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PARTICLE-ACCELERATOR DECOMMISSIONING

by

**J. H. Opelka, R. L. Mundis,
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B. Siskind, and M. J. Kikta**

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December 1979

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CONTENTS

	<u>Page</u>
ABSTRACT	1
CHAP. 1. OVERVIEW	1
References	4
CHAP. 2. PARTICLE-ACCELERATOR TECHNOLOGY	5
CHAP. 3. HISTORY OF PARTICLE-ACCELERATOR DECOMMISSIONINGS	13
References	17
CHAP. 4. REGULATIONS CONCERNING PARTICLE-ACCELERATOR DECOMMISSIONING	19
References	22
CHAP. 5. PLANNING THE DECOMMISSIONING	25
CHAP. 6. HEALTH PHYSICS AND SAFETY ASPECTS	33
Introduction	33
Health Physics of Generic Accelerator Categories	35
Anticipated Radiation Levels	37
Doses for Dismantling Four Prototypic Accelerators	40
Quantities and Concentrations of Induced Radioactivity	40
References	45
CHAP. 7. COST ESTIMATES FOR DECOMMISSIONING PROCEDURES	47
The Zero Gradient Synchrotron Decommissioning	48
The 60" Cyclotron Dismantlement	53
The 22-MeV Linac Dismantlement	54
The Tandem Van de Graaff Dismantlement	55
Summary of Cost Results	55
References	56
CHAP. 8. RECOMMENDATIONS	57
APPENDIX A. CENSUS OF PARTICLE ACCELERATORS	59
APPENDIX B. DETAILS CONCERNING THE DECOMMISSIONING OF FOUR PARTICLE ACCELERATORS	71
The Rochester Synchrocyclotron	71
The Carnegie-Mellon Synchrocyclotron	72
The Cambridge Electron Accelerator	74
The Yale HILAC	78
References	81

CONTENTS

	<u>Page</u>
APPENDIX C. SUGGESTED FORMS FOR ORGANIZING A PART. LE-ACCELERATOR DECOMMISSIONING	87
APPENDIX D. DETAILS OF THE ZERO GRADIENT SYNCHROTRON EXAMPLE	95
APPENDIX E. DETAILS OF THE 60" CYCLOTRON EXAMPLE	103
APPENDIX F. DETAILS OF THE 22-MeV ELECTRON LINAC EXAMPLE	107
APPENDIX G. DETAILS OF THE 9-MV TANDEM VAN de GRAAFF EXAMPLE	111
APPENDIX H. UNIT COSTS	115
References	118
APPENDIX I. DECOMMISSIONED PARTICLE-ACCELERATOR COMPONENTS STORED AT BROOKHAVEN NATIONAL LABORATORY	119

FIGURES

<u>No.</u>		<u>Page</u>
5.1	ZGS Decontamination and Decommissioning Functions	29
6.1	Radioactivation Survey Form Used by the Princeton-University of Pennsylvania Accelerator	38
7.1	ZGS Decontamination and Decommissioning Schedule and Staff	50
C.1	Section Number List	88
C.2	Disposition of Sections	89
C.3	Item Physical Description	90
C.4	Cost by Operation	91
C.5	Section Cost Summary	92
C.6	Project Cost Summary	93
I.1	Entrance to the Storage Yard	120
I.2	Remains of the Cosmotron from a Distance	120
I.3	Storage of the Cosmotron Magnets	121
I.4	Copper Bars, Trim Coils, and Magnets from the Cosmotron	121
I.5	Storage of the Cosmotron Magnets	122
I.6	Cosmotron Copper Trim Coils	122
I.7	Miscellaneous Parts from the Cosmotron	123
I.8	Miscellaneous Parts from the Cosmotron	123
I.9	Magnets from the Cambridge Electron Accelerator	124
I.10	Cambridge Electron Accelerator Vacuum Chambers	124

TABLES

<u>No.</u>	<u>Page</u>
3.1 Decommissioned Accelerators	16
5.1 Possible Sequences of Decommissioning Activities	26
5.2 Dismantling Support Activities	30
5.3 Major Equipment Categories	31
6.1 Relative Production of Induced Radioactivity in Particle Accelerators	34
6.2 Summary of Reported Radiation Measurements	39
6.3 Induced Radioactivity from Electron Beams	41
6.4 Radioactivity Expected in Three Categories of Components from Various Types of Accelerators	42
6.5 Mass of Radioactive Waste from Selected Accelerators	44
7.1 Estimated Costs of Dismantlement and Immediate Disposal of Four Prototypic Accelerators	56
A.1 Proton Synchrotrons	59
A.2 Electron Synchrotrons	59
A.3 Positive-Ion Linacs	60
A.4 Electron Linacs	60
A.5 Cyclotrons	61
A.6 Synchrocyclotrons	62
A.7 Storage Rings	62
A.8 Electrostatic Accelerators	63
A.9 Medical-Application Cyclotrons	68
A.10 Codes for Funding Agencies and References	69
B.1 Salvageable Items of Accelerator Equipment	76
B.2 Survey of Radioactivity in CEA Synchrotron as of 1 June 1973 . . .	77
B.3 Statement of Costs Incurred and Recommended for Acceptance by HEW Audit Agency for 1 July 1973 through 31 December 1974	79
D.1 Estimated Radiation Dose Rates and Doses During Decontamination and Dismantling of the Zero Gradient Synchrotron	96
D.2 Estimated Period-Dependent Costs for ZGS Dismantling	97
D.3 Estimated Activity-Dependent Item-Cost Summary for ZGS Dismantling	98

TABLES

<u>No.</u>		<u>Page</u>
D.4	Estimated Wastes Associated with the Dismantling of the ZGS . . .	99
D.5	Estimated Packaging, Transportation, and Disposal Costs for the ZGS Disposal Option	100
D.6	Estimated Period-Dependent Costs for Mothballing of the ZGS . . .	100
D.7	Estimated Activity-Dependent, Packaging, Transportation, and Disposal Costs for Mothballing of the ZGS	101
D.8	Estimated Period-Dependent Costs for Entombment of the ZGS	101
D.9	Estimated Activity-Dependent, Packaging, Transportation, and Disposal Costs for Entombment of the ZGS	102
D.10	Estimated Waste-Disposal Costs for ZGS Dismantlement with Storage Option	102
E.1	Estimated Radiation Dose Rates and Doses During Decontamination and Dismantling of the 60" Cyclotron	104
E.2	Estimated Period-Dependent Organization-Staff Costs for 60" Cyclotron Dismantlement	104
E.3	Estimated Activity-Dependent Item-Cost Summary for 60" Cyclotron Dismantling	105
E.4	Estimated Wastes Associated with the Dismantling of the 60" Cyclotron at Argonne National Laboratory	106
E.5	Estimated Packaging, Transportation, and Disposal Costs for the 60" Cyclotron Disposal Option	106
F.1	Estimated Radiation Dose Rates and Doses During Decontamination and Dismantling of the Electron Linac	108
F.2	Estimated Period-Dependent Organization-Staff Costs for Dismantling a 22-MeV Linac	108
F.3	Estimated Activity-Dependent Item-Cost Summary for Dismantling a 22-MeV Electron Linac	108
F.4	Estimated Wastes Associated with Dismantling of the 22-MeV Electron Linac at Argonne National Laboratory	109
F.5	Estimated Packaging, Transportation, and Disposal Costs for the 22-MeV Electron Linac Disposal Option	109
G.1	Estimated Radiation Dose Rates and Doses During Decontamination and Dismantling of the Tandem Van de Graaff	112
G.2	Estimated Period-Dependent Costs for a 9-MV Tandem Van de Graaff Dismantlement	112
G.3	Estimated Activity-Dependent Item-Cost Summary for Tandem Van de Graaff Dismantlement	112
G.4	Estimated Wastes Associated with the Dismantling of the Tandem Van de Graeff at Argonne	113

TABLES

<u>No.</u>		<u>Page</u>
G.5	Estimated Packaging, Transportation, and Disposal Costs for the 9-MV Tandem Van de Graaff Disposal Option	113
H.1	Monthly Budget for Staff-Level Positions	116
H.2	Estimating Factors for Typical Demolition Activities	117
H.3	Costs for Legal and Overweight Payloads--Chicago, Illinois to Richland, Washington	118
H.4	Cost Factors for Packaging and Radiactive-Waste Disposal	118

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Abstract

Generic considerations involved in decommissioning particle accelerators are examined. There are presently several hundred accelerators operating in the United States that can produce material containing nonnegligible residual radioactivity. Residual radioactivity after final shutdown is generally short-lived induced activity and is localized in hot spots around the beam line. The decommissioning options addressed are mothballing, entombment, dismantlement with interim storage, and dismantlement with disposal. The recycle of components or entire accelerators following dismantlement is a definite possibility and has occurred in the past. Accelerator components can be recycled either immediately at accelerator shutdown or following a period of storage, depending on the nature of induced activation. Considerations of cost, radioactive waste, and radiological health are presented for four prototypic accelerators. Prototypes considered range from small accelerators having minimal amounts of radioactive material to a very large accelerator having massive components containing nonnegligible amounts of induced activation. Archival information on past decommissionings is presented, and recommendations concerning regulations and accelerator design that will aid in the decommissioning of an accelerator are given.

CHAPTER 1.

OVERVIEW

Over the past several years, there has been increasing concern over the accumulation of radioactive materials at various scientific, industrial, and other facilities in the United States, and increasing pressure to ascertain what is being done to assure that any potentially serious waste-disposal problems are not being overlooked. Of course, the nuclear-power industry has the major share of the problem and, therefore, commands most of the attention. However, in addition to the power industry, there exists a sizable variety of radioactive materials in medical and industrial products, as sources for radiation processing and sterilization, and as by-products from the operations

of particle accelerators. The subject of nuclear-facility decommissioning has been addressed by the Comptroller General in a 2 June 1977 report to the Congress.¹ The primary thrust of that report was toward the nuclear-power industry; however, other aspects of the problem, which include isotope usage and accelerator facilities, were recognized as potential problems.

The Department of Energy (DOE) has initiated a comprehensive study of the quantities and types of radioactive materials in existence both at its existing facilities and at the facilities formerly used as part of the Manhattan Engineering District/Atomic Energy Commission (MED/AEC) program. DOE, as the successor to the Atomic Energy Commission (AEC) and the Energy Research and Development Administration (ERDA), is the custodian of the sites and facilities that were constructed and used, over the past 35 years, for development of nuclear energy for scientific, domestic, and national-defense purposes. Most of the facilities, including a broad range of research-oriented particle accelerators, were originally designed for very specialized purposes; and, as the development programs for nuclear energy progressed, nuclear facilities became obsolete and in excess to program needs.

In the United States there are over 1200 particle accelerators currently operating, ranging in size from very small Cockroft-Walton and electron linear accelerators to multi-GeV research synchrotrons. At least 50 accelerators produce neutron fluxes that cause significant induced activation, and several hundred more are capable of producing neutron fluxes that could result in nonnegligible activation of various components of the accelerator facility. Almost all these accelerators producing nonnegligible activation are owned or funded by an agency of the federal government. The most up-to-date compilation presently possible of accelerators in the United States that produce a nonnegligible radiation environment at decommissioning is given in Appendix A.

In this report, the potential problems associated with decommissioning of all types of particle accelerators in the United States (excluding neutron generators) are evaluated. Inasmuch as there is a wide variety of accelerator designs, it is necessary to evaluate this problem in a generic way. To aid in spanning the potential problems that could occur in decommissioning an accelerator, four specific accelerators located at Argonne National Laboratory were examined. These are the Zero Gradient Synchrotron (ZGS) (designed by Argonne National Laboratory), the 60" fixed-frequency cyclotron (built by Cyclotron Corporation), the 22-MeV electron linac (built by ARCO), and a 9-MV Tandem Van de Graaff (pressure tank by High Voltage Engineering, accelerating system by National Electrostatics Corporation). The ZGS was chosen as prototype for large proton synchrotrons because it will be the next major accelerator to be decommissioned. The 60" cyclotron, an average-sized cyclotron, is representative of cyclotron and synchrocyclotron dismantlings. The electron linac was chosen as typical of the waveguide components of a linac, and to emphasize the different radiation environments at electron and ion accelerators. The Van de Graaff was chosen because electrostatic accelerators form the largest fraction of operating research accelerators, and also because it has a massive pressure tank despite its generally low-energy beam (tens of MeV). The choice of the Van de Graaff also serves to emphasize the difference in radiation environments at high- and low-energy ion accelerators. These four accelerators cover the range from small accelerators having minimal amounts of radioactive material to very large accelerators having massive components containing nonnegligible amounts of activation.

The cost estimates developed in this report for decommissioning of the four prototypes are given to illustrate the methodology for arriving at such estimates and to indicate the magnitude of the decommissioning costs. No attempt was made in this report to prepare cost estimates at a level of detail required for a contractor bid package. Care must be exercised in extrapolating these results to other accelerators, as each accelerator decommissioning will be a unique problem, especially considering the diversity in accelerators. Estimates of radioactive waste and radiation dose to workers for the four prototypes were also developed to indicate the magnitude of these problems.

There is a variety of decommissioning alternatives that can be implemented. The basic alternatives considered in this report are mothballing, entombment, dismantlement with storage of potentially reusable components, and dismantlement with disposal of all radioactive materials. The options considered cover the spectrum of available options from simply a general cleanup (mothballing) to the complete dismantlement and disposal of the accelerator. The decommissioning options considered are not independent of each other. For example, dismantlement could follow either mothballing or entombment. Historically, some accelerators have been transferred intact to other facilities for reuse as injectors or boosters. In this case, the decommissioning is merely the transfer to the new facility.

Mothballing would involve a general cleanup around the accelerator, with loose contamination packaged for disposal. Following cleanup, access to the accelerator would be prohibited by blocking all entrances. Entombment would be similar to mothballing with the additional step of sealing all accesses to the accelerator with concrete. Because there is a relatively small amount of induced activity with short half-lives, a marked difference between decommissioning of an accelerator and that of other radioactive facilities (such as nuclear reactors) is the potential recycle of the accelerator-component materials. This reuse potential is directly addressed in the option of dismantling the accelerator and placing components in retrievable storage for a period of time to allow for radioactive decay. On dismantlement, the only components that would require storage are the potentially valuable ones not immediately claimed by other accelerator facilities for reuse. The option of dismantlement with disposal of all radioactive material, as addressed in this report, assumes no recycle of accelerator components and, therefore, gives an upper bound on the magnitude of the problem both in terms of cost and quantities of radioactive waste.

In most cases, the induced radioactivity is confined to relatively few parts of the machine, and disposition of these parts (assuming no recycle potential) is through normal radioactive-waste channels without complication. The radioactivity is generally low level (less than 100 R/h at the surface) and has a short half-life (5.26 yr for ^{60}Co). The waste-disposal problem is complicated because most research accelerators leave a legacy of low-level induced radioactivity in massive components (10 to 1000 Mg). Examples of such items are large magnets, shield blocks, beam stops of concrete, earth, or iron, and even the walls and floors of the building itself. These massive components need to be dealt with in a manner so as to pose no potential health hazards to persons in the vicinity or the public at large.

A comparison with decommissionings of nuclear-fuel-cycle facilities is not particularly useful due to differences in the decommissioning procedures involved.²⁻⁴ The major difference results from the much lower levels of contamination at an accelerator facility compared to that at a nuclear reactor. (The only exception to this is the Clinton P. Anderson Physics Facility at Los Alamos National Laboratory.) The decommissioning activities at an accelerator will be hands-on, whereas the major activities around a reactor will be done remotely.

REFERENCES FOR CHAPTER 1

1. "Cleaning Up the Remains of Nuclear Facilities--A Multibillion Dollar Problem." United States General Accounting Office, EMD-77-46, 16 June 1977.
2. "Technology, Safety, and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant." NUREG-0278, Battelle-Pacific Northwest Laboratory, October 1977.
3. "Technology, Safety, and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station." NUREG/CR-0130, Battelle-Pacific Northwest Laboratory, June 1978.
4. "Technology, Safety, and Costs of Decommissioning a Reference Small Mixed Oxide Fuel Fabrication Plant." NUREG/CR-0129, Battelle-Pacific Northwest Laboratory, February 1979.

CHAPTER 2.

PARTICLE-ACCELERATOR TECHNOLOGY

Since the development of the X-ray tube, a broad range of particle-accelerator systems has appeared. These systems may be classified in terms of the following general characteristics: particle accelerated, method of acceleration, and application of the radiation produced. In the case of small, commercially produced accelerators, the manufacturer's literature provides these general characteristics in detail. The general characteristics of large research machines are described in proposals, scientific reports, construction files, internal reports, and in some instances in users' manuals provided to experimental groups. In this chapter, a brief, general introduction to accelerator systems is provided for readers unfamiliar with accelerator design and components. Books recommended for readers wishing to learn more about accelerator characteristics are:

Robert R. Wilson and Raphael Littauer. "Accelerators - Machines of Nuclear Physics." Anchor Books, Doubleday and Co., Inc., Garden City, New York, 1960.

John J. Livingood. "Principles of Cyclic Particle Accelerators." D. Van Nostrand Company, Inc., Princeton, New Jersey, 1961.

M. Stanley Livingston and John P. Blewett. "Particle Accelerators." McGraw-Hill Book Company, New York, New York, 1962.

M. Stanley Livingston (ed.). "The Development of High Energy Accelerators." Classics of Science, Volume III, Dover Publications, Inc., New York, New York, 1966.

For the purposes of this report low energy is defined to be less than 10 MeV and high energy is defined to be above 1 GeV. Intermediate energies are referred to as medium energy.

All accelerators depend on an interaction between an electrically charged particle and an electric field, and sometimes a magnetic field. The particles are either free electrons or are atomic ions, positive or negative, depending on a deficiency or excess of electrons attached to the atomic nuclei. The systems are thereby known as electron or ion accelerators. In a few accelerator systems, both positive and negative atomic ions are accelerated simultaneously. Also, it is possible to accelerate a beam of polarized particles (i.e. particles with a preferred spin direction). Beams of secondary particles, such as pions, can be produced as a result of a primary beam of electrons or atomic ions bombarding a properly designed target.

The choice of accelerator-design parameters is based on both intended use and economic considerations. The earliest accelerators were custom-built and (with a few exceptions) intended for research in nuclear physics. The accel-

erated-particle energy and beam intensity were of utmost importance and generally strained the limits of state-of-the-art design. As more advanced designs were developed, existing lower-energy accelerators were superseded and became supporting and training facilities, or were modified or supplemented for other uses such as nuclear chemistry or nuclear medicine. Initially, the only particles accelerated were protons, deuterons, alpha particles, and electrons. The higher-energy particle-accelerator designs generally constrained the accelerator to operate in a pulsed mode with a low duty cycle, resulting in low average currents—in the microampere range. Development of ion sources capable of producing heavy ions with a high-charge state permitted some accelerators, such as cyclotrons, to be used in the studies of nuclear transformations and heavy-ion therapy.

Inasmuch as an electromagnetic field will accelerate charged particles, accelerators are devices to produce the needed field. The electric field may be either constant or varying in time. Also, in the interest of conserving space and capital, many accelerators include magnetic-field-producing systems to curve the path of the moving particle and return it again and again to the accelerating system.

The principle of operation of direct-voltage time-independent particle acceleration was known as early as 1640. Primitive electrostatic accelerators were developed during the first two decades of the twentieth century. In the case of the first X-ray tubes, electrons were evaporated from a filament and accelerated toward a positively charged receptor. Voltage multipliers (a transformer and rectifier system to produce a constant potential) were developed by 1921, but the starting point in the history of accelerator-physics research must be reckoned from 1932 when the disintegration of lithium by electrically accelerated protons with energies of 150 to 700 keV was accomplished by Cockroft and Walton using voltage-multiplying circuits. Following this, Robert Van de Graaff developed the electrostatic charging system (bearing his name) that has been used for multimillion-volt acceleration of both ions and electrons by electrostatic fields not varying in time. All of the above systems and variants thereon (notably, the Pelletron by Herb of National Electrostatic Corporation and the Dynamitron by Radiation Dynamics, Incorporated) have been used, in one form or another, not only as primary research machines, but as injectors or preaccelerators for accelerators of higher energy.

Three different designs may be defined for the Van de Graaff. In one, a negatively charged, high-potential electrode encloses a source that produces electrons. The electrons are accelerated to ground potential and may impinge upon a target to produce X rays or be brought through a thin window for direct electron therapy or surface treatment. Energies are low enough that induced activity is absent or negligible, requiring no more than verification. Another design uses a positively charged, high-potential electrode housing a source that produces positively charged ions. The ions are accelerated to ground potential where they may be injected into another accelerator or used directly in low-energy physics or chemistry research or in an industrial process. Induced radioactivity may be present, depending on the ion accelerated and on the terminal potential that defines the ion energy. The third design incorporates a positively charged, high-voltage terminal at the midpoint of a supporting and accelerating structure. The terminal houses a charge-exchange

channel through which negatively charged ions pass. The ions are injected at the ground end of the accelerating column. In the charge-exchange channel a large fraction of the ions lose the extra electrons that had made them negatively charged, become positively charged, and are further accelerated to ground potential at the opposite end of the accelerator. Thus, the ion energy is twice that due to the terminal potential. This configuration, designated a Tandem Van de Graaff or its equivalent, is a large machine weighing about 10 to 100 Mg. The limit of potential of electrostatic accelerators is on the order of 10 MV, above which breakdown (sparking) occurs. Thus, the particle energy of a Van de Graaff is limited to about 30 MeV.

The betatron, developed in 1940 by Kerst, is an example of a direct-voltage accelerator utilizing magnetic-field confinement. In the betatron, electrons are accelerated in a constant-radius orbit by electromagnetic induction due to an increasing magnetic flux passing through the orbit. The field in the magnet gap in which the electrons travel also increases as the energy increases. This is proportioned to the accelerating flux to maintain the orbit radius at the constant value. A fundamental relation between the accelerating flux and the orbit field limits the latter to one-half its otherwise-possible value.

A second general class of accelerators operates on a resonance principle. Concepts of a time-varying electric field were developed to overcome breakdown problems associated with electrostatic systems and to achieve higher energies. The concept of a linear time-varying-field accelerator was developed as early as 1928 by Wideroe. In so-called linear accelerators, acceleration occurs along a series of straight (linear) lengths. There are standing-wave and traveling-wave linear accelerators. The standing-wave type comprises a series of spaced, tubular electrodes that are charged from a high-frequency power source to provide a sinusoidally time-varying potential. Ions are accelerated in the gaps between electrodes when the electrostatic fields between the electrodes are of the proper polarity (i.e. properly designed phase). The remainder of the time, the particles are shielded from the fields while passing through the drift tubes. Different methods are used to charge the electrodes and are generally known by the names of their inventors. These are the Sloan-Lawrence, Wideroe, and Alvarez designs, with the last-named one being the most common. In all the designs an initial velocity is imparted to the particles by a constant-field preaccelerator or injector. The electrodes and gaps become longer as particle velocity and energy increase. A substantial fraction of the particle stream from the injector is lost even though a system known as a "buncher" is placed between the injector and the linear accelerator to gather the charged particles into bunches and introduce them in phase with the accelerating field. Focusing magnets contained within the electrodes are generally used to minimize beam excursions.

The Clinton P. Anderson 800-MeV proton accelerator at Los Alamos Scientific Laboratory, commonly referred to as the Los Alamos Meson Physics Facility (LANPF), is a standing-wave accelerator injected by a 750-keV constant-potential accelerator. The accelerating system consists of a 200-MeV output-energy Alvarez structure of long cylindrical cavities followed by a modified, higher-frequency structure of short side-coupled cylindrical cavities, which accelerates the protons to 800 MeV.

The second, widely used linear accelerator is the traveling-wave type. It consists of a sequence of small cylindrical cavities with coaxial openings for the accelerated-particle beam and for electrical coupling. The series of cavities form a disc-loaded waveguide that is excited by high-power radio-frequency amplifiers connected to the input end. This type is used for the acceleration of electrons. Examples range in energy from a few MeV used for industrial and medical radiography and medical therapy to the 10 GeV of the Stanford Linear Accelerator.

The major drawback of linear accelerators is the requirement of additional linear length to produce higher energies. The two-mile Stanford accelerator represents about the limit of linear-accelerator design.

At about the same time linear accelerators were being developed, other accelerator designers inserted magnetic fields to produce confined-particle orbits (closed or spiral) to provide a greater spectrum of accelerated particles and energies in limited-space research facilities. Accelerators with confined-particle orbits are generally known as cyclic accelerators. The first machine using synchronized circular orbits and radio-frequency accelerating fields was the fixed-field cyclotron conceptualized by Lawrence and Wideroe in 1929.* The first model was built in 1930 by Lawrence and Edelfsen, and definite proof of the acceleration of particles was established by Livingston in 1931.

In a cyclotron, positive ions released from a centrally located source between two dees are accelerated by the electric field between the dees. The ions then coast at constant speed in the region within the dees, free of applied electric fields. A substantially uniform magnetic field bends the path into a semicircle, and when the interelectrode gap is again reached, the potentials have reversed (resonance), leading to a second acceleration. This process continues, the ions spiraling outward toward the bounds of the magnetic confinement as velocity increases. So-called isochronous cyclotrons of variable beam energy were developed using a preset but variable resonant frequency and magnet-trim coils. Above about 25 MeV the relativistic mass effects make the constant-magnetic-field-cyclotron principle inoperable. In response to this limit, accelerator designers developed the synchrotron (1945) and the synchrocyclotron (1946). The synchrocyclotron avoids the energy limitation of the fixed-frequency cyclotron by the expedient of varying the resonant frequency of the electric field between the dees. For this reason, a synchrocyclotron is alternatively known as a frequency-modulated (FM) cyclotron. The beam current of a synchrocyclotron is greatly reduced compared to a cyclotron, because groups of ions must be conducted through the resonant-frequency modulation. Though synchrocyclotrons have been built to accelerate protons up to 730 MeV (about 30 times the highest energy reached in cyclotrons), the time-averaged yield of particles is reduced by a factor of about 1000. Synchrocyclotrons of greater energy require larger magnets (to

*Wideroe had contemplated the notion of orbits in a magnetic field much earlier, but had determined that large currents (in the ampere range) would cause competing induction fields. Of course, modern accelerators are far below the ampere-range beam currents envisioned by Wideroe.

contain the orbits), the mass of iron increasing roughly as the cube of the pole diameter. The magnet mass of the 730-MeV synchrocyclotron is about 3900 Mg.

