**CONCEPTUAL DESIGN OF A HIGH-INTENSITY POSITRON SOURCE
FOR THE ADVANCED NEUTRON SOURCE**

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December 1994

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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TABLE OF CONTENTS

LIST OF TABLES	v
LIST OF FIGURES	vii
ACRONYMS	ix
ACKNOWLEDGMENTS	xi
EXECUTIVE SUMMARY	xiii
1. INTRODUCTION	1-1
1.1 PROJECT PURPOSE AND SCOPE	1-1
1.2 GOALS AND REQUIREMENTS	1-1
2. JUSTIFICATION	2-1
2.1 PHYSICS APPLICATIONS	2-1
2.1.1 Detection of Defects in Solids by Doppler Broadening Spectroscopy	2-2
2.1.2 Determination of Electronic Structures of Solids	2-3
2.1.3 Structure Determinations by Diffraction	2-3
2.1.4 Positronium Spectroscopy Techniques	2-3
2.1.5 Positron-Induced Auger Electron Spectroscopy	2-10
2.1.6 Positron Reemission Microscopy	2-10
2.1.7 Positron Channeling	2-10
2.1.8 Positron Microprobe Methods	2-13
2.2 PRESENT CAPABILITIES	2-13
2.3 STRATEGIC NEEDS	2-13
3. GENERAL PROJECT DESCRIPTION	3-1
3.1 PROJECT OVERVIEW	3-1
3.2 BEAM GENERATION AND MODERATION	3-4
3.2.1 Beam Source	3-4
3.2.2 Configuration and Electron Optics of the Primary Moderator	3-9
3.2.3 Remoderators and Principles of Brightness Enhancement	3-12
3.3 IRRADIATION AND TRANSPORT	3-13
3.3.1 Hydraulic Flight Tube	3-13
3.3.2 Pneumatic Flight Tube	3-15
3.3.3 Rabbits	3-15
3.3.4 Hot Cells	3-15
3.3.5 Motive System	3-17
3.4 CHAMBER ASSEMBLY	3-17
3.4.1 Source Pan	3-17
3.4.2 Mechanical Systems	3-17
3.4.3 Moderator Substrate	3-18
3.4.4 Liquid Nitrogen Shield	3-18
3.4.5 Beam Conditioning System	3-18

3.4.6	Vacuum Chamber	3-22
3.4.7	Mounting Frames	3-23
3.5	AUXILIARY SYSTEMS	3-23
3.5.1	Helium Refrigeration System	3-23
3.5.2	Liquid Nitrogen System	3-24
3.5.3	Vacuum Pumping System	3-24
3.5.4	Baking System	3-25
3.5.5	Remoderator Annealing System	3-25
3.5.6	Neon Storage and Injection System	3-25
3.5.7	Intervention Systems	3-25
3.5.8	Process Cooling System	3-26
3.6	RADIATION SHIELDING	3-26
3.7	POWER AND INSTRUMENTATION	3-27
3.7.1	Electric Power and Communication Systems	3-27
3.7.2	Instrumentation and Controls	3-27
3.8	BEAM PIPE	3-29
3.9	DETECTORS	3-29
3.10	POSITRON SPECTROSCOPY BUILDING	3-29
3.11	SUMMARY OF ALTERNATIVES	3-30
4.	SIGNIFICANT FACTORS	4-1
4.1	TECHNICAL AND OPERATIONAL UNCERTAINTIES	4-1
4.1.1	Technical Uncertainties	4-1
4.1.2	Operational Uncertainties	4-1
4.2	OPERATIONAL CONSIDERATIONS	4-2
4.3	SPECIAL REQUIREMENTS	4-2
4.4	CONSTRAINTS	4-2
4.5	INTERFACES	4-2
5.	REFERENCES	5-1
APPENDIX A. ACTIVATION CROSS SECTIONS FOR ISOTOPES IN NATURAL COPPER AND SUBSEQUENT DECAY PROCESSES		A-1

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1.1 ANS positron spectroscopy facility goals and requirements	1-1
3.1 Positron emitter parameters	3-5
3.2 Source activity and dose rates after three irradiation cycles	3-26
4.1 Estimated dose rates inside source cell	4-1

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2.1 Doppler broadening of positron annihilation radiation	2-2
2.2 Angular correlation of annihilation radiation (ACAR)	2-4
2.3 Contour plot of electron momentum distribution in the yttrium barium copper oxide (YBCO) superconductor, determined by ACAR	2-5
2.4 Intensity of positron diffraction from the (110) planes of indium phosphide (InP)	2-6
2.5 Positron lifetimes measured as a function of temperature for epoxy polymers having different degrees of cross-linking	2-7
2.6 Free volume in polymer films, measured as a function of depth by means of injected positrons	2-8
2.7 Doppler broadening s-parameters, and positronium fractions, measured as functions of positron injection energy for a film of SiO ₂ on silicon	2-9
2.8 Positron annihilation—induced Auger electron (PAES) spectra for palladium (Pd) deposited on a copper (100) substrate, measured for different annealing temperatures	2-11
2.9 Positron reemission microscopy of nickel surface	2-12
3.1 Positron spectroscopy facility schematic.	3-1
3.2 Positron spectroscopy facility cell module plan	3-2
3.3 Section through vacuum chamber	3-3
3.4 Simplified diagram of source.	3-7
3.5 An illustration of the rationale for the design of the source and moderator configuration for the ANS high-intensity positron source	3-10
3.6 Ray tracing calculations for low-energy (10-eV) positrons emitted from the neon film on the side of the barrel moderator	3-11
3.7 Brightness enhancement of a high-energy, high-divergence positron beam by a tungsten moderator film	3-14
3.8 Rabbit concepts	3-16
3.9 Barrel moderator acceptance vs aspect ratio	3-19

<u>Figure</u>	<u>Page</u>
3.10 Barrel moderator acceptance vs radial gap	3-20
3.11 Barrel moderator assembly	3-21
3.12 Vacuum chamber, viewed from various perspectives	3-22
3.13 ANS positron facility electrical power supply	3-28

ACRONYMS

ACAR	angular correlation of annihilation radiation
ANS	Advanced Neutron Source
AT&T	American Telephone and Telegraph Company
BNL	Brookhaven National Laboratory
DOE	Department of Energy
HFBR	High Flux Beam Reactor
HVAC	heating, ventilation, and air conditioning
ID	inside diameter
INEL	Idaho National Engineering Laboratory
kVA	kilovolt-amperes
LEED	low-energy electron diffraction
LEPD	low-energy positron diffraction
LLNL	Lawrence Livermore National Laboratory
MMES	Martin Marietta Energy Systems, Inc.
OD	outside diameter
ORNL	Oak Ridge National Laboratory
PAES	positron annihilation-induced electron spectra
PCDAS	plant control and data acquisition system
PLC	programmable logic controller
PSF	positron spectroscopy facility
R&D	research and development
TIG	tungsten inert gas
UPS	uninterruptible power supply
Vac	volts ac
WBS	work breakdown structure
YBCO	yttrium barium copper oxide

ACKNOWLEDGMENTS

The authors wish to acknowledge the very substantial contributions of W. M. Fletcher, J. A. March-Leuba, M. E. Mathews, C. W. Parker, and D. L. Selby, all of Oak Ridge National Laboratory (ORNL), and J. M. Ray of Alexander and Associates, Oak Ridge, who performed major parts of the work reported herein. Special acknowledgment is due to A. P. Mills, AT&T Bell Laboratories, for suggesting a positron source at the Advanced Neutron Source (ANS); to J. B. Hayter, ORNL, who suggested using a variable geometry copper source; and to D. E. Pierce, ORNL, who first pointed out the advantages of fabricating the copper source in the form of microspheres. The many helpful comments from T. A. Lewis and Jun Xu, both of ORNL, are much appreciated.

This project has been reviewed by a special committee composed of positron physicists who, collectively, are responsible for over 50% of the major advances made in the field in the last 20 years. Members of this special committee are as follows:

Prof. K. J. Canter, Brandeis University
Dr. K. G. Lynn, Brookhaven National Laboratory
Dr. A. P. Mills, Jr., AT&T Bell Laboratories
Prof. R. N. West, University of Texas at Arlington

These members convened at Oak Ridge National Laboratory in August 1993. They presented papers pointing out the many applications of positron spectroscopy to materials science and contributed many useful suggestions that have enabled us to design better the positron source facility to serve the needs of the applied and fundamental scientists who will be using it. In many subsequent communications, they have been instrumental in determining the appropriate scope and requirements of an optimum facility.

A. Denison, Idaho National Engineering Laboratory, and B. M. Brown, Mt. Holyoke College, have authored several reports and papers on high-intensity positron sources. The expertise they offered to the August 1993 committee meeting was highly constructive.

Finally, we wish to acknowledge the able guidance given to our work by T. J. McManamy, ANS experiment systems task leader; by B. H. Montgomery, ANS task leader; and by C. D. West, director of the ANS Project.

EXECUTIVE SUMMARY

The Advanced Neutron Source (ANS) is a planned new basic and applied research facility based on a powerful steady-state research reactor that provides neutrons for measurements and experiments in the fields of materials science and engineering, biology, chemistry, materials analysis, and nuclear science. The useful neutron flux will be at least five times more than is available in the world's best existing reactor facility.

Construction of the ANS provides a unique opportunity to build a positron spectroscopy facility (PSF) with very-high-intensity beams based on the radioactive decay of a positron-generating isotope. The estimated maximum beam current is 1000 to 5000 times higher than that available at the world's best existing positron research facility. Such an improvement in beam capability, coupled with complementary detectors, will reduce experiment durations from months to less than one hour while simultaneously improving output resolution. This facility will remove the existing barriers to the routine use of positron-based analytical techniques and will be a giant step toward realization of the full potential of the application of positron spectroscopy to materials science.

The ANS PSF is based on a batch cycle process using the ^{64}Cu isotope as the positron emitter and represents the status of the design at the end of last year. Recent work not included in this report, has led to a proposal for placing the laboratory space for the positron experiments outside the ANS containment; however, the design of the positron source is not changed by that relocation. Hydraulic and pneumatic flight tubes transport the source material between the reactor and the positron source where the beam is generated and conditioned. The beam is then transported through a beam pipe to one of several available detectors. The design presented here includes all systems necessary to support the positron source, but the beam pipe and detectors have not been addressed yet.

A dedicated building will be provided on the ANS site to house up to four positron sources with the associated beams and laboratory complex. Initial operations will be based on a single positron source.

The design presented here includes all systems necessary to support the positron sources. The conceptual design for the beam transport system, the detectors, and the positron spectroscopy building is currently incomplete. Requirements for these elements are discussed briefly.

1. INTRODUCTION

1.1 PROJECT PURPOSE AND SCOPE

The purpose of the Advanced Neutron Source (ANS) positron spectroscopy facility (PSF) is to provide positron beams and detectors that will enable scientists to apply positron spectroscopy routinely to the solution of real-world problems with turnaround times that fit industrial processing schedules.

Construction of the ANS provides a unique opportunity to build a PSF with very high intensity beams based on the radioactive decay of a positron-generating isotope. The estimated maximum beam current is 1000 to 5000 times higher than that available at the world's best existing positron research facility. Such an improvement in beam capability, coupled with complementary detectors, will reduce experiment durations from months to less than one hour while simultaneously improving output resolution. This facility will remove the existing barriers to the routine use of positron-based analytical techniques and will be a major step toward realization of the full potential of the application of positron spectroscopy to materials science.

The technical objectives of the ANS PSF are

- to design and construct a positron source that provides a beam brightness per volt $\geq 2 \times 10^{15} \text{ s}^{-1} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$,
- to provide detectors with capabilities matched to the beam parameters, and
- to provide an integrated facility that supports the needs of the users.

