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ABSTRACT

This is the second of a series of three instnuctor manuals in x-ray science and engineering and is produced as part of a project of Oregon State University's Bureau of Radiological Health. This manual, and the two campanion manuals, have been tested in courses at Oregon State. These materials have been designed to serve as models for teaching and training programs in x-ray science and engineering. The manuals contain lecture outlines, laboratory exercises, and examinations. References, required equipment, and materials are listed. Each lecture and each laboratory exercise is essentially self-contained to permit other schools to select material on the basis of available time and equipment and the objectives of their instructional program. Equipment has been identified by model and manufacturer, but instructors may substitute equivalent equipment or alter course content to make use of available equipment. Fourteen lectures and six laboratory exercises are presented in this second volume. Among other topics, these deal with fundamental atomic structure; history and properties of x-ray; x-ray production; and use of dental, therapeutic, industrial, and medical radiographic equipment. (PEB)

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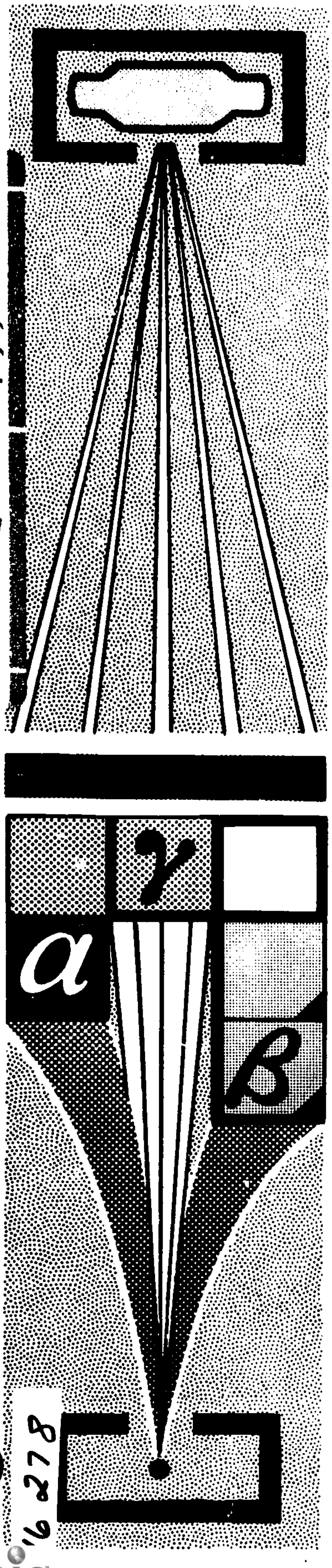

COURSE MANUAL for X-RAY MEASUREMENTS

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
FOOD AND DRUG ADMINISTRATION

SE 016 278

TECHNICAL REPORTS

Technical reports of the Division of Medical Radiation Exposure, Bureau of Radiological Health, are available from the National Technical Information Service, Springfield, Va. 22151, when a PB number is indicated after the title. Microfiche copies are $0.95; prices for paper copies are indicated after the PB number. Bulk order prices are available from NTIS. The PB number should be cited when ordering. Some reports are also available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, as indicated after the title.

PHS 1559	Physical Survey Manual Dental X-ray (PB 183 019 $6)
PHS 1582	Radiation Protection Survey Report Manual (PB 183 018 $6)
PHS 1663	KWIC Index to the Journal of the Health Physics Society (1958-1966) (PB 176 092 $6)
PHS 1831	KWIC Index to the Journal of Nuclear Medicine (1960-1967) (PB 179 074 $6)
PHS 999-RH-29	Tritium Contamination in Particle Accelerator Operation (PB 189 362 - $6)
PHS 999-RH-30	Reduction of Radiation Exposure in Nuclear Medicine (PB 178 129 $6)
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MORP 67-1	X-ray Emission from Shunt Regulator Tubes for Color Television Receivers (PB 184 546 - $6)
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MORP 68-10	Survey of the Use of Radionuclides in Medicine: Preliminary Report (Superseded by BRH/DMRE 70-1)

(continued on inside of back cover)

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BRH/DMRE Contract No. PH 86-65-92

COURSE MANUAL for X-RAY MEASUREMENTS

(O. S. U. Course GS-462)

Prepared by

The X-Ray Science and Engineering Laboratory
Oregon State University

under

Contract No. PH 86-65-92

Project Director:

E. Dale Trout, Director
X-Ray Science and Engineering Laboratory

Project Officer:

Arve H. Dahl, Acting Director
Division of Medical Radiation Exposure

JANUARY 1973

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
FOOD AND DRUG ADMINISTRATION
Bureau of Radiological Health
Rockville, Maryland 20852

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FOREWORD

The Bureau of Radiological Health implements a national program designed to reduce the exposure of man to hazardous ionizing and non-ionizing radiation.

Within the Bureau, the Division of Medical Radiation Exposure deals with 1) the reduction of unproductive ionizing radiation exposure of patients, workers and others exposed by the use of x rays and other machine-produced ionizing radiation, radioactive materials and radiopharmaceuticals, and 2) the improvement of radiological "systems" and methodology in the healing arts. A number of projects and studies are aimed at assessing and minimizing radiation exposure in the healing arts and increasing efficiency in the use of radiation in clinical practice. Several projects are directed toward assessing and improving the qualifications of x-ray users in the healing arts.

Results of intramural and contractor projects of general interest are published as technical reports by the Division of Medical Radiation Exposure and distributed to State and local radiological health program personnel, Bureau technical staff and advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press and other interested individuals.

Contract reports on highly specialized topics are printed and distributed without editorial revision. Copies of both general interest and limited distribution reports may be purchased from the National Technical Information Service.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

Since June 1965, Oregon State University's Department of General Science has been supported by the Bureau of Radiological Health through Contract No. PH 86-65-92 to organize, develop, and conduct a teaching and training program in x-ray science and engineering; and conduct related research, evaluation, and development activities. The project was made possible by the presence of the internationally recognized x-ray expert Dr. E. Dale Trout, Professor of Radiological Physics, who serves as the Project Director. The Assistant Project Director, John P. Kelley, Associate Professor, Department of General Science, is also a nationally recognized expert in the fundamentals and use of x-radiation.

This document, one of three instructor course manuals in x-ray science and engineering, is one of the project's significant contributions to radiological health. The three manuals have been tested in courses introduced into the university curriculum. They are presented in such form that they can be used as models for similar programs in other institutions.

It is appropriate to acknowledge other accomplishments of the project. The project has provided the following staff of the Bureau of Radiological Health with training and supervision in research, evaluation, and developmental work in x-ray science and engineering: Robert L. Elder, Sc.D.; Gregory J. Barone, Ph.D.; Bruce M. Burnett, M.S.; William S. Properzio, M.S,; Kenneth R. Envall, M.S.; Kenneth E. Weaver, M.S.; and Richard E. Gross, M.S.

Reports have been presented at professional meetings and published in the open scientific literature on evaluations of instruments used in x-ray measurements, methodology devised for evaluation of x-ray protective devices and materials, and methodology and instrumentation developed for measurement of x radiation. The project staff has also analyzed and reported to the Bureau regularly on related developments presented at annual meetings of the American College of Radiology, Radiological Society of North America, American Roentgen Ray Society, American Association of Physicists in Medicine, Health Physics Society, and the American Society of Radiologic Technologists.

A model complete x-ray instructional facility known as the X-Ray Science and Engineering Laboratory has been developed containing modern x-ray equipment, electronic and mechanical shops, classroom, office and support space.

Special acknowledgement is also made of the contract support provided to the project during the last 2 years by the National Institute for Occupational Safety and Health because of their need for research and development assistance on production of better quality radiographs for the coal miner pneumoconiosis control program. Acknowledgement is also made of past contributions in development of this project by Dr. Donald R. Chadwick, Mr. James G. Terrill, Jr., and Dr. Russell I. Pierce for the Bureau and by Dr. James H. Jensen, President of Oregon State University at the time the project was started, and Milosh Popovich, Dean of Administration for the University.

Arve H. Dahl, Project Officer

Acting Director
Division of Medical Radiation Exposure
Bureau of Radiological Health

CONTENTS

INTRODUCTION

There are three course manuals in this set. They are used by instructors in the Department of General Science at Oregon State University for planning and presenting a three-course sequence in x-ray science and engineering. The courses, which are offered each year, are open to both undergraduate and graduate students and must be taken in sequence. They are:

GS-461 Machine Sources of X Rays - Fall Term

GS-462 X-Ray Measurements - Winter Term

GS-463 X-Ray Applications - Spring Term

Each is a 3-credit-hour course and consists of two 1-hour lectures and one 3-hour laboratory each week. In the 6 years the course manuals have been used, classes have included students from programs in pre-dentistry, pre-medicine, pre-veterinary medicine, biology, oceanography, physics, engineering, chemistry, education, geology, pharmacy, physiology and agriculture. It is assumed that students will have no x-ray experience but that they will have had at least 1 year's work in college level physics and mathematics.

The course manuals contain lecture outlines, laboratory exercises, and examinations. References, required equipment, and materials are listed. Each lecture and each laboratory exercise is essentially self-contained to permit other schools to select material on the basis of available time and equipment and the objectives of their instructional program. In presenting the subject matter in as uncomplicated a form as possible, some concepts may have suffered from oversimplification, but the instructor can easily increase the degree of sophistication to the limit of student understanding. It is our belief that full appreciation and understanding of the subjects presented requires laboratory experience. Nonetheless, we are sure that the lecture material alone could be presented as review material or as indoctrination material to a group where x rays might be of peripheral interest. Selected sections from the course manuals have been used as source material for a one-quarter course in Continuing Education and for 2-day working topical seminars.

One of the most frustrating aspects of preparing teaching material is the ever-changing situation in regard to references. New books and technical papers make any list of references obsolete before it appears in print. The instructor must add references as they become available. The references cited must always reflect the experience, interests, and objectives of the instructor, the institution, and the students.

Equipment has been identified by model and manufacturer; instructors may substitute equivalent equipment or alter course content to make use of available equipment. This method of identification does not constitute a recommendation of particular equipment by either Oregon State University or the Bureau of Radiological Health, United States Department of Health, Education, and Welfare.

E. Dale Trout

E. Dale Trout, D.Sc., Project Director

Director
X-Ray Science and Engineering Laboratory
Oregon State University

GS-461 MACHINE SOURCES OF X RAYS

SECTION I

LECTURES

LECTURE NO. 1

TITLE: Fundamental Atomic Structure

PURPOSE: To familiarize the student with the fundamental concepts of atomic structure

TIME: One hour

VISUAL AIDS: Blackboard

HANDOUTS: 461 - 1 Atomic Building Blocks
461 - 2 Constants

REFERENCES:

Cember
Introduction to Health Physics

Holsington
Nucleonics Fundamentals

Johns and Cunningham
The Physics of Radiology

Kaplan
Nuclear Physics

Lapp and Andrews
Nuclear Radiation Physics

FUNDAMENTAL ATOMIC STRUCTURE

I. Structure of the Atom

A. Dense core (nucleus) with electrons traveling in specific orbits or energy levels about nucleus (Fig. 461-1)

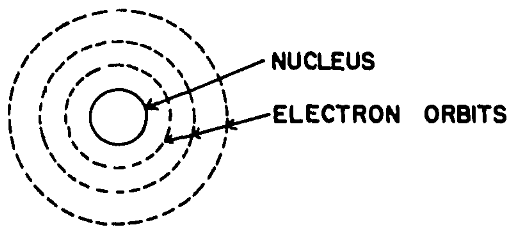


Figure 461-1 Structure of atom

1. Nucleus

   a. Protons--positively charged

   b. Neutrons--neutral

$$m_p \approx m_p$$

2. Forces in nucleus

   a. Coulomb forces from charged protons

      1. Repulsive force

      2. Force $\propto \; 1/r^2$

      3. Tends to disrupt nucleus

   b. Nuclear force--holds nucleus together

      1. Short range--acts at distances less than 10^{-13} cm

      2. Must overcome coulomb forces for nucleus to be stable

3. Electrons

   a. Approximately 1/2000 the mass of a neutron or proton

   b. Negative charge

c. Atom is electrically neutral if total electron charge equals total proton charge

d. Electrons bound to nucleus with negative energy

4. Coulomb force between electrons and nucleus

a. Force $\propto 1/r^2$

b. Inner electrons are more tightly bound to the nucleus than are the outer shell electrons

II. Ionization

A. Process whereby an orbital electron acquires sufficient energy to free itself from the atom

Result is a positive and negative ion

III. Excitation

A. Process whereby an orbital electron acquires enough energy to raise it from a lower energy state to a higher energy state

IV. Atomic Nomenclature

A. Classic

$$X^{A}_{Z} \rightarrow Co^{60}_{27}$$

B. Present

$$^{A}X \rightarrow {}^{60}Co$$

X → Chemical symbol

A → Mass number

Z → Atomic number

N → Neutron number = A - Z

V. Atomic Sizes

A. Nuclear radius--experimentally determined

$$R = r_o A^{1/3}$$

R = Radius of nucleus--cm

A = Mass number

$r_o = 1.37 \times 10^{-13}$ cm

B. Radius of atom approximately 10^5 times the radius of the nucleus

VI. Mass and Energy Units

A. erg = dyne · cm = g · cm^2 · sec^{-2}

B. joule = newton · m = kg · m^2 · sec^{-2}

10^7 ergs/joule

C. Electron volt--kenetic energy acquired by an electron accelerated through a potential difference of 1 volt

1. 1.6×10^{-12} erg = 1 eV
2. 1.6×10^{-19} joule = 1 eV
3. 1 MeV = 10^6 eV
4. 1 keV = 10^3 eV

D. Atomic mass unit--amu

1. 1 amu = 1/16 mass of $^{16}0$
2. Mass equivalent

   1.66×10^{-24} g = 1 amu
3. Energy equivalent

   $$E = mc^2$$
   $$= (1.66 \times 10^{-24} \text{ g/amu})\ (3 \times 10^{10} \text{ cm sec})^2$$
   $$= 14.9 \times 10^{-4} \text{ ergs/amu}$$
   $$= 931 \text{ MeV/amu}$$

VII. Nuclear Binding Energy

A. Mass of atom is less than the mass of the composite parts

Difference = mass defect (MD)

$$MD = Z \cdot m_p + N \cdot m_n + Z \cdot m_e - m_{atom}$$

B. Oxygen $^{16}O_8$

1. $Z \cdot m_p$ = (8) (1.007594) = 8.061 amu
2. $N \cdot m_n$ = (8) (1.008986) = 8.072
3. $Z \cdot m_e$ = (8) (0.000549) = 0.004