The oldest of the large machines still in operation are the synchrocyclotrons and cyclotrons. These are compact machines, characterized by a massive magnet surrounded with some combination of fixed and portable shielding. The accelerating structures have induced radioactivity: all of the machine and its shielding will require special handling because of induced activity. Some of these machines have dismantled, others have been shut down, and some have been converted to uses other than physics research. The largest cyclotrons that have been dismantled are synchrocyclotrons, such as the Carnegie-Mellon and Rochester facilities.

In a synchrotron, the particles being accelerated are constrained to oscillate about an essentially constant orbit by requiring the magnetic field to increase synchronously with the increase in energy. This is accomplished by using only a ring of magnets that encompasses the above-mentioned orbit, which is an approximate circle of large radius (much like the betatron). This design reduces the weight by an enormous factor. The accelerating cavities are small units located at one or more locations around the ring. Because the particle velocity increases along the circular path fixed in length, the frequency of the accelerating voltage must increase to remain in synchronism with the ions.

The beam current from a synchrotron is considerably less than from a synchrocyclotron, because after one pulse of ions has been brought to full energy, both the magnetic field and the oscillator frequency must be returned to their initial values before another pulse can be accelerated. For the larger synchrotrons, the repetitive period is on the order of seconds.

The first proton synchrotrons were of the weak-focusing or constant-gradient variety, i.e. the magnetic field decreases slightly with increasing radius. Several machines of the weak-focusing type were built at about the same time at Brookhaven, New York (2.3-GeV Cosmotron); Berkeley, California (6.2-GeV Bevatron); Birmingham, England (1.3 GeV); and Dubna, Russia. The 2.3-GeV proton accelerator (Cosmotron) at the Brookhaven National Laboratory on Long Island has been shut down and dismantled. Another, the Princeton-Penn 3-GeV proton accelerator at Princeton University, was sent to Argonne National Laboratory after a prolonged period in a mothballed state. The Cambridge Electron Accelerator at Harvard University, a 6-GeV electron synchrotron, has been shut down and dismantled. Two similar accelerators, the Bevatron (a 6.2-GeV proton synchrotron at the Lawrence Berkeley Laboratory) and the Cornell University 10-GeV electron synchrotron, are still in service. The 12.7-GeV Zero Gradient (proton) Synchrotron (ZGS) at Argonne National Laboratory was shut down on 1 October 1979. The mass of the magnet system of the ZGS was 4350 Mg.

Added impetus was given to synchrotron development by the application of the alternating-gradient-focusing principle, first postulated by Christophilos in 1950. The radial gradient of the magnet field alternates in sign as the azimuth changes at any given radius in regions where the magnetic field is not zero. This design permitted ion-beam apertures to be reduced by more than one

order of magnitude and allowed much higher energies to be reached with a reduction of about four in capital investments. The Brookhaven Alternating Gradient Synchrotron (AGS) and the Conseil Européen pour la Recherche Nucléaire (CERN) Proton Synchrotron in Geneva, Switzerland, were built to accelerate protons to 30 GeV and 28 GeV, respectively. Subsequently, a 70-GeV machine was completed at Serpukhov, Russia.

The next generation of the high-energy alternating-gradient separated-function synchrotron is represented by the 200- to 400-GeV accelerators at Batavia, Illinois (Fermilab) and CERN. The mass of the magnet system at Fermilab is 8900 Mg. It should be noted that the highest-energy synchrotrons often use one or two lower-energy synchrotrons as beam injectors.

The alternating-gradient principle has now been applied to cyclotrons. It is known by varying names such as aximuthally varying field (AVF), fixed field alternating gradient (FFAG), sector focused, and radial or spiral-ridged in cyclotrons of solid-pole design and in the more complex separated-sector cyclotrons.

Accelerators of the types just described are used for physics research, chemistry research, medical research and treatment, and industrial application. Physics-research installations are characterized by designs emphasizing maximum experimental flexibility. The overall facility has the accelerator and its ancillaries arranged to achieve ready access for internal-target placement, or to permit beam extraction to external targets and associated detection equipment. Study of secondary and tertiary interactions is the major objective of high-energy research. Experimental-space requirements may substantially exceed those for the accelerator proper; experimental areas are generally expanded during the life of the facility. The experimental areas comprise large halls with services such as power conduits or trenches, cooling-water lines, crane facilities, data-collection systems, and shielding that can be readily placed or removed. Several experiments may be operated in proximity, often on a time-sharing basis. Changes are easily accomplished as the experimental programs change.

On the other hand, the accelerator system exists in this physics-research complex for an extended period with little or no physical change, although technical improvements are incorporated as developed. Shielding of the accelerator is permanent for the most part, and consists of cast-in-place concrete or earth fill, with some movable shielding to permit access for assembly or service.

Ion accelerators have been utilized in chemistry-research facilities for production of the transuranic actinide elements. These chemistry-research accelerators accelerate ions of elements of high atomic mass number and high-charge state at low intensity. The chosen ion is accelerated to an energy at which additional electrons can be stripped from the outer shells by passage through a thin foil or a gas jet. The resulting higher specific ionization permits further acceleration. The experimental areas bear a resemblance to those used for physics research, but are less extensive. The half-lives of the synthetic transuranic elements are successively shorter at increasing atomic number; thus, targets and instrumentation are closely grouped. Heavy-ion currents are low, and shielding requirements are more modest than at physics-research installations.

Medical facilities for high-energy or heavy-ion research or therapy are generally an adjunct of accelerators designed for physics or chemistry research. Specialized facilities built around cyclotrons or linear accelerators exist in limited number. X-ray-treatment facilities with 4- or 6-MeV electron linear accelerators for rotational therapy are far more common.

In the use of high-energy or heavy-ion beam therapy, treatment of human patients is in an area simulating a hospital environment. Treatment periods are brief and beam-current requirements are low. The facility is heavily shielded and the specialized equipment includes custom-built patient-positioning and -rotating devices. Also, accelerator facilities can provide patient-treatment areas for neutron therapy or short-lived-isotope diagnosis. Such facilities have been built separately or as part of a medical complex. Shielding is heavy and permanent; no major changes are envisioned at the design stage and no particular experimental flexibility is provided. In many cases, the manufacturer of an electron linear accelerator provides the entire complement of equipment for installation in a specially designed hospital wing. The treatment room is of requisite size, includes the required shielding, a monitoring and control area, and necessary utilities.

Accelerators are used by industry for a variety of processing applications, as well as for industrial radiography. Applications of industrial processing include ion implantation, product sterilization, polymer crosslinking and curing, electron surface treatment, and research programs and military applications in food pasteurization and sterilization. Industrial accelerators operate at relatively low energies in shielded process lines. The installations are frugal of space, are well shielded for personnel protection during operation, and generally produce minimal to no residual activity in components or surroundings.

At the early synchrotrons, the high-energy beam impinged upon an internal target producing a variety of short-lived secondary particles that escaped from the target with a continuous spectrum of energies and angles. A portion of these particles were then channeled along beam lines by collimation to define the production angle, using bending magnets to select the charge and momentum (energy) of interest, quadrupole magnets to focus the beam, and electrostatic separators to separate the various types of particles (by velocity). The chosen particle's properties and interactions can then be studied by a variety of detector systems.

The use of internal targets results in intense, induced radioactivity in portions of the accelerator in the vicinity of the targets. Therefore, most of the higher-energy accelerators now extract the internal beam and use external targets for production of the particles to be studied. Several targeting stations are normally placed in one beam line. Sometimes, if experiments are compatible, targeting on each one using only a portion of the full intensity can be accomplished. The secondary particles produced in the target are channeled to a given experimental setup, and that portion of the initial beam that did not interact is refocused and transported to the next target if feasible.

Some very large detectors are stationary and used for many experiments; examples at the ZGS are the streamer-chamber facility and the 12-foot Bubble

Chamber formerly housed in its own building at the end of an external proton beam. Associated with a facility as large as this chamber are the required refrigeration equipment (liquid hydrogen, liquid nitrogen, and liquid helium), vacuum pumps, power supplies, control room, and computer.

The bending magnets used in the experimental area generally weigh between 10 and 60 Mg, whereas the quadrupole magnets are in the range of 2 to 20 Mg. Magnets associated with detection equipment, such as a spark-chamber magnet, can weigh as much as 100 Mg; the 12-foot Bubble Chamber magnet at the ZGS weighed 1600 Mg. Weights of the magnet power supplies vary from 0.4 Mg to 10 Mg. Shielding blocks vary from 0.2 Mg to 12 Mg.

With respect to the level of induced radioactivity, materials associated with an accelerator can be classified into a number of general categories. Those components or materials that were either directly struck by the accelerated-particle beam or in proximity to those points of beam interaction will contain the highest levels of induced activity. Examples of these types of components are targets, target holders and positioning mechanism, beam stops, collimators and beam-defining slits, extraction magnets and channels, beam pipes or inner chambers, and local shields around targets and slits.

Components that are part of the accelerator itself, and nearby auxiliary items that are subjected to irradiation by the scattered beam or secondary particles (neutrons, protons, etc.), will in general have lower concentrations of induced activity but may be suspected of having radiation levels similar to those of materials in the proximity category. Examples of these items are electrostatic shields, cyclotron vacuum chambers, magnet-pole tips (cyclotrons), magnet windings, bending and focusing magnets, synchrotron magnets and coils, and linac drift tubes.

A third general category includes materials used in the building structure housing the accelerator facility and any other similar materials having been subjected to low-level neutron irradiation. The residual induced activity in these types of materials would generally be of extremely low concentration, if any exists at all. Examples of these types of material are floors and walls of accelerator vaults (concrete), support structures (steel, concrete), cyclotron magnet yokes (steel), shielding blocks (iron, concrete, lead), earth surrounding underground vaults, and any materials or components located within the vault.

CHAPTER 3.

HISTORY OF PARTICLE-ACCELERATOR DECOMMISSIONINGS

Using information obtained from contract files and personal communications, the decommissionings of four AEC-funded accelerators were examined: the synchrocyclotrons operated by the University of Rochester¹ and Carnegie-Mellon University (CMU),² the Cambridge Electron Accelerator (CEA),³ and the Yale Heavy-Ion Linear Accelerator (HILAC).⁴ In addition to the documented information on these four accelerator shutdowns, some information was obtained via personal communication about the decommissioning of the Brookhaven Cosmotron.⁵

It is apparent that there is one feature common to all five decommissioning operations, i.e. components ranging from electronics to shielding to magnets were usually assigned and shipped to other laboratories. In particular, magnet frames and coils, even those exhibiting induced radioactivity, were generally used again elsewhere rather than disposed of, because of the expense of obtaining new steel and copper.

Other radioactive components and radioactive waste generated either during the operation or during the dismantling and decontamination of the accelerators were shipped to commercial radioactive-waste burial grounds for disposal. For example, the radioactive wastes from the dismantling at Rochester were shipped to the Nuclear Fuel Services burial site at West Valley, New York, for custodial care, i.e. the AEC and its successors retained title to and responsibility for the wastes. This unending responsibility was unacceptable to the AEC staff involved with the Carnegie-Mellon decommissioning, so the radioactive waste from the CMU synchrocyclotron was shipped to the Nuclear Engineering Company at Maxey Flats, Kentucky, for disposal.

In three of the cases considered--the Yale HILAC, the Harvard CEA, and the Brookhaven Cosmotron--the dismantling activities began shortly after the cessation of operation, but in the other two cases there was a period of several years between shutdown and dismantling. In the case of the Carnegie-Mellon synchrocyclotron, this hiatus allowed the CMU administrators to seek without success alternate funding from the National Cancer Institute for medical use of the accelerator.

Summaries of the five decommissionings follow. More detailed accounts of four of them are presented in Appendix B.

Operation of the 130-inch 250-MeV synchrocyclotron at the University of Rochester was terminated late in 1968. The accelerator was dismantled during the first five months of 1971. The steel main frame of the magnet was cut into blocks and shipped to the Fermi National Accelerator Laboratory for use as shielding. The radioactive parts were removed from the site and buried at West Valley, New York. The highest exposure level encountered was 140 mR/h

at the magnet-pole tips. The building was left intact for further use by the University. The cost of decommissioning (about \$104 500) was borne by the AEC.

The Cambridge Electron Accelerator, a 6-GeV electron synchrotron at Harvard, was shut down at the end of May 1973. Major components were assigned and shipped to other laboratories, but the title to some components was transferred to Harvard for the salvage value. Disassembly and demolition activities continued through July 1975. The contract termination resulted in the displacement of 83 people. The highest induced radioactivity found at the facility was 100 mR/h at the linac converter. Activities up to 1 mR/h were found on the tunnel walls a year after shutdown. Total recorded dose equivalent for the decommissioning was less than 0.67 man-rem. The cost of the decommissioning to ERDA was \$735 200, including \$96 500 paid to Harvard to assume responsibility for the final demolition activities.

The Nuclear Research Center owned by Carnegie-Mellon University was closed in 1969. The 130-inch 440-MeV synchrocyclotron was dismantled over a period starting in 1974 and continuing through 1975. All radioactive components were disposed of either by transfer within ERDA or burial as radioactive waste. Radioactive waste from the operations, which had been buried on site, was retrieved for reburial at Maxey Flats, Kentucky. Exposure levels up to 175 mR/h were encountered in the synchrocyclotron chamber. The site was decontaminated by removing all radioactive components, waste, and concrete in preparation for sale. The cost to ERDA was approximately \$504 000.

The Heavy-Ion Linear Accelerator at Yale University was dismantled during the six-month period beginning January 1975, immediately after cessation of operations. Most of the major components had been assigned to other laboratories and were shipped during the disassembly. Ten technicians and three of the scientific staff were displaced by the contract termination, although some were kept on during the dismantling. Induced radioactivity was present, but it did not result in significant exposure to personnel. Following the disassembly, the building was found to be radiologically clean. The \$105 000 cost of decommissioning was the responsibility of ERDA.

The Brookhaven Cosmotron, a 3-GeV proton synchrotron, was shut down on 31 December 1966. The machine was kept in standby condition for one year after shutdown, during which time the experimental area was dismantled and much of the equipment was transferred to the Alternating Gradient Synchrotron (AGS) facility, also located at Brookhaven National Laboratory (BNL). After the year had elapsed, authorization to proceed with the dismantling of the Cosmotron itself was granted by the AEC, the owner of the machine. The removal of reusable equipment and components was performed on a spare-time basis by BNL personnel. The actual disassembly of the synchrotron ring magnets was done by contract-technician labor over a three- or four-month period. The one-year waiting period resulted in a significant reduction of the induced-activity levels. The magnet segments, copper windings, vacuum chambers, and vacuum pumps were placed in the radioactive-material storage area at BNL, where most of them remain today. Pictures of this storage area are shown in Appendix I. The presence of induced radioactivity in these items precluded their release to scrap dealers. A number of magnet blocks have been used as shielding at the AGS and more recently for experiments at the Fermi National

Accelerator Laboratory. Because of the difficulty in removing the epoxy resin and fiberglass insulation bonded to the copper magnet windings, very few of these have been reused.

As an alternative to dismantlement, accelerators, especially smaller machines such as particle injectors, have been transferred in a relatively intact form to other accelerator facilities. For example, the AGS 50-MeV proton linac injector was moved to the Lawrence Berkeley Laboratory for use as an improved injector to the Bevatron, the 2.2-GeV Cornell Electron Synchrotron was sent to Argonne National Laboratory for use as a proton booster, the 450-MeV University of Chicago synchrocyclotron was shipped to the Fermi National Accelerator Laboratory where it has served as a particle spectrometer in the Muon Laboratory, and the Princeton-Pennsylvania 3-GeV synchrotron was sent to Argonne National Laboratory.

A list of known particle accelerators above 1 MV that have been decommissioned is presented in Table 3.1. The list is based on sources indicated in the cable. It should not be considered comprehensive and should serve only as an indication of the extent of the problem and its disposition.

Table 3.1. Decommissioned Accelerators

Institution	Identification	Disposition	Date
Brookhaven Nat'l Lab.	Cosmotron (3-GeV Proton Synchrotron)	Dismantled	1966
Brookhaven Nat'l Lab.	18" FF Cyclotron	Dismantled	1963
Univ. Cal., Los Angeles	41" Synchrocyclotron	Dismantled	1961
Univ. Cal., Los Angeles	50" AVF Cyclotron	Dismantled	1973
Cal. Inst. of Tech.	1.1-GeV Electron Synchrotron	Dismantled	1968
Carnegie Inst.	60" FF Cyclotron	Stored	1955
Carnegie Mellon Univ.	141" Synchrocyclotron	Dismantled	1973
Univ. of Chicago	170" Synchrocyclotron	Partially dismantled	
Univ. of Chicago	100-MeV Betatron	Dismantled	1955
Univ. of Chicago	32" FF Cyclotron	Dismantled	1944
Univ. of Chicago	170" FM Cyclotron	Dismantled	1971
Chicago Nuclear	3-MV Van de Graaff	Shut down	1972
Columbia Univ.	37" FF Cyclotron	Dismantled	1965
Columbia Univ.	5.5-MV Van de Graaff	Shut down	1970
Cornell Univ.	Cornell Electron Synchrotron (CES)	Dismantled	
Univ. of Florida	1-MV Van de Graaff	Dismantled	1965
General Electric Co., Schenectady	100-MeV Betatron	Dismantled	1973
Harvard Univ.	Cambridge Electron Accelerator (CEA)	Dismantled	1973
Univ. of Illinois	50" FF Cyclotron	Dismantled	1968
Univ. of Illinois	300-MeV Betatron	Dismantled	1968
Univ. of Illinois	25-MeV Betatron	Dismantled	1972
Indiana Univ.	45" FF Cyclotron	Dismantled	1968
Iowa State Univ.	70-MeV Electron Synchrotron	Mothballed	1972
Iowa State Univ.	4-MV Van de Graaff	Dismantled	1964
Johns Hopkins Univ.	1-MV Van de Graaff	Dismantled	1962
Johns Hopkins Univ.	3-MV Van de Graaff	Dismantled	1974
Knolls Atomic Power Lab., Schenectady	100-MeV Betatron	Scrapped	1970
Univ. of Texas	2-MV Van de Graaff	Dismantled	1962
Lawrence Lab., Berkeley	340-MeV Electron Synchrotron	To Smithsonian	1960
Lawrence Lab., Berkeley	32" FF Cyclotron	To Lawrence Museum	1940
Lawrence Lab., Berkeley	27" FF Cyclotron, 6 MeV	To museum	
Lawrence Lab., Berkeley	30-MeV Proton Linac	Decommissioned	1960
Lawrence Lab., Livermore	90" FF Cyclotron	Dismantled	1971
Lawrence Lab., Livermore	35-MeV Electron Linac	Dismantled	1970
Los Alamos Sci. Lab.	2.5-MV Van de Graaff	Dismantled	1965
Los Alamos Sci. Lab.	2.5-MV Van de Graaff	Dismantled	1963
Los Alamos Sci. Lab.	FF Cyclotron	Dismantled	1974
Los Alamos Sci. Lab.	Electron Prototype Accelerator (EPA)	Shut down (?)	~1970
Los Alamos Sci. Lab.	15-MeV Betatron	Junked	~1970
Los Alamos Sci. Lab.	10-MeV "Portable" Betatron (10 units)	Junked	1955
Los Alamos Sci. Lab.	10-MeV "Portable" Betatron	Junked	1955
Los Alamos Sci. Lab.	10-MeV "Portable" Betatron, modified	To Univ. of N.M.	1955
Louisiana State Univ.	1-MV Van de Graaff	Dismantled	1966
Mass. Inst. of Tech.	42" FF Cyclotron	Mothballed	1973
Mass. Inst. of Tech.	300-MeV Electron Synchrotron	Dismantled	1960
Mass. Inst. of Tech.	2-MV Van de Graaff	To Boston Mus. of Sci.	1950
Mass. Inst. of Tech.	17-MeV Electron Linac	Dismantled	1968
Mass. Inst. of Tech.	8-MV Van de Graaff	Stored	1970
Mass. Inst. of Tech.	4-MV Van de Graaff	Dismantled	1960
Univ. of Michigan	100-MeV Electron Synchrotron	Dismantled	1960
Univ. of Michigan	83", 35-MeV AVF Cyclotron	Dismantled	1978
Univ. of Michigan	50" FF Cyclotron	Mothballed	1970
Univ. of Minnesota	68-MeV Proton Linac	Dismantled	1968
Univ. of Minnesota	4-MV Van de Graaff	Dismantled	1966
Nat'l Bureau of Stds.	50-MeV Betatron	—	1965

Table 3.1. Continued

<i>Institution</i>	<i>Identification</i>	<i>Disposition</i>	<i>Date</i>
Naval Research Lab.	2-MV Van de Graaff	Dismantled	1966
Northwestern Univ.	4.5-MV Van de Graaff	Stored	1968
Oak Ridge Nat'l Lab.	63" FF Cyclotron	To museum	1962
Ohio State Univ.	2-MV Van de Graaff	Dismantled	1962
Ohio State Univ.	45" FF Cyclotron	Shut down	1972
Oregon State Univ.	37" AVF Cyclotron	Dismantled	1973
Univ. of Pennsylvania	12-MV Tandem Van de Graaff (EM)	Dismantled	1974
Penn. State Univ.	6-MV Van de Graaff, CM	Shut down	1973
Univ. of Pittsburgh	45" FF Cyclotron	Dismantled	1967
Princeton Univ.	3-GeV Proton Synchrotron (PPA)	Sent to ANL	
Princeton Univ.	35" Synchrocyclotron	Mothballed	1967
Purdue Univ.	37" FF Cyclotron	Dismantled	1968
Purdue Univ.	300-MeV Electron Synchrotron	Dismantled	1961
Rensselaer Poly. Inst.	30-MeV Betatron	Dismantled	1968
Univ. of Rochester	130" Synchrocyclotron	Dismantled	1968
Univ. of Rochester	240-MeV Electron Synchrotron	Stored	1968
Univ. of S. California	31-MeV Proton Linac	Dismantled	1967
Space Radiat. Eff. Lab.	Synchrocyclotron	Mothballed	1979
Stanford Univ.	Mark I Electron Linac	Extended to Mark II	1948
Stanford Univ.	Mark II 1200-MeV Electron Linac	Sent to Sao Paulo, Brazil	1949
Stanford Univ.	Mark III Electron Linac	Dismantled, parts replaced	1963
Univ. of Texas, Austin	17.5-MV 3-St. Tandem VdG (CM + EM)	Mothballed	1977
Tulane Univ.	3-MV Van de Graaff	Sold	1973
Univ. of Virginia	70-MeV Electron Synchrotron	Stored	1968
Washington State Univ.	2-MV Van de Graaff	Shut down	1973
Yale Univ.	HILAC	Dismantled	1974

Sources: "Nuclear Science: A Survey of Funding, Facilities and Manpower," NAS, 1975; "Physics in Perspective," Vol. II Pt. A, NAS, 1969; plus contributions from reviewers who helped update the list to mid-1978.

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2. AEC contract file numbers AT (11-1)-3066 and AT (30-2)-72.
3. AEC contract file number AT (11-1)-3063.
4. AEC contract file number AT (11-1)-3076.
5. M.J. Kikta. "Accelerator Decommissioning Trip Report: June 21-June 23, 1978." Argonne National Laboratory, memo to file at the Division of Environmental Impact Studies, 28 June 1978.

CHAPTER 4.

REGULATIONS CONCERNING PARTICLE-ACCELERATOR DECOMMISSIONING

Unlike nuclear power reactors that require a federal license to operate, an accelerator is not licensed by any federal agency. Rather, the operation of accelerators is generally regulated by the states in which the accelerators are located. Thus, when an accelerator is shut down, no federal agency oversees the decommissioning operations; this is the responsibility of the respective states. An important exception is for those accelerators located on federal lands such as national laboratories; the operation of such accelerators is controlled by the federal government. In assessing the role of the federal and state governments in accelerator decommissioning, it is necessary first to review the history of the interaction between these two levels of government in the area of radiation control.

The first law dealing with the use of radioactive materials was the Atomic Energy Act of 1954. This Act did not specify the role of the states in regulating the use of atomic energy. As a result of the concern expressed by some states, Section 274 of the Atomic Energy Act was enacted in 1959 to clarify the respective responsibilities of the state and the federal governments. Section 274 also provides a means by which the regulatory authority of the Atomic Energy Commission could be transferred to the states. This authority is now vested in the Nuclear Regulatory Commission (NRC). To date, 25 states have entered into such agreements.¹ The NRC regularly reviews these state programs to ensure that the public health and safety are maintained. The Atomic Energy Act of 1954 gave the federal government the authority to regulate the use of nuclear materials for the purpose of producing electricity. Exempted from this legislation was the regulation of X-ray machines, radium (and other naturally occurring radioactive materials, with the exception of uranium and thorium), and accelerator-produced radioactive materials. The responsibility for the regulation of these radiation sources remained with the states, where it still is today.

Interaction between the federal government and the states has increased substantially in the past few years, especially in the area of waste management. The federal government has, for the most part, encouraged states to participate. The NRC conducted a series of workshops for representatives of various states in the fall of 1978 to review NRC decommissioning policies. Although these workshops dealt mainly with the decommissioning of nuclear reactors and associated fuel-cycle facilities, the NRC reminded the state representatives of their own responsibilities in decommissioning accelerators.² The federal government has recently become involved in the regulatory aspects of decommissioning accelerators, which until now has been solely a state concern. The Resource Conservation and Recovery Act (RCRA) of 1976³ gave the United States Environmental Protection Agency (EPA) the authority to establish disposal criteria for radioactive-waste materials other than those under the jurisdiction of the NRC.