The scope of the ANS PSF includes the positron sources, the beam transport system, the detectors, and a positron spectroscopy building. **The scope of this report is restricted to the positron sources.** The beam transport system, the detectors, and the positron spectroscopy building will be discussed briefly because the conceptual design of those elements is currently incomplete.

1.2 GOALS AND REQUIREMENTS

The primary goal of this facility is to provide a positron beam that is at least 1000 times brighter than the most intense existing positron beam, with a duty cycle and lifetime that are appropriate to the investment and capabilities. The goals and requirements are summarized in Table 1.1.

Table 1.1. ANS positron spectroscopy facility goals and requirements

Brightness/volt @ beginning of cycle (requirement)	$2 \times 10^{15} \text{ s}^{-1} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot$
Brightness/volt @ beginning of cycle (goal)	$1 \times 10^{16} \text{ s}^{-1} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot$
Energy bandwidth, after first moderation	$\leq 10 \text{ eV}$
Energy bandwidth, after remoderation	$\leq 3 \text{ eV}$
Pressure, ^a at primary moderator	$\leq 10^{-7} \text{ Pa}$
Experiment cycle	$\geq 24 \text{ h}$
Experiment duty cycle	$\geq 75\%$
Experiment lifetime	$\geq 40 \text{ years}$

^aExcluding helium and hydrogen partial pressures, which must be $\leq 10^{-5} \text{ Pa}$.

2. JUSTIFICATION

2.1 PHYSICS APPLICATIONS

The two most common mechanisms by which positrons are generated are pair production, in the disproportionation of gamma rays having energies equal to or greater than 1.02 MeV, and the radioactive decay of certain isotopes having an overabundance of protons in their nuclei. In this report we are exclusively concerned with the radioisotope mechanism, but for purposes of understanding the nature of the positron, we will briefly review the Dirac theory,¹ which involves pair production.

The positron was predicted theoretically by Dirac in 1928 and observed experimentally by Anderson² in 1933. Dirac postulated that electrons can exist in negative energy states, lying 1.02 MeV or lower below the vacuum level. He explained the existence of the positron as a vacancy in these negative states and described how the motion of this vacancy can give the appearance of a particle having the mass of an electron with an equal and opposite charge. He described the production of an electron-positron pair by a gamma ray, having an energy equal to or greater than 1.02 MeV, as a photoelectric process in which an electron is promoted from a negative energy state to the vacuum level. The vacancy in the negative energy states disappears when an electron falls back into it, "annihilating" the positron. The annihilation process results in the emission of two gamma photons whose energies sum to 1.02 MeV.

Anderson discovered the positron in the course of his studies of cosmic rays, using a Wilson cloud chamber. He observed trajectories of particles having masses equal to those of electrons but with opposite charges. These could be explained, in terms of Dirac's concept, as having been generated by gamma rays induced by cosmic particles. The Dirac theory of the positron is quite useful to explain fundamental particle interactions. For the applied spectroscopist, however, it is usually sufficient to regard the positron as a positively charged electron.

The positron is a stable particle, and if isolated in a vacuum, excluded from interaction with electrons, it will exist for an infinite time. But if the positron is injected into a medium of high electron density, such as a metal, it will be annihilated in less than 2 ns. From the standpoint of the spectroscopist, however, the positron is considered to have a long lifetime, even in high electron density environments. In a human time frame, 2 ns is short, but in terms of atomic and molecular processes, it is quite long. For purposes of spectroscopy, its lifetime is, in fact, longer than that of the electron: an electron is a useful spectroscopic particle only so long as its energy is higher than thermal, allowing it to be distinguished from the rest of the electrons. Interacting with matter, the electron thermalizes in about 1 ps and loses its identity. The positron thermalizes in about the same time, but it continues to be distinguished by its positive charge. It will provide useful spectroscopic information until it annihilates. As will be described later, spectroscopic data are also provided by the annihilation process.

The practicality of positrons as spectroscopic tools is therefore not limited by their annihilation but rather by the difficulty of generating a sufficient current of them to produce spectra having good statistics. The justification for building a high-intensity slow positron source lies in the numerous applications that will be made possible.

Fundamentals of the interaction of positrons with matter are still under study, but there is now an impressive list of applied capabilities for the application of positron spectroscopy to materials science. The Division of Materials Science [Office of Basic Energy Sciences, U.S. Department of Energy (DOE)] recently sponsored a workshop³ where these capabilities were identified and discussed. The areas of application can be generally described as follows:

2.1.1 Detection of Defects in Solids by Doppler Broadening Spectroscopy

Positrons injected into solids become thermalized within a picosecond or less, after which they diffuse through the solid until they are annihilated, resulting in the emission of pairs of gamma photons traveling in opposite directions from each other. If a thermalized positron is annihilated by a thermalized electron, the energies of both gamma rays will be identical, and they will both be recorded in the spectrum as a single peak having an energy of 511 keV. Measurable departures from 511 keV usually occur, however, because the energies of the gamma rays are quite sensitive to the kinetic energies of the electrons with which annihilation occurs. Consider, for example, the case where the pair of gamma photons depart along a line that is parallel to the direction of approach of an electron that has a kinetic energy of 1 eV. To conserve momentum, the gamma ray emitted in the forward direction will be increased by about 500 eV, and the gamma ray emitted in the reverse direction will be decreased by the same amount. Not all shifts will be this large because the lines along which the gamma photons depart are randomly oriented with respect to the directions of motion of the electrons.

Thermalized positrons traveling in solids are attracted to certain defects, such as vacancies, dislocations, and voids, where positive charge from atomic nuclei is rarefied. As they pass these sites, they may become trapped. Because core electrons from atoms are less available, the average energies of the electrons with which annihilation occurs are considerably lower. Less Doppler broadening of the 511-keV peak therefore occurs when positrons are annihilated at defect sites. Positrons annihilating in the more nearly perfect regions of the solid do so with electrons of significantly higher energy, which cause larger Doppler shifts.

Figure 2.1 is an excerpt from the work of Triftshäuser and Kögel⁴ that shows two superimposed 511-keV peaks, measured with a germanium (Ge) detector. The peak with the larger amount of

Fig. 2.1. Doppler broadening of positron annihilation radiation. Defects produced in the nickel specimen by He⁺ ion irradiation capture positrons and cause them to be annihilated by low-energy electrons, for which Doppler broadening is reduced. From Triftshäuser and Kögel, ref. 4.

Doppler broadening was recorded for an annealed nickel specimen, which had a minimum of defects; the positrons annihilated with electrons had higher average kinetic energies. The more narrow peak was recorded for a nickel specimen that had been irradiated with helium ions, which created a high concentration of atomic vacancies; many of the positrons were trapped at defect sites and annihilated by electrons having lower-than-average kinetic energy.

The degree of Doppler broadening is measured by the "s-parameter" width of the 511-keV annihilation peak. The s-parameter is the ratio of the area of the midportion of the peak to the total area of the peak. The midportion is selected such that the s-parameter for nondefected material is about 0.5. Larger values of the s-parameter indicate less Doppler broadening and are usually effected by positron annihilation events at defect sites. The Doppler broadening technique is commonly used to determine "defect profiles" (variations of defect concentrations with depth) at surfaces of solids and at interfaces between solids (e.g., p-n junctions). This is done by measuring the s-parameters as a function of the energy with which the positrons are injected into the solids.

2.1.2 Determination of Electronic Structures of Solids

Angular correlation of annihilation radiation (ACAR) is a spectroscopic technique that can be used to measure electron momentum distributions. Figure 2.2 shows the principle schematically: An electron with momentum appreciably greater than that of thermal electrons annihilates the positron. To conserve momentum, the resulting pair of annihilation photons depart from each other at angles less than 180° . Through repeated measurement of the angles of departure for the correlated pairs of annihilation gamma photons, the momentum distribution of electrons in the solid can be determined. Figure 2.3 shows the results of Haghighi et al.,⁵ who have recently used the ACAR method to detect Fermi surfaces in the 123-oxide superconductor. Discontinuities in the electron momentum distributions can be seen, indicating the presence of Fermi surfaces.

2.1.3 Structure Determinations by Diffraction

The diffraction of positrons and electrons in solids involves multiple scattering events. To interpret the data requires that the interatomic potentials be accurately calculated. This can be done with considerably less complication for positrons because they travel exclusively between the atomic rows of atoms. Electrons travel both inside the atomic cores and between them. The data of positron diffraction are therefore easier to interpret than those of electron diffraction, and they provide more direct information about the structures of solids and surfaces. Figure 2.4 shows the results of Chen et al.,⁶ who have demonstrated that low-energy positron diffraction (LEPD) provides better information about the structure of semiconductor surfaces than low-energy electron diffraction (LEED).

Diffraction studies of positronium are being attempted. This technique will supply information exclusively about structures of the outermost atomic layers of surfaces.

2.1.4 Positronium Spectroscopy Techniques

The formation of positronium atoms, which are neutral particles consisting of bound pairs of electrons and positrons, is a very important phenomenon with respect to the utility of positron spectroscopy. Positronium atoms have two spin states; if the positron and electron spins are parallel, the total spin is 1, and the particle is designated orthopositronium. For the parapositronium atom, the positron and electron spins are antiparallel, summing to 0. The orthopositronium atom is a quasi-stable particle, which if left unperturbed in vacuo has an average lifetime of 141 ns. Orthopositronium atoms

Fig. 2.2. Angular correlation of annihilation radiation (ACAR). Because of the requirement that momentum be conserved, the forward motion of the electron causes forward scattering in the gamma photons produced by the annihilation of the positron.

Fig. 2.3. Contour plot of electron momentum distribution in the yttrium barium copper oxide (YBCO) superconductor, determined by ACAR. White indicates high momentum; black indicates low. The stark contrast between the black and white distributions indicates the presence of Fermi surfaces in the material. From Haghighi et al., ref. 5.

tend to form at external surfaces of solids, and under these circumstances, the average lifetimes often approach that of the vacuum condition. If the solid surface has high electric or magnetic fields, the lifetime of orthopositronium is considerably reduced. In the presence of high electron densities, such as exist in solids, positronium atoms usually do not form.

If positrons are injected into solids containing free volumes or voids, they will escape into these regions as orthopositronium atoms. At thermal energies, the velocity of the positronium atoms is approximately 10^5 m/s, and they strike the walls of the voids with very high frequencies. The lifetimes of the positronium atoms are significantly reduced under these circumstances because the collisions will eventually result in the positrons being picked off by electrons having opposite spins, converting the orthopositronium atoms to the para state. The average lifetime of the parapositronium is about 1000 times shorter than that of orthopositronium. Thus, the lifetimes of the positronium atoms are determined for the most part by the rate at which they are converted to the para state. This rate of conversion is approximately inversely proportional to the void volume. By measurement of the lifetimes of positrons injected into solids containing voids, the void sizes can be determined.

Fig. 2.4. Intensity of positron diffraction from the (110) planes of indium phosphide (InP). Solid lines are the calculated fit to the experimental points. The high quality of fit between calculated and experimental intensities indicates that the model for the surface structure of the planes is correct. From Chen et al., ref. 6.

Figure 2.5, taken from the work of Jean et al.,⁷ demonstrates that positron lifetime spectroscopy can be used to determine glass transitions in epoxy polymers. In this figure, the lifetimes of positronium, formed by injecting positrons into the plastic, are measured for different temperatures of the plastic. It is seen that at certain temperatures the epoxy begins to form free volume interstices, causing the positrons to be trapped as positronium atoms.