Total	16.137 amu
$-m_{atom}$	-16.000
MD =	0.137 amu

C. Energy equivalent

$E = (0.137 \text{ amu})\ (931 \text{ MeV/amu}) = 128 \text{ MeV}$

D. Binding energy per nucleon

$BE/n = 128 \text{ MeV}/\ 16 = 8 \text{ MeV/nucleon}$

VIII. Particles of the Nucleus:

A. Neutrons (n)

1. 1.008986 amu

2. No charge

3. As a free particle it decays

a. $n \rightarrow e + p + \nu$

b. $T_{1/2} = 12.5$ min

B. Proton (p)

1. 1.0075[illegible]4 amu

2. Charge = [illegible] e = 1.6×10^{-19} coulombs

3. Stable

C. Electron (e)

1. If emitted from a nuclide called a beta (β) particle

2. 0.000549 amu

D. Positron (e^+)

1. Positive electron

2. β^+ if emitted from nuclide

E. Alpha particle (α)

1. Nucleus of He atom $\rightarrow He^{++}$

2. It has 2 n and 2 p so A = 4

3. Charge = +2e

F. Photons--electromagnetic radiation

1. Gamma rays

2. X rays

G. Nucleon

1. Particle of the nucleus

2. n or p

H. Nuclide

Atom characterized by properties of the nucleus

I. Isotopes--same number of protons (Z)

${}^{16}_{8}\mathrm{O}$, ${}^{17}_{8}\mathrm{O}$, ${}^{18}_{8}\mathrm{O}$

J. Isotones--same number of neutrons (N)

${}^{15}_{7}\mathrm{N}$, ${}^{16}_{8}\mathrm{O}$, ${}^{17}_{9}\mathrm{F}$

K. Isobars--same mass number (A)

${}^{17}_{8}\mathrm{O}$, ${}^{17}_{7}\mathrm{N}$, ${}^{17}_{9}\mathrm{F}$

Handout 461-1

Atomic Building Blocks

Unit	Symbol (Common and Alternate)	Relative Mass amu	Charge (Electrical) Coulombs	esu	Relative
Fundamental					
Proton	p, ${}^{1}H$	1.007596	1.6×10^{-19}	4.8×10^{-10}	+
Electron	e, ${}^{1}\beta^{-}$	0.000549	1.6×10^{-19}	4.8×10^{-10}	-
Neutron	n, ${}^{1}_{0}n$	1.008986	0	0	0
Generated					
Positron	e^{+}, β^{+}	0.000549	1.6×10^{-19}	4.8×10^{-10}	+
Derived					
Deuteron	d, ${}^{2}_{1}H$	2.014187	1.6×10^{-19}	4.8×10^{-10}	+
Alpha	a, ${}^{4}_{2}He$	4.002777	3.2×10^{-19}	9.6×10^{-10}	+

Handout 461-2

Constants To Be Used In GS-461

Constant	Symbol	Value
mass of proton	m_p	1.6724×10^{-27} kg
" " "	"	1.007596 amu
mass of neutron	m_n	1.6747×10^{-27} kg
" " "	"	1.008986 amu
mass of electron	m_e	9.1084×10^{-31} kg
" " "	"	0.0005488 amu
atomic mass unit	amu	1.65983×10^{-27} kg
Plank's constant	h	6.63×10^{-27} erg·sec
Boltzmann's constant	k	8.62×10^{-5} eV/^{o}k
Avogadro's number	N_o	6.03×10^{23} molecules per mole
velocity of light	c	3.00×10^{10} cm/sec
charge of electron	e	4.80×10^{-10} esu
" " "	"	1.60×10^{-19} emu
Angstrom	Å	10^{-8} cm
energy conversion factor	--	1eV = 1.60×10^{-12} ergs
mass-energy conversion	--	1 amu = 931 MeV

GS - 461 MACHINE SOURCES OF X RAY

Homework Problems

1. Briefly describe the basic structure of the atom including component parts, configurations, forces, etc.

   Ans: The atom consists of a small positively charged nucleus of matter surrounded by even smaller negatively charged particles which circulate in a series of orbits or energy levels around the nucleus. Atomic radii are about 10^{-8} cm while nuclear radii are about 10^{-13} cm. The nucleus consists of neutrons (neutral charge) and protons (positive charge) which have masses of 1.675×10^{-27} kg and 1.672×10^{-27} kg respectively. The nucleus is held together by short-range nuclear force. The orbiting particles are electrons (negative charge) with a mass of 9.108×10^{-31} kg and are restrained to the nucleus by coulombic force.

2. Define the following:

   a. Ionization
   Ans: The process or result of any process by which a neutral atom or molecule acquires either a positive or negative sign.

   b. Excitation
   Ans: The addition of energy to a system, thereby transferring it from its ground state to an excited state.

   c. Mass defect
   Ans: The difference between the mass of the intact atom and that of the sum of the individual components of the atom.

   d. Binding energy
   Ans: Energy that must be added to separate the particles completely.

   e. Electron volt
   Ans: The kenetic energy gained by a particle with charge e when accelerated by a potential difference of one volt.

f. Coulomb force

Ans: Electrical force between charged particles which decreases as the inverse square of the distance between them.

g. amu

Ans: Atomic mass unit.

3. Nuclear radii may be approximated by $R = r_o A^{1/3}$ where R = nuclear radius, A = mass number and $r_o = 1.37 \times 10^{-13}$ cm.

a. Show that the nuclear density is essentially the same for all atoms.

Ans: $R = r_o A^{1/3}$

$$\frac{4}{3}\pi R^3 = \frac{4}{3}\pi r_o^3 A$$

$$\rho = \frac{m}{v} = \frac{(A)\ (1.67 \times 10^{-27}\ \text{kg})}{\frac{4}{3}\pi R^3} = \frac{1.67 \times 10^{-27}\ \text{kg}}{\frac{4}{3}\pi r_o^3}$$

where 1.67×10^{-2} kg $\cong$ mass of neutron or proton

$$\therefore \rho = \text{constant} = \frac{3.98 \times 10^{-28}\ \text{kg}}{r_o^3}$$

b. Calculate the density in g/cm^3. How does this compare with the density of water?

Ans: $r_o = 1.37 \times 10^{-13}$

$$\rho = \frac{3.98 \times 10^{-28}}{(1.37 \times 10^{-13})^3} = 1.55 \times 10^{11}\ \text{kg/cm}^3$$

$\rho = 1.55 \times 10^{14}$ g/cm^3 or approximately 10^{14} times as dense as water (1 g/cm^3)

4. Calculate the total binding energy and the binding energy per nucleon of ^{16}O. Show all work.

Ans:

8 protons	=	8 (1.00759 amu)	=	8.0607
8 neutrons	=	8 (1.00898 amu)	=	8.0718
		Total neucleon mass	=	16.1325

mass of ^{16}O atom	=	16.00000
mass of 8 electrons	=	- .00440
mass of ^{16}O nucleus	=	15.9956
mass difference	=	0.1369 amu

Total binding energy = (0.1369 amu) (931 MeV/amu)
= 127.5 MeV

Average binding energy $= \frac{127.5}{16} = 7.97$ MeV per nucleon

5. Approximately what fraction of a ^{12}C atom is occupied by matter?

Ans: Assuming that essentially all of the matter is contained in the nucleus:

radius of nucleus $\cong 10^{-13}$

radius of atom $\cong 10^{-8}$

fraction occupied by matter $\cong \frac{(10^{-13})^3}{(10^{-8})^3} \cong 10^{-15}$

LECTURE NO. 2

TITLE: History and Properties of X Rays

PURPOSE: To review the discovery of x rays and the fundamentals of electromagnetic theory

TIME: Two hours

VISUAL AIDS: Blackboard

HANDOUTS: 461-3 Electromagnetic Spectrum

REFERENCES: Eisberg
Fundamentals of Modern Physics

Glasser
Dr. W. C. Rontgen

Sears and Zemansky
College Physics

HISTORY AND PROPERTY OF X RAYS

I. "Discovered" in 1895 by W. C. Roentgen (Röntgen)

A. Roentgen was working with evacuated tubes and studying cathode rays (electrons).

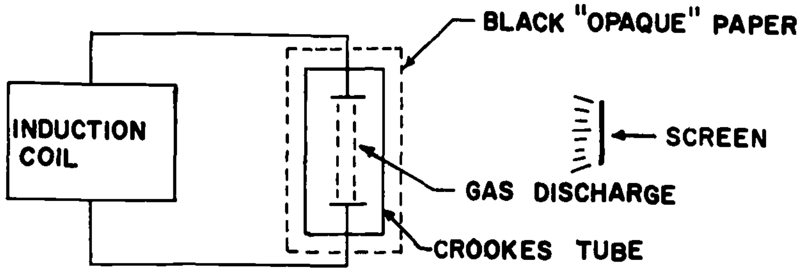


Figure 461-2 Roentgen's experimental apparatus

B. He covered tube with opaque paper to block the fluorescent glow of the discharge from within the tube (Fig. 461-2)

1. He noticed that a nearby barium platinocyanide screen was glowing

2. Concluded that it could only be the result of "light" from the tube; but the tube was covered with a light opaque shield.

3. He concluded that the unknown rays were of great penetrating power and coming from the tube

4. Roentgen called these unknown rays "x rays".

II. Electromagnetic Radiation

A. Maxwell - 1856

1. Predicted the nature of electromagnetic waves

2. Proposed that an oscillating charged particle could produce (be source of) electromagnetic waves

3. Velocity given by $v = 1/\mu\epsilon$

a. μ = permeability

b. ϵ = permitivity

4. For air

a. $\mu = 4\pi \times 10^{-7}$ henry/m

b. $\epsilon = 1/36\pi \times 10^{-9}$ farad/m

c. $v = 3 \times 10^{8}$ m/sec

B. Hertz - 1888

1. Experimentally confirmed Maxwell's theory

a. By oscillating a charged particle he produced a transverse electromagnetic wave

b. Used oscillating electric circuit (Fig. 461-3)

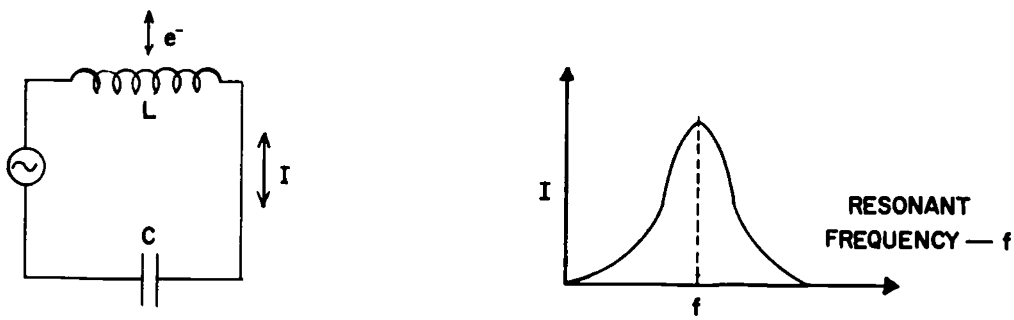


Figure 461-3 Hertz experimental setup

c. Hertz detected electromagnetic waves with tuned resonant circuit. Radio simile:

1) Output (station) $f_1 = \frac{1}{2\pi L_1 C_1}$

2) Receiver (radio) $f_2 = \frac{1}{2\pi L_2 C_2}$

3) Tune radio by C_2 so $f_1 = f_2$

d. Electromagnetic radiation as produced by Hertz could be <u>reflected</u>, <u>diffracted</u> and <u>polarized</u> as could light

e. The velocity of electromagnetic radiation was the same as light so Hertz concluded that light was electromagnetic radiation

III. Properties of X Rays

A. Roentgen's experiments in the six weeks following his discovery of x rays confirmed the nature of x rays as electromagnetic radiation.

B. X rays exhibited the following properties

1. Polarized - assume definite form
2. Transverse vibration
3. Refracted
4. Diffracted (Lave - 1912)
5. Reflected (Bragg 1914, Kirkpatrick 1947)
6. Travel at the velocity of light
7. Travel in straight lines
8. Are unaffected by electromagnetic field
9. Exhibit dual nature
10. Are extranuclear
11. Are pure energy
12. Are differentially attenuated
13. Produce excitation and ionization

IV. Dual Nature of Radiation

A. Radiation--definition

1. Energy transferred through space
   a. The kenetic energy of a particle
   b. An electromagnetic wave

B. Dual nature behavior

1. Black body radiation
   a. Thermal radiation from a black object at a given temperature (perfect absorber and radiator)
   b. Raleigh - Jeans
      1) Used a pure classical approach

2) Results held for large λ

3) Oscillating concept with any frequency and energy possible

c. Plank - 1901

1) An oscillating particle may have any frequency but the energy is quantitized.

2) $E = nh\nu$

a) ν = frequency of vibration

b) h = constant = 6.625×10^{-34} joule·sec

c) $n = 1, 2, 3 \ldots\ldots$

d) Example - calculate energy carried by one photon of $\lambda = 1.0$ Å or 10^{-10} m

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^{8}}{10^{-10}} = 3 \times 10^{18}$$

vibrations/sec

$E = (1)\ (6.625 \times 10^{-34})\ (3 \times 10^{18}) =$ 19.88×10^{-16} joules = 12,400 eV = 12.4 keV

e) $E = h\nu = \dfrac{hc}{\lambda} \qquad E_{eV} = \dfrac{12,400}{\lambda\ (\text{Å})}$

3) When an oscillating particle emits radiant energy it does so in the form of electromagnetic waves and only in "chunks" or "packets"

d. Photoelectric effect - Einstein - 1905 (Fig. 461 - 4)

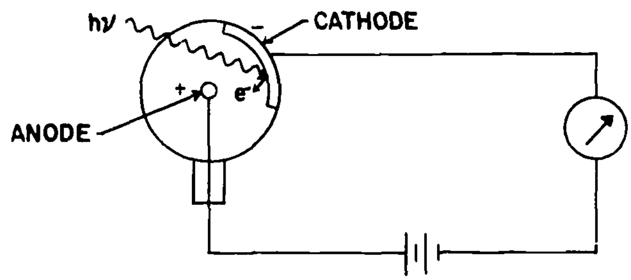


Figure 461 - 4 Photoelectric Effect

1) Classically, the field causes electrons to oscillate
   a) The electron ejection should be intensity dependent, i.e. cause the electron to oscillate and, when its amplitude is large enough, be ejected
   b) For certain frequencies there is no ejection no matter how large the intensity
   c) A lower intensity should take longer time to eject an electron than a higher intensity
   d) However an electron is immediately ejected when struck by light
2) Quantum interpretation by Einstein
   a) Electromagnetic waves are quantized and consist of discrete quanta called photons
   b) Each photon has energy depending only on its frequency or wavelength
   c) $E = h\nu = h\frac{c}{\lambda}$
   d) Energy of ejected electron
      $E_e = 1/2\, m_e v^2 = h\nu - W$ where
      W is the work function

e. Millikan - 1916

1) Experimentally verified the photoelectric effect

2) Used an electric field to prevent e^- from reaching the anode

3) Verified value of h

f. Quantum relations

1) $E = h\nu$

a) E = energy in ergs, h = Planks constant in erg · sec (6.67×10^{-27}), ν = frequency in cps or hertz (Hz)

