
written procedures, 71-74
x-rays, 15-17