Under the RCRA, the EPA was given the responsibility for developing criteria and standards for the acceptable management of all hazardous waste materials, excluding those radioactive materials already under the jurisdiction of the NRC by authority of the Atomic Energy Act of 1954 as amended. The radioactive components from decommissioned accelerators fall into the RCRA category, along with naturally occurring radioactive-waste materials. This general radioactive-material category is commonly termed "NARM" for naturally occurring and accelerator-produced radioactive materials. (Excluded from NARM is source material; i.e. uranium and thorium.)

The RCRA is not meant to preempt the authority of states to control the disposition of decommissioned accelerator components. Rather, this act gives the EPA the authority to establish guidelines that may be implemented by the states for the safe disposal of all hazardous materials. (The EPA has not yet finalized the guidelines to be used for decommissioned accelerators.) The states are encouraged to accept this responsibility, with technical and financial assistance provided by the federal government if necessary. However, if a state fails to adopt a suitable program to regulate the disposal of hazardous wastes, the RCRA empowers the EPA to assume this responsibility.

The RCRA requires that all federal agencies involved in the handling and disposal of hazardous material cooperate with the EPA in implementing these guidelines. Thus, the means of storage or disposal of radioactive components from the decommissioning of accelerators located on federal lands would be subject to the criteria developed by the EPA under this act.

The EPA's authority to regulate the disposal of radioactive components from decommissioned accelerators is contingent on this material being classified as wastes. If some components are not to be treated as wastes but are to be reused, the RCRA does not empower the EPA to dictate its disposition. Inasmuch as limitations on the use of materials containing induced activity do not presently exist, the EPA does not have a role at this time, but will when the regulations are published.

If the metal from a decommissioned accelerator were sold to a smelting company to be recycled, it would be necessary to obtain an NRC or Agreement-state license for this material if it contained certain radioisotopes in excess of the exempt quantities, as discussed in 10 CFR 30. This would apply to reuse of metals from some components of the large, high-energy accelerators. The smaller machines may not have the requisite amount of induced isotopes to require this licensing. Thus, although the accelerator itself may not have been licensed while it was operating, on shutdown and reuse it may be necessary to license the material of which the accelerator was composed. Some industrial machines, such as the Varian linear electron accelerators, use depleted uranium for shielding. Because depleted uranium is a by-product material of the nuclear fuel cycle, this uranium is licensed and the license would go with the uranium on decommissioning. In Agreement states, these materials would be licensed by the state; in non-Agreement states, this responsibility would rest with the NRC.

As mentioned previously, the states are responsible for regulating the operation of accelerators within their boundaries, except for those accelera-

tors located on federal land. Therefore, there are different sets of regulations or guidelines for decommissioning accelerators for the various states. Some states have more than one regulating agency for accelerators. For example, the four agencies that may be responsible for regulating the use of accelerators in the state of New York are: the New York Departments of (1) Health, (2) Labor, and (3) Environmental Conservation and (4) the New York City Department of Health. In Illinois, the Department of Public Health regulates all accelerators except those at state universities, which are regulated by the Department of Education.

A review of state regulations indicated that, in general, no state had specific guidelines or regulations for decommissioning accelerators. Several states indicated that they had regulations not written explicitly for decommissioning an accelerator, but applicable for this purpose. One state mentioned that it would use Regulatory Guide 1.86⁴ as a guide. However, all guidelines that were mentioned pertaining to acceptable radiation levels for release to the general public dealt only with surface contamination on equipment and materials. No state had guidelines pertaining to acceptable induced-activity levels for reuse by the general public following decommissioning.

The Bureau of Radiological Health, with the cooperation of state and federal agencies, has published suggested state regulations for radiation control. The Suggested State Regulations for Control of Radiation (SSRCR) were initially published in 1962 and have been updated and revised in 1964, 1966, 1970, 1974, and 1978.⁵ The SSRCR call for the licensing of all radioactive material and the registration of all other sources of ionizing radiation not under the jurisdiction of the NRC. However, no recommendations that would be directly applicable to accelerator decommissioning are given. These suggested regulations deal mainly with the radiation exposure around operating accelerators. The waste-disposal criteria given in the SSRCR would not be particularly helpful in the decommissioning of a large particle accelerator, as the issue of reusability is not addressed.

Not only are the laws pertaining to accelerator decommissioning incomplete, but the registration and licensing programs conducted by the states are not all satisfactory. The following quotation is taken from a recent report issued by the General Accounting Office:⁶

State health agencies are supposed to submit an annual inventory of accelerators to the Food and Drug Administration, Department of Health, Education, and Welfare; but not all States provide this data. The ones that do, submit only the number of accelerators, not the size, type, or use. . .

We tried to obtain more definitive information, particularly the number of accelerators above or below 4 megavolts, by sending a questionnaire to each State health agency. Our efforts were unsuccessful. Some States did not respond. Some responded but did not provide data, and the data we did receive could not be reconciled to the Food and Drug Administration data. For example, one State reported to the Food and Drug Administration that 127 accelerators were located in the State in fiscal year 1975. The

State officials informed us, however, that there are 36 accelerators in the State and only 5 have ever been decommissioned. We also visited several State health agencies and were advised by State officials that they did not know size, type, and usage of accelerators in their State.

The U.S. Department of Transportation (DOT) has the regulatory responsibility for safety in the transportation of radioactive materials in interstate or foreign commerce except postal shipments. Truck shipment of radioactive materials within a state is subject to control by the state. Implementation of the various decommissioning options involves the transportation of radioactive materials. The DOT regulations are given in Title 49, Code of Federal Regulations, Parts 170 thru 179. These criteria cover the required packaging, labeling, and marking of the radioactive materials being shipped. The requirements for packaging are dependent on the radioisotope being shipped, the quantity of radionuclides, and the form of the radioisotope. The DOT regulations also limit the levels of radiation at or near the package and of removable surface contamination on the package. Postal shipments of radioactive materials are under the jurisdiction of the U.S. Postal Service.

Some overlap does exist between the NRC and the DOT authorities in regard to shipping radioactive materials. A memorandum of understanding signed in 1966 and revised in 1973⁷ generally delineates the authority of DOT as setting standards for marking, labeling, safety in shipment, regulating shippers and carriers, and approving various packaging designs. The authority of the NRC is generally to review and approve shipping containers for fissile materials and large quantities of radioactive materials. The NRC criteria for shipping radioactive materials are given in 10 CFR 71. The two agencies (NRC and DOT) have agreed to cooperate via exchange of information in the development and enforcement of these regulations.

The state and local regulations for the transport of radioactive materials are normally limited to those directly affecting vehicular traffic, such as gross vehicle weight and dimensions. Overweight shipments are sometimes subject to limitation on routing and time of operation. Other types of regulation include speed limits, advance notification, inspection, escorts, and special training of drivers.

REFERENCES FOR CHAPTER 4

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3. The Resource Conservation and Recovery Act. Public Law 94-580, 1976.
4. Regulatory Guide 1.86. "Termination of Operating Licenses for Nuclear Reactors." U.S. Nuclear Regulatory Commission, June 1974.
5. "Ionizing Radiation Category of the Suggested State Regulations for Control of Radiation." Prepared by Conference of Radiation Control Program Directors, Inc.; U.S. Nuclear Regulatory Commission; U.S. Environmental Protection Agency; and the U.S. Department of Health, Education, and Welfare; October 1978.
6. Report to the Congress by the Comptroller General of the United States. "Cleaning Up the Remains of Nuclear Facilities--A Multibillion Dollar Problem." United States General Accounting Office, EMD-77-46, 16 June 1977.
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CHAPTER 5.

PLANNING THE DECOMMISSIONING

As in all nuclear-project terminations, the decision-making process for decommissioning a particle accelerator covers the period from the date the termination or shutdown of accelerator operation is announced until the time the last accelerator component is either entombed, mothballed in place, buried, reused, scrapped, or otherwise accounted for. The most difficult activity that may occur during this final disposition period is the physical dismantling of the equipment and the preparation of it for shipment.

The impending shutdown of an accelerator may be known to the scientific research community several years in advance of the formal announcement and final date of beam production. This foreknowledge will initiate a certain measure of planning within the operating organization and among component scavengers. Operations at the experimental area may already be curtailed due to funding restrictions or an attitude of "deserting a sinking ship". However, when a shutdown date is announced, planning becomes more specific, and dismantlement of the experimental areas commences. Other groups within the laboratory may request equipment, and other laboratories will consider in earnest the prospects of obtaining needed equipment from the dismantled inventory.

The residual radiation at an accelerator is due primarily to neutron-induced activity, and there is generally no surface or airborne contamination to contend with. Thus, in the past, components and entire accelerators have been mothballed in place or stored at aboveground retrievable sites with nominal surveillance. The time necessary for radioactive components of accelerators to decay to essentially background-radiation levels is less than 100 years for most accelerator components, rather than thousands of years as for components of reactors, principally the reactor pressure vessel and reactor internals. Thus, dismantlement for eventual scrap-value sale of components is a definite possibility and has occurred at several accelerator facilities. At past decommissionings, entire accelerators or selected components have been reused to modify or upgrade other accelerators or accelerator experimental areas. A brief period of mothballing in place, between the shutdown date and the actual decommissioning, may be advisable based on health-physics and economic considerations. Within several months the radiation exposures to workers will be substantially reduced and work can proceed with less-costly radiological protection.

In Table 5.1, the activities of dismantling, temporary storage, component recycle, reuse of the entire accelerator, scrap use, radioactive burial, mothballing, and entombment are organized into potential-event sequences. Triangles at the ends of certain sequences indicate that material considered radioactive is still accessible in the environment. When components are sold for scrap, they are considered as no longer radioactive and no longer of

Table 5.1. Possible Sequences of Decommissioning Activities (Δ - material considered radioactive is still accessible in the environment.)

Entomb			
Mothball Δ			
Mothball		reuse entire accelerator	Δ
Mothball		dismantle	waste ^a
Mothball		dismantle	recycle Δ
Mothball		dismantle	scrap ^b
Mothball		dismantle	storage waste
Mothball		dismantle	storage recycle Δ
Mothball		dismantle	storage scrap
Mothball		dismantle	mothball
Dismantle		mothball	Δ
Dismantle		storage	Δ
Dismantle		storage	waste
Dismantle		storage	recycle Δ
Dismantle		storage	scrap
Dismantle		waste	
Dismantle		recycle	Δ
Dismantle		scrap	
Dismantle		reuse entire acc.	tor Δ

^aWaste is material considered radioactive and buried in a commercial nuclear-waste burial ground.

^bScrap is material considered no longer radioactive.

regulatory concern. Disposal through normal waste-removal channels of non-radioactive materials can be performed at any time during the sequence, probably early in the process, and is not considered in the decommissioning concepts presented in this report. However, it should be noted that for large accelerators almost the entire mass is in the magnet and drift tubes, which do become radioactive. The average volumetric radioactivity is generally small in large components; the portions containing greater amounts of activity can be cut out and handled separately from the vast amount of material containing low levels of radioactivity. Temporary storage after dismantling can occur in a specially prepared (occasionally available) service building, in an open or

partially protected area, or in the accelerator building itself (mothballing). Mothballing provides a period for substantial radioactive decay prior to dismantling.

Entombment is a highly unlikely option because intense induced-radiation levels are localized, decay times are rapid, and there is generally little or no danger of airborne contamination. The recycle of accelerator components becomes less likely as storage time increases, due to technological obsolescence. In some cases, storage in retrievable storage areas at the accelerator site (mothballing) has become a quasi-permanent solution.

The chart of possible sequences of decommissioning activities given in Table 5.1 begins on the first day of shutdown and extends at most several centuries, at which time radiation levels in any option will be imperceptible. Immediately after shutdown—dismantling, mothballing, or entombment will take place. Dismantlement and salvage of experimental areas at large research facilities begins on the date shutdown is announced and requires a separate chart with an earlier, shorter time horizon. The event sequences could apply to single components as well as to the entire accelerator. Technically, a chart analysis would be performed for each component of an accelerator (or segment thereof, once dismantled). This level of detail is beyond the scope of this generic study.

The decommissioning option to recycle the entire accelerator or portions thereof, especially a large research accelerator, is subject to the needs of research, medical, and industrial interests at the time of shutdown, rather than economic or health-physics incentives. If the decision were made to maintain the accelerator intact in expectation of future operation, this decision would have to be reviewed on a periodic basis.

The accelerator management should first develop files bearing on the following pertinent general issues:

1. All contractual agreements between the funding agency (in many cases an agency of the federal government) and the operating contractor that bear on site-decommissioning responsibility. In all the AEC-ERDA-DOE contract files related to decommissionings that were investigated, binding contractual arrangements with the funding agency concerning fiscal/managerial responsibility were significant.
2. Employee policies bearing on reassignment, termination, etc., to permit staff planning if the operating staff is to be restructured for the dismantling process.
3. Any agreements with craft and trade unions or organizations whose members would participate in the operations. Availability of onsite rigging services will influence subcontract requirements.
4. Applicable codes covering any modifications to the site or buildings. The construction of a storage facility for dismantled components, if necessary, must be initiated in order to proceed on schedule with the dismantling.
5. Site- and building-engineering conditions affecting the dismantling requirements. Occasionally the shielding or magnet forms an integral

part of the building structure. Also, the housing facility is occasionally built around the accelerator without an exit large enough for some components.

6. Radiation-safety and industrial-accident requirements and safety orders. These will be well known at major facilities such as national laboratories.
7. An inventory system for allocation of components for potential reuse as research equipment, or to scrap or radioactive waste. A system for handling requests for excess equipment should be developed if one (such as the federal system) does not already exist. Arrangements for purchase of components for reuse at other research facilities should be made as far in advance as possible.
8. Pertinent details concerning the shipment of radioactive components to a radioactive-waste burial ground.
9. A centralization of engineering drawings of the original accelerator and upgrades.

These nine general issues would be considered to a much lesser extent for entombment or mothballing than for dismantling.

Figure 5.1 shows a suggested organization for the planning and execution of a major-facility dismantling. The physical work of dismantling might be done in part or in whole by in-house technician and labor staff in the operating organization, or by contract services where in-house staff is not available. For small projects, one person may cover several or perhaps all the manager-level positions. Even for large projects, individual responsibility may be assigned to several submanagerial tasks, such as dismantling vacuum and air-conditioning systems. Nonetheless, it is necessary that a comprehensive plan be established and a staff organized.

If the dismantling occurs shortly after shutdown, it may be carried out by the existing research, medical, or industrial organization as an ongoing responsibility. If several years have elapsed since shutdown or since any active planning or work on dismantling has been done, it will be necessary to set up a new organization to do the work. Additional organizational- and professional-staff expenses will be incurred while the new organization familiarizes itself with any uniqueness of the accelerator design. For large accelerator facilities, this could amount to a 10% to 20% increase in professional-staff costs.

Table 5.2 is a list of expected necessary support activities for the dismantling. Suggested classes of major equipment are given in Table 5.3. Suggested forms to be used for an accelerator decommissioning are shown and discussed in Appendix C.

Health-physics services may be available on site, but may require extra personnel. Neither equipment nor material should be permitted to leave the site without health-physics determination of its radiological status. The cost of the total health-physics effort, from whatever source, should be included in the dismantling budget.

Salaried staff
(Period Dependent Costs)
to include secretarial
and clerical staff.

Figure 5.1. ZGS Decontamination and Decommissioning Functions.

Table 5.2. Dismantling Support Activities

<u>Health Physics</u>	<u>Security</u>
Site surveys and records	Site-access control
Film-badge and dosimeter services	Theft detection
Hand and foot counters	Guard service
Operations monitoring	
Radioactive monitoring	
Radioactive-waste identification	
<u>Site Safety</u>	<u>Building & Site Standards</u>
Industrial-accident standards	Code requirements
Accident prevention	Site requirements
Emergency services	

Security services may be available without cost as inherent site services. Access control to areas of disassembled and valuable (and sometimes radioactive) components must be afforded to prevent theft.

Site safety may require one or more safety engineers, depending on the size and complexity of the facility. Industrial accidents are far more frequent than any due to nuclear-radiation hazard. Electrical shock is the most insidious and requires rechecking of all power-supply circuits and capacitor-bank grounding before dismantling of any component is started. Personnel who may be unfamiliar with powered equipment to be used in the dismantling must be alerted to potential hazards.

Building and site standards will require enforcement if scarfing of cast-in-place concrete is needed to remove induced radioactivity. Replacement must meet building codes and site standards. The same is true of any affected building structure or any permanent closure of pits or building refurbishing. Building-inspection services would be needed, but to only a very limited extent.

The general order of dismantlement operations is as follows: radiation-field survey and assessment of other health-physics concerns; activities to render the facility safe (e.g. electrical disconnections); preparation for special handling of highly radioactive (≥ 10 R/h contact reading) or contaminated sections; disassembly into manageable segments by unbolting, torch cutting, etc.; removal of components or component segments by riggers or wrecking crews; and demolition and removal of shielding and buildings (as required). Overlap of these operations can be anticipated in the interest of time, economy, and physical safety.

Table 5.3. Major Equipment Categories

<u>Mechanical Equipment</u>	<u>Electrical Equipment</u>
Tanks	Magnets
Support structures	Transformers
Compressors	Switchgear
Pumps	Rectifiers
Piping & vaulting	Power supplies
Water processing	Cabling
Moveable shielding	
<u>Cryogenics and Refrigeration Equipment</u>	<u>Vacuum Equipment</u>
Cryostats	High-vacuum pumps
Dewars	Backing pumps
Transfer lines	Roughing pumps
Helium liquifiers	Vacuum gauges
Refrigeration evaporators	Vacuum valves
Refrigeration liquifiers	Vacuum pipes
<u>Controls & Instrumentation</u>	
Transducers	
Displays	
Interlock systems	
Computers	
Beam-line devices	

Costs can be broken down according to activity and period dependency. Activity-dependent costs are those incurred in performing specific dismantling and removal activities, either under subcontract or by organization-staff labor. Examples of activities are the unbolting of magnet segments, torch cutting of magnets, rigging of components, and scarfing of concrete. Period-dependent costs are those that occur during the dismantling period in which specific activities occur. Examples of period-dependent costs are equipment rental, additional site security, and health-physics monitoring. To the extent that period-dependent costs are directly associated with an activity (such as health physicists overseeing torch cutting), they should be so noted.

CHAPTER 6.

HEALTH PHYSICS AND SAFETY ASPECTS

INTRODUCTION

The purpose of this chapter is to develop a methodology to assess the scope of radiological-health problems resulting from the full gamut of de-commissioning activities, and to point out other potential health and safety problems. Health-physics considerations in the decommissioning of particle accelerators center around two primary aspects. One is the consideration of radiation doses that decommissioning personnel receive in the course of the work of dismantlement, decontamination, and preparation for shipment of the radioactive components of the accelerator. The second aspect is the consideration of the potential radiation exposure of members of the general population resulting (1) from the transport and disposition of the radioactive material in onsite or offsite retrievable storage or offsite waste disposal and (2) from reuse of accelerator components, materials, or structures containing induced radioactivity. The word dismantling, as used herein, describes both the physical dismantlement and any necessary cleanup of loose contamination or other health hazards.

The primary factors that determine the magnitude of the radiological hazard to be expected at an accelerator facility include: the type and size of the accelerator, the energy and beam current of the accelerated particles, the species of particle accelerated, the age of the facility, and the primary use of the facility. These factors will determine the levels of induced radioactivity in various machine components and systems and also the physical quantity of activated materials that will need to be handled and shipped as radioactive waste. The extreme diversity in types, energies, and uses of accelerators results in health-physics and waste-management considerations that are essentially unique to each installation. Aside from the actual operating parameters of an accelerator, there are a number of other factors that will impinge on the problem. These include such things as the accessibility of the accelerator to rigging and material-handling equipment, the method of assembly used on a particular accelerator, and the potential for reusability of either the accelerator components or the buildings.

There exist potential nonradiological health and safety problems that could be associated with the dismantling or mothballing of accelerator facilities. Examples of these are the possible presence at the facility of chemically toxic materials such as beryllium, cadmium, lead, mercury, etc., which will need hazard evaluation and appropriate control measures. Work in confined spaces, heavy rigging, and other associated activities all have their industrial-safety aspects and will require appropriate surveillance and control.

The radiation environment at a shutdown accelerator facility is governed primarily by the induced activity present. In Table 6.1 are data summarizing the potential for production of induced activity for various types of accelerated particles and various energy ranges, as taken from the National Bureau of Standards Handbook 107.¹ Also shown in the table is the likelihood of encountering radiation dose rates above 2.5 mrem/h in the vicinity of the accelerator. The 2.5-mrem/h value is the maximum-permissible dose rate for long-term occupational conditions, as cited in 10 CFR 20 and ERDAM 0524. The term "target" refers to the experimental targets as well as collimators, system magnets, beam scrapers, beam dumps, or any component of the accelerator in direct contact with the beam(s)—either deliberately or incidentally—during the normal mode of operation. In the remainder of this chapter, "target" generally includes anything directly in the path of the accelerator beam(s). The term "vicinity" refers to the ring building (large synchrotron), accelerator vault (cyclotron), or room housing the accelerator proper. As shown in the table, any accelerator with a particle energy greater than 10 MeV will produce induced activity. This indicates that as the energy of accelerators used for medical and industrial application increases above the 10-MeV level, the problem of induced activity will need to be addressed as part of the eventual decommissioning of these machines. Also, on a per-particle-per-MeV-accelerated basis, electrons are much less efficient in the production of induced activity than are protons or other positive ions, due to much lower reaction cross sections. This distinction between proton- and electron-accelerator radiation environments has an impact on decommissioning planning.

The dismantlement of an accelerator having significant quantities of induced activity (i.e. resulting in radiation levels > 2.5 mrem/h) should be planned in such a manner as to reduce the exposure of the personnel as much

Table 6.1. Relative Production of Induced Radioactivity
in Particle Accelerators

Accelerated Particle	Energy Range (MeV)	Induced Activity ^a in		Induced Activity > 2.5 mrem/h at one inch ^b	
		Target	Vicinity	Target	Vicinity
Electrons	< 1.67	None	None	None	None
	1.67 - 10	Limited	Very slight	Very slight	None
	> 10	Probable	Suspect	Limited	Very slight
Protons, helium ions	< 1	Limited	None	Very slight	None
	1 - 10	Limited	Suspect	Limited	Very slight
Deuterons, tritons	Any energy	Limited	Suspect	Limited	Very slight
All ions of light atomic weight	> 10	Certain	Suspect	Probable	Limited

^aData from National Bureau of Standards Handbook 107.

^bData developed for purposes of this report.

as possible. As noted in Chapter 5, it might be highly desirable to allow a period of time to elapse between shutdown and the start of dismantlement for health-physics considerations (i.e. to permit decay of short-lived induced activity).

The main source of radiation exposure during dismantling work is in the components classified as "target". For the high-energy high-intensity accelerators, the machine components in the vicinity of these "in-beam" components will also be significantly activated due to secondary-particle interactions. In addition to the components directly activated by the beam and secondary particles, there are other components that are potential problems. For example, cooling-water systems may accumulate and concentrate activated corrosion products. Possibly, vacuum or ventilation systems may be similarly contaminated. Accelerators that have been used for isotope production or for acceleration of radioactive ions (e.g. tritium) or used with targets of radioactive materials (e.g. transuranic elements) also present a radiological hazard from the potential presence of surface contamination on components that can, in turn, result in bodily intake and internal radiation exposure to the dismantling personnel.

Depending on specific circumstances, dismantling would proceed in one of two patterns. One pattern would have the work start with the components or segments that have the lowest levels of induced activity and proceed to those with higher levels. This has the advantage of allowing additional decay time for the most-radioactive items. The second general pattern would have the items with high levels of activity removed, possibly by remote-handling techniques, and placed in shielded storage at the beginning of dismantlement. This would result in lower radiation intensities during the rest of the work. The choice of disassembly sequence will depend on the specific conditions and circumstances existing at a particular accelerator. The important point is that the radiological hazards will need to be evaluated and the recommendations of the health-physics staff factored into the planning at an early stage. Any specialized equipment or techniques such as use of remote-handling equipment or fabrication of local shielding will require an appropriate amount of lead time and advance planning.

If circumstances should merit, certain types of dismantling operations will require specialized or more comprehensive hazard-control measures. Examples would include operations such as the sawing and abrasive cutoff or flame cutting of metal, and scarfing and abrasive cutting or jack hammering of concrete. Evaluation of the actual activation levels and isotopes involved by the health-physics staff may indicate that respiratory protection and/or local ventilation with filtered exhaust would be necessary for protection of the workers and prevention of the spread of loose contamination. The dismantlement and decontamination of accelerators that have surface contamination as well as induced activity will require use of appropriate protective clothing and contamination-control measures.

HEALTH PHYSICS OF GENERIC ACCELERATOR CATEGORIES

Health-physics aspects of the decommissioning plan vary widely with different generic accelerator categories. For electrostatic positive-ion accelerators (Van de Graaffs, Cockroft Waltons, dynamitrons, pelletrons, and

insulated-core transformers), health-physics activities would generally be limited to radiation surveys of accelerator and beam-line components for potential induced activity and segregation of activated items for proper disposal or storage to await decay. Control of radiation exposure to decommissioning personnel would not be a problem due to the minimal radiation levels from induced activity. Personnel monitoring would be done for verification purposes. Other than the beam-line components and the accelerating column, all other equipment can be treated as ordinary scrap material and handled accordingly. There would be no need for building decontamination unless accelerator operations and experiments (e.g. with radioisotopes) had resulted in surface contamination of building components.

For small electron accelerators (medical linacs, dynamitrons, Van de Graaffs, betatrons, etc.), the level of potential induced activity is again very low. Health-physics activities would include confirmatory surveys to verify the absence of induced activity and to segregate any active items for proper handling. The dismantlement work would be performed without any special precautions. There would be no need for any decontamination of the building unless work with radioisotopes had resulted in contamination of surfaces.