Fig. 2.5. Positron lifetimes measured as a function of temperature for epoxy polymers having different degrees of cross-linking. When the polymers undergo crystal-to-glass transitions at the T_g temperatures, the positrons are able to form positronium more readily, and their lifetimes become longer. Polymers having more cross-linking have higher T_g points. From Jean et al., ref. 7.

Positronium atoms formed in the ground state have no net angular momenta, and their translational momenta are very small, causing the annihilation gamma rays to have negligible Doppler broadening. Doppler broadening spectra can be measured quickly and easily, thus providing a simple method of qualitatively determining the extent of positronium formation in solids. Figure 2.6 is taken from the work of Wallace et al.,⁸ in which Doppler broadening spectroscopy has been used to determine the weatherability of paints. The Doppler broadening spectrum for a specimen exposed to ultraviolet light and water is compared to that of a control specimen that was given no weathering. Positrons with energies varying up to 60 keV were injected into the specimens. The Doppler peaks were measured such that an increase in the parameter corresponds to an increase in positronium formation. It is seen that the unweathered paint sample had a higher degree of positronium formation because of a larger content of free volume in the organic binding material. The free volume content of the weathered paint sample was decreased because of cross linking induced in the binding material. The differences in the free volume become insignificant for the higher positron energies because the weathering decreases as a function of depth into the sample.

Orthopositronium can undergo annihilation without being converted to the para state, but because of the requirement that spin be conserved, 3-gamma ray emission must occur. The orthopositronium atoms have total spins of 1; photons can have spins of -1 or $+1$; therefore, for spin to be conserved, two photons with $+1$ spins and one with -1 spin are emitted. The total energy contained by the three photons is approximately 1.02 MeV, the same as for two-photon emissions, but at least two of the photons will necessarily have energies less than 511 keV. The low-energy photons resulting from

Fig. 2.6. Free volume in polymer films, measured as a function of depth by means of injected positrons. The s -parameter, measured from Doppler broadened annihilation peaks, is plotted as a function of the energy with which the positrons were injected into the film. The abscissa of the plot is linear in injection energy but nonlinear in depth of penetration. The s -parameters measured for shallow depths are lower for the films that were weathered, indicating that cross-linking has occurred in the films.

direct annihilations of orthopositronium atoms are recorded as a continuous distribution in spectra measured by germanium detectors.

Under most circumstances, positrons injected into inorganic solids do not form orthopositronium, but the positrons can escape voids, if they happen to be present within the solids, and form positronium. The data shown in Fig. 2.7, for positrons injected into a junction, formed by a 52-nm layer of SiO_2 on silicon, demonstrate such a case. These measurements were taken by Rubloff et al.⁹ at a rather high temperature of 530°C, which is conducive to the formation of orthopositronium atoms at surfaces. The values for the positronium fraction ordinate, on the right side of Fig. 2.7, were calculated from the amounts of 3-gamma photon annihilation that occurred. Positronium fractions were measured as a function of the energy with which the positrons were injected into the specimen. Note that the positronium fraction measurements go through a maximum at an injection energy corresponding to the thickness of the SiO_2 layer. This is indicative of the presence of microvoids at the SiO_2 /silicon interface. The injected positrons escaped into these voids and formed orthopositronium atoms. The fact that the orthopositronium atoms exist as such until they undergo 3-gamma photon annihilation indicates that the microvoids are greater than 1 nm in dimension.

The most significant feature of the plot of the orthopositronium fraction in Fig. 2.7 is the maximum corresponding to the SiO_2 /silicon interface. The continuous distribution of the positronium fraction on both sides of the peak is misleading. It does not mean that the positrons come to rest at various depths within the solid and form orthopositronium in the nondefected regions of the solid. When the positrons come to rest inside the solid, some of them diffuse back to the outer surface, where they form orthopositronium and undergo 3-gamma ray annihilation. The probability that the positron will diffuse back to the surface decreases with injection energy. The continuous distribution underneath the peak is therefore only a measure of how many positrons diffused back to the surface

Fig. 2.7. Doppler broadening s -parameters, and positronium fractions, measured as functions of positron injection energy for a film of SiO_2 on silicon. The maxima in the two curves, corresponding to the interface of the two solids, indicate the presence of large voids (>1 nm). From Rubloff et al., ref. 9.

before they underwent 2-gamma ray annihilation. Difficulties may arise in the interpretation of measurements of this sort, but the data provide information that can be obtained by no other technique.

Figure 2.7 shows that the s-parameter measurements have a distribution similar to that of the positronium fractions. This means that positrons in the parapositronium state are also undergoing annihilation in the voids at the interface and at the outer surface.

2.1.5 Positron-Induced Auger Electron Spectroscopy

Auger electron spectra are usually excited by means of electron or X-ray photon bombardment of surfaces. Because the energies of the emitted electrons are low, they mostly arise from the outermost surface atoms. The technique has been used to significant advantage for analysis of the surfaces of metals and alloys. Electron and photon bombardment can cause significant alterations to nonmetallic surfaces, however. For example, oxides are reduced to the metallic form when bombarded by electrons. Also, electron bombardment generates a very large background of secondary electrons, and the sensitivity of the method is significantly reduced.

The positron-stimulated Auger electron spectroscopy technique is a more sensitive method for surface analysis than its electron counterpart, and alterations in surface compositions are much less. The energies of the bombarding positrons are adjusted to levels less than the electron binding energies of the elements of interest. The positrons come to rest at the outermost atomic layers of the solids and remove core electrons by annihilation rather than by collisional processes. The background resulting from secondary electron emission is much less than that generated by electron bombardment, and the Auger electrons emitted are exclusively from the outermost atomic layers of the surface.

Figure 2.8 was taken from the work by Weiss et al.¹⁰ for a copper surface. Note that this is a first-order differential spectrum, measured directly from the surface, and that the background under the copper peak is quite low. Measurement of a spectrum such as this is impossible if electron excitation is used because of the secondary electron background; it would be necessary to use the second differential spectrum to discern the peak above background.

2.1.6 Positron Reemission Microscopy

This type of microscopy uses positrons of less than 3 eV, as compared to transmission electron microscopy where the energies of electrons are typically 100 keV. Positrons are injected into the backs of moderator film substrates and are thermalized and reemitted at low energies from the front side. As the positrons are reemitted, they interact with defects in the surface and are scattered and absorbed by molecules. The contrast produced results exclusively from surface effects. The low energies of the positrons cause the contrast in the micrographs to be the result of subtle effects, such as vacancies and dislocations and variations in the chemical nature of the film.

Figure 2.9 was taken from the work of Chen et al.⁶ Defects near the surface of nickel are contrasted. When the film was annealed, the defects disappeared.

2.1.7 Positron Channeling

Positrons move between the rows of atoms in solids and penetrate very little into the atomic cores. For this reason, the channeling patterns of positrons are more easily interpreted than those of electrons. The channeling of positron beams can be used to probe the structure of solids and to distinguish atoms in interstitial sites from those in substitutional positions.

Fig. 2.8. Positron annihilation-induced Auger electron (PAES) spectra for palladium (Pd) deposited on a copper (100) substrate, measured for different annealing temperatures. At the higher temperatures the Pd is absorbed beneath the surface, leaving the substrate exposed. From Weiss et al., ref. 10.

Fig. 2.9. Positron reemission microscopy of nickel surface. Positrons are captured by defects in the surface and not allowed to escape. White areas indicate the presence of defects. From Chen et al., ref. 6.

2.1.8 Positron Microprobe Methods

All of the preceding methods can be applied as microprobe techniques by reducing the size of the monoenergetic positron beam. But the reduction of positron beam diameters to those of electron devices requires sources much more intense than those currently available. The justification for the construction of such a source is given by the preceding examples of application.

2.2 PRESENT CAPABILITIES

There are, in general, two types of high-intensity slow positron sources: those based on electron linacs and those based on nuclear reactors. The linac-based sources generate positrons by positron-electron pair production. In the United States there are linac-based sources at Lawrence Livermore National Laboratory (LLNL)¹¹ and at Oak Ridge National Laboratory (ORNL).¹² Linac-based sources have been built in Europe and in Japan also. The maximum currents of slow positrons that have been achieved are in the range of 10^8 – 10^9 /s. Beam diameters have been in the range of 20–30 mm. At Brookhaven National Laboratory (BNL), slow positron beams of the same order of magnitude in current, with smaller diameters, have been generated by means of ^{64}Cu activated in a nuclear reactor. Using brightness-enhancement techniques, which will be explained in Sect. 3.2.3, it is possible to reduce the beam diameters to less than 1 mm, having fluxes as high as $10^{14} \text{ s}^{-1} \cdot \text{m}^{-2}$. The total current of positrons in such beams is impractically low, however, and spectral data taken with them have poor statistics.

2.3 STRATEGIC NEEDS

All of the materials science applications in Sect. 2.1 can be enhanced and made more readily available to industrial needs if more intense sources of monoenergetic positrons are developed. With the construction of the positron source described in this design report, an increase by factors of 1000–5000 in beam intensities will become available. The primary moderation step will produce a current of approximately 10^{12} slow positrons per second, having a diameter of about 40 mm. With two stages of brightness enhancement, a beam with a diameter less than 2 mm and a flux greater than $10^{17} \text{ s}^{-1} \cdot \text{m}^{-2}$ will be generated. With an intensity this large, many of the previously mentioned materials science applications will become semiroutine.

Present methods in materials analysis using the electron microscope provide such information as elemental composition and crystal structure. Large defects, such as dislocations, and vacancy and interstitial clusters can be contrasted. Positron spectroscopy will add to these the capabilities of imaging arrays of point defect clusters and the determination of electron momentum distributions in microcrystals. It will also be possible to analyze exclusively the outermost atomic layers of solids. The determination of surface structures by LEPD will become the preferred method over the LEED counterpart.

R. N. West,⁵ University of Texas, Arlington, reports that ACAR measurements such as that of Fig. 2.3 require several months of data accumulation. He has shown that if a high-intensity beam were available and if a multiple detector array were used, such measurements could be made in a matter of hours, advancing the method to a semiroutine status.

3. GENERAL PROJECT DESCRIPTION

3.1 PROJECT OVERVIEW

The ANS PSF is based on irradiating ^{63}Cu in a high neutron flux to produce ^{64}Cu , which emits positrons in one of its decay modes. The ^{64}Cu half-life is 12.7 h, and approximately 19% of the decay events result in positrons with energy in the range $0 \leq E \leq 650$ keV. Naturally occurring copper is approximately 69% ^{63}Cu , with the remainder being ^{65}Cu . These isotopes, when subjected to neutron irradiation, transmute to ^{64}Cu and ^{66}Cu , neither of which produces an appreciable quantity of long-lived radioactive waste in its decay chain, hence ^{63}Cu enrichment is unnecessary.

The ^{64}Cu PSF concept is shown schematically in Fig. 3.1. Figure 3.2 shows the plan view of a cell module with two installed source chambers and a PSF hot cell. Figure 3.3 shows an elevation view of a source chamber installed in a source cell. The copper material, in the form of spherical shells plated onto aluminum microspheres ("BBs"), will be loaded into a capsule ("rabbit") in the hot cell. It is transported via a pneumatic flight tube from the PSF hot cell to a hot cell in the ANS reactor building. There it is transferred into a hydraulic flight tube and sent to the irradiation position in the ANS reflector vessel. The irradiation position is located approximately 0.5 m radially from the reactor core centerline and 0.5 m below the midplane. The perturbed neutron flux at that location is approximately $3.6 \times 10^{19} \text{ m}^{-2} \cdot \text{s}^{-1}$. After irradiation for two to four half-lives (24 to 48 h), the activated material will be returned via the aforementioned route to the PSF hot cell, where it will be removed from the capsule and inserted into the source chamber. The BBs will be deposited onto a

Fig. 3.1. Positron spectroscopy facility schematic.