2) $P = E/c$

a) P = momentum in $g \cdot cm \cdot sec^{-1}$, E = energy in ergs, c = velocity of light in $cm \cdot sec^{-1}$

3) $\lambda = c/\nu$

a) λ = wavelength in cm

Handout 461-3

The Electromagnetic Spectrum

Type of Radiation	Frequency - Hz	Wavelength	Photon Energy
Electric Waves	$< 1 \times 10^5$	$> 3 \times 10^5$ cm	$< 4.1 \times 10^{-10}$ eV
Radio Waves	1×10^5	3×10^5 cm	4.1×10^{-10} eV
	to		
	3×10^{10}	1.0 cm	1.24×10^{-4} eV
Infrared	3×10^{12}	0.01 cm	0.0124 eV
	to		
	3×10^{14}	10,000 Å	1.24 eV
Visible			
Red	4.3×10^{14}	7,000 Å	1.77 eV
	to		
	4.64×10^{14}	6,470 Å	1.92 eV
Orange	4.64×10^{14}	6,470 Å	1.92 eV
	to		
	5.13×10^{14}	5,850 Å	2.12 eV
Yellow	5.13×10^{14}	5,850 Å	2.12 eV
	to		
	5.22×10^{14}	5,750 Å	2.16 eV
Maximum Visibility	5.4×10^{14}	5,560 Å	2.24 eV
Green	5.22×10^{14}	5,750 Å	2.16 eV
	to		
	6.11×10^{14}	4,910 Å	2.53 eV
Blue	6.11×10^{14}	4,910 Å	2.53 eV
	to		
	7.07×10^{14}	4,240 Å	2.93 eV
Violet	7.07×10^{14}	4,240 Å	2.93 eV
	to		
	7.5×10^{14}	4,000 Å	3.1 eV

Type of Radiation	Frequency - Hz	Wavelength	Photon Energy
Ultra-violet	7.5×10^{14} to 3×10^{16}	4,000 Å – 100 Å	3.1 eV – 124 eV
X Ray			
Soft	3×10^{16} to 3×10^{18}	100 Å – 1 Å	124 eV – 12.4 keV
Diagnostic and Superficial Therapy	3×10^{18} to 3×10^{19}	1 Å – 0.1 Å	12.4 keV – 124 keV
Deep Therapy	3×10^{19} to 3×10^{20}	0.1 Å – 0.01 Å	124 keV – 1.24 MeV
Small Betatron	3×10^{21}	0.001 Å	12.4 MeV
Large Betatron	3×10^{22}	0.0001 Å	124 MeV
Proton Synchrotron	3×10^{23}	0.00001 Å	1,240 MeV
Gamma Rays	3×10^{18} to 3×10^{21}	1 Å – 0.001 Å	12.4 keV – 12.4 MeV
Cosmic Photons	$> 3 \times 10^{21}$	$<$ 0.001 Å	$>$ 12.4 MeV

LECTURE NO. 3

TITLE: X-Ray Production

PURPOSE: To study the mechanisms of x-ray production

TIME: Two hours

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES: Clark
Applied X-Rays

Compton and Allison
X-Rays in Theory and Experiment

Evans
The Atomic Nucleus

Kaplan
Nuclear Physics

X-RAY PRODUCTION

I. Introduction

A. There are two methods of x-ray production (Fig. 461-5)

1. Continuous

2. Characteristic

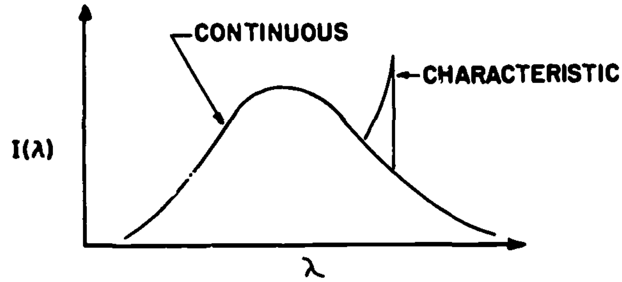


Figure 461 - 5 X-ray Spectrum

II. Continuous (Fig. 461 - 6)

A. Referred to as bremsstrahlung (breaking radiation) or "white" radiation

1. An incident electron passes close to nucleus of target atom and is strongly deflected by the attraction of the charged, positive nucleus

2. The electron is suddenly decelerated and loses energy which is emitted as x radiation

3. The energy emitted as x radiation depends upon the closeness of the electron path to the target nucleus

a. The energy emitted can be any value from zero to the total kenetic energy of the electron

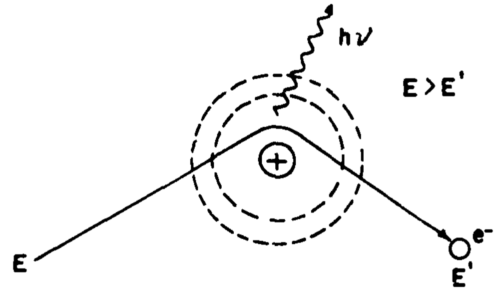


Figure 461 - 6 Diagram of Continuous Radiation Production

B. Classical theory

1. Predicts that electromagnetic radiation will be emitted whenever a charged particle undergoes an acceleration
   a. Predicts that every electron scatter is inelastic i.e. radiation is emitted.
2. Intensity of radiation $\propto$ (acceleration)^2
   a. Amplitude (A) $\propto$ acceleration (a)
      1) Intensity $\propto A^2$
   b. $\therefore I \propto a^2$ (Fig. 461-7)

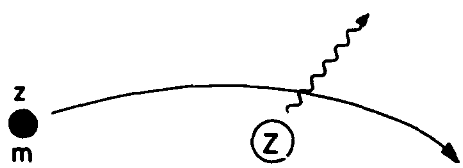


Figure 461-7 Classical Interaction

   c. $a = \dfrac{F}{m} = \dfrac{8\ Q}{r^2 m} = \dfrac{(ze)\ (Ze)}{r^2 m}$
   d. $I \propto a^2 = \dfrac{z^2 Z^2 e^4}{r^4 m^2}$
      1) Z = atomic number of nucleus
      2) z = charge of particle
      3) e = unit charge
      4) r = distance between particle and nucleus
      5) m = mass of particle

3. Important result

   a. $I \propto \frac{Z^2}{m^2}$

      1) This is why electrons are better than heavier charged particles in producing x rays since $I \propto 1/m^2$

      2) Example: consider electron and proton

         a) $\frac{m_e}{m_p} = \frac{9 \times 10^{-31}\ kg}{1 \times 10^{-27}\ kg} \approx 10^{-3}$

         b) Electron more efficient in producing x rays by factor of $(10^{-3})^2$ or 10^6

4. Classical theory, however, incorrectly predicts an emission in every collision

C. Quantum mechanics vs classical theory

1. A radiative event (inelastic scatter) is less probable than a non-radiative event (elastic scatter)

   a. The probability of inelastic scatter is 1/137 the probability of elastic scatter

2. Both quantum mechanics and classical theory predict same total energy emitted in form of photons, but:

   a. Classical → many small energy losses (photons)

   b. Quantum → fewer but larger energy losses (photons)

3. Experiment agrees with quantum mechanics theory

D. Quantum theory

1. Angular distribution

   a. Consider an electron with a kenetic energy of E_o

      1) $h\nu \leq E_o$

   b. Angle of emission for $E_o < m_oc^2$ can be in any direction

   c. For relativistic energies $E_o > 10\ m_oc^2$

      1) Average angle of emission $\theta \approx \frac{m_oc^2}{E_o}$

d. For low energies the maximum intensity is at right angle to the electron beam

e. As energy increases, x-ray production becomes more forward in direction

2. Thin target theory

a. Relative intensity (Fig. 461-8)

1) $I(\nu) = \left[\dfrac{\text{Energy}}{\text{Photon} \cdot \text{freq. interval}} \right]$

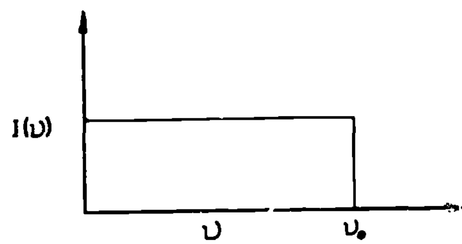


Figure 461-8 Thin Target Theory

2) The radiation in any direction resulting from electrons of a given energy E_o has an intensity which is constant for all photon energies and cuts off abruptly at $h\nu_{max}$. Therefore, there is a spectrum of energies

b. Conditions to be satisfied for a thin target

1) No ionization

2) Only one interaction

3) No multiple collisions

c. Experiment is in agreement with quantum theory

d. But we do not have thin targets, we have thick ones

3. Thick target theory

a. Consider that a thick target consists of a series of thin targets (Fig. 461-9)

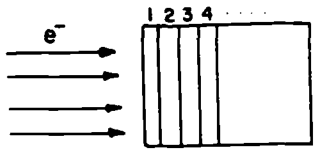


Figure 461 - 9 Thick Target Theory

b. An electron of energy E may interact in the first target layer and reach the second target layer with reduced energy E - dE, etc.

c. Total emission will be the sum of the individual interactions (Fig. 461 - 10)

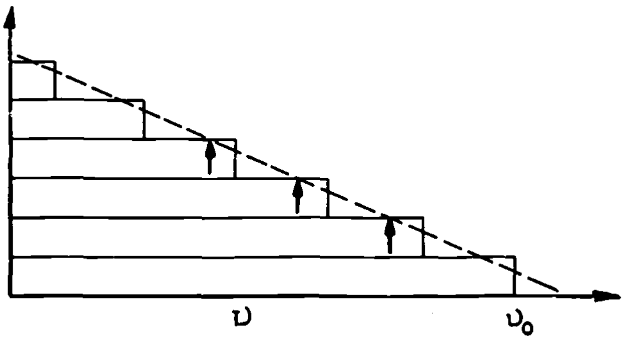


Figure 461 - 10 Individual Thin Target Interactions

d. Due to absorption of x rays in the target, the actual spectrum will be as shown in Fig. 461 - 11

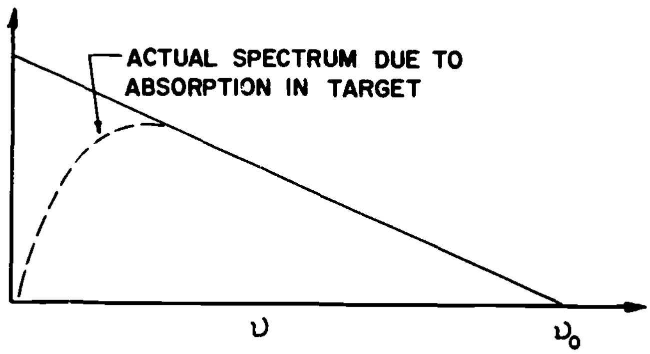


Figure 461 - 11 Spectrum with Target Absorption

e. Consider the relative intensity per unit wavelength I (λ) rather than per unit frequency I (ν)

   1) Since the total energy is the same, the area under both curves must be the same

2) $$A = \int_{0}^{\nu_o} I(\nu)\, d\nu = + \int_{\infty}^{\lambda_o} I(\lambda_o)\, d\lambda$$

$$= -\int_{\lambda_o}^{\infty} I(\lambda)\, d\lambda$$

3) $\therefore I\ (\nu)\ d\nu = -I\ (\lambda)\ d\lambda$

4) Since $\lambda = \frac{c}{\nu}$

$$-\frac{d\lambda}{d\nu} = \frac{c}{\nu^2} = \frac{\lambda^2}{c}$$

$$\therefore I\ (\lambda) = I\ (\lambda)\ \frac{c}{\lambda^2}$$

5) For a thin target, $I\ (\nu)$ = constant (Fig. 461-12)

a) $\therefore I\ (\lambda)$ = (constant) $\left(\frac{c}{\lambda^2}\right)$

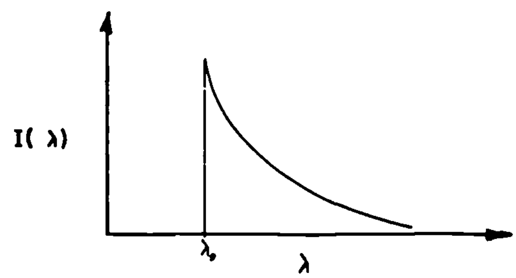


Figure 461 - 12 Thin Target Spectrum

6) For a thick target

a) $I\ (\nu) = a\ (\nu_o - \nu)$

b) $\therefore I\ (\lambda) = a\ (\nu_o - \nu)\ \frac{c}{\lambda^2}$

$$= a \left[\frac{1}{\lambda_o} - \frac{1}{\lambda} \right] \frac{c^2}{\lambda^2}$$

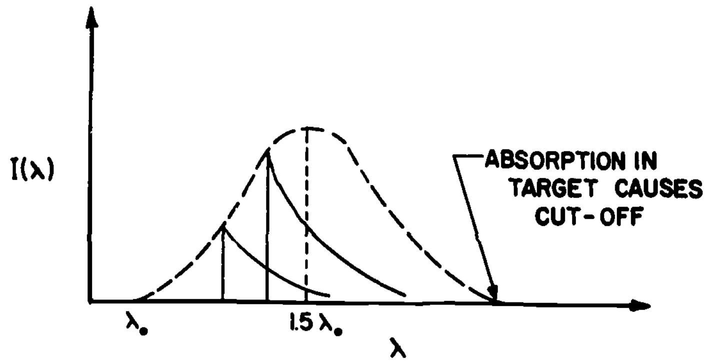


Figure 461 - 13 Thick Target Spectrum

III. Characteristic X Rays

A. Origin (Fig. 461 - 14)

1. High-speed electrons interact with orbital electrons resulting in ionization or excitation

2. Photons of specific energy are emitted as the shells fill and the atom returns to its ground state

3. Photons emitted are called characteristic x rays since their energy is characteristic of the atom and the type of transition.