For cyclotrons, synchrocyclotrons, and synchrotrons, the levels of induced activity in certain components will be initially high, and a delay to allow for radioactive decay will generally be advisable. Advance planning of the work sequence to minimize radiation exposure will be necessary. Preparation of shielded containers for storage or shipment of the active components will be needed. Maximum use should be made of any available remote-handling capabilities for removal of the target probe, beam-extraction components, and other highly activated materials. The remainder of the dismantlement could probably proceed using hands-on operation. Full-time health-physics surveillance would be necessary to maintain exposure control to as-low-as-practicable levels, to provide exposure-control input into the detailed day-to-day planning of the work, to segregate components and materials into activated and nonactivated categories, and to evaluate and control any potential surface-contamination problems. Personnel radiation-monitoring devices should be checked frequently during the initial phases of the work to evaluate the effectiveness of the exposure-control measures. Some building and structure decontamination or demolition may be required if induced activity or surface contamination is found. Health-physics documentation of all phases of the operation would be required. The length of delay between accelerator shutdown and dismantling, the use of remote-handling equipment, stringency of preplanning, and other health-physics activities will need to be scaled appropriately according to the actual radiation intensities encountered. Building decontamination or selective demolition may be needed to remove areas of induced activity in the vicinity of points of intense beam interactions.

For large electron accelerators (linacs and synchrotrons), health-physics problems will be comparable to the situation at cyclotrons, with a few notable differences. The induced activity in the accelerator itself will be generally lower by about two orders of magnitude than in a positive-ion machine of equal energy and beam current. Therefore, the health-physics exposure controls would not need to be as stringent. However, at target stations, beam switchyards, and beam dumps the requirement would be essentially identical to that

at synchrotrons and synchrocyclotrons. Again, building decontamination or selective demolition may be needed to remove areas of induced activity in the vicinity of points of intense beam interactions.

For the highest-energy proton linac in operation (the 800-MeV Los Alamos Meson Physics Facility), the levels of induced activity (considerably greater than 1000 R/h) in the primary target areas will require remote-dismantlement techniques unless a very long delay time is allowed prior to the start of decommissioning. The accelerator itself can probably be dismantled using hands-on techniques with the same health-physics requirements as at a synchrotron or synchrocyclotron. The best approach from the health-physics viewpoint would be to mothball or entomb the target areas for a long period. The length of time would be dependent on the actual activity levels existing at the time of decommissioning.

ANTICIPATED RADIATION LEVELS

Although there are basic differences between electrons and positive ions in the physical mechanisms involved in the production of induced activity, the species of isotopes produced are essentially identical. Patterson and Thomas² and Swanson³ provide extensive discussions of the production of induced activity by protons and electrons, respectively. An important consideration that influences evaluation of the radiation environment at an accelerator is the fact that there is generally a mixture of isotopes involved. Thus, it is extremely difficult to calculate an exact value for the total activity present at an accelerator facility.

To provide perspective regarding the radiation level to be expected at accelerators, data on measured radiation intensities have been obtained from a variety of accelerator facilities, primarily by communication with health-physics personnel. An attempt was made to include those accelerator facilities that would contain the highest levels of induced activity and hence the highest levels of radiation intensity. Generally, these data were reported in the form of radiation-survey maps recorded during periods of accelerator downtime or as a listing of contact-radiation measurements made on various accelerator components during maintenance work. A sample shutdown radiation survey is shown in Figure 6.1. Table 6.2 is a summary of radiation-level information obtained from health-physics personnel. Theoretical curves of decay of radiation level with time (e.g. the theoretical predictions of Sullivan and Overton⁴) can be used with the data obtained from actual radiation measurements to estimate radiation exposure of personnel during the dismantling phase of a decommissioning. The calculation of excessive radiation exposure in certain cases might suggest a mothballed period between accelerator shutdown and dismantling.

As indicated in Table 6.2, the observed radiation intensities depend very heavily on the primary function of the accelerator. Research cyclotrons generally have much lower induced-radiation levels than do isotope-production facilities. The ratio of operating time to downtime and the absolute beam intensity are the important parameters.

Figure 6.1. Radioactivation Survey Form Used by the Princeton-University of Pennsylvania Accelerator.

Table 6.2. Summary of Reported Radiation Measurements

Diameter or Length	Energy	Location	Time From Shutoff	Measured Radiation Exposure from			
				Accelerator Components	Accelerator Surface	External Beam- Line Components	Room or General Area
<u>Cyclotrons</u>							
31"	15 MeV	Duke U	Immed.	> 1 R/h @ (a) ft		< 2.5 mR/h to > 1 R/h @ contact	a
38"	22 MeV	Medi-Physica	4 h	0.5 to 5.5 R/h @ 3 ft		0.3 to 1.5 R/h @ 3 ft	30 mR/h
38"	22 MeV	NE Nuclear	Immed.	a	1.25 R/h @ 25 ft	a	a
38"	22 MeV	UCLA	2-3 wk	a	125 R/h @ 1 ft		
52"	28 MeV	U of Colorado	0.25 h	a	50-650 mR/h @ contact 14-400 mR/h @ 3 ft	30-650 mR/h @ contact 20-30 mR/h @ 3 ft	12 mR/h
60"	40 MeV	AML	a	a	25 mR/h @ 1 ft to 300 mR/h @ 2 ft	up to 50 mR/h	5-15 mR/h
60"	40 MeV	U of Washington	16 h	a	100 to 245 mR/h @ 3 ft	1-60 mR/h @ 3 ft	3.6-13 mR/h
67"	30 MeV	Michigan State	24 h	> 1 R/h @ (a) ft		> 2.5 to < 1 R/h @ 3 ft	a
76"	30 MeV	NRL	0.33 h	a	1-13 mR/h @ 3 ft	1-6 mR/h @ 3 ft	0.75-2 mR/h
83"	35 MeV	NASA/Lewis	0.5 h	a	0.16-2.0 R/h @ 3 ft	3.5-180 mR/h @ 3 ft	a
88"	60 MeV	LBL	0.2 h		< 1 R/h @ 3 ft	> 2.5 to < 1 R/h @ 3 ft	a
88"	60 MeV	Texas A & M	a	a	0-100 mR/h @ contact	a	0.2-2 mR/h
<u>Synchrocyclotrons</u>							
95"	160 MeV	Harvard U	a	a	0.3-3.0 R/h @ contact	1-800 mR/h @ contact	a
184"	730 MeV	LBL	a	> 1 R/h @ 3 ft	a	< 1 R/h @ 3 ft	a
197"	660 MeV	NASA/SREL	a				
<u>Synchrotrons</u>							
60'	3 GeV	PPA	8 d	5-7 R/h @ contact	250 mR/h @ contact	1-60 mR/h @ contact 1-4 mR/h @ 3 ft	1-80 mR/h
100'	6.2 GeV	LBL-Bevatron	32 h	a	2-800 mR/h @ contact 1.5 to 450 mR/h @ 12"	a	a
180'	12.5 GeV	AML-2GB	10 d		10-200 mR/h @ contact	a	7-60 mR/h
840'	33 GeV	BNL-AGS	a	> 1 R/h @ 3 ft	a	< 1 R/h @ 3 ft	a
3000'	300 GeV	FNAL	"short"	> 1 R/h @ 3 ft	a	> 1 R/h @ 3 ft	a
<u>Electron linacs</u>							
30'	35 MeV	IRT	a	< 1 mR/h @ 3 ft	< 1 mR/h @ 3 ft	a	
600'	400 MeV	NIT/Bates	"short"	a	2-60 mR/h @ contact	up to 110 R/h @ contact	a
10000'	22 GeV	SLAC	a	< 2.5 mR/h @ 3 ft	a	~ 1-2 R/h @ 3 ft	a
<u>Proton linacs</u>							
3600'	800 MeV	LAMPF	a	a	> 1 R/h @ contact	>> 10 ³ R/h @ contact	a

a Data not supplied.

DOSES FOR DISMANTLING FOUR PROTOTYPIC ACCELERATORS

Estimates of the total exposure values for a dismantling effort can be developed for selected accelerators based on the reported radiation levels and estimates of the man-hours of effort required. Such estimates can at best be good only to an order of magnitude due to uncertainties in estimates of both the radiation levels at the time operation ceases and the man-hours of effort involved. However, inasmuch as the radiation exposures are generally less than 1 R/h, total-exposure commitments will be entirely manageable through proper radiation-protection practices.

The estimates of dose for dismantling the Zero Gradient Synchrotron (ZGS) are based on two types of information, (1) the engineering estimates of man-hours required to perform each phase of the decommissioning work and (2) actual radiation-exposure measurements made around the accelerator during shutdown periods. Exposure due to the dismantling of the experimental area and external proton lines is not included. A reasonable estimate for the additional dose commitment due to work in the ZGS experimental area would be 10% of the values for the accelerator.

Twenty radiation surveys made at various times, ranging from immediately after shutdown to two months after shutdown, were used to obtain the range of radiation levels at selected locations around the ZGS. Weighted-average ranges of radiation intensities applicable to each phase were then developed based on the spatial distribution of the radiation intensity. The range of dose values is shown in Appendix D, Table D.1. The high-dose value (317 person-rem) would be expected if the work were done on the first day after the accelerator is turned off, which is an obvious physical impossibility but represents an upper bound. The low-dose value (94 person-rem) assumes a two-month delay and is based on radiation-survey data. The total indicated here would include the incremental-dose commitment due to packaging, loading, and other activities.

The methodology used for the ZGS-decommissioning dose-commitment estimate has also been applied to the 60" cyclotron, the electron linac, and the Tandem Van de Graaff, all located at Argonne National Laboratory. The results are summarized in Appendices E, F, and G; Tables E.1, F.1, and G.1; respectively. Decommissioning of the 60" cyclotron includes removal of the concrete shield vault because it is probable there will be some low-level induced activity present. The high- and low-radiation levels used in the estimates are actual measurements made within 25 hours after a shutdown. Immediate dismantlement of the cyclotron could result in a dose of 66 person-rem. The linac and the Tandem Van de Graaff would present no significant dose potential (0.003 and 0.01 person-rem, respectively) because the level of induced activity expected is essentially zero.

QUANTITIES AND CONCENTRATIONS OF INDUCED RADIOACTIVITY

The total quantity of induced activity at any accelerator at the time of disassembly will determine the waste-disposal or storage requirements for the components and materials. The method of estimation of this total quantity will be different for the various generic types of accelerators. It is

possible to evaluate radiation environments and decay characteristics accurately only in the simplest of cases. Therefore, for the purposes of this study, approximate methods will be employed to assess quantities of radioactive material at particle accelerators generically.

Estimates can be made of the total quantity of radioactivity contained in a high-energy proton accelerator by using approximations discussed by Gollon.⁵ The method of estimating the total radioactivity in an accelerator is based on the fact that, at equilibrium for constant conditions of operations, the decay rate of radioactivity is equal to the production rate. The assumptions used by Gollon are (1) a proton produces four nuclear stars for each 1.0 GeV of kinetic energy and (2) about 25% of the stars result in a nuclide with a half-life greater than one day. The isotopes produced are ²²Na in concrete, ²²Na and ²⁶Al in aluminum, ⁵⁴Mn in iron, ⁵⁷Co in nickel, and ⁶⁰Co and ⁶³Ni in copper. Using these assumptions, the number of curies per microampere of beam current is $170 \times E_p$, where E_p is the proton energy in GeV. For a beam current of 0.16 μ A, a 400-GeV beam will produce 10 kCi of activity at equilibrium, which is obtained after long operating times.

The estimation of radioactivity induced by high-energy electron beams and the associated bremsstrahlung has been reviewed by Swanson.³ The photons produced by electron beams produce radioisotopes by photonuclear-resonance reactions, the quasi-deuteron effect, and high-energy photospallation. The photonuclear and quasi-deuteron effects include the (γ, n), ($\gamma, 2n$), (γ, p), (γ, np), and (γ, α) reactions. High-energy photospallation is similar to the high-energy proton-cascade reaction, in which there is a multiplicity of secondary particles produced.

Table 6.3 is a summary of the long-lived isotope-production data calculated for electron beams with energies of 35 MeV and greater. The percent saturation attained for each isotope after an assumed 25-year operating life

Table 6.3. Induced Radioactivity from Electron Beams

Target Material	Isotope Produced	Half-Life	Saturation Activity ^a (Ci/kW)	Percent Saturation for 25-Year Operation	Actual Expected Activity (Ci/kW)
Concrete	²² Na	2.6 yr	0.1	99.9	0.10
Aluminum	²² Na	2.6 yr	0.28	99.9	0.28
	²⁶ Al	7.4×10^5 yr	8.8	0.0023	2.04×10^{-4}
Iron	⁵⁴ Mn	303 d	0.59	100.0	0.59
Nickel	⁵⁷ Co	270 d	5.9	100.0	5.9
	⁶⁰ Co	5.26 yr	0.1	96.2	0.096
Copper	⁶⁰ Co	5.26 yr	0.65	96.2	0.63
	⁶³ Ni	92 yr	0.45	17.0	0.077

^aFrom "Radiological Safety Aspects of the Operation of Electron Linear Accelerators," W.P. Swanson (SLAC), IAEA, Vienna, STI/DOC/10/, ISBN 92-0-00000-0, 1978.

has been calculated and is shown along with the expected production in terms of curies per kilowatt of beam power.

At electron energies below 35 MeV, the production cross sections involved in the reactions are rapidly varying functions of energy, generally falling to zero in the neighborhood of 10 MeV. Inasmuch as the saturation activity is a maximum at 35 MeV, using this value will provide an upper-limit estimate for all electron accelerators.

The radioactivity from any accelerator, positive ion or electron, is distributed among the various machine components and the external apparatus that intercepts the beam. The active materials associated with accelerator decommissioning can be classified into a number of general categories. Those components or materials that were either directly struck by the accelerated beam or were in proximity to those points of beam interaction will contain the highest concentrations of induced activity. The components that are part of the accelerator itself, and nearby auxiliary items that are subjected to irradiation by the scattered beam or secondary particles (neutrons, protons, etc.), will to some extent have lower concentrations of induced activity. A third general category would include materials used in the building structure that houses the accelerator facility and any other similar material subjected to general low-level neutron irradiation. The residual induced activity in this type of material would generally be of extremely low concentration, if present at all. Table 6.4 provides a summary of the various categories of waste material that would be expected to be definitely radioactive, possibly radioactive, or not radioactive.

Table 6.4. Radioactivity Expected in Three Categories of Components from Various Types of Accelerators

Accelerator Type	Energy	Categories of Radioactive Waste		
		Direct-Beam Components	Beam Surroundings	Building
Positive-ion electrostatic accelerators	< 1 MeV	None	None	None
Electron accelerators	< 10 MeV	None	None	None
Positive-ion electrostatic accelerators	> 1 MeV	a	b	None
Electron accelerators	> 10 MeV < 100 MeV	a	b	None
Cyclotrons, synchrocyclotrons, and electron accelerators	> 100 MeV	a	a	b
All proton synchrotrons and LAMPF		a	a	a

^aDefinitely radioactive.

^bPossibly radioactive.

In reality, the estimation of the quantity of waste material with induced activity is a twofold problem. One facet is the estimation of the amount and concentration of radioactivity as discussed above, the second is the estimation of the total mass and volume of material in which this radioactivity resides. The total mass and volume figures determine the true magnitude of the problem if disposal is required.

Table 6.5 summarizes the results of this study on the estimation of the eventual quantity of radioactive material that will require proper disposal. Emphasis is on the largest accelerators, with the specific goal of arriving at the total masses and volumes of potential radioactive waste that they represent. Most of the accelerator material involved is iron or copper. The shielding included in these totals is primarily iron or concrete.

These estimates are based partly on the information supplied by the health-physics or operating personnel at the accelerator facilities listed, and partly on estimates using data contained in a 1974 catalog of high-energy accelerators⁶ and a 1975 tabulation of cyclotrons.⁷ Specific radiation levels given in the table are based on information supplied by operating personnel at the accelerators. The total mass of active material is equal to the total mass of the accelerator increased by 10% to account for auxiliary components and miscellaneous materials. The estimated total amount of radioactivity for proton accelerators (except electrostatics) is calculated using the Collon equation and the reported energy and beam-intensity values. The time-averaged beam intensity is determined by multiplying the reported beam intensity by the reported fraction of time the accelerator is operating.

Table 6.5. Mass of Radioactive Waste from Selected Accelerators

Location	Energy	Diameter or Length	Funding Source	Estimated Mass of Material (> 1 R/h 0.1 m) (kg)	Reported Mass of Material (> 2.5 mR/h 0.1 m) (kg)	Reported Mass of Accelerator (kg)	Total Mass of Active Material (kg)	Estimated Amount of Radioactivity (Ci)	Time- Averaged Beam Current (nA)	Primary Use(s) of Accelerator ^a	Remarks
Positive-ion cyclotrons											
and synchrocyclotrons											
Duke U	15 MeV	31"	DOE/NSF/HEV	--	--	--	--	7.6 E+01	30	r	
Medi-Phy, Emeryville, CA	22 MeV	38"	Private	--	--	2.0 E+04	2.2 E+04	1.5 E+03	400	i	
Medi-Phy, So. Plainfield, NJ	22 MeV	38"	Private	--	--	2.0 E+04	2.2 E+04	1.5 E+03	400	i	
New England Nuclear	22 MeV	38"	Private	--	--	2.0 E+04	2.2 E+04	4.1 E+02	110	i, d	
UCLA	22 MeV	38"	DOE/UCLA	--	2.3 E+03	2.3 E+04	2.5 E+04	1.1 E+02	30	i	
U of Colorado	28 MeV	52"	DOE/State	--	2.8 E+03	9.0 E+04	9.9 E+04	7.6 E+02	160		
ANL	40 MeV	60"	DOE	4.8 E+01	8.7 E+03	2.9 E+03	3.2 E+03	--	--	r, i	
U of Washington (Seattle)	40 MeV	60"	--	1.1 E+02	2.7 E+04	1.1 E+03	1.2 E+03	--	--	r	
Michigan State U	50 MeV	67"	NSF/NSU	2.5 E+00	3.9 E+02	2.0 E+03	2.2 E+03	1.7 E+02	20	r	
NASA/Levitt	55 MeV	83"	NASA	5.4 E+01	2.3 E+03	2.3 E+03	2.5 E+03	2.3 E+02	25	r	
LBL	60 MeV	88"	DOE	1.4 E+01	6.7 E+02	3.0 E+03	3.3 E+03	1.9 E+03	190	r	
Texas A&M	60 MeV	88"	DOE/State/ Private	0	6.4 E+04	2.7 E+03	3.0 E+03	2.9 E+03	285	r	
Harvard U	160 MeV	95"	NSF	4.2 E+02	8.0 E+03	7.1 E+03	7.8 E+03	5.4 E+00	0.2	m, r	
LBL	720 MeV	184"	DOE	--	--	4.3 E+06	4.7 E+06	6.2 E+01	0.3	m	
NASA/SREL	600 MeV	197"	NASA/NSF/ State	2.0 E+04	1.2 E+03	2.6 E+06	2.9 E+06	2.0 E+03	2.0	r	Shutdown Aug 78
Indiana U	225 MeV	272"	NSF/IU	--	--	2.0 E+06	2.2 E+06	--	--	r	
Proton synchrotrons											
Princeton-Penn	3 GeV	60'	DOE	--	--	1.4 E+06	1.5 E+06 ^b	3.1 E+01	0.1	r	Shutdown 8 Apr 73
LBL-Bevatron	6.2 GeV	100'	DOE	--	--	9.8 E+06	1.1 E+07	9.3 E+02	0.9	r	v/50-MeV linac
ANL-ECB	12.7 GeV	180'	DOE	2.3 E+04	9.5 E+06	1.4 E+07	1.5 E+07	2.2 E+02	0.1	r	v/200-MeV linac
BNL-AGS	33 GeV	860'	DOE	6.0 E+06	3.7 E+07	1.8 E+08	2.0 E+08 ^b	2.2 E+03	0.4	r	v/200-MeV linac
PSAL	460 GeV	3000'	DOE	4.6 E+05	2.0 E+06	1.0 E+07	1.1 E+07 ^c	6.8 E+03	0.1	r	v/8-GeV booster synchrotron and 200-MeV linac
Electron synchrotron											
Cornell U	12 GeV	820'	NSF	--	--	1.3 E+05	--	--	0.8	r	
Electron linacs											
INT San Diego	35 MeV	30'	Private	0	3.1 E+02	1.0 E+04 to 1.0 E+05	--	--	500		
ANL	35 MeV	30'	DOE	0	4.0 E+01	4.0 E+04 ^d	--	--	--	r	Includes power supplies, etc.
MIT Bates Lab	400 MeV	600'	DOE	--	5.3 E+04 ^d	--	--	--	--	r	
SLAC	20 GeV	2 mi	DOE	--	3.4 E+03	--	--	--	30	r	
Proton linacs											
LAMPF	800 MeV	2600'	DOE	--	5.5 E+07	--	--	9.5 E+04	700 ^e	r	
Electrostatic accelerators											
ANL-Tandem	30 MeV		DOE	0	--	5.0 E+04	2.3 E+02	--	--		Heavy-ion work
U of Washington Tandem	--		--	0	--	5.0 E+04	3.0 E+00	--	--		

^aCode: r = research, i = isotope production, d = machine development, and m = medical.^bTotal includes some shielding.^cNo shield material.^dAccelerator tank and beam stops only.^eDesign goal (120 nA @ 1000 nA).

REFERENCES FOR CHAPTER 6

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CHAPTER 7.

COST ESTIMATES FOR DECOMMISSIONING PROCEDURES

The cost analysis presented in this chapter is for the decommissioning of an entire accelerator, including nonradioactive as well as radioactive components. The cost of dismantling allows for conveyance of all components out the facility door and onto railroad cars or trucks or into a temporary-storage building. Associated with all the decommissioning activities is the need to package, transport, and dispose of the radioactive wastes generated. The amount of waste is dependent on the decommissioning option chosen. The amount of waste generated by mothballing, entombment, or dismantlement with onsite storage would be substantially less than that generated by dismantlement with offsite disposal. In addition, what is termed "waste" is dependent on the final disposition of the accelerator components. For example, if many of the magnets are to be reused, they would be classified as "usable materials"; if they are to be discarded, they would be "wastes". In this chapter, no value is assigned to the potential for reuse of radioactive components. Costs associated with the disposal of nonradioactive material are not considered. In the case of radioactive components, the level of health-physics effort assumes radiation levels expected immediately after final shutdown.

Because each accelerator facility is unique in design and purpose, the decommissioning budget and waste management will be site specific. In some instances, the dismantling of the experimental area could be a more complex task than that of the accelerator itself (e.g. high-beam-intensity military-research applications). However, the dominant task will generally be the dismantlement of the accelerator proper. In addition to overall size (scale effects) and radiological concerns, two factors principally determine and potentially alter the magnitude, complexity, and cost of the decommissioning. First, the method of treatment of the radioactive portions of the permanent-shielding concrete (e.g. leaving in protected state, scarfing, demolishing) will greatly influence the cost estimate. The decision among these alternatives for the shielding depends on the potential reuse of the building, and on local regulations then in effect (see Chap. 4). Second, the cost of dismantling is generally also sensitive to the method of removal of the magnetic or electric components; e.g. arc cutting of magnets into reusable and/or manageable sections may be required instead of simple bulk removal. The term "manageable" essentially means that a crane exists that is capable of handling the entire magnet. The cutting of the magnets or other specially formed components limits reuse potential and should be avoided unless disposal (or bulk reuse as shielding or counterweight) is the decommissioning option chosen. If cutting is considered, the optimal-cut sizes are such that the resulting sections are the largest manageable under the decommissioning option chosen.

The monthly budget for staff-level positions and estimating factors for demolition activities are presented in Appendix H, as are unit costs for packaging, transportation, and radioactive-waste disposal.

An engineering evaluation of the costs associated with decommissioning four machines at Argonne National Laboratory is presented in this chapter using the procedures described in Chapter 5.¹⁻³ The four machines considered are: (1) the Zero Gradient Synchrotron, (2) a Collins 60" cyclotron, (3) an Arco 22-MeV electron linac, and (4) a High Voltage Engineering Company Model FN 9-MV Tandem Van de Graaff. Four decommissioning alternatives are considered for the ZGS: dismantlement with disposal of the radioactive materials in a radioactive-waste burial ground, dismantlement with storage in a specially constructed warehouse, mothballing, and entombment. In the last two options the ZGS is left essentially intact. For the other three machines, only the dismantlement-with-disposal option is considered, as the other options are either inappropriate or very easy to perform. As noted in Chapter 1, these four cases serve to illustrate the application of the methodology, primarily to cost engineering, and to a limited extent to categorization of component-reuse potential and preparation for radioactive packaging and disposal. They are developed to give guidance and insight to persons charged with decommissioning an accelerator in the future and to provide an estimate of the magnitude of costs involved. No attempt was made to provide the level of detail required in the preparation of an actual bid package for the dismantlement of the prototypes. No credit for equipment reuse, scrap, or salvage value is assumed.

THE ZERO GRADIENT SYNCHROTRON DECOMMISSIONING

Dismantlement and Immediate Disposal

In estimating the cost of dismantling the ZGS accelerator, it is assumed that all equipment and special structures inside the buildings that house the accelerator will be removed. Utilities will be retained and radioactive sections will be removed and replaced with new material. The high-voltage terminal and power supply, although probably not radioactive, are obsolete; so, for the sake of this estimate, they are assumed to be dismantled and scrapped.

The lining of the ring tunnel will be removed and scrapped as will the special structure of the ring tunnel above the permanent floor, and the movable floor. No allowance is included for either filling or covering the pit remaining in the floor. It is assumed that portions of the ring building will have suffered activation through neutron bombardment. An allowance is included for removal and repair of any radioactive spots remaining in the ring-tunnel concrete after removal of the operating floor.