Fig. 3.2. Positron spectroscopy facility cell module plan.

Fig. 3.3. Section through vacuum chamber.

round pan that will be mechanically vibrated to ensure that a monolayer of BBs is formed. A solid neon moderator is condensed on the inner surface of a vertical barrel positioned above the source pan. Positrons that strike the surface of this barrel will be moderated and, after exiting the barrel, will be electrostatically focused onto a tungsten remoderator, or brightness enhancer. After exiting the first remoderator, the positrons will be further focused and remoderated a second time. They then pass through an Einzel transfer lens, which can be used to adjust the focal point's axial position, followed by a spherical beam deflector and an Einzel trim lens. Positrons exiting the trim lens enter the beam transport pipe, which contains beam monitoring devices and ultimately connects to the detectors.

A positron spectroscopy building will be constructed on the ANS site. It will house up to four positron sources, with associated beams, detectors, and support functions.

3.2 BEAM GENERATION AND MODERATION

3.2.1 Beam Source

The source of positrons for this facility will be ^{64}Cu generated by thermal neutrons from the ANS. Natural copper, which contains 69% ^{64}Cu , will be the source material. Copper-64 has a half-life of 12.7 h. The yield of fast positrons by this decay process is 19%. The other decay mechanisms are by β^- production and internal conversion. The activation reactions for natural copper, and their cross sections, are listed in Appendix A.

In solid material, positrons have very limited ranges. Therefore, the activated copper must be fabricated such that its surface-to-volume ratio is large. The requirements of a large-area source, operated in a high-vacuum and high-radiation environment, coupled with a low-volume rabbit, drive the emitter geometry. The emitter shape must be readily interchangeable between the large-area source geometry and a compact rabbit volume. The source material processing must be reliable and repeatable while performed in a high-gamma-radiation field. The mechanisms must therefore be radiation hardened and also must be located outside the vacuum chamber or be vacuum compatible.

The preceding considerations have led to the selection of BBs as the preferred emitter form. The BBs, like a liquid, tend to seek the shape of their container. Using their liquid like flow properties and harnessing gravity as the prime mover allows most mechanisms to be located outside the vacuum chamber. Rabbit volume is directly proportional to the BB diameter, which must therefore be minimized. However, frictional rolling resistance is inversely proportional to diameter, and handling equipment mechanical tolerances are also proportional to diameter. A 0.5-mm diam has been judged a reasonable BB size, requiring a 40- to 50-mL rabbit, while being large enough to roll readily and to accommodate easily achieved machine tolerances in handling equipment. The beam source is formed by depositing the BBs onto a flat, round pan. The pan will be mechanically vibrated while it is tilted slightly to establish a monolayer of BBs.

The copper thickness should not greatly exceed the depths from which the positrons can escape because, although only the near-surface material produces moderatable positrons, the entire volume produces heat and radioactive waste. To minimize heating and excess activity, the BBs contain a 0.4-mm-diam pure aluminum core covered by a 50- μm -thick (~ 1.5 absorption lengths) copper shell. Other low-atomic-mass materials were considered as candidates for the core. The results of heat generation calculations, summarized in Table 3.1, indicate that there is very little difference in the heat generated in BBs with several different candidate core materials, except in the case of solid copper BBs. Aluminum was chosen as the core material because of cost advantages. Hollow BBs were also considered and rejected because of potential outgassing in the vacuum chamber.

Because positrons can escape only from the surface regions of the activated copper, the total number of positrons that can be obtained from a given mass of copper is simply proportional to the geometric area that it presents to the optical system that is collecting the positrons. Calculations

Table 3.1. Positron emitter parameters^a

BB parameters		Units	Cu ^b	Cu/Be ^c	Cu/Mg ^d	Cu/C ^e	Cu/Si ^f	Cu/Al ^g
Mass	Shell	grams	114	114	114	114	114	114
	Core	grams	120	25	23	25.5	31	36
	Total	grams	234	139	137	139.5	145	150
Heating	Neutron	W/g	1.35	1.38	1.51	1.37	1.39	1.27
	Prompt photon	W/g	18.0	9.71	13.7	11.8	10.7	10.1
	Fission gamma	W/g	1.8	1.0	1.4	1.2	1.1	1.0
	Decay	W/g	5.74	5.43	6.13	5.68	5.53	7.24
	Total, in reactor^h	Watts	6300	2400	3100	2800	2700	2900
	Slow decay beta ⁱ	W/g	1.38	1.32	1.49	1.37	1.35	1.24
	Slow decay gamma ⁱ	W/g	2.15	2.07	2.31	2.14	2.10	1.93
	Total, in vacuum^j	Watts	510	290	320	300	310	290
Neutronics	Perturbed neutron flux	$10^{19} \text{ m}^{-2} \cdot \text{s}^{-1}$	3.04	3.56	3.93	3.70	3.77	3.59
	Cu-63 absorption rate	$10^{20} \text{ m}^{-3} \cdot \text{s}^{-1}$	6.53	8.20	8.88	8.36	8.68	8.24

^aBased on 0.1-m² emitter surface area.^bCu = copper.^cCu/Be = copper/beryllium.^dCu/Mg = copper/magnesium.^eCu/C = copper/carbon.^fCu/Si = copper/silicon. Estimates more reliable than others because of better statistics.^gCu/Al = copper/aluminum. Estimates more reliable than others because of better statistics.^hPercent gamma energy estimated to be converted to vacuum heat is 100%. Total reactor = mass total × (neutron + prompt photon + fission gamma + decay).ⁱSlow decay = decay heat from long-lived isotopes (half-life >30 min).^jPercent gamma energy estimated to be converted to vacuum heat is 37%. Total vacuum = mass total (37% × decay gamma + 100% × decay beta).

indicate that an area approximately 0.1 m^2 , covered with the 0.5-mm-diam spheres, will yield a total current of about 10^{12} slow positrons per second. As shown in Fig. 3.4, which is a simplified diagram of the source to be built, the microspheres will be placed in a flat pan, 0.36 m in diameter, at the bottom of the apparatus. Fast positrons escaping from the pan will be intersected by the barrel-shaped surface, which will be coated with a solidified inert gas moderator. The height/diameter ratio of the barrel moderator is 2:1, which enables the intersection of 97% of all the fast positrons emitted in the forward direction. The low-energy positrons emerging from the moderator surface will be brightness-enhanced and focused to a narrow beam by the remainder of the apparatus. These details are described in Sect. 3.2.3; first we will discuss further the manner in which the total current of positrons has been estimated.

Limitations on the volume of copper that can be activated and on the manageable dimensions of the apparatus are the main constraints that limit the total current of slow positrons that can be generated. The maximum manageable rabbit volume is about 50 mL. If the copper is in the form of 0.5-mm BBs, 50 mL will hold enough BBs to cover an area of 0.1 m^2 , requiring a 0.36-m-diam pan and $\sim 400,000$ BBs. If, for example, one were to try to double the current of positrons produced by irradiating 100 mL of microspheres (in two rabbits), the diameter of the pan and several other dimensions would have to be increased by a factor of $\sqrt{2}$. Reasonable limits on equipment size and cost, as well as on radioactivity and associated parameters have led to the present design. Next, we estimate the total current of moderatable positrons that can be obtained from the 0.1-m^2 area of activated copper.

Monte Carlo calculations indicate that in order for positrons to be retrieved in the low energy state after they have been injected into a solid moderator, their energies must be less than $\sim 20 \text{ keV}$. Positrons of higher energy are buried deep within the moderator and cannot diffuse back to the moderator surface and escape before they are annihilated. The intensity of fast positrons of this energy range vary with distance within the solid radioisotope from which they escape. Experimental measurements¹³ suggest that the intensity of moderatable positrons is related to escape depth as follows:

$$dI_m = \frac{s \sin \theta}{2} \text{Exp} \left[-\mu \frac{z}{\cos \theta} \right] dz d\theta , \quad (1)$$

where

I_m is the intensity of positrons per unit area of source that are capable of being moderated,

z is the depth within the source from which they emerge,

μ is an attenuation coefficient,

θ is the angle along which the positrons emerge with respect to the surface normal,

s is the specific activity (isotropic emission rate) of the source, in positrons emitted per unit volume per unit time.

The use of the exponential attenuation function in this equation is based on empirical fit to data obtained by placing absorbing materials in front of a fast positron source.¹³ Performing a double

ANS Cu POSITION SOURCE CONCEPT

Fig. 3.4. Simplified diagram of source.

integration on the preceding expression, with z varying from 0 to ∞ and θ varying from 0 to $\pi/2$, we obtain the following:

$$I_m = \frac{s}{4\mu} . \quad (2)$$

I_m represents the total emission rate, integrated through 2π steradians, from the surface of the radioisotope source and has units of fast positrons (capable of being moderated) per unit time per unit area. For a given increment of surface area, the emission of moderatable positrons is not isotropic. The attenuation coefficient for positrons emitted from ^{64}Cu is about 28.5 mm^{-1} ; therefore, an "infinitely thick" source is only about $150 \mu\text{m}$ in depth.

Essentially all of the moderatable positrons emitted in the forward direction are intersected by the barrel moderator. If the moderation efficiency is ϵ and the source surface area is A_s , the total current of slow positrons, I_{sp} , emerging from the barrel moderator will be

$$I_{sp} = \frac{\epsilon \cdot s \cdot A_s}{4 \cdot \mu} . \quad (3)$$

A conservative estimate of the moderation efficiency of the solid neon moderator is 0.006. We calculate the specific activity of positrons being generated by the ^{64}Cu as follows:

$$\frac{dn^*}{dt} = n F \sigma - \lambda n^* . \quad (4)$$

where

n is the number of ^{63}Cu atoms per unit volume,

n^* is the number of activated ^{64}Cu atoms per unit volume,

F is the thermal neutron flux,

σ is the activation cross section,

λ is the decay rate constant of ^{64}Cu .

The solution to this equation is

$$n^* = \frac{n F \sigma}{\lambda} [1 - \text{Exp}(-\lambda t)] . \quad (5)$$

If the irradiation time is greater than three half-lives, the exponential term is essentially zero; therefore, the steady state value for n^* is

$$n^* \leq \frac{n F \sigma}{\lambda} . \quad (6)$$

The specific activity, s , of the ^{64}Cu is proportional to the decay rate of n^* . At $t = 0$, after removal of the activated copper from the reactor, s is given by

$$s = -\beta \frac{dn^*}{dt} = \beta \lambda n^* = \beta n F \sigma . \quad (7)$$

To evaluate s , we will use the following data:

$$\sigma = 4.4 \text{ E-28 m}^2$$

$$F = 3.6 \text{ E+19 s}^{-1} \text{ m}^{-2}$$

$$n = 5.9 \text{ E+28 m}^{-3}$$

$$\beta = 0.19$$

$$s = 1.8 \text{ E+20 fast positrons s}^{-1} \text{ m}^{-3}.$$

The total slow positron current yielded by the barrel moderator is thus estimated as follows:

$$I_{sp} = \frac{\varepsilon \cdot s \cdot A_s}{4 \cdot \mu} = \frac{0.006 \cdot 1.8\text{E+20} \cdot \text{s}^{-1} \cdot \text{m}^{-3} \cdot 0.1 \cdot \text{m}^2}{4 \cdot 28.5 \cdot \text{mm}^{-1}} = 9.5\text{E+11} \cdot \text{s}^{-1} . \quad (8)$$

3.2.2 Configuration and Electron Optics of the Primary Moderator

The configuration of the activated copper source and the barrel moderator was chosen empirically as an upscale of a neon-moderated source developed by Mills and Gullikson.¹⁴ In this work, a 3-mm source of ^{22}Na was located at the end of a cylinder 3 mm in diameter by 6-mm long. The cylinder was cooled to about 6 K to condense solid neon on the interior.