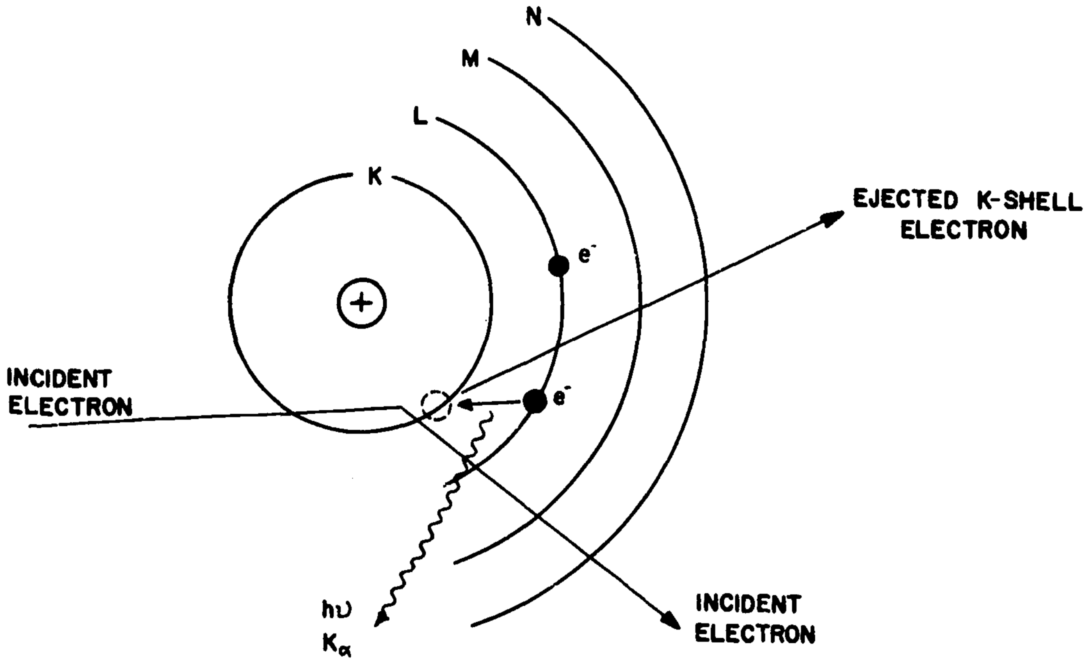


Figure 461 - 14 Production of Characteristic X rays

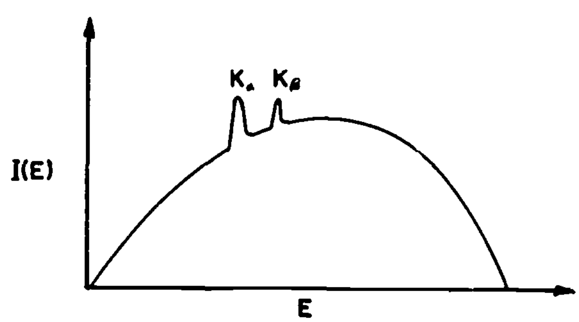


Figure 461 - 15 Spectrum with Continuous and Characteristic Radiation

B. Designated by type of transition

Transition	Characteristic x ray
L → K	K_α
M → K	K_β
N → K	K_γ
M → L	L_α
N → L	L_β

C. Characteristic radiation superimposes peaks on the bremsstrahlung spectrum (Fig. 461 - 15)

1. Contribute only a small percentage of the total

D. X-ray energy

1. Binding energy W
2. $K_\alpha = W_K - W_L$
3. For tungsten
   a. $W_K = 69.5$ keV
   b. $W_L = 12.1$ keV
   c. $W_M = 2.81$ keV
4. $\therefore K_\alpha = 69.5 - 12.1 = 57.4$ keV

IV. Efficiency of X-Ray Production

A. The fraction, F, of the electron's kenetic energy, E_o, which is converted to x-ray energy, is a function of the atomic number, Z, of the target material and the electron energy, E_o

1. $F = \frac{\text{x-ray energy}}{\text{electron energy}} = kZE_o$
2. The constant, k, has been imperically derived by various investigators and the values lie between 0.7×10^{-6} and 1.1×10^{-6} for E_o expressed in keV
   a. We will use the value 1.1×10^{-6}

B. Example

1. 100 kVp with tungsten target (Z = 74)
2. $F = (1.1 \times 10^{-6})\ (74)\ (100)$

   $= 8 \times 10^{-3}$

   $= 0.8\%$
3. Heat produced is 1.00 - 0.008 = 0.992 or 99.2% of the total energy

GS - 461 MACHINE SOURCES OF X RAY

Homework Problems

1. Derive the following expression relating the wavelength of an x-ray photon to its energy:

$$\lambda = \frac{12.4}{E} \quad \text{where } \lambda \text{ is in Å and E in keV}$$

Ans: $E = h\nu$ and $c = \lambda\nu$ therefore $\lambda = \frac{hc}{E}$

$$\lambda = \frac{(6.625 \times 10^{-27} \text{ erg} \cdot \text{sec})(3 \times 10^{10} \text{ cm/sec})(10^{8} \text{ Å/cm})}{(E_1 \text{ keV})(1.6 \times 10^{-12} \text{ erg/eV})(10^{3} \text{ eV/keV})}$$

$$= \frac{19.85}{1.6E} = \frac{12.4}{E}$$

2. Calculate the energy in keV and the frequency in hertz of electromagnetic photons of wavelength:

a. 1 Å

b. 0.5 Å

c. 0.1 Å

d. 0.05 Å

Ans: $E\ (\text{keV}) = \frac{12.4}{\lambda\ (\text{Å})}$ and $\nu\ (\text{Hz}) = \frac{c\ (\text{cm/sec})}{\lambda\ (\text{cm})}$

a. $E = \frac{12.4}{1} = 12.4$ keV $\quad \nu = \frac{3 \times 10^{10}}{(1)(10^{-8})} = 3 \times 10^{18}$ Hz

b. $E = \frac{12.4}{0.5} = 24.8$ keV $\quad \nu = \frac{3 \times 10^{10}}{(0.5)(10^{-8})} = 6 \times 10^{18}$ Hz

c. $E = \frac{12.4}{0.1} = 124$ keV $\quad \nu = \frac{3 \times 10^{10}}{(0.1)(10^{-8})} = 3 \times 10^{19}$ Hz

d. $E = \frac{12.4}{0.05} = 248$ keV $\quad \nu = \frac{3 \times 10^{10}}{(0.05)(10^{-8})} = 6 \times 10^{19}$ Hz

3. Calculate the wavelength in miles and the energy in electron volts for a 60 Hz electric wave.

Ans: $\lambda = \frac{c}{\nu} = \frac{1.86 \times 10^{5} \text{ mi/sec}}{60 \text{ Hz}} = 3.1 \times 10^{3}$ miles

$$E = h\nu = \frac{(6.625 \times 10^{-27} \text{ erg} \cdot \text{sec})(60 \text{ Hz})}{1.6 \times 10^{-12} \text{ erg/eV}} = 2.49 \times 10^{-13} \text{eV}$$

4. What is the fraction of energy that would appear as heat when 75 keV electrons are used to produce x rays in a thick target made of:

   a. Aluminum
   b. Copper
   c. Tungsten
   d. Gold

Is there a significant difference in the amount of heat generated? Is there a significant difference in the amount of x-ray energy produced?

Ans: $F = 1 \times 10^{-6}\, ZE$ where E is in keV. Fraction as heat, $Q = 1 - F$

a. $Q = 1 - (10^{-6})(13)(75) = 1 - 0.000975 = 0.999025$

b. $Q = 1 - (10^{-6})(29)(75) = 1 - 0.00218 = 0.99782$

c. $Q = 1 - (10^{-6})(74)(75) = 1 - 0.00555 = 0.99445$

d. $Q = 1 - (10^{-6})(79)(75) = 1 - 0.00594 = 0.99406$

There is no significant change in heat produced in that the difference in heat between aluminum and gold is approximately 0.5%. There is a significant difference in the amount of x-ray energy produced. There is approximately a two-fold increase between aluminum and copper and six-fold increase between aluminum and gold.

LECTURE NO. 4

TITLE:	Transformers
PURPOSE:	To review basic transformer theory
TIME:	One hour
VISUAL AIDS:	Blackboard Disassembled filament transformer Disassembled iron core inductor Small self-rectified tube head with cover removed
HANDOUTS:	None
REFERENCES:	Dillow Alternating Current Fundamentals Sears and Zemansky College Physics

TRANSFORMERS

I. Introduction

A. The transformer is a device for transforming electrical energy at one alternating voltage into electrical energy at another (usually different) alternating voltage without a change in frequency

B. The transformer depends for its action upon mutual induction and consists, essentially, of two electrical circuits which are coupled together magnetically

1. The coils are wound together on the same core

2. The core provides an alternating mutual flux linkage between the windings

II. Transformer Construction (Fig. 461 - 16)

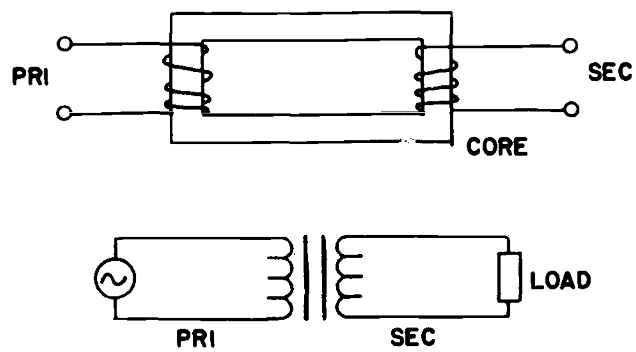


Figure 461 - 16 The Transformer

A. Primary winding (pri)

Receives energy from a.c. supply at one voltage

B. Secondary winding (sec)

Delivers energy to load at different voltage

C. Core

1. Air core, for use in certain high frequency, low power applications

2. Ferromagnetic core, commonly called an iron core transformer

   a. Provides a conductor (path) for the magnetic flux

   b. It couples both windings

   c. Iron has a higher permeability than air

   d. The core is usually constructed in either a core-type or shell-type configuration (Fig. 461-17)

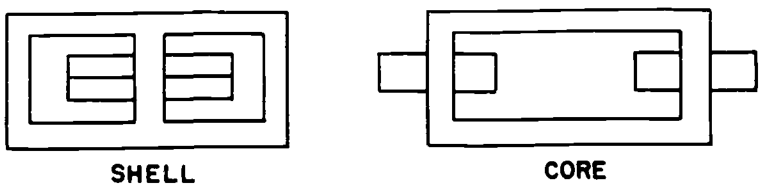


Figure 461 - 17 Transformer Core Configurations

3. The magnetic circuit usually consists of a stack of thin laminations

   a. Used to reduce eddy current losses

   b. At low frequencies the laminations are typically 0.01 -- 0.02 inches thick

   c. Common core material is silicon steel

III. Principle of Operation

A. Ideal transformer

1. Negligible losses

   a. Electrical power input to the primary equals the electrical power output of the secondary

   b. There is negligible magnetizing current

   c. There is negligible leakage reactance

   d. There is negligible internal capacitance

2. A changing magnetic flux will cause a current to flow in a conductor

a. The current in the primary produces a changing magnetic flux which induces a current flow in the secondary

b. Terminal voltages V_1 and V_2 for transformer (Fig. 461-18)

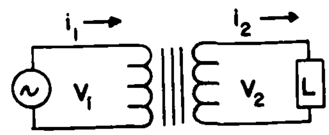


Figure 461-18 Transformer Terminal Voltages

1) $V_1 = L_1 \frac{di_1}{dt} - M \frac{di_2}{dt}$

2) $V_2 = M \frac{di_1}{dt} - L_2 \frac{di_2}{dt}$

3) Where L_1 and L_2 are the self-inductance of the primary and secondary windings, M is the mutual inductance, i_1 and i_2 are the primary and secondary currents

c. Relation between primary and secondary voltages

1) $V_1 = N_1 \frac{d\phi_1}{dt}$

2) $V_2 = N_2 \frac{d\phi_2}{dt}$

3) Where N is the number of turns of a winding and ϕ is the flux through that winding

4) For ideal transformer $\phi_1 = \phi_2$ so:

a) $\frac{V_1}{V_2} = \frac{N_1}{N_2}$

d. Relation between primary and secondary currents

1) $\phi_1 = \phi_2$ where $\varphi = \mu NiA$

a) μ = permeability of core, A = cross-sectional area of core

2) $\therefore \mu_1 N_1 i_1 A_1 = \mu_2 N_2 i_2 A_2$

3) For an ideal transformer

a) $\mu_1 = \mu_2$

b) $A_1 = A_2$

c) $\therefore \dfrac{N_1}{N_2} = \dfrac{i_2}{i_1}$

B. Regulation losses

1. Loss of voltage with increasing change in current

2 Resistance - R

a. Windings have resistance

1) Resistance is a function of the material (usually copper), its cross-section area and length

3. Reactance - X

a. Reactance is the resistance to a.c. current flow due to inductance and/or capacitance

b. X_L = inductive reactance

c. X_C = capacitive reactance

4. Impedance - Z

a. Impedance is the vector sum of the reactance and the resistance

b. Z = RjX

c. $/Z/ = R^2 + X^2$

5. Voltage drop across load impedance

$\Delta V = iZ$

6. Example: consider step up transformer with $Z = 40{,}000$ ohms (Fig. 461-19)

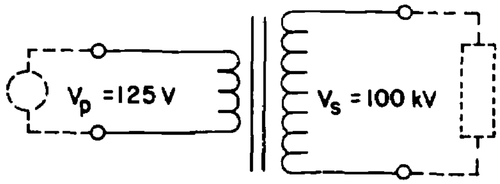


Figure 461 - 19 Regulation loss example

a. At $i = 5$ mA

$\Delta V = iZ = (0.005)\ (40{,}000) = 200$ volts (0.2 kV)

b. At $i = 300$ mA

$\Delta V = iZ = (0.3)\ (40{,}000) = 12{,}000$ volts (12 kV)

c. You compensate for regulation losses by increasing the primary voltage

1) With no load $i_s = 0$, $V_p = 125$, $V_s = 100$ kV

a) $$\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{100{,}000}{125} = 800$$

2) With load where $i_s = 300$ mA

a) $\Delta V = 12$ kV

b) $V_s = 100 - 12 = 88$ kV

c) But we want 100 kV at $i_s = 300$ mA

d) $\therefore$ we need V_s at $i = 0$ to be 100 kV + 12 kV = 112 kV

e) $V_p = V_s \dfrac{N_p}{N_s}$ at $i = 0$ so $V_p = \dfrac{(100 + 12)\text{ kV}}{800}$

and $V_p = 140$ volts

IV. Types of Transformers

A. Common two winding transformers

1. Step up $N_s > N_p$

2. Step down $N_s < N_p$

3. High voltage transformer

   a. Step up

   b. Provides high-voltage to operate the x-ray tube

   c. Typically 110/220 → 100,000 volts

   d. Requires suitable electrical insulation

      1) Usually oil

         a) Oil has 10-15 times the dielectric strength of air

         b) Oil deteriorates with heat and x-ray absorption to an organic acid and carbon

         c) Life of transformer oil is typically 5-15 years

         d) Oil also acts as a coolant

      2) Gas

         a) Sulfurhexafluoride - SF - 6

         b) Dichlorodifluoromethane-Freon

4. Filament transformer

   a. Step down

   b. Supplies power to the x-ray tube and to HV rectifier tube filaments

   c. Isolates the low voltage and high voltage parts of the circuit

   Requires suitable insulation

B. Autotransformer

1. Varies voltage applied to primary of HV transformer

2. Consists of a single winding on a core embodying both primary and secondary windings

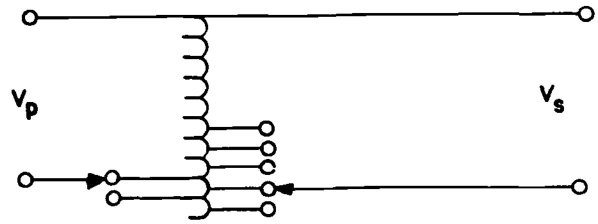


Figure 461-20 The autotransformer

3. Provides a method for varying voltage with little loss of power
   a. With a rheostat a large portion of the electrical energy is dissipated as heat
4. The input is variable to compensate for small changes in the input voltage
5. The output is variable to provide voltages for other circuit elements, i.e. HV transformer primary

Name ______________________

GS 461 -- Quiz 1 -- 1970-71

1. In an ideal transformer, what is the relationship between the primary and secondary voltage and current with respect to the transformer turns ratio?