The beam-line equipment between the high-voltage terminal and the linac will be dismantled, surveyed for radioactivity, and marked if radioactive. In this estimate, it is assumed that no activation of the permanent building or utilities has occurred in the vicinity of the linac beam line, so no allowance is made for building decontamination in this area. The linear accelerator itself has probably suffered some activation, so it is assumed to be radioactive. The linear accelerator consists of light framing, a copper-lined steel vacuum tank, removable drift tubes, and a great quantity of light plumbing. Therefore, the category of light piping is used in arriving at an esti-

mate of the man-hours required to dismantle and remove it (see App. H, Table H.2, "Estimating Factors"). The linear-accelerator accessories are treated as a separate item.

The main-ring magnets, totaling 4350 Mg, will be removed by unbolting and moving them out of the ring building using the existing crane and handling equipment. Because the heaviest pieces are within the capacity of the available handling equipment, no requirement for cutting or additional disassembly of blocks is foreseen.

A handling fixture for the coils is available. Therefore, the coils can be lifted until they are accessible and cut into pieces of convenient size for disposal (or reuse). Some scattering of radioactive copper and insulation is expected to occur as a result of cutting the coils.

Vacuum chambers are fabricated of thin titanium that can be removed with existing handling fixtures and subsequently crushed to reduce the volume of material to be shipped to a radioactive-waste burial site. No allowance is made in this cost estimate for compacting the vacuum chambers.

It is assumed that all cabling and wiring associated with the ZGS will be removed from the ring building, but that building utilities will be left intact. No attempt will be made to isolate and retain individual cables or circuits, as identification and preservation would be difficult and expensive. Cabling in wireways and trays is to be cut to convenient lengths and removed, leaving the trays clear for future use. All cabling in the control room and to other areas is to be removed by cutting to convenient lengths and pulling out. All ZGS-associated equipment and wiring will be removed, leaving building utilities complete and operable. The power building will be cleared of all ZGS-related equipment, leaving building utilities intact.

The dismantling of the ZGS is assumed to comprise four major periods. The first is an interval of twelve months prior to final shutdown during which final disposition of equipment is determined, major decommissioning responsibilities are defined, and senior-staff positions are identified and filled.

The second period is of a four-month duration and is occupied with bid-package preparation for contract support work, and the subsequent bidding and selection process. Also, the staff is augmented to provide engineering and health-physics support and monitoring services to the contract work crews.

The third period is of an eight-month duration and includes the contract support work for the dismantling and the clearing of the accelerator buildings. It is assumed that all highly radioactive targets, beam dumps, collimators, and any other separable components that have been struck by the beam have been removed and safely stored or disposed of by the operating crew shortly after final shutdown, even if a mothballed period is anticipated. During this period, the full-time staff is to provide health-physics monitoring, identify components for reuse or salvage, maintain necessary records, and provide supervision and inspection services.

The fourth period, of six months or less, is allocated to cleanup, settlement of contract claims, closing of files, transfer or termination of staff, and miscellaneous minor activities.

Figure 7.1 illustrates the aforementioned periods and the estimated staff buildup and effort during each period. The period- and activity-dependent costs for dismantling the ZGS are \$2.1 million and \$1.6 million, respectively. A detailed breakdown of these costs is presented in Appendix D.

Figure 7.1. ZGS Decontamination and Decommissioning Schedule and Staff.

The greatest single-item (as defined in App. C) activity-dependent cost for dismantling the ZGS is for removing the magnet steel (39%), as shown in Appendix D, Table D.3. About 57% of the dismantling cost of the accelerator is for the ring-magnet section. Because the magnet pieces are generally quite large, the rigging cost for these operations is based on the heavy-steel estimate of nine man-hours per ton (see App. H, Table H.2). The cost to remove the concrete operating floor of the ring building is projected to be about 6% of the total activity cost. However, the decontamination of the remaining ring concrete (primarily the walls) by scarifying 1% of the area to a depth of six inches is less than 2% of the total activity cost (\$24 700). If the entire ring

tunnel had to be removed to reuse the land for other purposes, the cost of removal would be about \$1.3 million, as much as all other activity costs combined. It can be inferred from this discussion that the activity-dependent cost for dismantling the ZGS can be approximated by calculating the total mass of the accelerator complex, multiplied by nine man-hours of labor per ton, multiplied by \$25 per man-hour, plus the cost of concrete decontamination.

In the option of dismantling with immediate disposal, disposing of all radioactive components of the ZGS is a complex and expensive procedure. About 5800 tons of radioactive material and 1700 tons of nonradioactive material will require disposal. A detailed breakdown by item is given in Appendix D. The disposal of massive pieces of metal such as magnet sections, merely because they contain small quantities of induced activity, would seem to represent a tremendous waste of natural resources. However, because there are presently no standards pertaining to acceptable amounts of induced activity in materials for release to the general public, disposal in radioactive-waste burial grounds is the method of disposition evaluated and estimated.

The costs of disposing of radioactive wastes only are considered herein. Nonradioactive wastes could be disposed of as ordinary trash in a local landfill. Large pieces of metal are assumed not to require packaging for transportation; only a small amount of material would require packaging, and this merely to aid the transportation and disposal procedures. An estimated 100 fiberglassed wooden boxes and 50 55-gallon drums would be required at a cost of \$41 000. Shipment of these wastes by truck to the NECO disposal site in Richland, Washington, would require 150 legal-weight shipments and 256 overweight shipments at an estimated cost of \$1 006 200. The overweight shipments would be for transporting the magnet sections. The disposal cost is estimated to be \$288 000, including \$78 000 for weight surcharge for magnet-section disposal. The total disposal cost of the radioactive wastes in the full-dismantlement option is estimated to be about \$1.3 million. A detailed breakdown of the disposal costs is given in Appendix D.

Mothballing

The mothballing option has also been considered for the ZGS. Mothballing is designed to minimize initial commitments of time and money, yet meet the requirements for protection of the public. Mothballing is an appropriate decommissioning mode if the use of accelerator components in next-generation accelerators or on a commercial basis in the future is a possibility. Inasmuch as radioactive isotopes in the accelerator are mostly short-lived (half-lives of months to several years), mothballing the accelerator for a short period before implementing a permanent decommissioning mode could greatly reduce radiation fields. The iron, steel, and copper in accelerators (especially large ones) have a potentially significant resale value. However, because this material is activated, it may not be possible to recycle it immediately. Temporary mothballing would allow for the activity to decrease, thus making reuse more likely.

Implementation of this decommissioning mode would involve general cleanup around the accelerator. Following cleanup, access to the accelerator would be prohibited by blocking all entrances. Locks would be placed on all doors to prevent inadvertent intrusion. If the accelerator were located at a national laboratory, it would not be necessary to have additional security personnel.

The cost to place the ZGS in a mothballed state, including waste disposal, is estimated to be about \$72 000. The period-dependent costs are for the professional and technical personnel who would plan and supervise the work, and total about \$37 000. The activity-dependent costs are for the required cleanup work, and total about \$34 000. (Due to roundoff, the approximate total cost is not the exact sum of the period- and activity-dependent costs.) Mothballing even a large facility such as the ZGS is estimated to require less than one month to complete, and because it would be a relatively simple procedure, no additional time is allotted for planning. The wastes generated by the decommissioning activities would be packaged and shipped to a radioactive-waste disposal site, requiring an estimated 10 boxes and 10 55-gallon drums. Details of the period- and activity-dependent costs are presented in Appendix D.

Entombment

The entombment option of the ZGS has also been evaluated. Entombment would consist of sealing the accelerator within a high-integrity durable structure. For this study, entombment is assumed to consist of sealing all accesses to the ZGS with concrete. Otherwise, implementation of this mode would be the same as that of mothballing. Assuming a three-foot-thick concrete plug at each access, the amount of concrete required is estimated to be 100 yd³. A cost of \$300/yd³ is estimated for installing these concrete plugs.²

The cost of entombing the ZGS, including waste disposal, is estimated to be about \$142 000. This consists of a period-dependent cost of about \$75 000 and an activity-dependent cost of about \$67 000. Entombment is estimated to require two months to complete. As with the mothballing alternative, a planning period is not included in this estimate, and an estimated 10 boxes and 10 55-gallon drums would be required to package the radioactive wastes for disposal. Details of the period- and activity-dependent costs are given in Appendix D.

Interim Storage Following Dismantlement

Finally, the option of interim storage has been considered in the case of the ZGS. In the interim-storage option, the accelerator would be dismantled and the reusable components would be placed in interim storage for future use. The storage mode would be used only for components for which immediate recycle is not available.

The dismantled components could be stored in place, or a building could be built explicitly for storage. If the components are to be stored in such a building, its cost must be included. It is assumed that this storage facil-

ity would be located near the accelerator building. Thus, there would be no increase in the length of time to implement this option as opposed to dismantlement with immediate recycle. The advantage of a separate storage building is the continued availability of the accelerator building as a research facility.

For the purpose of a cost estimation of storage for the ZGS, an architecture and engineering analysis of a reference structure was considered.⁴ This building is assumed to be 100 ft × 100 ft, with a height of 16 ft. The building would be constructed of prefabricated metal with two rolling overhead steel doors. Depending on the exact location of the building, it may be necessary to provide additional support with caissons. The floor loading in this building is assumed to be 2000 lb/ft², or 1 ton/ft². Thus, the building could store up to 10 000 tons. The cost of constructing such a facility is estimated to be \$500 000.⁴ The materials to be stored in it would be items such as the magnet sections, copper coils, and other massive pieces, which have potential recycle value but may contain induced activation. Inasmuch as the total amount of material that would require storage is estimated to be about 6000 tons, one such facility could store all these components. To move the components to this building, a heavy-duty diesel forklift would be required. The cost of such a forklift would be about \$150 000.

In dismantling the ZGS for storage, a certain amount of radioactive wastes would be generated that would not have future-use potential. For example, concrete that has been scarfed in the process of decontaminating the building would require disposal as radioactive waste. The cost of disposing of these radioactive wastes is about \$235 000. Details are presented in Appendix D. Therefore, the total cost to implement the storage option (excluding dismantling) is \$500 000 to build the storage facility, \$150 000 for the forklift, and \$235 000 for waste disposal, or \$885 000.

THE 60" CYCLOTRON DISMANTLEMENT

Attention must be given to two items that characterize large cyclotrons. If the magnet structure has been site-assembled by lamination of heavy plate, this would allow separation of the plates for disassembly and handling. If the magnet has been constructed of large forgings, it might be necessary to cut it into smaller pieces before removal.

The large cyclotrons (except a few AVF and separated-sector types) are all old machines and have little of value for reuse or salvage. Thus, extensive cataloging and other period-dependent costs, except for health physics, should be kept to a minimum. Small cyclotrons, either the early custom-built machines or the newer commercially built ones, will have little salvage value and do not justify any substantial period-dependent expenditures. Residual activity will require their treatment as radioactive assemblies. Health-physics monitoring and documentation will constitute the major period-dependent costs.

The cost estimate for dismantling the 60" cyclotron at Argonne National Laboratory is based on the assumption that the magnet components could be

moved by riggers through the dee door and outer-wall door to grade level outside the building for loading onto a heavy-duty low-bed truck trailer.*

It has been suggested by Bigge Power Constructors that rigging costs in this case are unaffected by a decision to flame cut large pieces of steel to smaller size before moving.³ The decision is based on rigging-equipment capabilities at the 60" cyclotron. The cost of cutting is offset by the economy realized in handling lighter pieces. Also, flame cutting would produce radioactive hazards, as already noted in Chapter 6. However, if reuse of a portion of the magnet is desirable (e.g. as shield blocks), then cutting should be included either directly in the dismantling budget or the budget of the receiver laboratory. Demolition of the shielding walls and roof of the vault does not include that portion of the foundation walls below grade adjacent to unexcavated areas.

The period-dependent cost for dismantling of the 60" cyclotron is about \$158 000. Activity-dependent costs total about \$629 000. In sharp contrast to the ZGS, the entire project will last only about four months. The majority of the effort (89% of activity-dependent costs, 84% of organizational-staff activity hours) is for concrete-shielding removal; of the remaining activity-dependent cost, 49% is spent on removal of the magnet. Because the cyclotron magnet is extremely massive, the cost of removal is based on nine man-hours per ton at \$25 per man-hour. Therefore, as was the case in the ZGS large-ring prototype, the cost of dismantling the 60" cyclotron can be approximated by calculating the total mass, multiplied by nine man-hours per ton, multiplied by \$25 per man-hour, plus the cost of concrete-shielding removal. Details of the period- and activity-dependent costs are given in Appendix E.

Associated with the dismantlement of the 60" cyclotron are 880 tons of radioactive material and 5200 tons of nonradioactive material. The disposal costs of the radioactive wastes of the 60" cyclotron total about \$280 000. In this estimate, it is assumed that the magnet has been cut into twelve 22-ton segments. Details of the disposal costs are presented in Appendix E.

THE 22-MeV LINAC DISMANTLEMENT

The 22-MeV electron linac at Argonne National Laboratory is comprised of easily dismantled modules. Some of these modules, such as the klystrons and vacuum pumps, have reuse potential. The water-cooling modules can be retained intact for possible use in experimental setups (if storage space is available). The modulator, amplifier power supply, and auxiliary power-supply modules are surplus unless an immediate use is apparent. Activity-dependent costs are estimated for the dismantlement and removal of the linac and the removal of the modules and control console. Removal of electrical-substation components is not included.

*This is not a physical possibility at ANL because the building was constructed around the massive cyclotron magnet with no portals for its exit. This is not an uncommon situation at cyclotron facilities.

The period-dependent cost for dismantling of the linac is about \$26 000. The activity-dependent cost is about \$35 000. For low-energy linacs, such as the one at ANL, there are essentially no health-physics staff requirements, although 0.1% of the total mass of such a linac is estimated to be radioactive. Work would be performed almost entirely by an outside contractor. Inasmuch as the modules of most linacs are not heavy, a cost of 16 man-hours per ton, multiplied by \$25 per man-hour, multiplied by the total mass of the linac facility gives a good approximation of the removal costs of this type of accelerator. In general, no decontamination of the concrete walls and floor surrounding smaller linacs will be required. Details of the period- and activity-dependent costs for the linac dismantling are shown in Appendix F.

Associated with the dismantling of the 22-MeV linac are 0.1 ton of radioactive waste and 43.1 tons of nonradioactive waste. The cost of disposal of the radioactive material is about \$3300. Details of the waste and disposal cost calculation are presented in Appendix F.

THE TANDEM VAN DE GRAAFF DISMANTLEMENT

Salvage value of the Tandem Van de Graaff at Argonne National Laboratory is no more than that of scrap unless the machine can be used in its entirety elsewhere. However, the negative-ion sources have many components useful elsewhere in the laboratory and would be returned to stock. An allowance of five man-months of technician labor has been made as a period-dependent cost for in-house dismantling of the negative-ion sources. There will be only a small contribution of effort for health-physics monitoring and contractor-services procurement. Less than 0.5% of the components of the Tandem Van de Graaff are estimated to be radioactive.

The period-dependent cost for the Argonne National Laboratory Tandem Van de Graaff is about \$69 000. The activity-dependent cost is about \$37 000. Details of the period- and activity-dependent costs are given in Appendix G. Because the Tandem Van de Graaff tank constitutes the bulk of the mass of the accelerator, and because it can be classified as light structural steel, the cost of dismantling the machine can be approximated by calculating the total mass, multiplied by 16 man-hours per ton, multiplied by \$25 per man-hour. There are no major costs associated with concrete-shielding removal or cleanup, because the radiation levels outside the Van de Graaff tank after shutdown are not considered to present a problem.

Associated with the dismantlement of the Tandem Van de Graaff is about 0.3 ton of radioactive waste and about 54 tons of nonradioactive waste. The cost to dispose of the radioactive waste is about \$3300, the same value as for the linac. Details of the waste and disposal cost calculations are given in Appendix G.

SUMMARY OF COST RESULTS

The costs of dismantlement and immediate waste disposal for the four prototypic accelerators are presented in Table 7.1. The totals have been increased 25% to allow for contingencies.

Table 7.1. Estimated Costs of Dismantlement and Immediate Disposal of Four Prototypic Accelerators^a

Facility	Costs (\$)				Total ^b
	Dismantling	Packaging	Transportation	Disposal	
ZGS	3.7 E+06	4.1 E+04	1.0 E+06	2.9 E+05	6.3 E+06
60" cyclotron	7.9 E+05	3.6 E+04	1.8 E+05	6.2 E+04	1.3 E+06
22-MeV electron linac	6.1 E+04	5.0 E+02	2.1 E+03	7.3 E+02	8.0 E+04
Tandem Van de Graaff	1.1 E+05	5.0 E+02	2.1 E+03	7.3 E+02	1.4 E+05

^a 1978 dollars.

^b Sum of dismantling, packaging, transportation, disposal, and a 25% contingency factor on all activities.

REFERENCES FOR CHAPTER 7

1. "Engineering/Cost Analysis of Particle Accelerator Decommissioning." W.M. Brobeck and Associates, Report No. 4500-39-20-R1, 15 November 1978.
2. "Cost Estimate for Decontamination and Decommissioning the Zero Gradient Synchrotron." W.M. Brobeck and Associates, Report No. 4500-39-20-R2, 15 November 1978.
3. "Engineering/Cost Analysis General Methodology and Applications to Decommissioning Certain ANL Accelerators." W.M. Brobeck and Associates, Report No. 4500-39-20-R3, 15 November 1978.
4. Memorandum from D.F. Warshall, Argonne National Laboratory, PS, to J. Opelka, Argonne National Laboratory, EIS, w/ attachments. "Cost Estimate for Heavy Equipment Storage." 14 May 1979.

CHAPTER 8.

RECOMMENDATIONS

Several recommendations have resulted from the study of past accelerator decommissionings and the analysis of the generic requirements involved in a particle-accelerator decommissioning.

In the future, consideration of the eventual decommissioning of accelerators should be incorporated during the design and construction phase. Historically, accelerators have been designed without consideration of eventual decommissioning. By considering the decommissioning requirements during the design of the accelerator, problems such as inaccessible components could be avoided. Materials used in construction and location of components can be chosen to minimize residual radioactivity whenever technologically feasible. Building components that double as structural material and radiation shielding can be designed to be readily separable at decommissioning. The desirability of the commitment of scarce resources to an accelerator's high radiation environment should be considered during the design phase.

Entombment should generally not be considered as a realistic option for decommissioning of particle accelerators. The radiation level in the vicinity of accelerators is not generally high enough to justify the consideration of the entombment option. Surface contamination is generally limited and readily decontaminated. Furthermore, entombment would unnecessarily preclude the future utilization of the accelerator. The only possible exception to this recommendation against entombment is the highly radioactive LAMPF facility.

Placing accelerator decommissioning under the auspices of the federal government should be considered, as this would allow a consistent and uniform decommissioning policy. In the future, the number of accelerators to be decommissioned will increase, especially in the medical-treatment and isotope-production areas. Even though the decommissioning of accelerators does not pose as serious a problem as decommissioning of other nuclear facilities, e.g. power reactors, it should be considered to be an integral part of the entire nuclear decommissioning picture. The principal difficulty in coordinating accelerator and other nuclear-facility decommissionings is the fact that accelerator decommissionings are under state jurisdictions, whereas decommissionings of other major facilities containing nonnegligible amounts of radioactivity are under federal jurisdiction.

Guidelines for reuse of material containing induced activity should be developed at the national level and be applicable to all radioactive material, regardless of how the activity was produced. Because limitations on the amount of permissible induced activity for release of material for unrestricted use do not exist, present practice often is to send unclaimed material (containing induced activity above natural radioactivity) from decommissioned

accelerators to other accelerator locations for reuse, to aboveground storage areas, or to radioactive-waste burial grounds for disposal. In past decommissionings, much of the radioactive material was absorbed by the accelerator community and reused, sometimes merely as additional shielding. However, with cutbacks in research funding and the subsequent reduction in construction of new research accelerators, it may not be possible to reuse the valuable material that has become slightly radioactive. Without guidelines for induced activity, it may be necessary to dispose of this material as radioactive waste. This would represent a waste of natural resources.

APPENDIX A. CENSUS OF PARTICLE ACCELERATORS

A directory of particle accelerators used for nuclear physics research in the United States is shown in Tables A.1 through A.8. Table A.9 lists cyclotrons whose main purpose is medical application or isotope production. Tables A.1 through A.9 constitute the most up-to-date compilation presently possible of accelerators in the United States that produce a nonnegligible radiation environment at decommissioning. However, they should not be considered to provide a comprehensive listing for planning purposes because of reference publication dates and constant advances in accelerator applications. Each machine at each location is listed with its maximum particle energy (proton or electron, unless otherwise noted), year of initial operation, and source of funding. The references and funding agencies for the information about each machine are given in Table A.10. The funding-agency indications are complete only for Department of Energy (DOE) installations. For all others, the funding agency is listed where known, otherwise ND, meaning "not DOE", is given. Injectors and boosters for larger machines are listed separately.

Table A.1. Proton Synchrotrons

Facility and Location	Proton Energy (GeV)	Initial Operation	Funding Agency ^a	Reference ^a
Zero Gradient Synchrotron ^b				
Argonne National Laboratory	12.7	1963	DOE	B,E
Intense Pulsed Neutron Source				
Argonne National Laboratory	0.5	1976	DOE	B,E
Alternate Gradient Synchrotron				
Brookhaven National Laboratory	33	1960	DOE	B,E
Bevatron				
Lawrence Berkeley Laboratory	6.2	1954	DOE	B,D,C
Fermi main ring				
National Accelerator Laboratory	4000	1972	DOE	B,E
Fermi booster				
National Accelerator Laboratory	8	1972	DOE	B

^a See Table A.10 for explanation of codes.

^b Decommissioning scheduled to begin in October 1979.

Table A.2. Electron Synchrotrons

Facility and Location	Electron Energy (MeV)	Initial Operation	Funding Agency ^a	Reference ^a
Ames Laboratory				
Iowa State University	70	1949	DOE	C
Ames Laboratory				
Iowa State University	70	1954	DOE	C
University of Oklahoma	70	1968	FVT	C

^a See Table A.10 for explanation of codes.

Table A.3. Positive-Ion Linacs

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Reference ^a
Super-HILAC Univ. of Calif. Berkeley	85/amu	1971	DOE	C,D
LAMPF Los Alamos National Lab.	800	1972	DOE	C,D
Linac injector National Accelerator Laboratory	200	1977	DOE	A,B
Linac injector to AGS Brookhaven National Laboratory	200	1960	DOE	A,B
FMMRI Univ. of Chicago, Franklin McLean Res. Hosp.	50		DOE	A,B
Rensselaer Polytechnic Inst.	100		DOE	A,B
Linac injector to ZGS Argonne National Laboratory	50	1963	DOE	A,B

^aSee Table A.10 for explanation of codes.

Table A.4. Electron Linacs

Facility and Location	Electron Energy (MeV)	Initial Operation	Funding Agency ^a	Reference ^a
Bates Mass. Inst. of Tech.	400	1972	DOE	C,D
Mark III S Stanford Univ.	2 000	1972	ONR/NSF	C
Mark III Stanford Univ.	1 200	1953	NSF	B
Stanford Linear Accel. Center	22 000	1966	DOE	B
Argonne National Laboratory	22	1969	DOE	B,C
Univ. of Calif. Livermore	35	1959	DOE	C
Univ. of Calif. Livermore	100	1970	DOE	C
Univ. of Chicago	50	1957	ND	C
Gulf General Atomics	100	1958	FVT	C
Univ. of Illinois	30	1970	NSF	C,D
NASA-SREL	10	1966	NSF	C
National Bureau of Standards	150	1966	DOC	C
Naval Postgraduate School	100	1965	DON ^b	C
Naval Research Laboratory	65	1964	DON	C
ORELA Oak Ridge National Laboratory	140	1969	DGE	C,D
Rensselaer Polytechnic Inst.	100	1961	DOE	C
Yale University	75	1961	DOE	C,D
Ohio State University	6		ND	A

^aSee Table A.10 for explanation of codes.^bPerforms some NSF work and currently has a DOE proposal pending.

Table A.5. Cyclotrons

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Reference ^a
<u>DOE owned and/or supported</u>				
60"AVF Brookhaven National Laboratory	36	1968	DOE	B,C
88"AVF Univ. of Calif. Berkeley	60	1962	DOE	C,D
20"AVF Univ. of Calif. Livermore	15 ^b	1969	DOE	C
52"AVF Univ. of Colorado	50	1962	DOE	C,A,D
31"AVF Duke University	15 ^b	1968	DOE	C
76"AVF Oak Ridge National Laboratory	66	1964	DOE	C,D
Cancer Research Hospital Univ. of Chicago	16		DOE	A
Sloan-Kettering Institute	20		DOE	A
60"FF Argonne National Laboratory	23 ^c	1952	DOE	A,C,D
90"FF Univ. of California	14	1955	DOE	C
50"FF Univ. of Michigan	9 ^c	1936	MI	C
105"AVF Univ. of Maryland	140	1969	DOE	C,D
88"AVF Texas A & M	60	1967	DOE	C,D
<u>Formerly DOE owned or supported</u>				
76"AVF Univ. of Calif. Davis	55	1965	CA	C,D
50"AVF Univ. of Calif. Los Angeles	50 ^b	1962	CA	C
260"AVF Univ. of Indiana	200	1975	NSF	C,A,D
67"AVF Michigan State Univ.	55	1965	NSF	C,D
76"AVF Naval Res. Laboratory	50	1967	DON	C
69"AVF Princeton University	56	1968	NSF	C,D
28"AVF Univ. of Connecticut	8	1967	PVT	C
37"AVF Oregon State Univ.	18	1969	OR	C
60"FF NASA-Lewis Research Center	21 ^c	1952	NASA	C
27"FF St. Louis University	3.5 ^c	1966	PVT	C
60"FF Univ. of Washington	21.5 ^c	1951	WA	C

^a See Table A.10 for explanation of codes.^c Deuteron.^b Negative hydrogen ion.

Table A.6. Synchrocyclotrons

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Refer- ence ^a
184" Univ. of Calif. Berkeley	730	1946	NIH	C
Nevis Columbia University	585	1950	NSF	B,C
197" NASA-Space Radiation Effects Laboratory	660	1967	NSF	B

^aSee Table A.10 for explanation of codes.