It is necessary to adopt heuristic methods for the design of moderators. Their operations are not fully understood. For example, if ray tracing calculations are done for the Mills-Gullikson configuration, one concludes that moderated positrons emerging from the rearmost surfaces of the cylinder must collide with the opposite surfaces to escape. Multiple collisions may in fact be the mechanism by which energy reduction occurs. In designing the primary moderator for this work, we have used the Mills-Gullikson configuration.

The diagram in Fig. 3.5 compares the barrel moderator chosen for this work with the Mills-Gullikson design. The barrel moderator is composed of four sections, insulated from one another, and has a hemispherical grid inserted in the output end. This will allow a voltage gradient to be imposed. Many ray tracing calculations have been done, using the SIMION¹⁵ program, for different voltage configurations. Figure 3.6 shows the best results that have been obtained. The condensing lens located at the top of the barrel moderator has been included in Fig. 3.6. The voltage configurations of the barrel moderator and the condensing lenses have been found to be interdependent. In Fig. 3.6, the entire barrel moderator, including the microsphere pan, has been biased +100 V with respect to the hemispherical grid. An additional 5000-V drop is imposed across the condensing lens, such that positrons coming from the barrel moderator strike the first brightness-enhancement moderator with about 5100 eV of energy.

The Mills-Gullikson inert gas moderators are very practical for use with radioisotopic sources. If a condensed neon surface is placed in front of the radioisotope, accepting 2π solid angle of the positrons being emitted, an efficiency of 0.006 or higher can be achieved. The positrons that escape

Fig. 3.5. An illustration of the rationale for the design of the source and moderator configuration for the ANS high-intensity positron source. The configuration on the bottom, by Mills and Gullikson (ref. 14), is 3 mm in diameter and has been shown to have high efficiency in the conversion of fast positrons to slow positrons. The configuration on the top will be 400 mm in diameter and is expected to have the same efficiency. The two spherical grids for the 400-mm source constitute the condensing lens that will focus the moderated positrons on a brightness-enhancement film.

POSITRON RAY TRACES IN ANS SOURCE

PM - PRIMARY MODERATOR
(5100 V)

SG1 - SPHERICAL GRID
(5000V)

SG2 - SPHERICAL GRID
(GROUND)

G - GUARD RINGS
(5000V)

BEF - BRIGHTNESS ENHANCEMENT FOIL
(GROUND)

Fig. 3.6. Ray tracing calculations for low-energy (10-eV) positrons emitted from the neon film on the side of the barrel moderator. The hemispherical grids of the condensing lens focus the positrons on the brightness-enhancement film.

from the surface will have energies less than 10 eV. Moderator surfaces are subject to loss in efficiency because of radiation damage and contamination. It is desirable for the moderator to be prepared in situ and not be exposed to atmospheric conditions before it is used. Special advantages of the inert gas moderators are that they can be easily prepared in situ and that they can be regenerated by simply subliming them away and condensing a new film. They can be annealed by varying the substrate temperature a few degrees.

In addition to neon, condensed krypton, xenon, and argon have also been found to be efficient moderators of positrons. Efficiencies are slightly lower, however. Neon has the highest moderation efficiency, but it also has the lowest solidification point, requiring the most refrigeration power. Having the barrel moderator at a lower refrigeration temperature may be an advantage, however, because it can be used to cryopump the system before the neon is admitted. For this reason, current plans are to use neon as the primary moderator. The design of the system will allow the use of the other inert gases as moderators, however, if future developments show them to have advantages.

3.2.3 Remoderators and Principles of Brightness Enhancement

At this point we will recapitulate the principles of moderation and brightness enhancement. The purpose of both the barrel moderator, which uses solidified rare gas, and the brightness-enhancement moderators, made of single crystal tungsten films, is to increase the brightness of the positron beam. Brightness is defined by the following relation:

$$B = \frac{N}{A} \frac{1}{E} \frac{1}{\alpha}, \quad (9)$$

where

B is in units of positrons per unit area per unit time per unit energy per unit solid angle,

N/A is the current density of positrons,

E is the energy of the positrons,

α is the solid angle describing the divergence of the beam.

Brightness is a conserved quantity so long as the positrons are acted upon only by conservative forces, such as those of electric and magnetic fields. If a beam of particles is initiated with poor brightness, it will not be possible, according to this relationship, to reduce its cross-sectional area and its divergence angle without either increasing its energy or suffering a loss in N . For example, it is not possible to extract efficiently monoenergetic positrons from the activated ^{64}Cu by means of a slit and magnetic sector; the yield would be less than 10^{-6} . It is possible, however, to use nonconservative forces to increase B . This is accomplished by capturing the positrons in specially prepared solids, such as condensed neon or tungsten single crystals. The positrons undergo inelastic collisions with the electrons of the moderating material, having their energies reduced to levels below 10 eV. A certain percentage of the low-energy positrons will be able to escape from the moderator before annihilation and be recovered.

The brightness-enhancement technique employs the same principle as the primary moderator. Figure 3.6 shows that the trajectories of the positrons being condensed on the first remoderator film have a very wide spread in angle. The energy of the positrons striking the remoderator is 5100 eV. By

Eq. (9), it is seen that a wide angular spread in the beam and high energy result in low brightness. To reduce these two quantities without causing proportionate reductions in the N/A quantity, the beam is allowed to collide with the remoderator film.

Figure 3.7 is a schematic representation of the action of the remoderator film. When the positrons enter the film, they are thermalized, after which they begin to diffuse toward both the front and back surfaces. When they reach these surfaces, they are ejected into the vacuum, acquiring about 2.5 eV of energy, because of the negative work function property of tungsten for positrons. The angular divergence of the beam emitted from the front side of the moderator will be less than 5° . The number of positrons emitted from the front side will be reduced by about a factor of 3 because not all of the positrons diffuse to the front side of the film, and some of them are lost by annihilation inside the film.

The relative brightness of the beam of positrons emerging from the front side of the film can be compared to that for the beam entering the back side by means of Eq. (9). From the ray tracing diagram of Fig. 3.6, it can be seen that the solid angle of the beam entering the back side of the film is about 1 steradian; using an energy of 5100 eV, the relative brightness of the beam before enhancement is calculated as

$$B_1 = \frac{N}{A} \times \frac{1}{1} \times \frac{1}{5100} = 0.00019 \frac{N}{A} . \quad (10)$$

After emerging from the front side of the brightness-enhancement film, the angular divergence is about 0.01 steradian, the energy is 2.5 eV, and the relative brightness is

$$B_2 = \frac{0.3N}{A} \times \frac{1}{0.01} \times \frac{1}{2.5} = 13 \frac{N}{A} . \quad (11)$$

It is seen that the brightness is increased by a factor of 68,000. The total number of positrons has been reduced by a factor of 3, but as indicated in Fig. 3.7, the beam can now be focused and collimated much better.

The tungsten moderator was first developed by Dale et al.¹⁶ Its principle of operation is different from the inert gas moderators, and if prepared in situ, under good vacuum conditions, it will produce a brighter beam. The energy spread of positrons coming from tungsten moderators is less than 0.2 eV, and the angular spread is much smaller. It is a practical impossibility to prepare tungsten surfaces in situ for use as the primary moderator, but for the remoderator films, its use is preferred.

There will be two ~100-nm-thick tungsten film remoderators. The first will be ~40 mm in diameter, the second ~10 mm in diameter. They will be annealed in vacuo during experiment commissioning and as necessary thereafter. Each remoderator will be fixed at a specified voltage potential.

3.3 IRRADIATION AND TRANSPORT

3.3.1 Hydraulic Flight Tube

The hydraulic flight tube design will be similar to that of the other ANS D₂O hydraulic flight tubes, but it requires up to a 50-mm-diam bore to accommodate the rabbit. A hydraulic stop located in the reflector vessel will allow a specified delay period between rabbit removal from the irradiation position and arrival at the hot cell. The hydraulic flight tube will be routed with other experiment hydraulic tubes that run between the reflector vessel and the reactor building hot cell complex.

Fig. 3.7. Brightness enhancement of a high-energy, high-divergence positron beam by a tungsten moderator film. The positrons injected into the back side of the film are thermalized, and some of them diffuse to the front side, where they are reemitted with lower energy and with smaller divergence angles.

3.3.2 Pneumatic Flight Tube

The rabbits will be transported between the PSF and the reactor building hot cell complex via pneumatic flight tube. The reactor building hot cell will be equipped for transferring the rabbits between the hydraulic and pneumatic flight tubes. The pneumatic tube routing will depend on several unresolved issues, including PSF siting, structural support for radiation shielding, security interfaces, etc.

3.3.3 Rabbits

The primary considerations driving the rabbit design are the large internal volume, the flight tube size constraints, the high heat-generation rate, and handling during material transfer. During irradiation, the BBs generate about 3000 W of heat. Calculations indicate that hydraulic cooling is required.

A cylindrical rabbit with ~10-mm inside diameter (ID) can be adequately cooled. Using a cylindrical rabbit design would require a chain of several rabbits with a total length exceeding 600 mm. A single annular rabbit, as shown in Fig 3.8, will provide adequate volume. Temperature limits (aluminum core melting) in the BBs require that the annulus cannot exceed ~7.5-mm radial thickness. The rabbit envelope dimensions would be about 45-mm outside diameter (OD) × 15-mm ID × 90-mm long. The annular rabbit provides adequate volume, is coolable, and appears to be readily handled (opened, closed, etc.) while accommodating a reasonably compact flight tube.

The rabbits will be machined from aluminum 8001, which is weldable without the use of filler metal. This alloy may embrittle during long-term irradiation, but a 48-h maximum irradiation period is short enough to prevent embrittlement. The baseline design specifies tungsten inert gas (TIG) welding during rabbit closure, but inertial (friction) welding is under investigation.

3.3.4 Hot Cells

The rabbit will be transferred between the hydraulic and pneumatic flight tubes in one of the ANS hot cells located on the third floor of the reactor building. The reactor building hot cell will contain hydraulic and pneumatic rabbit loading/unloading stations with associated valving and drains. The hydraulic loading/unloading station will be similar to other experiment loading/unloading stations. The rabbit loading and unloading, as well as the operation of valves located in the hot cell, will be performed using the hot cell manipulators. The rabbit will not be opened in the reactor building hot cell.

The PSF cell module will be concrete-shielded. Each hot cell will be equipped with a window, manipulators, and the mechanical equipment required to perform the tasks described in the next paragraph. A cell module comprises a hot cell and the two source cells that it services.

Fresh material processing steps in the hot cells include (1) receive an irradiated rabbit at a pneumatic rabbit unloading station; (2) retrieve the rabbit from the unloading station; (3) cut the rabbit open; (4) deposit the rabbit contents (~400,000 0.5-mm-diam BBs) into a funnel or other receptacle that is fixed in a specific location; and (5) deposit the used rabbit into a retrievable, shielded waste container. Spent material processing steps include (1) receive a new rabbit, in two pieces; (2) receive the BBs from the source chamber; (3) raise the BBs to work elevation; (4) deposit the BBs in the rabbit; (5) close the rabbit by TIG seal welding; (6) helium leak test the rabbit; (7) radiograph the rabbit if possible; (8) pressure test the rabbit at ambient and elevated temperatures; (9) load the rabbit in a pneumatic rabbit loading station; and (10) send the rabbit to the reactor for irradiation.