Ans: $\frac{N_p}{N_s} = \frac{E_p}{E_s} = \frac{I_s}{I_p}$

2. Why are electrons, rather than protons, alpha particles or deuterons used for the production of x rays?

Ans: $I \propto \frac{1}{m^2}$ where I = intensity of radiation and m is the mass of the particle

3. Why are two rectifiers rather than one used in half-wave rectified x-ray units?

Ans: To remove a.c. from both HV cables

LECTURE NO. 5

TITLE:	Basic X-Ray Circuit
PURPOSE:	To introduce a basic x-ray machine circuit
TIME:	One hour
VISUAL AIDS:	Blackboard
HANDOUTS:	461-4 (Figure 461-22) X-ray machine circuit diagram
REFERENCES:	Bloom, Hollenbach and Morgan Medical Radiographic Technic
	General Electric Technical Publication Principles of X-ray Generation
	Ter-Pogossian Physical Aspects of Diagnostic Radiology

BASIC X-RAY CIRCUIT

I. Introduction

Over the past 75 years, x-ray equipment has evolved from the simple combination of components used by early investigators into the presently modern sophisticated equipment. To understand the operation of modern x-ray equipment we must begin with the basic components.

II. The X-Ray Machine

A. Basic features include:

1. Control circuits
2. A high-voltage generator
3. The x-ray tube

B. Refinements include:

1. Ease and precision of control
2. Safeguards

III. Basic Circuit

A. Block Diagram

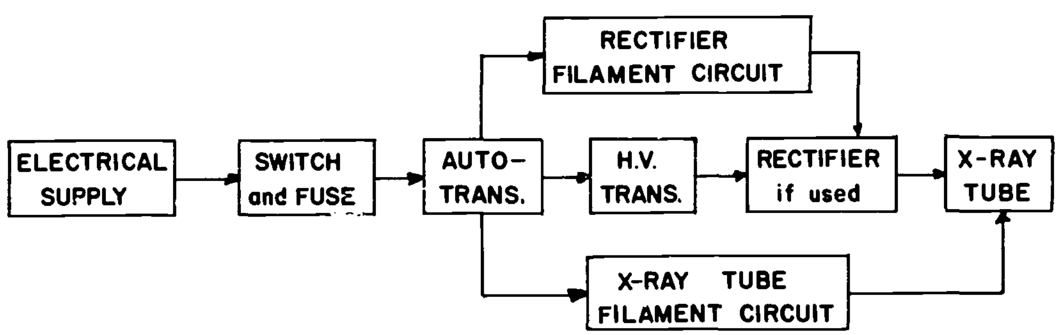


Figure 461-21 Block Diagram of a Basic X-Ray Circuit

B. X-ray machine circuit diagram (Fig. 461-22 handout)

IV. Basic Components

A. The electrical supply

1. Voltage range

2. Frequency

3. Regulation

B. Line switch

1. It may be of the circuit breaker type or use fuses

2. Often provided with a line "on" pilot light

C. Autotransformer

1. Single winding on a core

2. It provides a variable voltage output to the HV transformer

3. It provides a fixed output voltage taps for:

a. X-ray tube filament

b. Rectifier filament

c. Lights and relays

d. Timer

4. It provides for input voltage compensation

5. Variable output taps often calibrated in kVp

D. X-ray timer

1. Can be mechanical (old) or electrical (modern)

2. Timer controls the length of the exposure

3. It actuates the x-ray contactor to start and stop the exposure

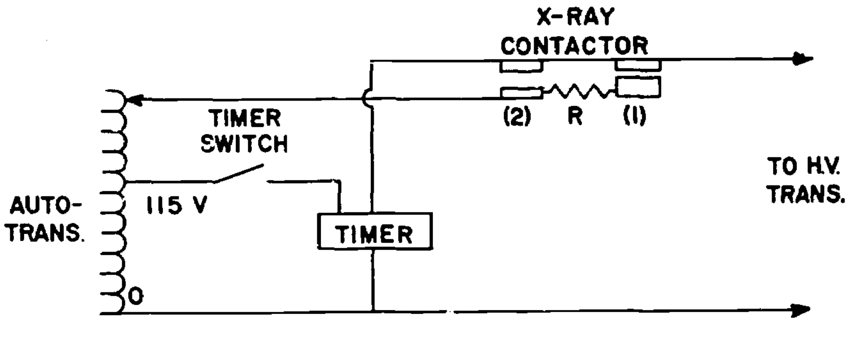


Figure 461-23 X-ray contactor circuit

E. X-ray contactor (Fig. 461-23)

1. A multiple contact relay

2. First contacts (1) close

   a. Places R in series with the HV transformer primary

   b. Reduces switching transients

3. Second set of contacts (2) close moments later

   a. Shorts out R

   b. Applies full voltage to the HV primary

F. X-ray tube filament control

1. Varies the filament transformer primary voltage

   a. Varies the temperature of the filament

   b. Varies the x-ray tube current.

G. Inverse reducer

1. Consists of diode with a power resistor in parallel.

2. It is used to decrease the unused half cycle peak voltage. (Fig. 461-24)

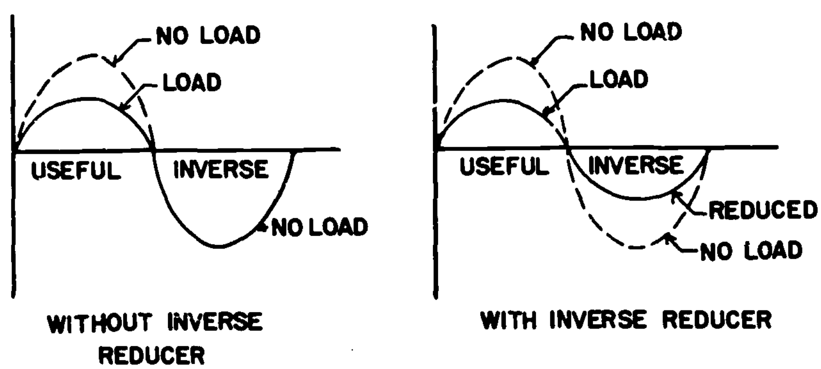


Figure 461-24 Voltage waveforms with and without inverse reducer

H. HV transformer

1. Steps up voltage

2. The maximum rating is controlled by the transformer insulation

3. Center-tapped and grounded secondary (Fig. 461-25)

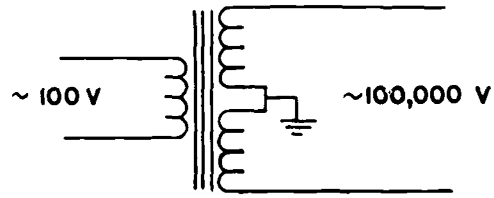


Figure 461-25 Transformer with center-tapped secondary

I. X-ray tube filament transformer

1. Steps down voltage, steps up current
2. Electrically connected to the HV transformer
   Requires high electrical insulation
3. Supplies power to the x-ray tube filament

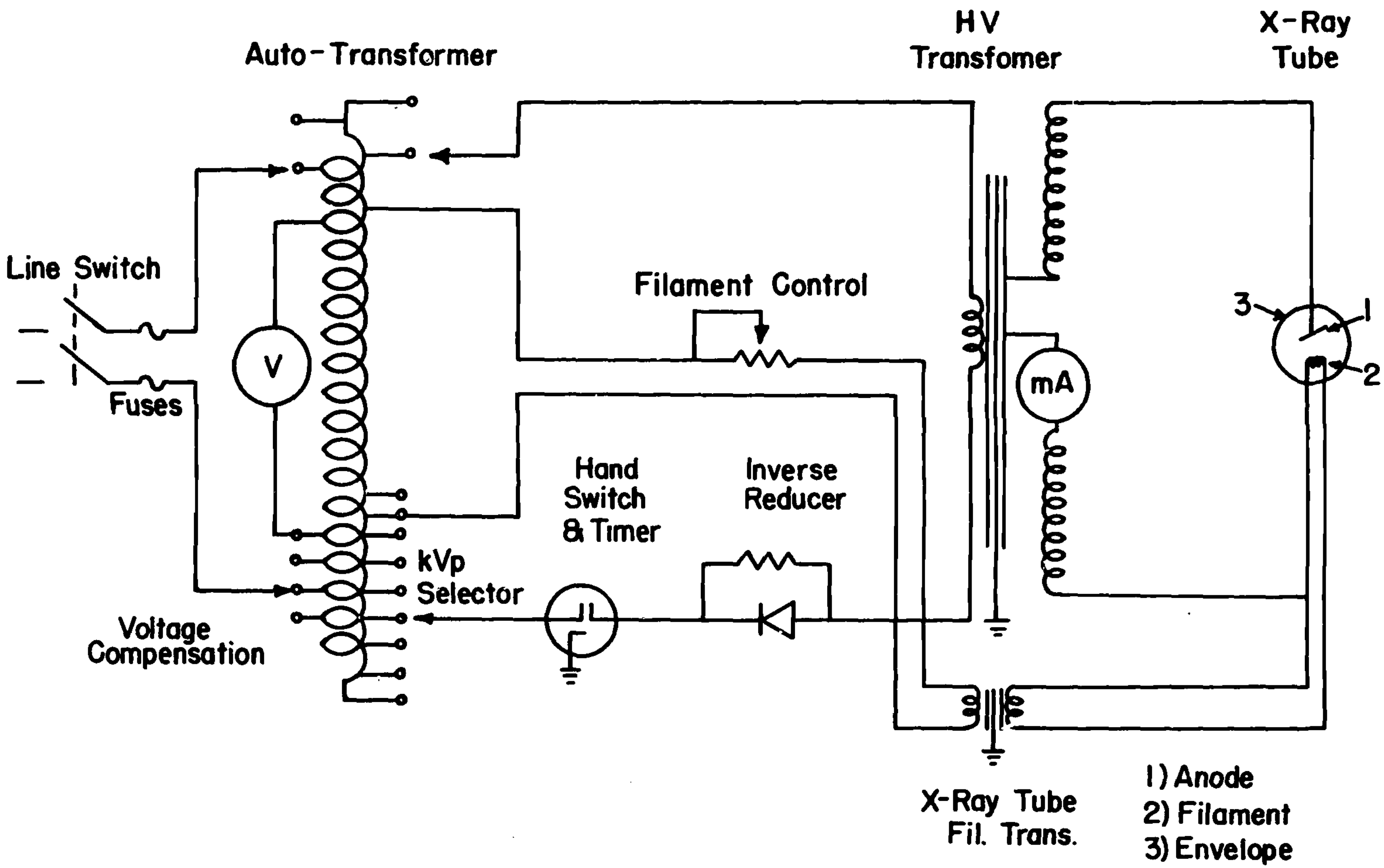
J. X-ray tube

1. Special vacuum tube
2. It is basically a diode
   a. Anode +, cathode -, tube conducts
   b. Anode -, cathode +, tube does not conduct
3. Pure tungsten filament
4. Three main types
   a. Stationary anode
   b. Rotating anode
   c. Transmission anode

K. Metering circuits

1. a.c. voltmeter to measure autotransformer input and/or output voltage
2. d.c. milliammeter
   a. Reads average tube current
   b. Connected in HV transformer secondary at grounded center
3. a.c. milliammeter (if used)
   a. Reads filament (x-ray tube) primary current
   b. It is sometimes calibrated to indicate secondary filament current
   c. It is used to pre-select the x-ray tube current

FIGURE 461-22



X-Ray machine circuit diagram

LECTURE NO. 6

TITLE: Rectification

PURPOSE: To discuss rectifiers and their use in single-phase x-ray equipment

TIME: One hour

VISUAL AIDS: Blackboard
Solid-state high-voltage rectifier
Thermionic high-voltage rectifier
Dental x-ray tube

HANDOUTS: None

REFERENCES:

Eastman Kodak
The Fundamentals of Radiography

Gustafson
High-Tension Generation and its Use in Radiography

Malmstadt, Enke, and Toren
Electronics for Scientists

Ter-Pogossian
Physical Aspects of Diagnostic Radiology

RECTIFICATION

I. Introduction

With the HV transformer connected directly to the x-ray tube, the tube acts as a rectifier conducting during one-half of the electrical cycle and blocking during the other half of the cycle. However, if the tube anode becomes hot enough to emit electrons, reverse conduction can occur and result in the destruction of the filament. A device called a rectifier placed in the HV circuit will forestall reverse conduction since the rectifier passes current in one direction only. Rectifiers can also be used to invert the unused half-cycle of the voltage waveform so that the x-ray tube will conduct during both halves of the cycle.