Table A.7. Storage Rings

Facility and Location	Electron Energy (MeV)	Initial Operation	Funding Agency ^a	Refer- ence ^a
SPEAR Stanford Lin. Accel. Ctr.	2500	1972	DOE	E
Tantalus I Univ. of Wisconsin	240	1968	NSF	E

^aSee Table A.10 for explanation of codes.

Table A.8. Electrostatic Accelerators

<i>Facility and Location</i>	<i>Proton Energy (MeV)</i>	<i>Initial Operation</i>	<i>Funding Agency^a</i>	<i>Refer- ence^a</i>
<u>DOE owned and supported</u>				
Tandem dynamitron Argonne National Laboratory			DOE	A,F
Dynamitron Argonne National Laboratory	4	1969	DOE	A
Van de Graaff Argonne National Laboratory	2		DOE	A
Pulsed-electron Van de Graaff Argonne National Laboratory	3 ^b		DOE	A
Tandem Van de Graaff (FN) Argonne National Laboratory	18	1967	DOE	A,C,D
Tandem Van de Graaff Brookhaven National Laboratory	30	1970	DOE	E,C
Van de Graaff Brookhaven National Laboratory	4	1954	DOE	A
Dynamitron Brookhaven National Laboratory	3		DOE	
Tandem Van de Graaff (FN) Oak Ridge National Laboratory	13	1962	DOE	C,D
Van de Graaff Oak Ridge National Laboratory	6	1950	DOE	E,F
Van de Graaff Oak Ridge National Laboratory	3	1948	DOE	C
3-stg Tandem Van de Graaff (FN) Los Alamos Scientific Laboratory	24.5	1964	DOE	C,F
Van de Graaff Los Alamos Scientific Laboratory	9	1950	DOE	C
Van de Graaff Los Alamos Scientific Laboratory	3	1969	DOE	
Tandem Van de Graaff Yale University	22	1966	DOE	A,D
Van de Graaff Notre Dame Univ.	2		DOE	A
Tandem Van de Graaff Univ. of Calif. Livermore	27	1971	DOE	C,F

See footnotes at end of table.

Table A.8. Continued

<i>Facility and Location</i>	<i>Proton Energy (MeV)</i>	<i>Initial Operation</i>	<i>Funding Agency^a</i>	<i>Refer- ence^a</i>
<u>DOE owned and supported (continued)</u>				
3-stg Tandem Van de Graaff Duke University	32	1968	DOE	C,D,F
Van de Graaff Duke University	3.3	1961	DOE	C
Van de Graaff Duke University	4.2	1952	DOE	C
Tandem Van de Graaff Ohio University	11	1970	DOE	A,D
Van de Graaff Univ. of Chicago, Franklin McLean Res. Hosp.	2		DOE	A
Tandem Van de Graaff Kansas State Univ.	12	1969	DOE	A,C,F
Tandem Van de Graaff Univ. of Wisconsin	12	1960	DOE	A,D,F
Tandem Van de Graaff Univ. of Minnesota	20	1966	DOE	A,D,F
<u>Not DOE owned, but formerly DOE supported</u>				
Van de Graaff Johns Hopkins Univ.	3	1963	DOE	A
Van de Graaff Columbia University	5.5	1955	COL	C
Tandem Van de Graaff Rice University	12	1961	ND	C,D,F
Van de Graaff Rice University	5.5	1953	ND	C,F
Tandem Van de Graaff West Michigan Univ.	12	1969	SHI	C,F
Tandem Van de Graaff Purdue University	15	1969	SIN	C,F
Van de Graaff Univ. of Kansas	4	1963	ND	C

See footnotes at end of table.

Table A.8. Continued

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Refer- ence ^b
<u>Not DOE owned, but formerly DOE supported (continued)</u>				
Van de Graaff Univ. of Maryland	3.5	1958	MD	C
Tandem Van de Graaff Florida State Univ.	18	1970	MD	C,F
Van de Graaff Brigham Young Univ.	2.5	1965	BYU	C
Van de Graaff Brigham Young Univ.	4	1970	BYU	C
Van de Graaff Case Western Reserve Univ.	3	1958	MD	C
3-stg Tandem Van de Graaff, (CN & EN) Univ. of Texas - Austin	17.5	1963	STX	C,D,F
Van de Graaff Univ. of Texas - Austin	4	1963	STX	C
<u>Not DOE owned and never DOE supported</u>				
3-stg Tandem Van de Graaff (EN & EN) Univ. of Pittsburgh	18	1967	NSF	C,D,F
3-stg Tandem Van de Graaff (FN & FN) Univ. of Washington	25.5	1967	SWA	C,D,F
Tandem Van de Graaff (T-8) Aerospace Res. Lab.	8	1967	USAF	C
Van de Graaff Aerospace Res. Lab.	2	1953	USAF	C,F
Tandem Van de Graaff (FN) Army Nuclear Eff. Lab., Edgewood Arsenal	15	1969	USA	C,F
Tandem Van de Graaff (EN) Calif. Inst. of Tech.	10	1961	NSF	C
Tandem Van de Graaff (FN) State Univ. of New York, Stony Brook	17	1968	NSF	C,D,F

See footnotes at end of table.

Table A.8. Continued

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Refer- ence ^b
<u>Not DOE owned and never DOE supported (continued)</u>				
Tandem Van de Graaff Notre Dame Univ.	15	1968	NSF	C,D,F
Van de Graaff Notre Dame Univ.	4	1956	ND	C
Tandem Van de Graaff (EN) Univ. of Pennsylvania	12	1962	NSF	C,F
Tandem Van de Graaff (MP) Univ. of Rochester	20	1966	NSF	C,D,F
Tandem Van de Graaff (FN) Rutgers University	18	1964	NSF	C,D,F
Tandem Van de Graaff (FN) Stanford University	19	1965	NSF	C,D,F
Van de Graaff Stanford University	3	1960	NSF	C
Van de Graaff (CN) Univ. of Arizona	5.5	1968	NSF	C,F
Van de Graaff (CN) Bartol Res. Found.	5.5	1952	FVT	C,F
Van de Graaff Univ. of Georgia	5	1970	ND	C
Van de Graaff (CN) Univ. of Iowa	6	1964	ND	C,F
Van de Graaff Univ. of Iowa	2	1961	ND	C
Van de Graaff (CN) Univ. of Kentucky	6	1964	NSF	C,F
Van de Graaff (CN) Lowell Tech. Inst.	6	1969	FVT	C,F
Original Van de Graaff Mass. Inst. of Tech.	9	1951	FVT	C
Van de Graaff (CN) Naval Research Lab.	5.5	1953	DON	C
Van de Graaff Oregon University			NSF	D
Van de Graaff (CN) Ohio State Univ.	6	1963	ND	C,F

See footnotes at end of table.

Table A.8. Continued

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Refer- ence ^a
<u>Not DOE owned and never DOE supported (continued)</u>				
Van de Graaff (CN) Penn. State Univ.	5.5	1963	ND	C,F
Van de Graaff (CN) Univ. of Virginia	6	1966	ND	C,F
Homemade Van de Graaff Calif. Inst. of Tech.	0.6	1952	ND	C
Homemade Van de Graaff Calif. Inst. of Tech.	2.8	1949	ND	C
Van de Graaff Carnegie Inst.	4	1938	ND	C
Van de Graaff Univ. of Florida	4.2	1964	ND	C
Van de Graaff Georgetown Univ.	0.4	1964	NSF	C
Van de Graaff Georgetown Univ.	2	1966	NSF	C
Van de Graaff Lockheed Corp.	3	1958	ND	C
Van de Graaff Montana State Univ.	3.5	1971	ND	C
Dynamitron NASA-SREL	3 ^b	1966	NASA	C
Van de Graaff Nat. Bur. of Standards	2	1955	DOC	C
Dynamitron State Univ. of New York, Albany	4	1970	SUNY	C
Van de Graaff Univ. of Oregon	4.5	1966	NSF	C
Van de Graaff Univ. of South Carolina	0.5	1962	ND	C
Van de Graaff Chicago Nuclear (formerly Texas Nuclear)	3.2	1956	FYT	C
Van de Graaff Tulane Univ.	3	1967	FYT	C

See footnotes at end of table.

Table A.8. Continued

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Refer- ence ^a
<u>Not DOE owned and never LJE supported (continued)</u>				
Van de Graaff Virginia Polytechnic Inst.	4	1968	ND	C
Van de Graaff Washington State Univ.	2	1965	ND	C
Van de Graaff West Virginia Univ.	2 ^c	1964	ND	C
Van de Graaff Worcester Polytechnic Inst.	2	1959	ND	C

^aSee Table A.10 for explanation of codes.^bElectron.^cDeuteron.

Table A.9. Medical-Application Cyclotrons

Facility and Location	Proton Energy (MeV)	Initial Operation	Funding Agency ^a	Refer- ence ^a
CS15(20") Washington Univ. Medical School	15	1976		G
54"AVF Mallinckrodt Inst. of Radiology	13	1965		C,D
Allis Chalmers Massachusetts Genl. Hospital				G
CS22(29") New England Nuclear	22		FVT	G
CS30(40") New England Nuclear	30	1976	FVT	G
CS22(29") Medi-Physics	22		FVT	G
CS22(29") Medi-Physics	22		FVT	G
CS15(20") Univ. of Chicago-Franklin McLean Res. Hosp.	15			G
CS30(40") Mt. Sinai Hospital	30		FVT	G
CS22(29") UCLA Medical School	22		FVT	G

^aSee Table A.10 for explanation of codes.

Table A.10. Codes for Funding Agencies and References

Code	Funding Agency - Reference
BYU	Brigham Young University
CA	University of California
COL	Columbia University
DOC	Department of Commerce
DOE	Department of Energy
DOM	Department of the Navy
MI	University of Michigan
NASA	National Aeronautics and Space Administration
ND	Not-DOE funded
NIH	National Institutes of Health
NSF	National Science Foundation
ONR	Office of Naval Research
OR	Oregon State University
PVT	Private funding
SIN	State of Indiana
SMI	State of Michigan
SIX	State of Texas
SUNY	State University of New York
SWA	State of Washington
USA	United States Army
USAF	United States Air Force
WA	University of Washington
A	"AEC Owned Accelerators." Provided by J.J. Nelsen, USDOE/CORO/OES, 1978.
B	"American Accelerators Above 200 MeV." Provided by E.T. Ritter, USDOE, Div. Physical Research, 1978.
C	"Physics in Perspective." Vol. II, Part A (The Bromley Report) NAS, 1969. Table 11-5: Census of Accelerators in Basic Nuclear Physics Research.
D	"Future of Nuclear Science." (The Friedlander Report) NAS, 1976. App. G: Accelerators Funded for Nuclear Science.
E	"Catalogue of High Energy Accelerators." 16th International Conference on High Energy Accelerators, SLAC, May 1974.
F	"The Development of Electrostatic Accelerators." Nuclear Instruments and Methods, Vol. 122, Nov-Dec 1974. Tables 1-4.
G	A.P. Wolf. "Medical Cyclotrons." IAEA Symposium on Medical Radionuclide Imaging, BNL 22021, CONF-761060-10, Oct 1975.

APPENDIX B. DETAILS CONCERNING THE DECOMMISSIONING OF FOUR PARTICLE ACCELERATORS

This appendix presents details that supplement the history given in Chapter 3 concerning the decommissioning of four particle accelerators. Although all four were AEC-owned at the time, the problems encountered and the means for solving them are typical of those that will be encountered under present policy by any owner of an accelerator scheduled for decommissioning. Particular emphasis is placed on the possibility for reuse (recycle) of many components and the ways that recyclings were accomplished in the past.

THE ROCHESTER SYNCHROCYCLOTRON

The 130-inch 250-MeV synchrocyclotron at the University of Rochester produced its first high-energy protons on the last day of 1948. During the following year protons with energies of up to 240 MeV and currents of up to 0.1 μ A were produced. In the opinion of one of the original users, Dr. Sidney W. Barnes, the most notable discovery made with the \$1.5 million device during its two decades of use was the orientational effect in proton-proton scattering.^{1,2}

Operation of the synchrocyclotron was terminated late in 1968. Planning for the removal of the synchrocyclotron components, in particular the magnet, was begun early in 1970 because of the University's need for additional space.^{3,4} Much of the about 1000 tons of steel constituting the magnet could have been used either in a relatively intact form as a spectrometer or cut into smaller pieces for shielding. If the former option had been chosen, the yoke, weighing about 848 tons, would have been unwelded at the seams, so that the original six main beams could then have been loaded into railroad cars for shipment. The recipient of the steel, the Fermi National Accelerator Laboratory (FNAL) in Batavia, Illinois, chose the latter option, so the yoke was to be cut into pieces each weighing less than 40 tons,² and loaded for shipment. The FNAL agreed to pay for the transportation and unloading with its AEC funds.⁵

The major components to be dismantled consisted of the following:⁶

- (1) the magnet frame, consisting of six large C1010 carbon-steel forgings, four measuring 49 inches by 68-1/2 inches by 324 inches, and two measuring 49 inches by 616 inches by 137 inches, weighing a total of 851.2 tons, and various studs, nuts, and washers weighing a total of 8.2 tons;
- (2) the magnet poles, two cylindrical steel forgings each 130 inches in diameter and 44 inches in height with a total weight of 164.4 tons;
- (3) the pole tips, two cylindrical steel forgings each 130 inches in diameter and 8 inches in height with a total weight of 27.2 tons;
- (4) the exciting coils, two cylindrical assemblies largely of aluminum that were placed around each of the magnet poles, measured about 44 inches high, and extended 4 feet beyond the diameter of the pole pieces; and
- (5) the vacuum-tank frame, consisting of stainless-steel welded plate about 1 inch thick with dimensions of 13 feet by 16 feet by 28 inches.

The magnet-frame pieces were welded together. The pole pieces and pole tips were bolted onto the magnet frame with 3-inch- and 4-inch-diameter studs.

Radiation levels ranging from 20 to 140 mR/h at the pole tips were reported in December 1970, about two years after shutdown. Because of this induced radioactivity, the possibility existed that airborne radiation could pose a problem during the cutting operations, and thus the wearing of respirators could be required of persons in the vicinity of these operations.⁷ (Radiation levels one day after shutdown ranging from 100 to 700 mR/h may be inferred from the reported values just cited using theoretical decay curves.⁸)

The work by the contractor, MIF Industries, began in January 1971 with the disassembly of the magnet coils, the removal of which was necessary so that the large steel members could

be dealt with.⁹ The work proceeded more slowly than had been expected because of difficulty in cutting the aluminum bars making up the coils, but this stage of the operation was completed by the end of the month.¹⁰

A cutting torch was assembled at the end of January 1971 for cutting up the main magnet frame.¹⁰ The preliminary cuts proved to be unsatisfactory to the AEC Project Engineer monitoring the operation.¹¹ Although the upper frame members, when cut, had irregularly cut surfaces, they were still expected to serve adequately as shielding at FNAL.¹² The Project Engineer's less-than-satisfactory rating of the admittedly difficult cutting work contrasted rather strongly with a generally favorable account of the cutting operation presented in a welding trade journal.¹³ It was noted in the latter account that, "Before it hired MIT [the] AEC found that almost nobody knew much about cutting 49-inch steel accurately" (emphasis added). It was also noted that the torch had been fueled by propane, not acetylene as had been specified in the solicitation for bids.⁶ By the beginning of May, all the pieces had been cut, removed from the synchrocyclotron building, and loaded into the railroad siding in preparation for shipment to Batavia.¹⁴ (This shipment was delayed by a railroad strike.¹⁵)

Some radioactive portions of the assembly were shipped to the Nuclear Fuel Services burial ground at West Valley, New York. These portions included the coil material, the vacuum-tank frame, the pole pieces, and the pole tips. It was specified in the contract between the AEC and the NFS that about 3750 ft³ of synchrocyclotron components and scrap generated during the dismantling would be shipped to the West Valley site for burial and custodial service¹⁶ (i.e. the AEC retained title to and ultimate responsibility for the buried components.)

MIT Industries was paid \$100 500 by the AEC for the dismantling, cutting, and delivery of the magnet and other components. NFS received \$3476.80 for accepting radioactive materials from the dismantling operation for burial and custodial service. It cost the University of Rochester \$1652.86 for the health-physics inspection and radiation monitoring that it had provided.¹⁷

THE CARNEGIE-MELLON SYNCHROCYCLOTRON

The 130-inch 440-MeV synchrocyclotron operated by Carnegie-Mellon University (CMU) was located at the Nuclear Research Center at Saxonburg, Pennsylvania. In January 1952 it was announced that after four years of construction the university (then called Carnegie Institute of Technology) had completed its \$2.5-million synchrocyclotron and had produced 400-MeV protons. Financial support had been provided in part by a gift from the Buhl Foundation as well as through contracts with the Office of Naval Research and the AEC.¹⁸

The Nuclear Research Center was closed in June 1964.¹⁹ The site itself was owned by CMU, but the AEC had a contractual obligation to dismantle the facility,²⁰ which consisted of the synchrocyclotron and equipment and the material used to support the operations—all AEC property.²¹ In mid-1972 a proposal from CMU was submitted to the National Cancer Institute (NCI) to develop a radiotherapy program using the synchrocyclotron; in the event of such funding the title to the facility as well as the concomitant responsibility for dismantling could have been transferred to the NCI.²² Because the NCI did not fund the proposed program, the AEC proceeded with plans for dismantling the synchrocyclotron and for restoration of the site.²³ To help defray these costs, it was decided that laboratories receiving the excess AEC property from the Saxonburg site would pay dismantling costs as well as the usual transportation costs from their own AEC budgets.²⁴ Because of the lengthy AEC and GSA procedures for the distribution or disposal of excess property, it was further decided that once a laboratory had selected an item of equipment, that laboratory would be required to receive the item (and presumably to pay the associated dismantling and transportation costs).²⁵

The major task of the dismantling operation was the removal of the synchrocyclotron magnet,²⁶ the parts of which were allocated as follows:²⁷

- (1) to MIT: two steel pole pieces, each 2.29 feet thick, 13.67 feet in diameter, 81.8 tons; two steel side yoke pieces, each 3.68 feet wide, 7.25 feet high, 17.37 feet long, 112.8 tons; and two steel horizontal yoke pieces, each 4.25 feet wide, 4.12 feet high, 27.72 feet long, 120.8 tons;
- (2) to LANS: six steel horizontal yoke pieces, each 4.35 feet wide, 4.12 feet high, 27.72 feet long, 120.8 tons; and any remaining steel pieces (except the two pole tips);
- (3) to BNL: two copper coil ring pieces encased in stainless steel, each 1.2 feet high, 3 feet wide, 16.67 feet in diameter, 87 tons; and
- (4) to disposal site: two steel pole tip pieces, each 8 inches thick, 12.5 feet in diameter, 23.8 tons.

The Laboratory for Nuclear Science (LNS) at MIT had requested the magnet pieces for use in an LNS experiment at the Intersecting Storage Ring facility at CERN, the European Council for

Nuclear Research.²⁸ In addition to the magnet yokes, coils, and pole pieces, it was estimated that there were about 12 600 ft³ of radioactive equipment, material, and supplies to be dealt with, over 95% of which consisted of metals, largely iron and copper.²⁹

In the course of a radiation survey in January 1973, exposure levels up to 175 mR/h were found in the vicinity of the magnet and up to 430 mR/h in some loose irradiated copper.³⁰ The radiation levels had declined from a November 1968 survey, during which activities of several R/h were found at the copper dees and the steel pole tips.³¹ The prominent activities found in the copper dees were (with their percentage contribution to the total activity and their half-lives) ⁵⁴Mn (10%, 300 days), ⁵⁶Co (23%, 77 days), ⁵⁷Co (1%, 270 days), ⁵⁸Co (46%, 71 days), and ⁶⁰Co (20%, 5.2 years). In the magnet the most intense radiation originated from ⁵⁴Mn with some contribution from ⁵¹Cr (28 days) and ⁴⁶Sc (84 days). (Percentages were not given.) Samples of copper from the coil area exhibited an activity of about 0.5 mR/h. The main part of the magnet "iron"—the yokes and the main pole pieces—were found to be considerably less active than the pole tips, but no number was given for this activity. It was also noted that ²²Na (2.6 years) produced the only activity found in the aluminum vacuum chamber.³¹

In July 1973 an understanding was reached between CMU and the AEC regarding the decommissioning at the Saxonburg site.³² Because CMU wished to prepare the site for sale, the AEC would discharge its responsibility for site restoration by providing the required funds in FY 1974 and FY 1975. In FY 1974, the funds (estimated at \$40 000) would provide for the following: the removal and burial of the "radioactive synchrocyclotron internals" (e.g. diffusion pumps, condenser, vacuum chamber, dees, targets, and beam line) exclusive of the main magnet and its coils; the disinterment and reburial of six sets of radioactive items (which later proved to number twelve), which had been buried on site; the disposal of other property in accordance with normal excess-property procedures; and the maintenance of physical security and site facilities as required. The removal of the main magnet and the main magnetic coils was planned for FY 1979 at an estimated cost of about \$210 000.³⁰

The contract for dismantling the magnet was awarded to Norge Associates, Inc., of Sea Cliff, New York. The thirteen bids received by the deadline ranged from the low bid of \$141 000 by Norge to \$451 500, with three below the \$162 000 government estimate and eight below the \$210 000 average of the bids.³³ (This cost figure would be changed in subsequent contract modifications.) The contractor proposed to complete the dismantling, loading for shipment, and cleanup in a period of 120 days from the notice to proceed,³⁴ which was sent out on 27 March 1975.³⁵ During the initial stages of cutting, the contractor found that the oxygen-lance and the burning-bar methods could be used for the cutting process.³⁶ Because the cutting operations had to be halted at times because of airborne contamination, it was necessary to utilize asbestos blankets and sheet-metal shields to contain sparks and contaminations.³⁷ The ground under the cutting area was covered with polyethylene sheet and sand.^{37,38} About 90% of the dismantling and rigging inside the building and 80% of the originally constructed heavy cutting had been completed by the end of May 1975.³⁹ Additional cutting of the pieces destined for MIT was then requested by ERDA, so that more time was required for completion. By the beginning of August 1975, almost all the dismantling and rigging inside the building, almost all the loading and rigging outside the building, and all the heavy cutting had been completed.⁴⁰ Only about half the cleanup, repair, and miscellaneous tasks were still to be completed.

Another necessary task was the removal of the radioactive substances that had been buried on the site. As it was put in one AEC memo, "CMU is thinking of selling this property to a land developer . . . [and] it wouldn't do much for the Commission's image to have some radioactive materials turn up in someone's back yard."⁴¹ At first it was thought that there were six burials on site,²¹ consisting of five 50-gallon concrete-filled drums and a concrete-covered pit, the drums loaded with an unknown inventory of radioactive materials and the pit filled with cable and other miscellaneous materials.⁴¹ However, there were 13 burials of radioactive materials recorded in the relevant health-physics records.⁴² It was proposed by CMU that the buried waste be removed with a back hoe and air hammer.⁴³ On removal, only 11 individual burials were found in addition to the pit; two containers had been buried in one location although the records indicated only one container per burial location.⁴⁴ The exhumed wastes were shipped for reburial to the Nuclear Engineering Company (NECO) burial ground at Maxey Flats, Kentucky.⁴⁵

Although radioactive wastes from the decommissioning of the Rochester synchrocyclotron had been shipped to the Nuclear Fuel Services (NFS) burial ground at West Valley, New York, the AEC staff recognized a problem with the continued disposal of radioactive wastes at West Valley, viz. the requirement that the owner of the wastes retain title to them. Thus, if NFS would ever be required to retrieve and rebury any of the material at the West Valley site, the owner would be responsible for the costs of retrieval and reburial. Because it was felt by the AEC staff involved in the CMU decommissioning that the AEC could not assume such a never-ending liability, it was suggested by the AEC staff that arrangements for future burials be made with NECO at Maxey Flats.²⁶

Radioactive-contamination levels in the buildings and grounds of the Saxonburg site were to be reduced to below 0.08 mR, which is twice background in the vicinity.⁴⁶ The principal activities reported⁴⁷ were ²²Na, ⁶⁰Co, and, inexplicably, ¹⁵²Eu. Some of the concrete in the walls of the synchrocyclotron pit had become activated during the operation of the synchrocyclotron.⁴⁵ In addition, as a result of the dismantling of the synchrocyclotron magnet there were areas of soil that, in spite of the measures taken to contain contamination, had become impregnated with radioactive slag, copper, and stainless steel, with levels up to 0.8 mR/h.⁴⁸ It was necessary to remove and dispose of this contaminated material.

Eventually, \$214 000 was authorized as payment to Morge Associates for its dismantling, cutting, and delivery activities.⁴⁹ CMU submitted a final cost estimate for decommissioning of \$289 838.⁵⁰ The total cost for decommissioning based on these two figures is about \$504 000.

THE CAMBRIDGE ELECTRON ACCELERATOR

The Cambridge Electron Accelerator (CEA) was an alternating gradient synchrotron designed to accelerate electrons up to energies of 6 GeV in a pulsed mode at 60 pulses per second with an expected beam intensity of 10^{11} electrons per pulse. The CEA laboratory and administration building was occupied in April 1958, with the accelerator scheduled for completion in April 1961.⁵¹ Injection studies began toward the end of 1961 and by August 1962 the beam energy was taken up to 6.2 GeV. The beam characteristics were studied to improve performance, and a beam intensity of 1.5×10^{10} electrons per pulse was attained. By December 1962 experiments were begun.⁵²

The CEA budget was cut in February 1970; about 70 of the 212 staff members were terminated immediately. About September 1971, Harvard was notified that the next year's budget would be for decommissioning⁵³ and the accelerator was turned off on 31 May 1973.⁵⁴ Because personnel voluntarily left for new positions before the shutdown of the CEA, only 83 people had to be relocated afterward:

- 43 CEA personnel terminated as of June 1973,
- 3 Harvard Corporation personnel terminated as of June 1973,
- 3 Harvard Corporation personnel terminated as of June 1974,
- 3 retired in June 1973,
- 22 kept for closeout activities,
- 5 transferred to other Harvard positions, and
- 4 kept for a short time until contracts or appointments ran out.