The PSF hot cell will be designed so that in the event of a spill, 99.9% of the BBs can be readily recovered, and no BBs will cross the hot cell containment boundary. Nonrecyclable BBs will

Fig. 3.8. Rabbit concepts.

be discarded into a retrievable, shielded waste container. Provisions will be made for waste removal without personnel entry. Personnel access hatches will be provided for maintenance and repair.

The PSF hot cells will be designed to accommodate decontamination. Only beta and gamma radiation will be present, hence no activation of the hot cell structures and components is expected. The contamination expected in the hot cells includes ^{64}Cu and ^{65}Zn from the activated copper BBs. Provisions are required for removing spent rabbits, spent BBs, etc., without personnel entry.

3.3.5 Motive Systems

The hydraulic and pneumatic systems that control rabbit transport through the flight tube will be similar in design to the other ANS flight tube motive systems. The hydraulic fluid will be D_2O from the reflector vessel. The pneumatic fluid will be air.

3.4 CHAMBER ASSEMBLY

3.4.1 Source Pan

The beam source is formed by depositing the BBs onto a 0.36-m-diam ($\sim 0.1 \text{ m}^2$ surface area) flat, smooth pan. The pan will be mounted on mechanical components that effect the motions required during BB loading and unloading. The pan wall will be fitted with a removable or hinged section through which the BBs will pass when the pan is tilted.

To minimize the cost of the helium refrigeration system that cools the moderator substrate, it is necessary to remove as much heat as possible through the source pan. Hence, it will be made from copper or aluminum to maximize conduction and will be cooled by liquid nitrogen. Conduction heat transfer was estimated using a model proposed by Peterson and Fletcher,¹⁷ which indicates that most of the decay heat can be removed by conduction to the pan.

3.4.2 Mechanical Systems

A number of mechanical components will be required to control BB dynamics. These include components that ensure that (1) the BBs move reliably through pipes, valves, and interlocks; (2) the BBs are properly loaded into the source pan, and a monolayer is established; (3) the BBs are removed from the source chamber and returned to the hot cell; and (4) the BBs are not lost as a result of some component or system failure. All of the mechanical systems described below require further concept development.

Several valves and pumping ports are required between the hot cell and the source chamber to provide vacuum interlocks and a baking chamber. Provisions must be made to ensure that BBs do not become trapped in valve recesses or drawn into the evacuation lines by the gas flow. Careful interlock design and valve selection can minimize these problems, but additional controls certainly will be needed.

To establish a BB monolayer at the source, the source pan will be vibrated during BB loading and briefly thereafter. Mock-ups have shown that horizontal vibrations combined with low-angle, controlled pan tilting will reliably promote the formation of a BB monolayer. The optimum parameters appear to be 0.5-g, 120-Hz, square-wave vibration and ± 2 to 3° of tilt. Fortunately, the lattice behavior is not sensitive to small variations in these parameters for horizontal forced excitation. Mock-ups showed that vertical vibration also can be used to establish a monolayer, but the lattice is, in that case, quite sensitive to the system parameters. The lattice behaved poorly at low frequencies and when

the pan was **slightly** inclined. It was also very sensitive to the vibration amplitude. When the vibration amplitude became high, the vertical bouncing of BBs produced new vacancies and caused the formation of multiple layers at the low point if the pan was off level.

BB removal will be accomplished by tilting the pan to $\sim 15^\circ$ off level and retracting a section of the retaining wall. This will allow the BBs to roll off the pan and into a funnel that will direct them into a pipe leading to a vacuum interlock chamber connected to the hot cell.

A combination of deflectors with a "bucket" at the bottom of the source chamber can be used to contain any BBs that may be lost because of poor control or because of a failure of the loading or transport systems. BBs in gas flow in the event of a vacuum leak can be prevented by installing small-cell honeycomb in the vacuum pipes upstream of the turboprops.

3.4.3 Moderator Substrate

One reason for specifying a 2:1 barrel moderator aspect ratio, discussed briefly in Sect. 3.3.2, is to maximize solid angle coverage. Any aspect ratio greater than 1:1 will provide good solid angle coverage, as shown in Fig. 3.9, but a 2:1 aspect ratio provides 97% of 2π theoretical solid angle coverage and also provides a large surface area for cryopumping. Losses resulting from the inevitable axial gap between the source pan and the barrel's lower end reduce actual solid angle coverage to about 83% of 2π for a 10-mm gap. This loss can be partially recovered, as shown in Fig. 3.10, by making the barrel diameter greater than the source pan diameter. A 20-mm radial gap is chosen, giving 88% of 2π actual solid angle coverage and barrel dimensions of 0.40-m diam by 0.80-m length.

The barrel moderator assembly is made from four identical flanged copper cylinders that are electrically insulated from each other, allowing the voltage potential on each cylinder to be tuned to optimize the beam optics. The assembly is shown in Fig. 3.11. Neon gas will be injected through orifices in the cylinder walls and cryocondensed onto the cold walls, which will be helium cooled to ~ 5 K.

3.4.4 Liquid Nitrogen Shield

The helium-cooled structures will be shielded from ambient surfaces by liquid nitrogen-cooled surfaces. These surfaces include the source pan and a liquid nitrogen shield. The liquid nitrogen (LN_2) shield is a 300 series stainless steel barrel with a "washer" welded at its OD to one end of the barrel. The shield is traced with stainless steel cooling tubes. During source chamber assembly, the shield will be lowered over the barrel moderator and conical guard ring assembly. The top washer will provide heat shielding from the top of the vacuum vessel while allowing the beam to pass. The cylindrical part of the shield contains large holes near the turbopump ports to accommodate mechanical vacuum pumping on the source region.

3.4.5 Beam Conditioning System

The beam conditioning system comprises several components and assemblies that electrostatically focus and guide the beam. The electrostatic condensing lens, which is located immediately above the barrel moderator and which includes the conical array of guard rings, focuses the slow positrons emerging from the barrel moderator onto the first remoderator film. As the brightness-enhanced positron beam escapes from the first remoderator film, it is focused by a cylindrical guard ring assembly onto the second brightness-enhancement film. The image of the spot, from which the beam is emitted by the second film, is transferred by an Einzel lens to the spherical

Fig. 3.9. Barrel moderator acceptance vs aspect ratio (pan diameter = barrel diameter).

Fig. 3.10. Barrel moderator acceptance vs radial gap. Radial gap is measured between source pan OD and barrel ID. Acceptance calculations assume a 10-mm axial gap between the source pan and the barrel.

Fig. 3.11. Barrel moderator assembly.

deflector. Depending on where the image is transferred into the spherical deflector, the beam will emerge either collimated or focused to another spot beyond the spherical deflector. Specified voltages, ranging from 15–25 kV, are applied to the components of the beam conditioning system to shape the electrostatic fields as required to transport properly the beam out of the source.

3.4.6 Vacuum Chamber

The vacuum chamber comprises several stainless steel vessels. The source chamber, shown in Fig. 3.12, consists of a 0.90-m-diam cylindrical vessel, flanged at both ends, about 1.30-m long, with one stiffening ring, a top flange, and a shaped head. The top flange reduces to a 0.40-m ID and is mated to the upper spool pieces described in the next paragraph. The shaped head is a standard elliptical or torispherical head welded to a short cylinder that is also 0.90 m in diameter and flanged to mate with the cylindrical vessel. The shaped head provides support for most of the hardware inside the source chamber. This permits ready access to the internal hardware during source chamber assembly, with the cylindrical vessel section being lowered into position after much of the internal assembly work is completed. Ports are provided for vacuum pumps, the lower remoderator annealing system, BB ingress and egress, and electrical and coolant feed-troughs. Several extra ports are provided for

Fig. 3.12. Vacuum chamber, viewed from various perspectives.

miscellaneous use or for future upgrades. The source chamber has not at this time been structurally analyzed; however, it is a common geometry, and a quick calculation indicates that it is substantially overdesigned.

Three large upper spools are provided to reduce chamber volume and to simplify assembly. A vertical spool, 0.40 m in diameter by 0.33-m long, mates with the source chamber top flange. The vertical spool includes a port for the upper annealing system. An ell spool is made from a standard, short radius, 0.40-m-diam ell that is flanged at the ends. It is modified by the addition of one port for beam surveying and monitoring during experiment commissioning. Finally, a monitoring spool, 0.40 m in diameter by 0.47-m long, is mated to the ell. The monitoring spool contains beam monitoring devices that will be used to confirm beam performance during experiment commissioning and that can provide troubleshooting assistance if detectors are receiving substandard beam.

3.4.7 Mounting Frames

Several structural mounting frames will be required. An aluminum structure will support the chamber assembly to the floor. Mounting frames inside the vacuum vessel will include support frames for the internal mechanical system components, the barrel moderator and LN_2 shield, and the beam conditioning system assemblies. Internal frames will be stainless steel.

3.5 AUXILIARY SYSTEMS

3.5.1 Helium Refrigeration System

A helium refrigerator will provide cooling to the moderator substrate. The estimated refrigeration load is about 80 W with freshly irradiated BBs, decreasing to about 40 W after 24 h of decay. There are at least three possible operating scenarios.

In the first case, a refrigerator with $\geq 80\text{-W}$ capacity will be operated as a closed-cycle refrigerator. The helium will be circulated as gas, entering the moderator substrate cooling pipes at $\sim 5\text{--}5.5\text{ K}$ and exiting at $\sim 6.5\text{--}7\text{ K}$. The required flow rate would be $\sim 5\text{--}6\text{ g/s}$, with a pressure drop of about 0.1 MPa. The refrigeration load would decrease with heat load during the decay cycle.

The refrigerator would be used as a liquefier in the second scenario, liquefying into a dewar positioned near the cold box. Liquid would be withdrawn from the dewar to cool the moderator substrate by nucleate boiling, and cold vapor would be returned to the cold box. The maximum required flow rate and pressure drop are $\sim 5\text{ g/s}$ and 60 kPa, respectively, with boiling in the pipes at $\sim 0.15\text{ MPa}$ absolute pressure. As the heat load decreases, the coolant flow rate will also decrease. This scenario would permit the use of a smaller refrigerator than the closed-cycle refrigerator scenario. In the liquefier scenario, the refrigerator could be continuously operated at full capacity, with the dewar providing a load management function. Early in the ^{64}Cu decay cycle, the heat load would exceed the refrigeration capacity, and the liquid inventory in the dewar would be decreasing. Late in the decay cycle, refrigeration capacity would exceed demand, and the liquid inventory would be increasing. As a result of the load management, this operating scenario would also provide some reserve capacity in the event of a short-term refrigerator failure and would allow the beneficial use of refrigeration capacity during the no-load periods that will occur during BB batch changes. Operation in the liquefier mode is feasible if the pressure can be maintained above atmospheric pressure but well below helium's critical pressure (0.23 MPa) and if bubble-induced flow blockages can be prevented.

A third possible operating scenario is to operate in mixed mode, a combination of the first two scenarios. This, however, requires a (probably supercritical) gas flow loop and a liquid flow loop and introduces the complexity of managing parallel loops at differing pressures and temperatures.

Operation as a liquefier with a load management dewar is the recommended operating scenario provided that piping pressure drops can be held within the narrow range of viable working pressures. If the liquefier operation is not viable, closed-cycle refrigeration is recommended. Mixed mode operation is discouraged.

3.5.2 Liquid Nitrogen System

A liquid nitrogen system will provide nitrogen to the liquid nitrogen shield and the source pan coolant lines. The nitrogen cooling load is estimated to range from about 240–410 W, with the maximum load corresponding to the beginning of the ^{64}Cu decay cycle. Hence, the required flow rate ranges roughly from 6–12 L/h, with cooling accomplished by pool boiling.