II. Rectifier Description

A device which allows current flow in one direction only

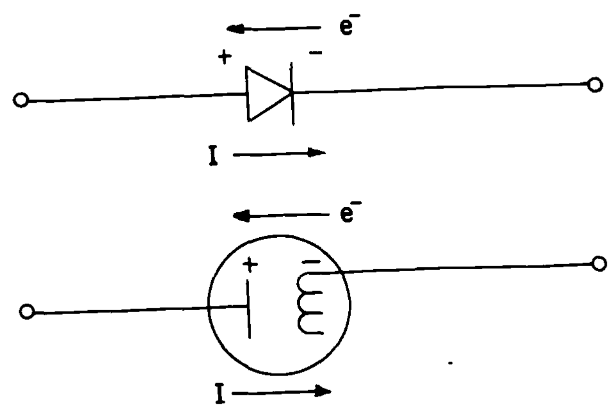


Figure 461-26 Rectifiers

III. Types of Rectifiers

A. Thermionic rectifiers (Fig. 461-27)

1. Two element (anode and cathode) vacuum tube.

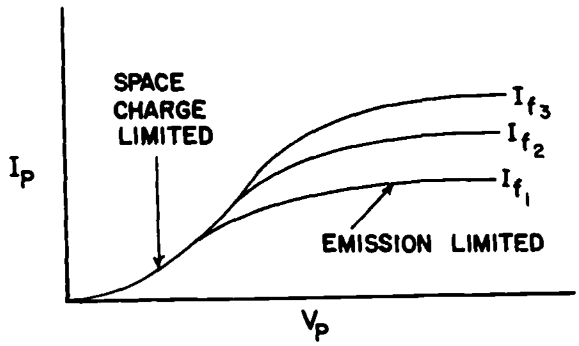


Figure 461-27 Plate current vs plate voltage

a. Emission limited region

1) I_p is independent of V_p

2) I_p is dependent on I_f

b. Space charge limited region

1) I_p is independent of I_f

2) I_p is dependent on V_p

c. Difference between x-ray tube and rectifier operation

1) X-ray tube operates in the emission limited region

2) Rectifier operates in the space charge limited region

2. Construction and operation

a. Cathode filament is capable of emitting a large number of electrons

b. Anode has a large surface area

1) Low power is dissipated over a large area

2) It has a hooded configuration

c. Only a few kilovolts drop across the rectifier will produce currents equal to x-ray tube current

d. If space charge operation is lost, the rectifier can act as an x-ray tube

e. Filament life is limited

f. A filament power supply is required

g. The rectifier emits a significant amount of heat

3. Other names for rectifiers

a. Diodes

b. Valves

c. Kenotrons

B. Blocking layer (solid state) rectifiers

1. Consist of stacked cells

a. Made of thin layers of blocking material

b. Allows electron flow in one direction only

1) Copper oxide

2) Germanium

3) Selenium

4) Silicon

c. Silicon is most widely used

d. They have a theoretically infinite life

e. There is no heat dissipation

f. No power supply is required

g. Disadvantages

1) Relatively high cost--silicon > selenium > thermionic

2) Selenium has a relatively high voltage drop

IV. Self-Rectified Operation

See circuit and analysis in Lecture 7 (Fig. 461-28)

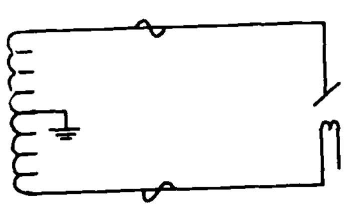


Figure 461-28 Self-rectified secondary circuit

V. Half-Wave Rectified Operation

A. See circuit and analysis in Lecture 8 (Fig. 461-29)

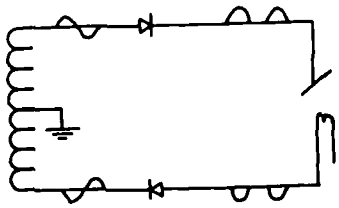


Figure 461-29 Half-wave rectified secondary circuit

B. Prevents inverse emission

C. Permits higher tube heating

D. Inverse reducer still may be required

E. Removes a.c. from HV cables

VI. Full-Wave Rectified Operation

A. See circuit and analysis in Lecture 7 (Fig. 461-30)

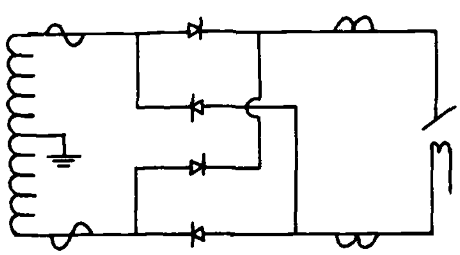


Figure 461-30 Full-wave rectified secondary circuit

B. Inverse reducer is not used

C. No inverse emission

1. Higher maximum current ratings are possible

2. Decreased exposure time can result

D. Overall efficiency is increased

VII. High Voltage Cables

A. Used to connect HV transformer to x-ray tube

1. Smaller tube housing results

2. There is increased flexibility of movement

B. Constructed as shown below (Fig. 461-31)

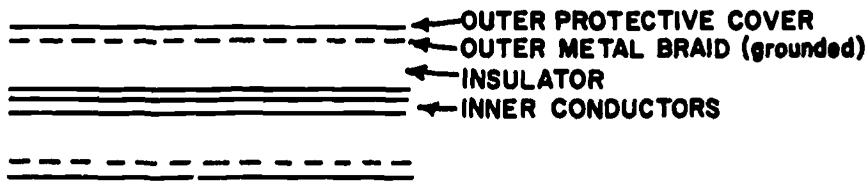


Figure 461-31 HV cable construction

1. Basically a coaxial cable
2. They act as a tubular electrical capacitor
   a. Total capacitance is proportional to cable length
   b. Typical cable capacitance is 40-70 pF/ft
3. Cable effect is inversely proportional to the tube current
4. Capacitance increases the average value of the voltage
5. Cables are charged when voltage is applied and the stored charge is released when the voltage from transformer decreases (Fig. 461-32)

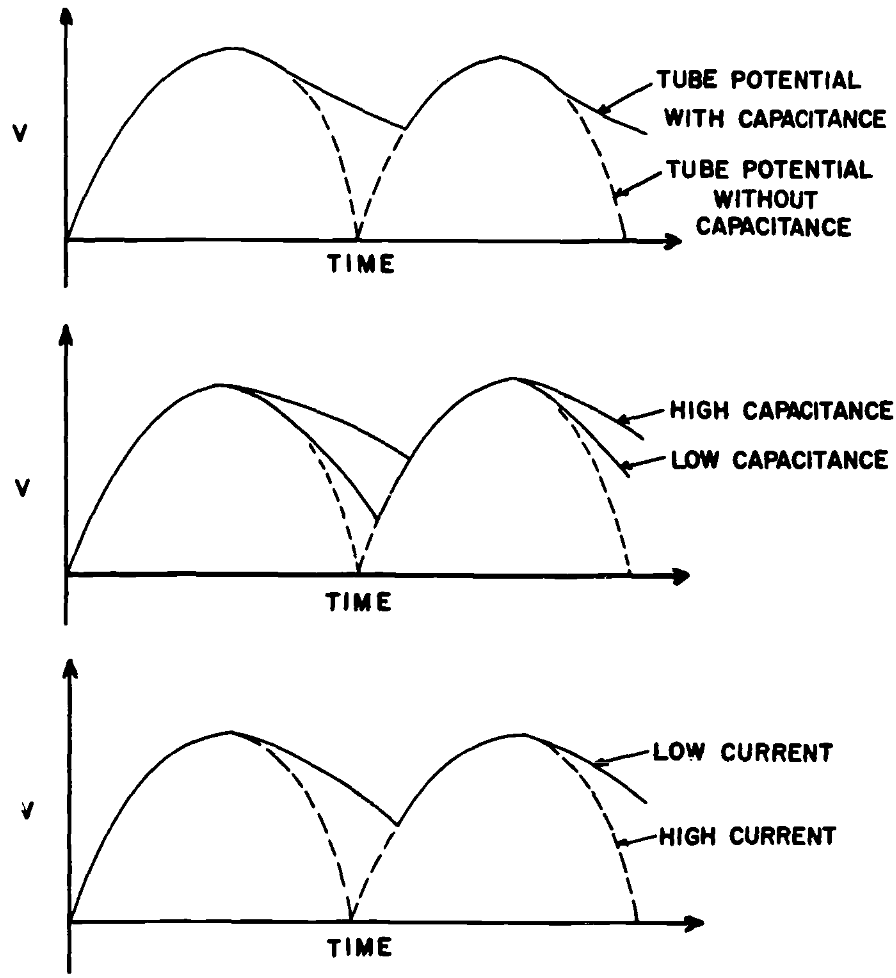


Figure 461-32 Effect of HV cable capacitance on voltage waveform

LECTURE NO. 7

TITLE:	Poly-Phase, High-Frequency and Other Modern X-Ray Generators
PURPOSE:	To review single-phase, three-phase, high-frequency and capacitor discharge x-ray systems
TIME:	Two hours
VISUAL AIDS:	Blackboard Overhead projector for circuit and voltage waveform transparencies Slide projector for slides of typical x-ray systems
HANDOUTS:	461-5 (Figures 461-33-40, Tables 461-I-IV) Circuit diagrams, voltage waveforms and sequence of rectifier event tabulation for single- and three-phase systems
REFERENCES:	Schaefer Rectifier Circuits Ter-Pogossian Physical Aspects of Diagnostic Radiology

Poly-Phase and Special Purpose X-Ray Systems

I. Introduction

The development of x-ray equipment in the United States has been based on operation from a single-phase line voltage supply. As a result, single-phase self-rectified, half-wave rectified and full-wave rectified generators are extensively used. In Europe, where the power distribution systems would not permit operation of high capacity single-phase generators, three-phase systems have been in common use for many years. Recent technological developments in rectification and solid-state switching have resulted in the development and use of poly-phase x-ray generators in this country.

II. Review of Single-Phase Systems

A. Self-rectified

1. The x-ray tube acts as a rectifier
   a. Conducts when anode is positive with respect to cathode.
   b. Blocks when anode is negative with respect to cathode.
   c. One x-ray pulse with a maximum duration of 1/120 second is produced every 1/60 second for a 60 Hz line.
2. Referring to Figure 461-33 and Table 461-I
   a. Simple high-voltage circuit
   b. Voltage waveform at anode (a) and cathode (c).
      1) Peak voltage across x-ray tube is sum of peak voltages on anode and cathode with respect to ground
      2) Tube conducts when anode is positive
   c. Time intervals
      1) Interval 1, first 1/120 sec, tube conducts
      2) Interval 2, second 1/120 sec, tube blocks
      3) Etc.

B. Half-wave rectified system

1. High-voltage rectifiers in x-ray tube anode and cathode circuits
   a. Usually use high-voltage cables between transformer/rectifier component and x-ray tube
   b. Rectifiers block inverse half-cycle of voltage waveform
      1) Pulsating d.c. on high-voltage cables
      2) Pulsating d.c. on x-ray tube
2. Referring to Figure 461-34 and Table 461-II
   a. Simple half-wave rectified circuit
   b. Voltage waveform at transformer (points S 1 and S 2)
      1) Same as self-rectified circuit
      2) Peak voltage sum of peak voltages at S 1 and S 2 with respect to ground
   c. Voltage at anode (a) and cathode (c)
      1) During useful half-cycle
      2) Zero during "inverse" half cycle
   d. Time intervals (sequence of events)
      1) Interval 1, first 1/120 sec.
         a) Rectifiers conduct
         b) X-ray tube conducts
      2) Interval 2, second 1/120 sec.
         a) Rectifiers block
         b) X-ray tube does not conduct
      3) Interval 3, third 1/120 sec.
         a) Same as interval 1
         b) Etc.

C. Full-wave rectified system

1. High-voltage bridge rectifier
   a. Rectifies inverse half cycle and makes it useful
   b. Pulsating d.c. on high-voltage cables and x-ray tube

2. Referring to Figure 461-35 and Table 461-III
    a. Simple full-wave rectified circuit
    b. Voltage waveforms at transformer (S1 and S2) and at x-ray tube (a and c)
3. Time intervals (sequence of events)
    a. Interval 1, first 1/120 sec.
        1) Rectifiers II and IV conduct
        2) Rectifiers I and III block
        3) X-ray tube conducts
    b. Interval 2, second 1/120 sec.
        1) Rectifiers I and III conduct
        2) Rectifiers II and IV block
        3) X-ray tube conducts
    c. Interval 3, third 1/120 sec.
        1) Same sequence as interval 1
4. System can be considered as two alternately connected half-wave rectified systems

III. Poly-Phase Systems (Three-Phase)

A. Effective energy
1. In single-phase systems the voltage on the x-ray tube varies from zero to the peak and back to zero every half cycle (1/120 sec.)
2. If voltage did not drop to zero (i.e. constant potential) a higher effective photon energy could be achieved for the same peak voltage and a greater quantity of photons produced for the same tube current.
3. Three-phase x-ray generator systems provide a "low ripple" constant potential on the x-ray tube

B. Three-phase, six rectifier system (Figs. 461-36 and 461-37, Table IV)
1. Voltage waveforms peak every 120 electrical degrees
2. System operates like three full-wave rectified systems alternately connected during electrical cycle (1/60 sec.)

3. Simple six rectifier system
    a. Delta primary, wye secondary
    b. Provides proper phasing
4. Voltage waveforms at transformer terminals. Alternate 1/120 cycle phasing
5. Voltage waveform at x-ray tube anode (a) and cathode (c)
    a. When voltage on anode is maximum, voltage on cathode is minimum
    b. Results, when waveforms added, in six "pulses" every electrical cycle (1/60 sec.)
6. Theoretical minimum voltage 86.6% of peak voltage
    a. Ripple voltage 13.4%
    b. Waveform and ripple change with loading (mA)
7. Time intervals (sequence of events)
    a. Interval 1, first 1/360 sec.
        1) Rectifiers III, V and VI conduct
        2) Rectifiers I, II and IV block
        3) X-ray tube conducts
        4) Degree of rectifier conduction changes during interval
    b. Interval 2, second 1/360 sec.
        1) Rectifiers I, III and V conduct
        2) Rectifiers II, IV and VI block
        3) X-ray tube conducts
    c. Sequence continues as shown in Table IV

C. Three-phase, 12-rectifier system (Figures 461-38, 39 and 40)
1. Voltage waveforms peak every 60 electrical degrees
2. System operates like two six-pulse systems phased 60 degrees

3. Simple 12 rectifier system
    a. Two delta primaries
    b. One delta and one wye secondary
    c. Provides proper phasing
4. Voltages at transformer terminals
5. Voltage at x-ray tube
    a. Six alternating voltage peaks at anode and cathode
        1) When anode voltage maximum, cathode voltage minimum
        2) Results, when anode and cathode voltages are added, in 12 "pulses" every electrical cycle (1/30 sec.)
6. Theoretical minimum voltage 96.6% of peak
    a. Ripple voltage 3.4%
    b. Ripple voltage and waveform change with loading (mA)
7. Time interval sequence of events like two alternating six-rectifier systems and too complicated to tabulate

IV. Special Bedside or Mobile Systems

A. Battery operated, high frequency systems (Fig. 461-41)

1. A 120 V d.c. nickle-cadmium battery is used to power 60 and 500 Hz inverters
2. The 60 Hz inverter supplies power to the x-ray tube filament, rotating anode tube stator and control circuits
3. The 500 Hz inverter supplies power to the high-voltage transformer primary

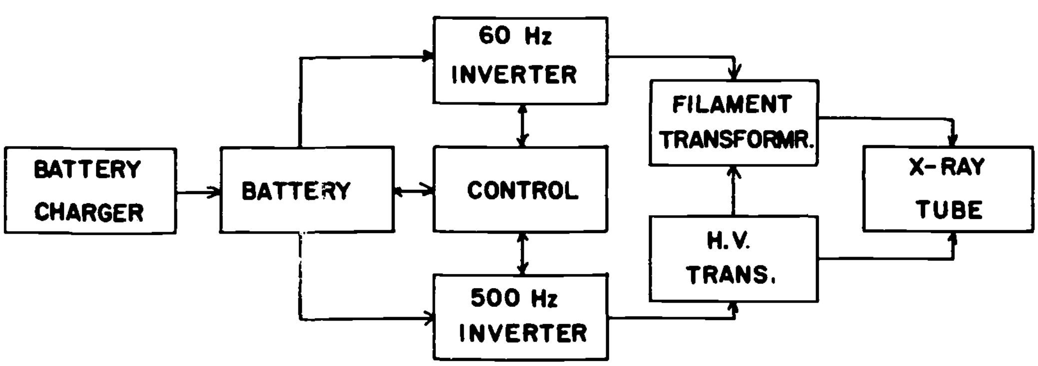


Figure 461-41 Block diagram of high-frequency system

4. System uses full-wave bridge rectifier
5. Operates at fixed, stabilized 100 mA tube current and voltages up to 110 kVp
6. Voltage ripple of 10-20 kVp (depending on model) is constant regardless of kVp
7. System provides radiographic exposures similar to three-phase, 12 pulse