Of the old CEA staff, 33 remained at Harvard in some position as of June 1978.⁵⁵

A committee consisting of a core of five AEC staff members was set up by the Chicago Operations Office of the AEC to negotiate with the Harvard administration and thus facilitate the progress of the closeout operations.⁵⁵ Other AEC staff were designated as committee members from time to time by the Director of the Division of Physical Research. The facility remained relatively intact through 1973 and it was early in 1974 when it was noted in an AEC progress report that it had become "quite evident to Harvard that the accelerator machine will be removed."⁵⁶ According to the terms of the original contract with Harvard, the AEC was required to remove all of the CEA and restore the land to its original condition if the AEC ever removed any part of the CEA.⁵⁶ The AEC staff would have liked to relinquish all AEC responsibility for the CEA site but still take everything of value for distribution to other AEC contractors. Not surprisingly, the Harvard negotiators preferred that the AEC remove the unwanted structures and completely restore and landscape the site; a compromise was expected.⁵⁶

The negotiators for Harvard also sought the right to sell the synchrotron for salvage. As early as October 1973 it was claimed by a Harvard spokesman⁵⁷ that the cost of removing the ring tunnel, the power building, the switchgear area, the cryogenics room, and the engineering-support building, as well as the cost of restoration, could be met by the sale of the synchrotron or parts thereof for salvage. The initial estimate of the credit for salvageable material was \$80 000,⁵⁸ but this figure was revised downward to \$45 000 based on a revised list of salvagable items.⁵⁷ (The final list of salvagable items is given later on.)

While the negotiations about the finances of the closeout proceeded, the closeout itself began. There was some possibility that FNAL would take the whole machine, an outcome the AEC staff preferred because, in that event, "no unwanted residue" of the movable parts would remain.⁵⁹ Certain parts would not be removed and, as already noted, could yield perhaps \$30 000 or more as salvage.⁵⁹ Early in 1974 it was decided that the accelerator would not go as a unit to FNAL, but instead would be split into components that, after inventory, would be assigned on the basis of need to laboratories requesting these components.⁵⁶

In March 1974 it was noted in a progress report on the closeout that the disposal of nonaccelerator components, such as ancillary electronics, was three to four weeks behind schedule, a delay caused by the demands on the time of CEA personnel by the removal of the accelerator components by the recipients of the equipment. Some of the recipients, e.g. SLAC, required little assistance from the CEA personnel other than help in finding local labor and transportation,⁶⁰ but others, e.g. FNAL, utilized 100% of the CEA work force for most of the week that they were there.⁶¹

A preliminary agreement between Harvard and the AEC regarding the CEA closeout was reached in April 1974.⁶² For \$75 000 (a figure later revised to \$96 500, as noted below) and some components with salvage value, Harvard would assume all responsibility for the demolition of the buildings. By this time, all but 650 of the about 7000 items on the inventory list had been allocated to requesting laboratories such as the AEC accelerator labs, the Cornell Electron Synchrotron, and the major AEC-funded high-energy physics groups at universities. The unrequested items were allocated to CH (Chicago Operations Office) for appropriate disposal by the standard excessing procedures, i.e. they would first be offered to AEC contractors, then to other federal agencies, and finally, if still unallocated, stripped of all usable parts and sold as scrap.⁶³ About 75% to 80% of the assigned items had been shipped by this time. The power switchyard and its substations had been left intact because they were still required for the decommissioning operations, but it was planned that they would be removed in May under a contract funded by the recipient labs (ANL, LBL, SLAC, and LASL). It was planned further that the slightly radioactive ring magnets would be shipped to BNL. The actual disassembly of the switchyard gear was started on 6 June by the subcontractor, Hallamore Companies, Inc., and was to be completed, according to the contract, within 60 days.⁶⁴

In a summary of the AEC involvement with the CEA closeout activities as of mid-June 1974, it was noted that since completing the closeout inventory in August 1973 the AEC had negotiated an agreement with Harvard setting the terms of the contract closeout, had reassigned equipment worth about \$10 000 000, and had completed the physical relocation of most of this equipment. It was hoped that the AEC responsibilities at the CEA site could be completed by August.⁶⁴ As a result of a contract modification,⁶⁵ all responsibilities for the demolition of and closing off of passageways in the CEA structures were transferred to Harvard in return for a \$96 500 payment from the AEC.

According to this contract modification Harvard would receive, in addition to the \$96 500, title to CEA buildings and title to certain "salvageable" items (listed in Table B.1). In return, Harvard agreed to accept responsibility for completion of the closeout activities as follows:

- Removal of the "salvageable" items from the buildings and structures to be demolished;
- Demolition of the ring tunnel, underground passageways, power building, switchgear area, cryogenics room, linac building, engineering-support building, and "appurtenant structures";
- Closing of the door openings from the experimental hall to the engineering-support building; and
- Closing of the openings left by ring-tunnel removal.

In other words, the AEC would not be responsible for these final closeout activities.⁶⁶

Demolition of the underground tunnel, now a Harvard responsibility, was begun in November 1974 and was completed in July 1975. Some of the five- to six-foot-thick concrete retaining walls were left intact because vibrations from the wrecking ball shook neighboring houses. Due to mechanical problems of this kind, to cost underestimation, and to overestimation of the resale value of the copper scrap, the cost of demolition was greater than \$96 500.⁶³

It was noted in an internal AEC memo, in February 1975, that the accumulation of a significant amount of equipment that was obsolete, in extremely poor condition, or had major components missing posed a problem for closeout activities.⁶⁷ It was suggested that a continuous review of all subcontractor activities might be useful in the future to assure the timely disposal of excess equipment and scrap during the course of a contract.

A radiation survey of the CEA was made on 1 June 1973, the day after shutdown.⁶⁴ The survey was undertaken chiefly to establish reference points that, in conjunction with future measurements, would furnish a basis for judging the rate of decrease of radioactivity. The highest reading was 100 mR/h at the converter of the linac. The highest reading in the circular tunnel was 2 mR/h. The measurements were made with a Victoreen Radector III, 9-1/2 hours after the machine was turned off. During the measurements, the detector was in the closest possible contact with the object being measured without removing any shielding (see Table B.2).

Table B.1. Salvageable Items of Accelerator
Equipment (CEA)

-
1. All copper bus bar
 2. All cable in buildings to be demolished
 3. 60-ton choke and pulse choke
 4. Vacuum roughing pipe, 6-in diameter
 5. Ring power supplies and pulsers (Westinghouse)
 6. Old RF system
 7. Old linac
 8. Water-tower piping (not pumps or deionizers)
 9. 4 ring magnets (2 prototypes and 2 used as chokes)
 10. All wave guides
 11. 4 "Acme 300" power supplies
 12. Rectifier bank for "Acme 400" power supply
 13. Experimental magnet (Magnolia)
-

*List taken from letter from Marvin J. Laster, Chairman,
CEA Closeout Negotiation Panel, to Mr. Richard G. Leahy,
Office of the Associate Dean, Faculty of Arts and
Sciences, Harvard University, dated 23 April 1974.*

Table A.2. Survey of Radioactivity in CEA Synchrotron as of 1 June 1973 (mR/h)^aCircular Tunnel

Upstream end of straight section 5:	1
Midway along beamrun portion from inner wall of circular tunnel to straight section 28:	2
All the rest of the circular tunnel (including target area, bypass, beamrun 5, store of spare ceramic and epoxy vacuum chambers, old ARCO linac):	~ 0

Linac Tunnel

Junction between waveguides 2 and 3:	30
4 and 5:	10
Immediately downstream from waveguide 3:	10
Immediately upstream of, also north of, also downstream from, converter assembly:	100 ^b
Fittings downstream from waveguide 5:	70 ^b
Several locations along east beamrun from those fittings to the concrete wall at downstream end of tunnel:	70
On the floor beneath above-mentioned fittings:	5 ^{b,c}
On floor 16 in east and 30 in north of center of converter:	7 ^{b,c}
On north wall directly opposite (4 ft north of) center of converter:	1.5
All the rest of linac tunnel:	Small compared to the above

Synchrotron Radiation Room

Zero everywhere

^a From attachment to letter from William A. Shurcliff, Radiation Safety Officer, CEA, to Philip Thompson, AEC-Cambridge, MA, 8 June 1973.

^b These levels were found to be unchanged within 20% three days later.

^c Most of this originated in the beamrun, not the wall or floor.

By early August 1973, a limited radiation survey had been made with an Eberline E-120 with an HP-190 thin end-window probe.⁶⁸ There was no indication of removable contamination from smears taken in the new-linac-tunnel, experimental-hall, and circular-tunnel areas. Concrete floor and wall areas in the circular tunnel, the new linac tunnel, and the experimental hall were monitored. In the concrete at the converter, located in the new linac tunnel, readings in the range of 0.05 to 0.15 mR/h were recorded. Although, according to a spokesman for the Massachusetts Bureau of Radiation Control, there were no restrictions by the state on the burial of concrete rubble with radiation levels below 1 mR/h, it was suggested by an AEC health physicist that a level of at least 0.1 mR/h at contact be chosen as the criterion for waste concrete.⁶⁸ The radiation levels within the concrete were later found to be within this 0.1-mR/h limit.⁵⁹

As noted above, radiation levels of up to 100 mR/h were present in the new linac tunnel. Material with such levels would have to be treated as radioactive waste if scrapped. A number of magnets in the circular tunnel were found to have readings of up to 5 mR/h. Because of the large quantity of material with substantial scrap value it was recommended that the magnets be transferred to another AEC location for temporary storage rather than buried as radioactive waste.⁶⁸ Those straight-section tanks that were examined all exhibited external-radiation levels in the 0.1- to 10-mR/h range and would also have to be treated as radioactive waste. The magnet-support grinders and other components of the main-ring magnets, such as water piping,

power cables, and bus bars, showed no activity. It would be necessary to monitor the exposure of personnel to radiation during dismantling activities involving removal of components located in the circular tunnel and the new linac tunnel, but such monitoring should not be necessary during structural demolition. Health-physics coverage for removal and shipment of components to other AEC sites would be the responsibility of the receiving laboratory.⁶⁸ It was proposed several months later by the AEC safety staff that anything with an above-background reading should be temporarily stored at a federally controlled site (e.g. BNL) or buried as radioactive waste. It was further noted that the AEC had been reluctant to establish criteria for release of scrap materials containing induced radiation to commercial purchasers.⁵⁶

Radiation levels 2 to 20 times background resulted from preliminary measurements of radioactivity present in both the copper and the steel inside the magnets after removal of the vacuum chambers.⁵⁷ The RF cavities, straight sections, and vacuum chambers also gave readings more than twice background.⁵⁷

In mid-July 1974, a radiological survey of accelerator components exhibiting induced radioactivity was performed by the health-physics staff of CEA using an Eberline #120 beta-gamma counter with a flexible probe and a thin (2 mg/cm²) window.⁶⁹ The radiation levels found were at most a few times natural background. Radiation levels of some portions of the walls at the downstream end of the linac tunnel were found to be as high as 1 mR/h; this tunnel would be filled with earth in a few weeks.⁶⁹

The AEC contracts-management staff requested that the circular-tunnel wall, which exhibited radiation levels up to 0.24 mrem/h, be shielded to reduce these levels to 0.1 mrem/h and appropriately marked with a warning sign.⁷⁰

The total exposure accumulated by the CEA decommissioning staff was recorded. It was less than 0.67 man-rem.⁷¹

An estimate of the cost for the decommissioning of the CEA was sent to the AEC in March 1974.⁷²

Demolition	\$120 000
Face exposed section and close opening of experimental building	35 000
Restoration of grounds	25 000
	<hr/> \$180 000
Salvage credit	(45 000)
	<hr/> \$135 000

The second and third items were considered necessary to comply with assurances given by Harvard to the surrounding residential community. About a month later, an AEC estimate of the funding for the CEA closeout read as follows:⁶²

FY 1974 CEA operating costs	\$600 000
FY 1975 CEA operating costs	100 000
Contract-termination cost	79 000
Removal of ring magnets	35 000

The last two items were expected to be FY 1975 costs.

The total costs for the CEA contract from its inception, as well as the costs for the closeout period, are given in Table B.3.

THE YALE HILAC

The construction of a \$1.2-million heavy-ion linear accelerator (HILAC) at Yale University was announced by the AEC in mid-1954. It was intended that the device accelerate "heavy particles," i.e. ions with atomic masses ranging from 9 (beryllium) to 20 (neon), to an energy of 10 MeV per nucleon for the purpose of studying the physics of heavy-particle interactions.⁷³ The machine consisted of two sections. The first consisted of 36 drift tubes that were used to accelerate the ions to about 1 MeV per nucleon. The stripper, between the two sections, was a

Table B.3. Statement of Costs Incurred and Recommended for Acceptance by HEW Audit Agency under Contract No. AT (11-1)-3063 [formerly AT (30-1)-2076] for the Period 1 July 1973 through 31 December 1974, Harvard University, Cambridge, Massachusetts (inclusive of the \$96 500 building-demolition payment)

Cost Category	Current Period	Cumulative
	1 July 1973 through 31 December 1974	Inception in April 1958 through 31 December 1974
Salaries and wages	\$416 577	\$18 532 259
Fringe benefits	60 290	2 124 375
Equipment	-	9 232 393 ^a
Supplies	12 542	9 787 034 ^a
Travel	5 222	264 648
Purchased services	8 007	440 484 ^a
Computer services	15 042	1 026 064
Building expense	17 783	3 227 998 ^a
Other expense	16 893	786 619 ^a
Total direct costs	\$652 356	\$45 421 874 ^b
Indirect costs (overhead)	82 866	1 669 223 ^b
Emergency repairs	-	51 177 ^b
Total costs	\$735 222	\$47 142 274

Taken from "Supplemental Agreement Between President and Fellows of Harvard College and the U.S. Energy Research and Development Administration," Modification No. 37-6, Supplemental Agreement to Contract No. K(11-1)-3063, Exhibit A.

^a Although the University's completion-voucher total amount agrees (\$47 142 274), cost-category-amount deficiencies are due to the University's different identification of a particular cost in the completion-voucher presentation.

^b Emergency repairs shown separately above include overhead of \$1491, which, when added to the indirect-cost amount shown above, would agree with overhead amount shown on the completion voucher.

jet of mercury vapor that was used to remove more electrons from the ions. The second section consisted of 67 drift tubes that accelerated the ions further.⁷⁴

By letter dated 27 May 1974, the AEC informed Yale University of the decision to terminate support for the HILAC after almost two decades of use.⁷⁵ Because the shutdown was planned for 31 December 1974, the AEC requested a revision in the FY 1975 budget "to permit an orderly closeout by the end of the calendar year 1974." It was implied in the letter that the shutdown resulted in part from the construction of newer and better accelerators. In the reply from Yale,⁷⁶ it was admitted that "the early demise of the Yale Heavy Ion Accelerator Laboratory was an accepted fact in the abstract," but that neither the timing nor the time scale of the shutdown had been anticipated. It was noted that there were two basic problems in carrying out an orderly shutdown:

- (1) Research programs in progress would have to be replanned in order to conclude these programs with completed work in publishable form, as it was unlikely that many of these programs would be continued elsewhere.
- (2) The facility would have to be decommissioned after accelerator operation was concluded:
 - (a) Components and systems desired by some other AEC facility would be disassembled and prepared for shipment.
 - (b) The building would be cleared of equipment that was not desired either by AEC facilities or Yale. This work would be carried out mostly by outside contractors, but it would have to be supervised by experienced Yale staff. It would also be useful to keep certain of the building systems intact for future use.
 - (c) The ten technicians as well as three of the scientific staff on yearly appointments would have to be laid off or relocated.

The AEC agreed to this rough outline of a plan for shutdown and decommissioning.⁷⁷ In November 1974, AEC and Yale health-physics staff jointly produced what they called a first draft of the dismantling program for the HILAC.⁷⁸

A more detailed proposal, which had evolved from this first draft, was submitted by Dr. Beringer, Director of the Yale Heavy Ion Accelerator Laboratory, to the AEC in December 1974.⁷⁹ In this proposal, it was noted that at a property-disposal conference held at Yale on 18 November 1974 almost every major component except for the bare accelerator tanks had been assigned either to one of the national laboratories or to the Wright Nuclear Structure Laboratory at Yale. It was further noted that the accelerator was AEC property, that the cost of the disassembly and final removal of components was (or perhaps, should be) an AEC responsibility, and that the building of certain features and equipment would (or perhaps, should) remain at Yale with the title transferred to Yale. The disassembly was divided into stages as follows:

Stage 0. The magnet cave and target areas were to be surveyed at the beginning of the year shortly after shutdown for radioactivity by the Yale Health Physics Group. Radioactive items would be removed and placed in shielded, posted storage areas.

Stage 1. The shielding would be removed and shipped. Disassembly of the SE and SW beam caves would begin after 1 January 1975, and the shielding blocks thus freed would be shipped regularly to MIT or BNL. By 15 January removal of the water pipes, beam pipes, and services attached to the wall blocks of the magnet cave could begin, followed by removal of the magnet-cave roof for shipment to LASL. Then the removal of the wall blocks of the magnet cave for shipment to MIT or BNL could begin. The crucial factor in this stage would be the availability of trucks and the cooperation of the truckers. The 60 wall blocks and 30 roof blocks would make up about 35 truck loads needing six weeks (until the end of February 1975) for shipment, assuming six loads per week. The university's responsibility would be limited to disassembly of the accelerator and the loading of the blocks with the 10-ton bridge crane. MIT, BNL, and LASL would be responsible for making contractual arrangements with the truckers.

Stage 2. The preparation of major components for shipment to the national laboratories would be phased in as manpower became available during Stage 1. The major components considered here were those external to the accelerator tanks, e.g. the RF system, diffusion-pump systems, and drift-tube power supplies. Most of this stage was planned for completion in the two-month period from 1 March to 30 April except for "bits and pieces" afterward.

Stage 3. The post-stripper drift tubes and the quadrupole magnets that each of them contains would be removed. A specially modified vertical milling machine would be required to cut away the copper shells. It was estimated that a two-month period, from 15 March to 15 May, would be required for this operation.

Stage 4. The bare tanks would be removed. At the start of this stage there should be a bare accelerator bay, provided that all the items from the previous stages have been shipped. This stage would be carried out by an outside rigging or scrap contractor. Assuming no delays in any of the earlier stages, the earliest this operation could begin would be 1 June 1975.

In general, the proposed plan was followed and the schedule was met. In a final report on the closeout activities it was noted that, as planned, when one phase of the operation was being completed the next phase was started so that "the whole project progressed at an orderly pace."⁸⁰ One of the last tasks to be completed was the dismantlement, cutting, and disposal of the accelerator tanks. Completion of the dismantling, set for 30 June 1975, was accomplished by 24 June.

As noted above, almost every major component of the Yale HILAC was assigned to another laboratory except for the bare accelerator tanks. Sixty shielding blocks from the SE and SW beam caves went to MIT and BNL; the 30 blocks from the magnet-cave roof went to LASL. One each of the 300-cfm Kinney pumps went to LRL and LASL; outside riggers (i.e. non-Yale personnel) were required to prepare these pumps for shipment. All 67 of the quadrupole magnets from the post-stripper drift tubes were assigned (35 to MIT, 12 to LASL, 13 to ANL, 7 to BNL). Scrap generated by the disassembly, e.g. piping, wire, structural steel, non-reusable fasteners, etc., would be sold as scrap and credited to the AEC account.⁷⁹

The proposal for disassembly of the HILAC submitted by Yale to the AEC included plans for a radiological survey of the facility immediately after shutdown.⁷⁹ A preliminary understanding was reached between Yale and AEC-CH health-physics personnel regarding the monitoring procedures for releasing potentially radioactive materials into the "civilian environment" as scrap. A low-level counting facility with NaI and Ge(Li) detectors was to be used to measure the activity

level of the various components that were exposed to or near the accelerator beams. The radiological criteria for release of such components to the environment were not set at that time. It was noted that "... much of the material [would go] to national laboratories and thus [would be] exempt from this environmental stricture."⁷⁵

Establishing the radiological criteria proved to be a problem. In December 1974 Dr. Beringer wrote AEC-CH regarding the absence of criteria.⁸¹ He maintained that the criterion set in the 13 November draft dismantling procedure,⁷⁸ viz. a criterion of less than three standard deviations above background, was meaningless unless background were quantified, e.g. ($\mu\text{rem}/\text{min}$)/lb or $\mu\text{Ci}/\text{lb}$ of material. In addition, he believed that it would be desirable to ascertain which isotopes contributed significantly to the radioactivity so that the appropriate spectral regions could be studied. Some five-year-old copper target holders that had been bombarded with heavy ions showed activity due to ^{60}Co (20%) and ^{65}Zn (80%) with half-lives of 5.27 years and 244 days, respectively.⁸² The absolute levels were in the range of 0.2 to 0.1 μCi for the 3.5-lb target holders. In a later letter,⁸³ Dr. Beringer reported an additional radioisotope, ^{22}Na , in aluminum components. The Yale staff defined "measurable activity" as ~ 1 nCi for any of these three radioisotopes using a Ge(Li) detector at 10 inches for a 30-minute counting period. Components with at least such activity were treated as radioactive waste.⁸⁴ These criteria were reviewed and approved by the AEC staff at the Chicago Operations Office.⁸⁵

All beam pipes and components exposed to the direct 10-MeV/amu beam showed activity, in some cases measurable on survey instruments, in other cases on samples in the counting facility. These items were disposed of as radioactive waste in steel drums by Yale's waste contractor. The bore tubes and the adjacent parts of the shells of the post-stripper drift tubes containing the quadrupole magnets also displayed activity measurable by survey instruments. The use of cutting oil during the quadrupole-magnet recovery operations was expected to contain the chips of radioactive material in the initial cuts so that all waste could be disposed of without contaminating the machine or its operation.⁸³

Smears and meter surveys were carried out in every room and in the main-accelerator area after completion of the disassembly.⁸⁶ Surveys were made about 1 cm above the floor surface. All results indicated that the area was radiologically clean within the detection limits of the instruments. It was further noted that exposure to contract personnel was "random and minimal" when it occurred at all.⁸⁷ There were no onsite burials of radioactive materials from the contract activities, nor were there any known instances of significant radioactive contamination from either normal operations or accidents.⁸⁸

In December 1974 an estimate of costs for the period from 1 January through 30 June 1975 was sent from Dr. Beringer to the AEC.⁷³ These costs were broken down as follows:

Direct salaries	\$ 51 243
Materials and services	10 200
Indirect costs	43 332
	<hr/> \$104 775

The amount of money obligated by the government under the contract was increased by \$117 000 from \$3 350 708 to \$3 467 708. The \$117 000 consisted of \$105 000 for dismantling (a cost presumably identical to the \$104 775, but rounded off) and \$12 000 for unanticipated power costs (apparently as a result of unanticipated usage charges).⁸⁹

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APPENDIX C. SUGGESTED FORMS FOR ORGANIZING A PARTICLE-ACCELERATOR DECOMMISSIONING

To assist an orderly dismantling operation, a series of six forms is suggested. These are displayed in Figures C.1 through C.6. The first four are, in increasing order of component specificity, "Section Number List," "Disposition of Sections," "Item Physical Description," and "Cost by Operation." The last two are "Section Cost Summary" and "Project Cost Summary." Items associated with the accelerator should be organized according to sections (such as injector accelerator). Sections are readily separable or delineated fractions of the accelerator facility. Examples of sections are the control room, shielding ring or vault housing the accelerating sections, main power supply, cooling towers, heat exchanger, and injector accelerator. For this discussion, the items are components or assemblies that meet at least one of the following criteria:

1. Salvage value estimated to exceed \$50 000;
2. Large and/or heavy, requiring special dismantling procedures to be readily handled;
3. Radioactive, or otherwise hazardous, requiring decontamination, cleanup, or disposal at special sites;
4. Requested for use in other installations or for future use at the existing site; or
5. Likely to be suitable for use in other laboratories.

Examples of such items are the massive magnet segments of synchrotrons or the waveguides of larger experimental linear accelerators.

The forms should also provide a handy tabulation of radioactive and nonradioactive material, and indicate recommendation of storage for salvage versus scrap. These forms could serve as a systematic beginning for distribution lists of available types of equipment.

Section _____ Description _____ Location _____
Job No. _____ By _____ Checked _____ Date _____ Sheet _____ of _____

[illegible]

89

Page ____ of ____

**Decontamination and Decommissioning
Form 3**

Item Physical Description

Project _____ Section No. _____ Item No. _____

Job No. _____ By _____ Date _____

Location _____ Bldg. _____ Area _____

Item Description _____

Quantity _____ Weight _____

Material _____

Size (l x w x h) _____

Disassembly or dismantling required for removal? _____

How (torch, unbolt, etc.?) _____

Preserve for future use? (Show method under Special Considerations) _____

Lift fixtures available? _____

Crane available and functional? _____

Type and capacity _____

Mobile crane access _____

Rig out _____

Special Considerations (R/A, fragile, flammable, toxic, etc.) _____

Figure C.3. Item Physical Description.

Section No. _____ Item No. _____ Location of Item _____

Job No. _____ By _____ Checked _____ Date _____ Sheet _____ of _____

[illegible]

Figure C.4. Cost by Operation.