The PSF is equipped with a conventional liquid nitrogen system. The liquid nitrogen inventory will be stored in a large dewar located near the positron spectroscopy building. Vacuum-jacketed pipe with an 18-mm ID inner pipe will transport the liquid nitrogen from the storage dewar to each positron source. A control dewar will be located near each positron source, providing a local reservoir to manage changing load demand and to suppress surges caused by demand irregularities or a fault elsewhere in the system. The control dewar also will provide a reserve liquid inventory, which will reduce the probability of operational interruptions caused by a fault in the main nitrogen system. A small dewar on the return side will be used for phase separation, ensuring that no liquid is exhausted. The phase separation dewar will exhaust to the PSF nitrogen exhaust header. The control and phase separation dewars will communicate so that if the phase separation dewar becomes filled with liquid, it can be emptied into the control dewar. The required flow rates are so small that pressure losses throughout the system, except across control valves, will be negligible. The operating pressure can therefore be any convenient pressure between the storage pressure and atmospheric pressure.

3.5.3 Vacuum Pumping System

The vacuum requirement is $\leq 10^{-7}$ Pa inside the barrel moderator volume for all gases except helium and hydrogen. Allowable helium and hydrogen partial pressures are $\leq 10^{-5}$ Pa. Other pressure requirements are total pressure $\leq 10^{-4}$ Pa near the beam and $\leq 10^{-3}$ Pa elsewhere. The system is designed with the goal of achieving pressure everywhere one decade lower than the requirements (e.g., $\sim 10^{-5}$ Pa near the beam).

The source chamber is pumped by a combination of turbopumps and cryopumping. Two ~ 2000 -L/s turbopumps pump directly on the chamber, both exhausting to a single ~ 300 -L/s turbopump backed by a Roots blower/rotary piston pump combination. This system can pump the vacuum chamber to the 10^{-6} Pa range with no internal cryopumping. The small turbopump is required to provide a hydrogen compression ratio adequate to achieve the hydrogen partial pressure requirement.

The barrel moderator, when cooled to ≤ 10 K, becomes a high-speed cryopump. Its speeds range from 100,000 L/s to 240,000 L/s for the common, cryocondensable air constituents, depending on gas species and molecular temperature. After the turbopumps have pumped the chamber to the 10^{-6} Pa range, the barrel moderator will be cooled to ~ 5 K, with the additional pumping speed lowering the total partial pressure of condensable gases inside the barrel to the low 10^{-8} Pa range. The hydrogen and helium partial pressures would remain in the 10^{-6} Pa range.

The contaminant frost is not harmful if it is covered by the moderator (i.e., the positron source must “see” the moderator frost). Therefore, the source chamber will be cryopumped to the required pressure, with contaminant frost condensing directly onto the barrel moderator walls. The neon moderator will then be injected into the source chamber, and the neon frost layer will cover the contaminant frost layer, presenting only clean neon to the positron source.

The vacuum interlock chambers are connected to a common header, which is pumped by a 50-L/s turbopump with a 40-L/min rotary vane forepump.

All pump exhaust gases will be monitored for radioactivity and routed through multiple filtering stages to the plant normal stack.

3.5.4 Baking System

A baking system is provided to bake the vacuum-exposed surfaces. A heating jacket will be provided for the source chamber. Custom baking jackets are provided for the gate valves that mate with the chamber. Heaters and insulation are provided on one of the interlock chambers, where the BBs can be baked briefly before introduction into the source chamber. The goal is to bake to approximately 150°C.

3.5.5 Remoderator Annealing System

After the tungsten remoderators are installed, they must be annealed in vacuo at ~2000°C. This accomplishes two objectives: (1) it reduces vacancy and dislocation content, which can trap positrons, and (2) it sublimates the tungsten oxide surface contamination. Surface contamination also can trap positrons. It can convert positrons to neutral positronium atoms, and it decreases beam brightness by lateral beam scattering. All of these effects reduce remoderator efficiency. Annealing is accomplished by heating the tungsten film with an electron beam. If the tungsten is exposed to atmosphere after annealing, the surfaces will reoxidize. The treatment must then be repeated at $\geq 1600^\circ\text{C}$, tungsten oxide's in-vacuo sublimation temperature.

The remoderator annealing system consists of a linear actuator, vacuum spool pieces and fittings, electrical feed-through, a viewport, an electron beam gun, and a gate valve. During annealing, the remoderator is withdrawn by the linear actuator into the annealing chamber, and the gate valve is closed to separate the annealing chamber and the source chamber. The tungsten film is then heated by the electron beam. The film temperature is monitored by a pyrometer that "looks" at the film through the viewport. During annealing, the annealing chamber is pumped by the interlock chamber pumps.

3.5.6 Neon Storage and Injection System

The neon moderator will be introduced into the source chamber in gaseous form, then cryocondensed onto the barrel surface. The feed gas will be stored in a gas cylinder. After pressure regulation to ≤ 1 MPa, it will be introduced into the source chamber through a variable leak valve. The neon will be routed through a manifold, shown in Fig. 3.11, to injection ports located in the barrel moderator walls at roughly uniform pitch. During neon injection, the pressure in the chamber must be maintained at $\leq 10^{-3}$ Pa, or thermal control will be compromised.

3.5.7 Intervention Systems

The intervention systems are the mechanical systems that effect an abort sequence or that are used to recover from an aborted or failed process. An example might be a system or device to recover a rabbit that is stuck in a valve in the flight tube or to recover spilled BBs. No further definition of this system exists, but funds and time have been allotted in the cost and schedule estimates.

3.5.8 Process Cooling System

The process cooling system includes heating, ventilation, and air conditioning (HVAC) and cooling water. HVAC will be provided to maintain 250-Pa negative pressure in the cell modules. The exhaust will be monitored for radioactivity and routed through multiple filtering stages to the plant normal stack. Cooling water will be provided to the helium refrigerator at ~2400 L/h, $\leq 23^{\circ}\text{C}$ supply temperature, and ≥ 0.3 MPa inlet pressure. The turbopumps require approximately 80 L/h.

3.6 RADIATION SHIELDING

The extremely high gamma radiation field requires extensive radiation shielding. Shielding includes personnel protection shielding at the cell modules and the flight tubes and equipment shielding inside the source cells.

Source activity and dose rates after three irradiation cycles are summarized in Table 3.2. When the rabbit is ejected from the reactor, a 1.5-m-thick concrete shield would reduce the dose rate at the shield outer surface to ~18 mrem/h. This dose rate is dominated by ~1.8-MeV gammas from the ^{28}Al , with a 2.25-min half-life, and ^{66}Cu , with a 5.1-min half-life. After 30 min of decay, the dominant 1.8-MeV gamma flux has decreased by a factor of 20,000, and the remaining 0.23-mrem/h dose rate is dominated by 1.3-MeV gammas from the ^{64}Cu . Hence, personnel shields will be 1.5-m-thick concrete. After ejection from the reactor, the rabbit will be held for 30 min in a delay station located in the reflector vessel to allow the 1.8-MeV gamma flux to decay. In the event that an off-normal event would require bypassing the delay station (not currently foreseen), the radiation dose would still be well within the limits for short-term exposure.

Table 3.2. Source activity and dose rates after three irradiation cycles

	Activity, kCi	Personnel dose rate ^a	Equipment dose rate ^b
Freshly irradiated	340	18	88
1/2-h decay	260	0.23	67
2-h decay	240	0.19	62
24-h decay	70	0.56	19

^amrem/h, behind 1.5-m-thick concrete shield.

^bkrad/h, unshielded, 1 m from source.

Calculated equipment dose rates show that shielding is required for equipment such as vacuum pumps and valves to attain a reasonable operating lifetime. Equipment lifetimes of 5–10 years can be attained with ~50-mm-thick lead-equivalent equipment shields.

The source cell's inside dimensions will be about 5 × 6 × 5-m high. Crane access will be provided through a large overhead hatch. One personnel access way may be provided through the side wall. Penetrations will be provided for the beam pipe, the utility pipes, the power and instrumentation cables, and the HVAC ductwork. A plan view layout of the source cells is shown in Fig. 3.2.

3.7 POWER AND INSTRUMENTATION

3.7.1 Electric Power and Communication Systems

The ANS non-Class 1E power distribution system, shown in Fig. 3.13, will supply electric power for the PSF. The largest electrical loads—cryogenic compressors and vacuum pumps—will use 480-Vac power. Other voltages will be provided as needed. If necessary, small transformers will provide special voltages required for the positron equipment.

Uninterruptible power (UPS) will supply PSF controls and instrumentation. UPS power may come from the non-Class 1E UPS system or may be supplied by a small UPS unit dedicated to the PSF control system.

The PSF is not expected to require Class 1E power. However, standby ac power, if needed, may be provided by the Class 1E power system through an approved isolation device. The isolation device will prevent electrical faults in the PSF from adversely affecting the Class 1E power system.

Cabling located inside the cell modules must be radiation hardened to withstand the high radiation field. Cabling terminations will be made with special connectors that allow disconnection and connection with master-slave manipulators so failed electrical equipment and wiring may be replaced remotely. Raceways (including electrical enclosures) must be made of materials (e.g., stainless steel) that will withstand the radiation environment and cell decontamination procedures (e.g., washing with acidic solutions). Raceway routing and installation methods will reduce the number of "catch points" for dust and particles that make cell decontamination more difficult.

Communications systems will be provided to connect the PSF to the ANS experiment systems network. ANS standard communication outlets will be provided at work stations.

3.7.2 Instrumentation and Controls

The instrumentation and controls to be provided for the positron source will be used to control and monitor the process. The process instrumentation will monitor and control a high vacuum level in the vessel and will control the product movement through the rabbit tubes. All the instruments provided will be designed and procured with the high radiation levels in the facility as a constraint. The vacuum will be monitored and controlled by a system of Pirani gauges and ion gauges. The cryocondensing pump will be equipped with nuclear-grade Type E thermocouples and silicon diode cryogenic sensors. All instrumentation components will be individually shielded for the radiation levels expected. The control of the process will be through a commercially available programmable logic controller (PLC), and data acquisition will be accomplished through a digital data acquisition system that is either interfaced to the ANS plant control and data acquisition system (PCDAS) or that is a terminal of the PCDAS. All signals will be routed through facility containment by use of commercial nuclear-grade feed-troughs. A radiation-hard camera will be provided to determine the product status inside the vessel. This will necessitate lighting the vessel. A method of doing this is to provide two sight ports at right angles to each other and to illuminate through one while recording video through the other. It needs to be determined if this technique is compatible with the high vacuum level required in the source chamber. Another method under consideration is the use of hardened fiber optics and specialized vacuum feed-troughs.

Beam monitors will be provided to assist in beam alignment and brightness measurements. The beam monitors are slotted plates that can be moved across the beam region. As the plates are moved across the beam, part of the beam is intercepted by the plates, changing the beam cross section. The positrons that pass through the slots strike a blank flange in either the ell spool or the monitoring spool, depending on the configuration of the beam conditioning system. These collisions produce gammas. A gamma counter then is used to infer information about beam alignment, cross section, and

Fig. 3.13. ANS positron facility electrical power supply.

divergence angle. A single slotted plate at the same elevation as the lower annealing system is used primarily for initial beam alignment. A pair of slotted plates in the monitoring spool will be used to measure beam brightness. This system can be used before the detectors are on-line to verify that the positron source design goals have been achieved.

The flight tube operation will be controlled by the PLC used to control the process. At this time the plan is to equip the tubes with a series of coils to indicate the positions of the rabbits.