B. Capacitance discharge systems
1. Capacitor charged to high voltage and then discharged through x-ray tube
2. Rate of discharge depends upon capacitance and current
3. System operation (Fig. 461-42)

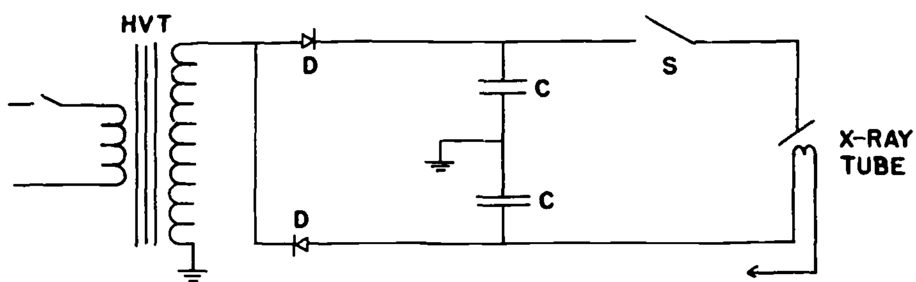


Figure 461-42 Capacitance discharge system

a. Rectifiers (D) convert AC voltage from high-voltage transformer (HVT) to pulsating DC to charge capacitors (C)
b. When switch (S) is closed capacitors are connected to x-ray tube
   1) Discharge through tube
   2) Voltage and current decreases during discharge
   3) Time of exposure determined by opening of switch (S)

4. Typical circuit and analysis (Fig. 461-43)

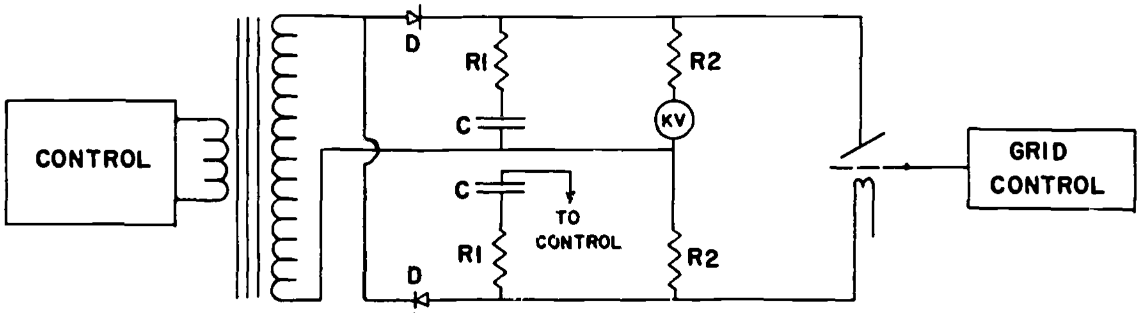


Figure 461-43 Typical capacitance discharge system

. The capacitors, C, are charged through the HV transformer and rectifier, D, system to a potential selected at the control

b. Resistors R2 form a high resistance voltage divider across the x-ray tube

   1) There will be a small current flow through the divider

   2) Current flow ∝ R and V

   3) KV meter is microammeter calibrated in kilovolts

c. Grid control of x-ray tube biased to cutoff preventing tube current

d. Grid voltage typically - 600 to - 1800 volts for cutoff with tube voltage 40 to 100 kV

e. Resistors R1 limit current from capacitors C when grid bias removed

f. Removing grid bias initiates exposure, restoring grid bias terminates exposure

g. Timer calibrated in mAs. Both kV and mA decrease as exposure time increases (Fig. 461-44)

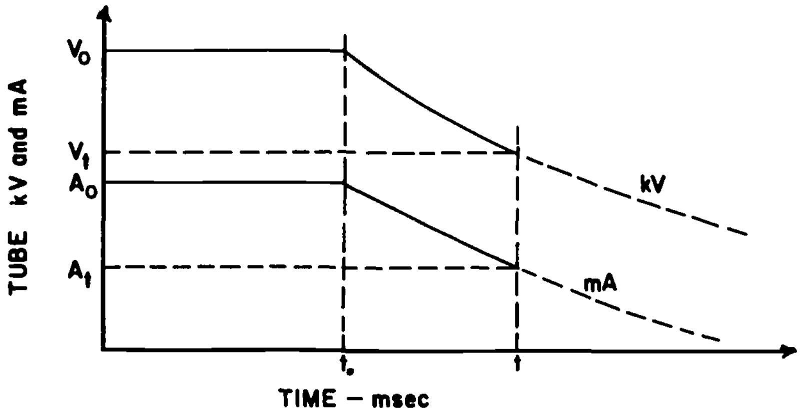


Figure 461-44 Voltage and current waveforms

1) Voltage drops from V_o to V_t during exposure
2) Tube current drops from A_o to A_t during exposure
3) Exposure time $t - t_o$
4) Limited maximum exposure

h. Bias cutoff to end exposure does not remove residual voltage from high-voltage system

V. Special Purpose Equipment

A. Generally single-phase, full-wave or three-phase, 12-pulse

B. Include equipment for:

1. Tomography
2. Angiography
3. Bi-plane
4. Catheterization
5. Mass chest
6. Mobile fluoroscopic
7. Other special procedures

FIGURE 461-33

SINGLE-PHASE SELF-RECTIFIED SYSTEM

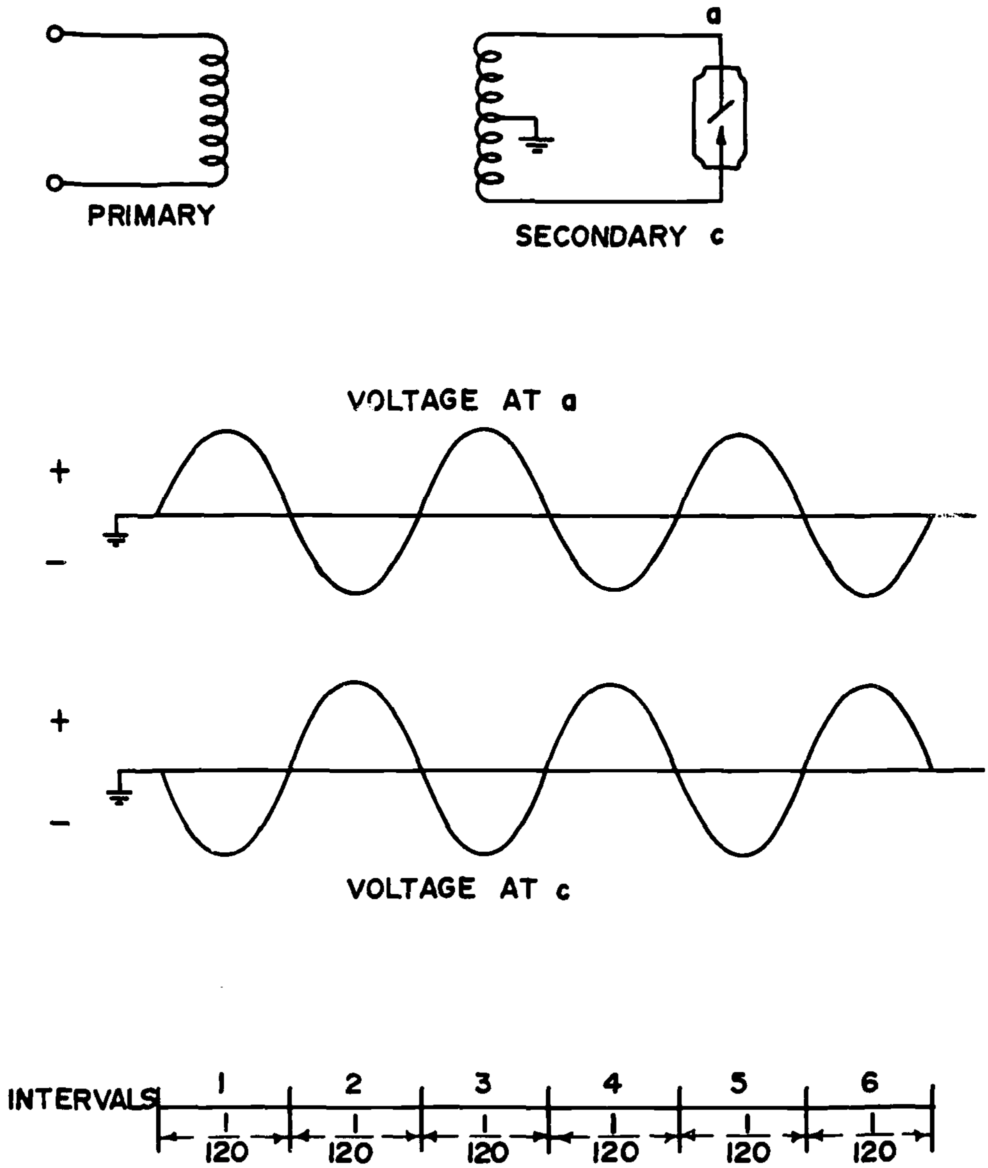


Table 461-1

SINGLE-PHASE SELF-RECTIFIED SYSTEM

Tabulation of Rectifier (X-Ray Tube) Events

Interval	X-Ray Tube
1	Conduct
2	Block
3	Conduct
4	Block
5	Conduct
6.	Block

FIGURE 461-34

SINGLE – PHASE HALF - WAVE RECTIFIER SYSTEM

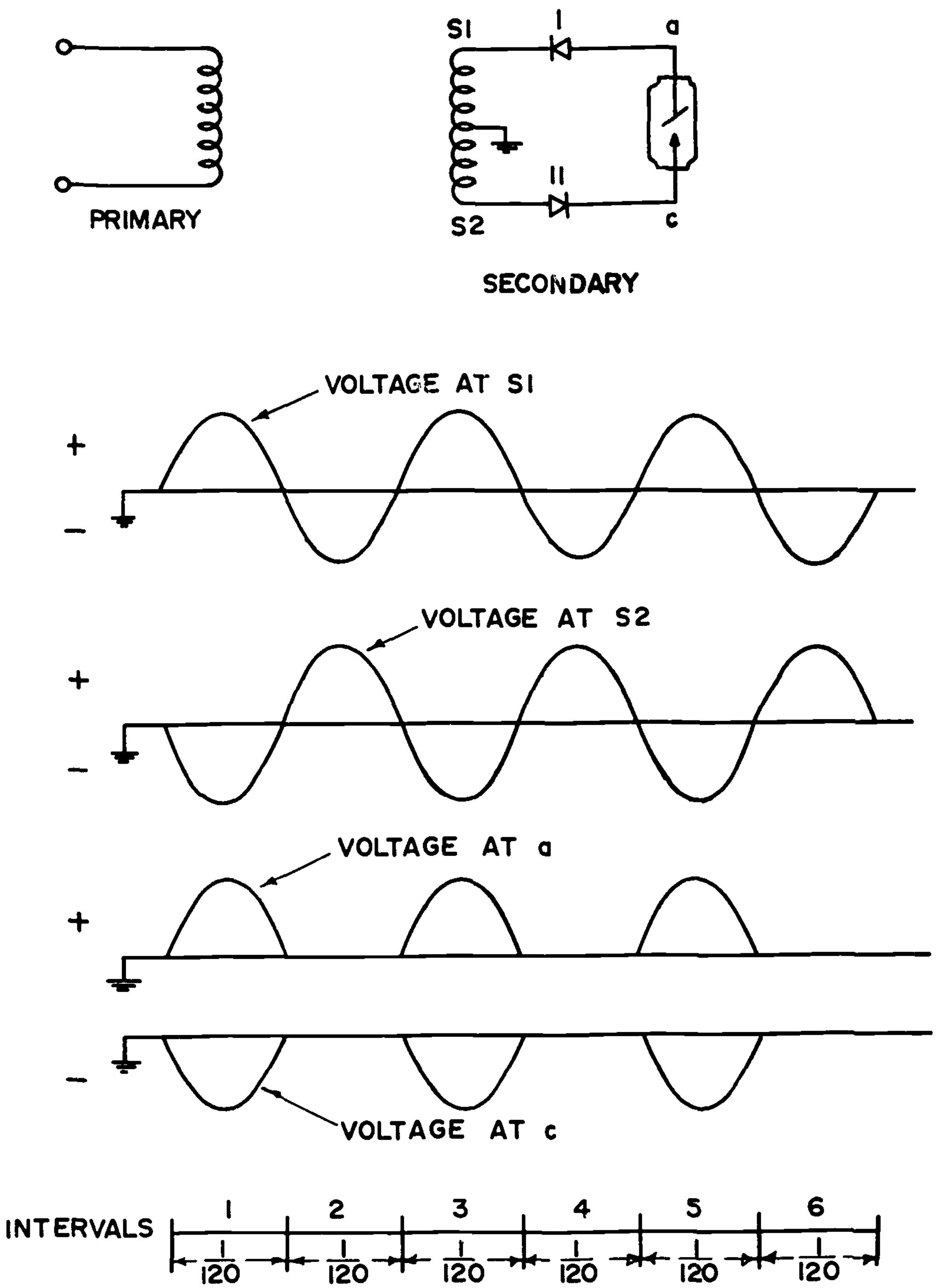


Table 461-II

SINGLE-PHASE HALF-WAVE RECTIFIED SYSTEM

Tabulation of Rectifier Events

Interval	R I	R II
1	Conduct	Conduct
2	Block	Block
3	Conduct	Conduct
4	Block	Block
5	Conduct	Conduct
6	Block	Block