Section No. _____

Job No. _____ By _____ Checked _____ Date _____ Sheet _____ of _____

[illegible]

92

Project _____ Contract No. _____

Job No. _____ By _____ Checked _____ Date _____ Sheet _____ of _____

[illegible]

93

APPENDIX D. DETAILS OF THE ZERO GRADIENT SYNCHROTRON EXAMPLE

Table D.1. Estimated Radiation Dose Rates and Doses
During Decontamination and Dismantling
of the Zero Gradient Synchrotron

		Radiation Dose Rate (mrem/h)		Estimated Dose (person-rem)	
Phase of Dismantlement Involving Radiation Exposure	Estimated Man-Hours	Two- Month Delay	Imme- diate	Two- Month Delay	Imme- diate
Removal of:					
Upper pole pieces	11 320	1.6	6.7	18.1	75.8
Yoke pieces	1 295	1.6	6.7	2.1	8.7
Coils	268.5	1.6	6.7	0.4	1.8
Inner vacuum chambers	150	1.6	6.7	0.2	1.0
Lower pole pieces	11 320	1.6	6.7	18.1	75.8
Straight sections	1 240	36	75	44.4	92.4
All other work	7 894	0.1	0.1	0.8	0.8
Total for ring:	33 467.5		84.1		256.3
Linac	1 020	1	20	1.0	20.4
50-MeV beam line	390	2	30	0.4	11.7
All other work	2 325	0.1	0.1	0.2	0.2
Total for injector:	3 735			1.6	32.3
Total for ZGS:	37 202.5			85.7	288.6
External beam lines (est.)	3 720			8.6	28.9
Total for facility ^a	40 922.5			94.3	317.5

^aThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest man-hour or the nearest person-rem.

Table D.2. Estimated Period-Dependent Costs for ZGS Dismantling^a
(in chronological order of assignment)

Position	Pay Scale ^b (\$/mo)	No. of Persons	Duration (mo)	Cost (\$)
General manager	7 500	1	24	180 000
Administrative manager	6 500	1	30	195 000
Secretary	2 850	1 & 1	30 & 24	153 900
Property manager	5 250	1	18	94 500
Clerk	2 500	1 & 3	18 & 12	135 000
Health-physics coordinator	4 750	1	24	114 000
Health-physics technician	3 500	2 & 4	12 & 6	168 000
Mechanical-equipment manager	7 000	1	16	112 000
Electrical-equipment manager	7 000	1	16	112 000
Facility-services manager	7 000	1	18	126 000
Site-security guards	3 500	4	9	126 000
Safety engineer	5 250	1	9	47 250
Inspector	5 250	1	12	63 000
Junior engineer	5 000	9	6	270 000
Engineering associate	3 500	8	6	168 000
Average	4 478			
Total			461	2 064 650 ^c

^a1978 dollars.

^bIncludes general and administrative overhead and contract fees, at about 1.85 times direct salary.

^cThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

Table D.3. Estimated Activity-Dependent Item-Cost Summary for ZGS Dismantling^a

Item Description	Costs (\$1000)				Activities Performed by Organization Staff ^b	
	Contract	Supply	Activities Performed by Outside Contractor	Total	(hours)	Costs (\$1000)
<u>Ring</u>						
Magnet steel	--	27.0	598.0	625.0	2893	101.3
Magnet coils	5.0	20.0	19.7	44.7	210	7.4
Vacuum chamber	--	10.0	5.8	15.8	40	1.4
Ring supports	--	1.0	13.5	14.5	54	1.9
Operating floor	--	5.0	90.4	95.4	300	10.5
Cabling	1.0	--	15.7	16.7	63	2.2
Accessory equipment	2.0	2.1	44.8	48.9	160	5.6
Straight sections	--	1.0	31.0	32.0	600	21.0
Decontaminate building	7.5	--	17.2	24.7	200	7.0
Ring subtotal ^c	15.5	66.1	836.1	917.7	4520	158.3
<u>Injector - linac</u>						
High-voltage terminal	--	--	2.0	2.0	8	0.3
High-voltage power supply	--	--	1.3	1.3	--	--
High-voltage-terminal room	--	0.5	8.0	8.5	--	--
Beam line - source to linac	--	0.2	2.3	2.5	10	0.4
Linac	--	1.0	31.5	32.5	100	3.5
Linac accessories	--	--	34.2	34.2	100	3.5
Beam line - linac to ring	--	--	9.8	9.8	40	1.4
Remove remaining equipment	--	--	4.5	4.5	20	0.7
Decontaminate and final cleanup	5.0	--	6.0	11.0	50	1.8
Injector - linac subtotal ^c	5.0	1.7	99.6	106.3	328	11.6
<u>Center building</u>						
Remove all equipment	--	--	355.0	355.0	--	--
Center-building subtotal	--	--	355.0	355.0	--	--
<u>Control room</u>						
Equipment and cabling	--	--	90.0	90.0	--	--
Cleanup and repairs	5.0	--	14.0	19.0	--	--
Control-room subtotal	5.0	--	104.0	109.0	--	--
<u>Power building</u>						
Motor generator	--	--	71.3	71.3	--	--
Clear generator control room	--	--	4.0	4.0	--	--
Exciter room	--	--	1.4	1.4	--	--
Cabling	--	--	2.6	2.6	--	--
Switch-gear room	--	--	10.1	10.1	--	--
Mechanical equipment	--	--	4.0	4.0	--	--
Minor building decontamination	--	--	26.7	26.7	--	--
Power-building subtotal ^c	--	--	120.1	120.1	--	--
Total ^c	25.5	67.8	1514.8	1608.1	4848	169.9

^a1978 dollars.^bFor bookkeeping purposes, these expenditures are considered to be period dependent.^cThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

Table D.4. Estimated Wastes Associated with the Dismantling of the ZGS

Item Description	Waste Amount (ton)	
	Radioactive	Nonradioactive
<u>Ring</u>		
Magnet steel	4787	
Coils	64.2	
Vacuum chamber	1.8	
Ring supports	60	
Operating floor	559	
Cables	126	
Assessory equipment	70	
Straight sections	62	
Concrete	38	
<u>Injector</u>		
High-voltage terminal	0.2	
High-voltage power supply		2
High-voltage-terminal room		20
Beam line	23	
Linac	41	
Linac accessories		133
Miscellaneous	10	25
<u>Center building</u>		
Machinery		570
Piping		190
<u>Power building</u>		
Motor-generator set		540
Spare shaft		30
Machinery		92
Cables		3.5
<u>Control room</u>		
Machinery and cables		120
<u>Total</u> ^a	5842.2	1725.5

^a The number of significant figures shown is for computational accuracy and does not imply precision to the nearest ton.

Table D.5. Estimated Packaging, Transportation, and Disposal Costs for the ZGS Disposal Option^a

<i>Item Description</i>	<i>Cost^b (\$1000)</i>
<u>Packaging</u>	
100 boxes @ \$400 each	40
50 55-gallon drums @ \$20 each	1
Packaging subtotal	41
<u>Transportation</u>	
150 legal-weight shipments @ \$2100 each	315
256 overweight shipments @ \$2700 each	691.2
Transportation subtotal	1006.2
<u>Disposal</u>	
42 000 ft ³ @ \$5/ft ³	210
Weight surcharges	78
Disposal subtotal	288
<u>Total^c</u>	<u>1335.2</u>

^a Does not include potential reuse or recycle of any radioactive components.

^b 1978 dollars.

^c The number of significant figures shown is for computational accuracy and does not imply precision to the nearest ten thousand dollars.

Table D.6. Estimated Period-Dependent Costs for Mothballing of the ZGS^a (one month)

<i>Employee</i>	<i>Unit Cost (\$/mo)</i>	<i>Cost (\$)</i>
General manager	7 500	7 500
Administrative manager	6 500	6 500
Secretary	2 850	2 850
Health-physics coordinator	4 750	4 750
Health-physics technician (2)	3 500	7 000
Safety engineer	5 250	5 250
Engineering associate	3 500	3 500
Total		37 350

^a 1978 dollars.

Table D.7. Estimated Activity-Dependent, Packaging, Transportation, and Disposal Costs for Mothballing of the ZGS^a

<i>Expense Item</i>	<i>Units</i>	<i>Unit Cost (\$)</i>	<i>Cost (\$)</i>
Laborer (5)	5 man-months	4 000/man-month	20 000
Packages	10 boxes	400/box	4 000
	10 55-gallon drums	20/drum	200
Transportation	2 shipments	2 100/shipment	4 200
Disposal ^b	1 160 ft ³	5/ft ³	5 800
Total ^b			34 200

^a1978 dollars.

^bThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

Table D.8. Estimated Period-Dependent Costs for Entombment of the ZGS^a (two months)

<i>Employee</i>	<i>Unit Cost (\$/mo)</i>	<i>Cost (\$)</i>
General manager	7 500	15 000
Administrative manager	6 500	13 000
Secretary	2 850	5 700
Health-physics coordinator	4 750	9 500
Health-physics technician (2)	3 500	14 000
Safety engineer	5 250	10 500
Engineering associate	3 500	7 000
Total		74 700

^a1978 dollars.

Table D.9. Estimated Activity-Dependent, Packaging, Transportation, and Disposal Costs for Entombment of the ZGS^a

Expense Item	Units	Unit Cost (\$)	Cost (\$)
Laborer (5)	5 man-months	4 000/man-month	20 000
Concrete	110 yd ³	300/yd ³	33 000
Packages	10 boxes 10 55-gallon drums	400/box 20/drum	4 000 200
Transportation	2 shipments	2 100/shipment	4 200
Disposal ^b	1 160 ft ³	5/ft ³	5 800
Total^b			67 200

^a1978 dollars.^bThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.Table D.10. Estimated Waste-Disposal Costs for ZGS Dismantlement with Storage Option^a

Item Description	Cost (\$1000)
Packaging	
100 boxes @ \$400 each	40
50 55-gallon drums @ \$20 each	1
Packaging subtotal	41
Transportation	
66 legal-weight shipments @ \$2100 each	138.6
Disposal	
11 000 ft ³ @ \$5/ft ^{3b}	55
Total^b	234.6

^a1978 dollars.^bThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest ten thousand dollars.

APPENDIX E. DETAILS OF THE 60" CYCLOTRON EXAMPLE

Table E.1. Estimated Radiation Dose Rates and Doses During Decontamination and Dismantling of the 60" Cyclotron

Activity	Estimated Man-Hours	Radiation Dose Rate (mrem/h)		Estimated Dose (person-rem)	
		High ^a	Low ^a	High ^a	Low ^a
Remove dees, vacuum tank, and accessories	225	245	25	55.1	5.6
Remove coils and tanks	234	25	2.5	5.9	0.59
Remove magnet	1 325	2.5	0.1	3.3	0.13
Demolish and remove concrete vault					
Clear mechanical-equipment room					
Clear electrical-equipment room	16 923	0.1	0.1	1.7	1.7
Cleanup work (miscellaneous)					
Clear out control room and cabling					
Total	18 707			66.0 ^b	8.02 ^b

^aBased on extremes measured 25 hours after shutdown.^bThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest 0.1 person-rem.Table E.2. Estimated Period-Dependent Organization-Staff Costs for 60" Cyclotron Dismantlement^a

Position	Pay Scale ^b (\$/mo)	Months of Labor	Cost (\$)
Administrative manager	6 500	4	26 000
Secretary	2 850	4	11 400
Property manager	5 250	3	15 750
Clerk	2 500	3	7 500
Senior engineer	7 000	2	14 000
Safety engineer	5 250	2	10 500
Inspector	5 250	2	10 500
Health-physics coordinator	4 750	4	19 000
Health-physics technician (3)	3 500	12	42 000
Total			157 650

^a1978 dollars.^bBased on 1.85 times direct salary to account for general and administrative overhead and contract fees.

Table E.3. Estimated Activity-Dependent Item-Cost Summary for 60"
Cyclotron Dismantling^a

Item Description	Costs (\$1000)				Activities Performed by Organization Staff ^b	
	Contract	Supply	Activities Performed by Outside Contractor	Total	(hours)	Costs (\$1000)
<u>Cyclotron</u>						
Vacuum tank, dees	--	--	5.6	5.6	20	0.7
Coils and tanks	--	--	5.8	5.8	24	0.8
Magnet	--	--	33.1	33.1	130	4.5
Cyclotron subtotal ^c	--	--	44.5	44.5	174	6.0
<u>Shielding</u>						
Demolish concrete vault	--	--	557.8	557.8	1500	52.5
Shielding subtotal	--	--	557.8	557.8	1500	52.5
<u>Mechanical-equipment room</u>						
Mechanical equipment	--	--	14.6	14.6	50	1.7
Mechanical-equipment-room subtotal	--	--	14.6	14.6	50	1.7
<u>Electrical-equipment room</u>						
Electrical equipment	--	--	5.8	5.8	10	0.4
Electrical-equipment-room subtotal	--	--	5.8	5.8	10	0.4
<u>Dee storage and hot lab</u>						
Dee storage	2.0	--	1.2	3.2	40	1.4
Hot lab	--	--	--	--	--	--
Dee-storage and hot-lab subtotal	2.0	--	1.2	3.2	40	1.4
<u>Control room</u>						
Equipment and cabling	--	--	2.9	2.9	8	0.3
Control-room subtotal	--	--	2.9	2.9	8	0.3
Total ^c	2.0	--	626.8	628.8	1782	62.3
Total (excluding shielding) ^c	2.0	--	69.0	67.0	282	9.8

^a1978 dollars.

^bFor bookkeeping purposes, these expenditures are considered to be period dependent.

^cThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

Table E.4. Estimated Wastes Associated with the Dismantling of the 60" Cyclotron at Argonne National Laboratory

Item Description	Waste Amount (ton)	
	Radioactive	Nonradioactive
<u>Cyclotron</u>		
Magnet	265	
Coils and tanks	26	
Accessories (vacuum tank, dees, etc.)	7.5	
<u>Shielding</u>		
Concrete	565	5083
<u>Mechanical-equipment room</u>		
Machinery		65
<u>Electrical-equipment room</u>		
Machinery		26
<u>Dee storage and hot lab</u>		
Miscellaneous	12	
<u>Control Room</u>		
Machinery and cable		13
<u>Total</u> ^a	875.5	5187

^aThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest ton.

Table E.5. Estimated Packaging, Transportation, and Disposal Costs for the 60" Cyclotron Disposal Option

Item Description	Cost ^a (\$1000)
<u>Packaging</u>	
90 boxes @ \$400 each	36
20 55-gallon drums @ \$20 each	0.4
Packaging subtotal	36.4
<u>Transportation</u>	
72 legal-weight shipments @ \$2100 each	151.2
12 overweight shipments @ \$2700 each	32.4
Transportation subtotal	183.6
<u>Disposal</u>	
11 500 ft ³ @ 5/ft ³	57.5
Weight surcharges	4.68
Disposal subtotal	62.18
<u>Total</u> ^b	282.18

^a1978 dollars.

^bThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one thousand dollars.

APPENDIX F. DETAILS OF THE 22-MeV ELECTRON LINAC EXAMPLE

Table F.1. Estimated Radiation Dose Rates and Doses During Decontamination and Dismantling of the Electron Linac

Activity	Estimated Man-Hours	Radiation Dose Rate (mrem/h)	Estimated Dose (person-rem)
Remove linac assembly	32	0.1	0.003
Dismantle and remove RF system	265	0	0
Dismantle and remove cooling system	150	0	0
Dismantle and remove controls	36	0	0
Total	483		0.003

Table F.2. Estimated Period-Dependent Organization-Staff Costs for Dismantling a 22-MeV Linac^a

Position	Pay Scale ^b (\$/mo)	Duration (mo)	Cost (\$)
Property manager	5 250	2	10 500
Secretary	2 850	2	5 700
Inspector	5 250	1	5 250
Junior engineer	5 000	1	5 000
Total			26 450

^a1978 dollars.^bBased on 1.85 times salary to cover administrative and general overhead and contract fees.Table F.3. Estimated Activity-Dependent Item-Cost Summary for Dismantling a 22-MeV Electron Linac^a

Item Description	Costs (\$1000)				Activities Performed by Organization Staff ^b	
	Contract	Supply	Activities Performed by Outside Contractor	Total	(hours)	Costs (\$1000)
Linac assembly	--	--	0.8	0.8	--	--
RF system	10.0	--	6.6	16.6	--	--
Cooling system	7.5	--	3.8	11.3	--	--
Control console	5.0	--	0.9	5.9	--	--
Total ^c	22.5	--	12.1	34.6		--

^a1978 dollars.^bFor bookkeeping purposes, these expenditures are considered to be period dependent.^cThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

Table F.4. Estimated Wastes Associated with
Dismantling of the 22-MeV Electron Linac at
Argonne National Laboratory

Item Description	Waste Amount (ton)	
	Radioactive	Nonradioactive
Linac	0.1	1.9
RF system		32.2
Cooling system		5
Control console		4
Total	0.1	43.1 ^a

^aThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest tenth of a ton.

Table F.5. Estimated Packaging,
Transportation, and Disposal Costs for the
22-MeV Electron Linac Disposal Option^a

Item Description	Cost (\$)
<u>Packaging</u>	
1 box @ \$400	400
5 55-gallon drums @ \$20 each	100
Packaging subtotal	500
<u>Transportation</u>	
1 legal-weight shipment @ \$2100	2100
<u>Disposal</u>	
145 ft ³ @ \$5/ft ³	725
<u>Total</u> ^b	3300

^a1978 dollars.

^bThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

APPENDIX G. DETAILS OF THE 9-MV TANDEM VAN de GRAAFF EXAMPLE

Table G.1. Estimated Radiation Dose Rates and Doses During Decontamination and Dismantling of the Tandem Van de Graaff

Activity	Estimated Man-Hours	Radiation Dose Rate (mrem/h)	Estimated Dose (person-rem)
Dismantle equipment in tank	100	0.1	0.01
Remove tank	704	0	0
Remove controls and cabling	90	0	0
Total	894 ^a		0.01

^aThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest ten man-hours.

Table G.2. Estimated Period-Dependent Costs for a 9-MV Tandem Van de Graaff Dismantlement^a

Position	Pay Scale (\$/mo)	Months of Labor	Cost (\$)
Property manager	5 250	3	15 750
Secretary	2 850	3	8 550
Senior engineer	7 000	2	14 000
Inspector	5 250	2	10 500
Technician (2)	4 000	2.5	20 000
Total			68 800

^a1978 dollars.

Table G.3. Estimated Activity-Dependent Item-Cost Summary for Tandem Van de Graaff Dismantlement^a

Item Description	Costs (\$1000)				Activities Performed by Organization Staff ^b	
	Contract	Supply	Activities Performed by Outside Contractor	Total	(hours)	Costs (\$1000)
Tandem Van de Graaff	10.0	--	20.1	30.1	--	--
Ion source	--	--	--	--	800	20.0
Controls and accessories	5.0	--	2.3	7.3	--	--
Total ^c	15.0	--	22.4	37.4	800	20.0

^a1978 dollars.

^bFor bookkeeping purposes, these expenditures are considered to be period dependent.

^cThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

Table G.4. Estimated Wastes Associated with the Dismantling of the Tandem Van de Graaff at Argonne

Item Description	Waste Amount (ton)	
	Radioactive	Nonradioactive
Tandem Van de Graaff	0.3	44
Controls and accessories		10
Total	0.3	54

Table G.5. Estimated Packaging, Transportation, and Disposal Costs for the 9-MV Tandem Van de Graaff Disposal Option^a

Item Description	Cost (\$)
<u>Packaging</u>	
1 box @ \$400	400
5 55-gallon drums @ \$20 each	100
Packaging subtotal	500
<u>Transportation</u>	
1 legal-weight shipment @ \$2100	2100
<u>Disposal</u>	
145 ft ³ @ \$5/ft ³	725
<u>Total</u> ^b	3300

^a1978 dollars.

^bThe number of significant figures shown is for computational accuracy and does not imply precision to the nearest one hundred dollars.

APPENDIX H. UNIT COSTS

Table H.1 presents a list of the approximate monthly budget, including general and administrative overhead and contract fees, for staff-level positions required in decommissioning activities. The estimating factors for typical demolition activities provided by riggers, listed in Table H.2, are taken from Bigge Power Constructors, a large west-coast firm specializing in heavy-equipment moving, construction, and dismantling. The cost of all rigger activities listed in the table is assumed to be \$25 per man-hour.

All shipments of radioactive wastes to a burial site are assumed to be made by truck. For calculational purposes, the radioactive wastes are assumed to be shipped from Chicago, Illinois, to Richland, Washington; a one-way distance of about 2000 miles. The gross vehicle weight (GVW) for truck shipments is assumed to be less than 45 000 lb for legal-weight shipments. At \$1.05/mi,¹ the cost per shipment is \$2100.

The maximum-allowed GVW varies from state to state, with the majority of states having limits in the vicinity of 73 000 lb. Thus, overweight shipments are assumed to have a maximum GVW of 73 000 lb. The overweight charges vary from state to state,¹ but an analysis of the shipping route from Chicago to Richland for a GVW shipment of 73 000 lb yields an estimate of the overweight charge of about \$200 per shipment. This charge will apply only to those shipments with a GVW greater than 45 000 lb. Inasmuch as the carrier would impose a surcharge of \$0.21/mi for overweight shipments,¹ the 2000-mi trip from Chicago to Richland entails a total overweight charge of about \$600 per shipment. The GVW of an unloaded truck is assumed to be 28 000 lb; therefore, the payload per shipment is 17 000 lb for legal-weight shipments and 45 000 lb for overweight shipments. The costs per shipment used in this study are summarized in Table H.3.

For this study it is assumed that all shipments will be legal weight except those involving very heavy objects such as magnet sections. Because it may be cheaper to have more overweight shipments and fewer total shipments, the approach used herein introduces some conservatism to the cost estimates.

Two types of packages are considered necessary for disposal of the radioactive waste associated with an accelerator dismantling. The contaminated material from the accelerators that requires packaging would be placed in 1.2-m × 1.2-m × 2.13-m fibreglassed wooden boxes, and the tools, protective clothing, and rags that have become contaminated during the decommissioning of the accelerator would be put in 55-gallon drums. The cost of the fibreglassed wooden boxes is estimated to be \$400 each and that of the 55-gallon drums to be \$20 each.² The costs for disposal of radioactive wastes is based on the waste-disposal rates of the Nuclear Engineering Company, Inc. (NECO), in Richland, Washington.³ Based on expected surface-radiation levels, a charge of \$5/ft³ is used. There is assumed to be no radioactivity surcharge. The weight surcharge is given as \$50 plus \$0.01/lb above 10 000 lb up to the capacity of the site equipment. The site equipment is assumed to be able to handle all shipments. The basic cost data used for packaging and waste disposal at a commercial radioactive-waste burial ground are summarized in Table H.4.

Table H.1. Monthly Budget
for Staff-Level Positions

<i>Position</i>	<i>Approximate Rate^a (\$/mo)</i>
General manager	7500
Administrative manager	6500
Secretary	2850
Property manager	5250
Clerk	2500
Health-physics coordinator	4750
Health-physics technician	3500
Mechanical-equipment manager	7000
Electrical-equipment manager	7000
Facility-services manager	7000
Site-security guard	3500
Safety engineer	5250
Safety inspector	5250
Junior engineer	5000
Engineering associate	3500

^a Includes overhead, general and administrative costs, and contract fee at about 1.85 times direct salary (1978 dollars).

Table H.2. Estimating Factors for
Typical Demolition Activities

Operation	Unit Effort (man-hours)
Heavy machinery	5/ton
Light machinery	9/ton
Structural steel, heavy	9/ton
Structural steel, light	16/ton
Piping, heavy (of 6" or more)	15/ton
Piping, light	30/ton
Concrete slab, 6"	0.27/ft ² (14.58/yd ³)
Concrete slab, 8"	0.36/ft ²
Concrete walls, 6"	0.24/ft ²
Concrete walls, 8"	0.29/ft ²
Concrete walls, 4" block	0.04/ft ²
Concrete walls, 8" block	0.07/ft ²
Concrete mass	0.16/ft ³ (~ 0.6/ft ² for a 4-ft wall)
Spalling 6" of concrete ^a	0.45/yd ³

Source: Bigge Power Constructors, a large firm specializing in heavy equipment moving and construction dismantling. Equipment rental and miscellaneous materials are not included.

^aAssumption is that spalling is three times as difficult as demolition. Estimate not provided by Bigge Power Constructors.

Table H.3. Costs for Legal and Overweight Payloads--Chicago, Illinois, to Richland, Washington

Status	Maximum Payload (lb)	Gross Vehicle Weight (lb)		Cost ^a (\$)	
		Loaded	Unloaded	per Shipment	per Mile
Legal	17 000	45 000	28 000	2 100	1.05
Overweight	45 000	73 000	28 000	2 700	1.35 ^b

^a 1978 dollars.^b Rate calculated for specific routing from Chicago, Illinois, to Richland, Washington.

Table H.4. Cost Factors for Packaging and Radioactive-Waste Disposal

Operation	Cost ^a (\$)
Packaging	
Fiberglassed wooden boxes	400 each
55-gallon drums	20 each
Radioactive-waste disposal	
Base rate	5/ft ³
Overweight charge	50 + 0.01/lb above 10 000 lb

^a 1978 dollars.

REFERENCES FOR APPENDIX H

1. "Technology, Safety, and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station." NUREG/CR-0130, Battelle-Pacific Northwest Laboratory, Sec. I.4, June 1978.
2. "Technology, Safety, and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station." NUREG/CR-0130, Battelle-Pacific Northwest Laboratory, Table I.2-1, June 1978.
3. Letter from A. Crase, Nuclear Engineering Company, Inc., to J.M. Peterson, Argonne National Laboratory, w/ attachments, 16 October 1978.

**APPENDIX I. DECOMMISSIONED PARTICLE-ACCELERATOR COMPONENTS
STORED AT BROOKHAVEN NATIONAL LABORATORY**

Figure 1.1. Entrance to the Storage Yard.

Figure 1.2. Remains of the Cosmotron from a Distance.

Figure 1.3. Storage of the Cosmotron Magnets.

Figure 1.4. Copper Bars, Trim Coils, and Magnets from the Cosmotron.

Figure 1.6. Cosmotron Copper Trim Coils.

Figure 1.5. Storage of the Cosmotron Magnets.

Figure 1.7. Miscellaneous Parts from the Cosmotron.

Figure 1.8. Miscellaneous Parts from the Cosmotron.

Figure 1.9. Magnets from the Cambridge Electron Accelerator.

Figure 1.10. Cambridge Electron Accelerator Vacuum Chambers.