The instrumentation and controls to be furnished are currently based on all nuclear-qualified components, but a study is required to determine what signals from the PSF impact the operation of the reactor as to scram and power cutback. These signals will require routing to the reactor protection system and input to the PSF data acquisition system through qualified isolators.

3.8 BEAM PIPE

The beam pipe design will be developed in the near future.

3.9 DETECTORS

The detailed detector design falls outside the scope of the present work; nevertheless, the detectors impose specific requirements on the facility, so a brief discussion of detectors is relevant.

To assess the quality of the beam (i.e., the intensity and collimation), microchannel plate and thallium-doped sodium iodide [NaI(Tl)] detectors will be used in combination with mechanical apertures. Microchannel plate detectors have phosphor screen outputs and are very convenient for quickly locating the beam and qualitatively determining its spatial distribution. Using the microchannel plate output, coarse adjustments of voltages on the electron optical components will be made. Quantitative measurements of the positron current will be done with NaI(Tl) detectors. The area and angular spread of the beam will be determined by measuring the NaI(Tl) output as a function of the position of the mechanical apertures.

The beam will be used in experiments of the nature described in Sect. 2.2 and will require several different types of detector systems. For Doppler broadening measurements, germanium detectors, which provide high resolution of the 511-keV peak, will be used. BaF₂ detectors, which have high efficiency and fast response for the 511-keV peak, will be used for positron lifetime measurements. Many experiments will use the germanium and BaF₂ detectors for coincidence measurements of Doppler broadening and lifetimes. Positron reemission microscopy, positron diffraction, and positron-induced Auger electron spectroscopy will make use of microchannel plate detectors.

High-resolution ACAR measurements will be a very important application of the ANS PSF and will require an array of NaI(Tl) position-sensitive detectors placed at up to 25-m radii from the point of injection of the positrons into the specimen.

3.10 POSITRON SPECTROSCOPY BUILDING

A dedicated positron spectroscopy building will be constructed on the ANS site. The building layout and siting are currently incomplete. The building will incorporate the following features and requirements.

Space will be provided to accommodate two cell modules like that shown in Fig. 3.2, yielding up to four positron sources, but only one source cell and one hot cell will initially be equipped. Laboratory space will accommodate a 50-m diam by 45° included angle ACAR camera array as well

as several smaller detector laboratories and staging/calibration space. Radiation shielding will be provided around all laboratories. A large, crane-equipped high bay work area will be provided, as well as space to accommodate support functions including mechanical equipment, a control room, a change/break area, and modest office space.

One of the most challenging requirements imposed on the PSF is to provide dynamic stability for certain detectors. The ACAR detectors should be dynamically stable to within approximately ± 0.1 mm for periods of several minutes in order to attain acceptable position resolution. The stated stability applies to the sample chamber and opposing cameras in a relative reference frame (i.e., none of the three components is allowed to move more than ± 0.1 mm with respect to either of the other components). Hence common mode deflections can be accommodated. For the positron annihilation microprobe to operate at its 0.1- μ m ultimate resolution, ≤ 0.1 -mm dynamic stability is required over a several hour period, between the primary source and the demagnifying stages of the microprobe.

The building layout will segment the various functions. For example, laboratories and offices will be readily accessible; access to mechanical equipment will be somewhat restricted; and access to the sources will be very restricted. These access restrictions will be integrated into the ANS access plan.

Other miscellaneous requirements include low gamma and radio frequency noise background for certain detectors and minimum restrictions on experimenter access to the facility and types of samples that can be brought into the facility. The PSF will rely on the main ANS complex for support services including security, fabrication shops, computing, library, cafeteria, offices and conferences rooms.

3.11 SUMMARY OF ALTERNATIVES

The first technology considered for the positron source was based on ^{79}Kr . This was originally thought to provide a relatively simple and inexpensive source. Krypton-78 would be irradiated in a "bulb," using either pressurization or condensation to achieve high density in the bulb. In the source chamber, the krypton would be cryocondensed onto a surface, much like covering a surface with copper in the present concept. Transporting the gas between the reactor and the source chamber is obviously much simpler than transporting a solid. However, in the event of a vacuum leak in the source chamber, thermal control would be lost and a radioactive gas leak would ensue. Double containment of the entire system would be necessary to prevent such an occurrence. Double containment would be quite expensive and would complicate assembly and maintenance, especially in a facility where the source is located far from the reactor. Cobalt-58 has also been suggested as an alternative technology, but this would require a substantial chemical processing facility for which the ANS has no plans.

Other ^{64}Cu concepts considered include foil, nested or stacked forms, and evaporative deposition. The earliest ^{64}Cu concept used foil but was abandoned because of the difficulty of transferring foil between the rabbit and the source chamber. Nested or stacked forms likewise present challenging material-transfer obstacles. Evaporative deposition is the method currently used in the High Flux Beam Reactor (HFBR) positron source at BNL. There it has been found that controlling the copper deposition onto a 10^{-4} m² surface area is quite tricky; successful extension to a 0.1-m² surface is considered unlikely. The radiation hazard poses a serious challenge for all of the previously mentioned concepts. These and other concepts will be considered further in the near future. If an improved concept is developed, it can be integrated into the present design with minimal perturbation to most of the hardware configuration.

Among the rare gas moderators, neon and krypton were considered. Mills¹⁴ has successfully used neon, which has an experimentally demonstrated efficiency of ~ 0.006 with a 10-eV energy bandwidth. Krypton efficiency is slightly lower, ~ 0.004 – 0.005 , but also has a narrower energy bandwidth of 5 eV. Both are most efficient when operated near their sublimation temperatures, which are 6.5 K for neon

and 32 K for krypton, respectively, at 10^{-8} Pa. To attain the required vacuum, cryopumping at the moderating surface is needed, with temperature ≤ 10 K. Neon was chosen because it is slightly more efficient, and its operating temperature is in the temperature range necessary for effective cryopumping.

The suggested rabbit geometry requires a relatively large diameter and length, both of which impose some difficult design constraints on the flight tube. An alternative is to use multiple smaller rabbits, operated in a "rabbit chain," to attain the total required volume. This will require processing multiple rabbits during each batch cycle. The extra processing time will reduce beam availability or beam strength as compared to the present concept.

4. SIGNIFICANT FACTORS

4.1 TECHNICAL AND OPERATIONAL UNCERTAINTIES

4.1.1 Technical Uncertainties

A number of technical uncertainties exist that must be resolved by analysis, research and development (R&D), or a combination of the two. Some technical uncertainties must be resolved to ensure that the design will meet all requirements. These uncertainties include detailed structural and heat transfer analyses, BB handling, and moderator injection parameters. Other uncertainties are simply matters of design optimization (i.e., they involve choosing parameters to optimize the performance or cost), although the nonoptimized design will meet the requirements. These include decisions such as the specification of the barrel moderator aspect ratio and whether to use radiation-hardened equipment or to shield the equipment.

4.1.2 Operational Uncertainties

The operational issue of greatest concern is the potential loss of control of BBs. The number, size, and transportability of the BBs make it probable that there will be spills. All spills **must** be contained inside shielding. Assuming that this requirement is met, the spilled BBs must be recovered. The hot cell will be designed so that almost all BBs spilled outside the source chamber can be recovered remotely. Considering the complexity of the source chamber assembly, the probability of successful remote recovery operations there seems quite low. Clearly, long-lived radioactivity will make recovery from a spill in the source chamber very difficult at best and maybe impossible.

Estimated radiation dose rates inside the source cell, at a distance of 1 m from the source, are shown in Table 4.1 for various source material histories. Dose rates have been estimated assuming that the BBs were subjected to a number of irradiation cycles, where one cycle represents 24 h of irradiation and 24 h of decay. After a number of irradiation cycles, irradiation ceases and continuous decay ensues. The dose rates for a full charge of BBs, modeled as a point source, are tabulated after decay periods of 7, 14, and 30 d.

Table 4.1. Estimated dose rates^a inside source cell

Decay time, d	Number of cycles ^b				
	1	3	5	7	15
7	6.8	7.5	7.9	8.5	13
14	0.017	0.20	0.59	1.2	5.6
30	0.009	0.17	0.54	1.1	5.3

^aDose rates in rem/h, at 1 m from source.

^bCycle is 24 h irradiation followed by 24 h decay.

The short-lived isotopes are still contributing substantially to the dose rate 7 d after the last irradiation, but by 14 d the ⁶⁵Zn, with a 244-d half-life, dominates. During the early cycles, the asymptotic dose is quite low, because the ⁶⁵Zn activity increases roughly with the number of

irradiation cycles squared. It appears that by discarding the BBs after three or four cycles, corresponding to 5 or 7 d, the asymptotic dose rates inside the shield can be held sufficiently low to allow short-term work inside the source cell. Because the tabulated dose rates are for a full charge of BBs, they represent maximum values. Additionally, about half the ^{65}Zn dose rate is attributed to nonpenetrating ($\sim 10\text{-keV}$) gammas, which can be stopped by shield thicknesses typical of temporary shielding. Although it appears that it will be possible to resolve the potential spill problem, the interruption to operations would be quite severe. Clearly we must ensure that such events are infrequent. A reliable material handling system is an absolute requirement of the BB concept.

Only beta and gamma radiation are present, so there is no structural activation. The BBs are therefore the sole radiation source, and when all BBs are removed, the source chamber will be readily accessible for maintenance. However, a very small fraction of the BBs are likely to become trapped, spilled, stuck, etc., during each batch cycle. This may impose an estimated 3- to 7-d delay between batch removal and personnel entry inside the source cell at every maintenance access.

4.2 OPERATIONAL CONSIDERATIONS

Many experimenters are expected to be visiting scientists who will have competing schedule demands and who cannot alter their plans. The PSF should operate therefore on a reliable and predictable schedule that is developed in advance. The detectors should be readily accessible, with minimum training and security requirements, to visiting personnel. The source itself should be inaccessible to most visiting scientists and should be operated by a trained and experienced operations crew.

Because of the radiation considerations discussed in Sect. 4.2.2., unirradiated BBs will be used during the initial facility shakedown. Very-low-activity BBs will be used during beam alignment and commissioning activities.

4.3 SPECIAL REQUIREMENTS

Generally, the requirements imposed on the ANS apply to the PSF as well. Additionally, the extreme environmental conditions will require the equipment to tolerate gamma radiation, cryogenic temperatures, and/or high vacuum.

4.4 CONSTRAINTS

The most important constraints are imposed by the advanced state of the ANS conceptual design. The PSF must meet its requirements while accommodating established facility parameters. Fortunately, there is still considerable flexibility in the ANS design, which makes these constraints much less rigid than those imposed on upgrades to existing facilities. Schedule constraints also will be imposed by the overall ANS funding profile and by interfaces with the construction of other ANS elements.

4.5 INTERFACES

The operation of the PSF will necessarily be subordinate to reactor operation. Reactor operation should not be affected by any PSF fault, but the PSF will experience operational interruptions resulting from reactor system faults.

The flight tube routing must be integrated with the ANS reactor complex design. A space has been reserved for the irradiation location and for the penetration through the reflector vessel. Flight tube routing has not been determined yet, and space is limited. The flight tube shielding is bulky and costly, so the route requiring the least additional shielding is preferred. Further design development is needed to ensure that the reserved spaces, the load supports, the cooling, etc., are adequate to support the PSF requirements.

The positron spectroscopy building layout and siting have not been completed. This building must be effectively integrated into the ANS site plan and plant systems. Critical interfaces include numerous technical entities and support functions.

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APPENDIX A

**ACTIVATION CROSS SECTIONS FOR ISOTOPES IN NATURAL
COPPER AND SUBSEQUENT DECAY PROCESSES**

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