FIGURE 461-35

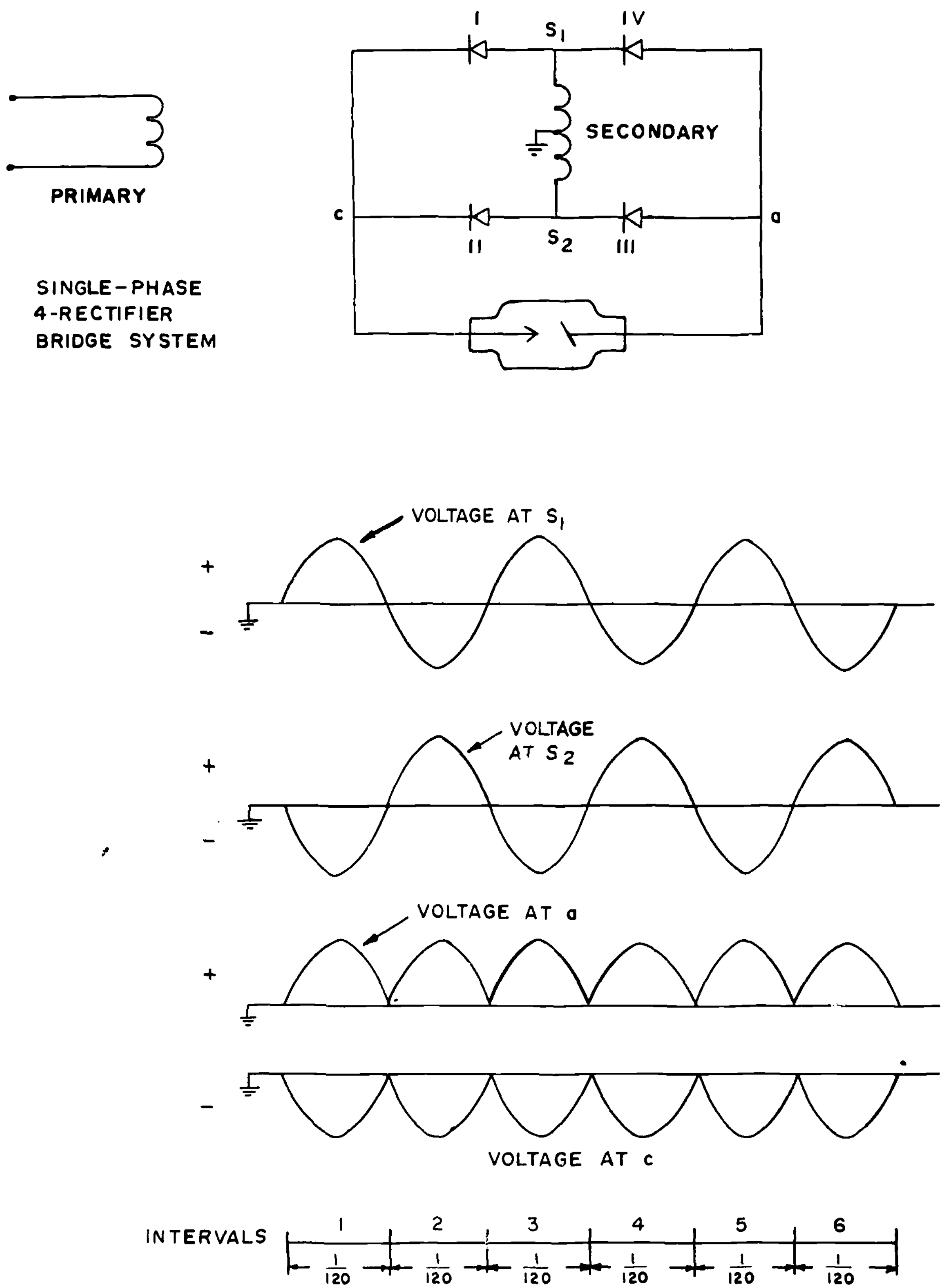


Table 461-III

SINGLE PHASE 4-RECTIFIER BRIDGE SYSTEM

Tabulation of Individual Rectifier Events

Interval	R I	R II	R III	R IV
1	Block	Conduct	Block	Conduct
2	Conduct	Block	Conduct	Block
3	Block	Conduct	Block	Conduct
4	Conduct	Block	Conduct	Block
5	Block	Conduct	Block	Conduct
6	Conduct	Block	Conduct	Block

FIGURE 461-36

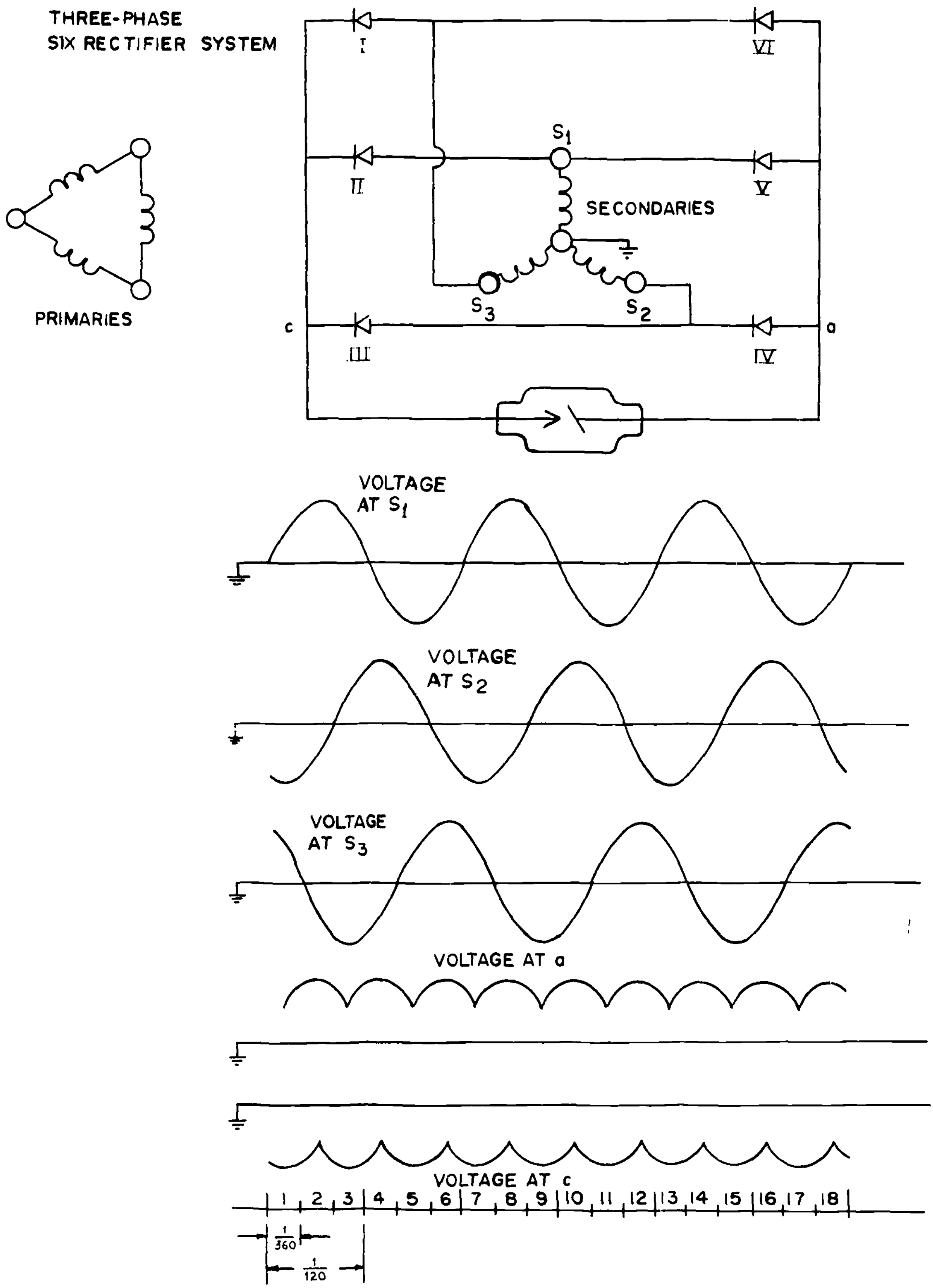
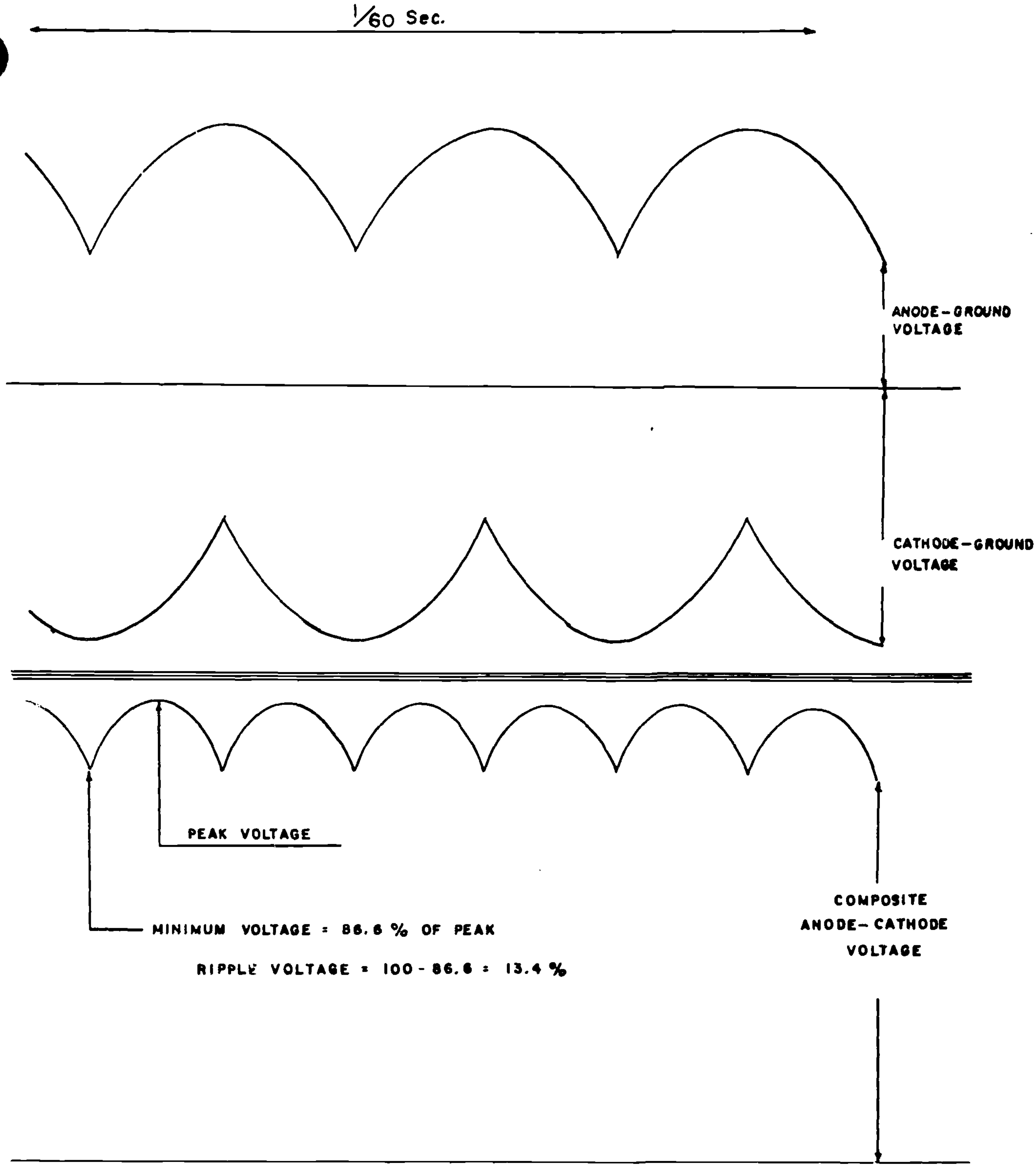


FIGURE 461-37



THEORETICAL VOLTAGE OUTPUT OF 6-RECTIFIER SYSTEM

THREE-PHASE, 6-VALVE RECTIFIER SYSTEM

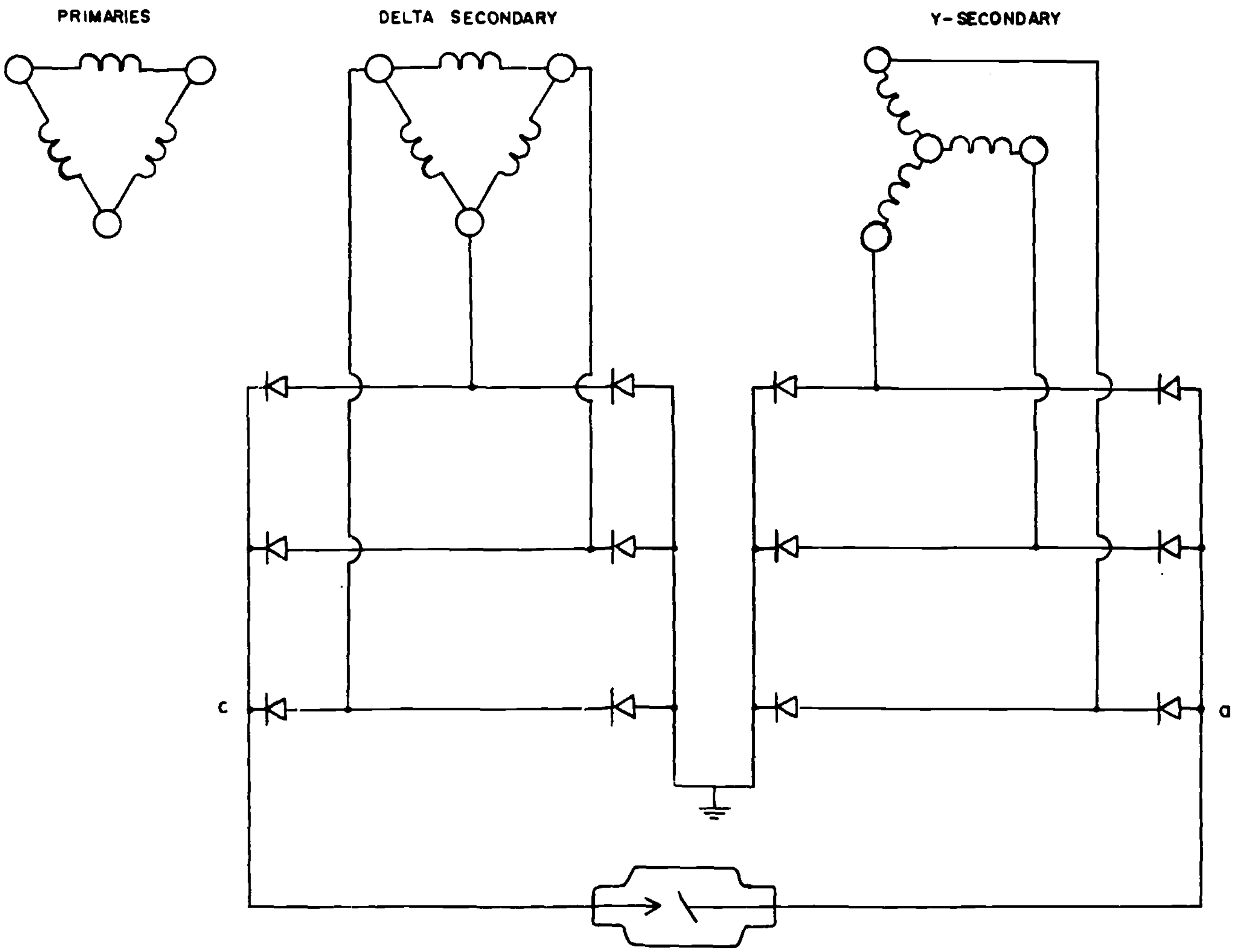
Tabulation of Individual Rectifier Events

Interval	R I	R II	R III	R IV	R V	R VI
1	B	B	C	B	C	C
2	C	B	C	B	C	B
3	C	B	B	C	C	B
4	C	C	B	C	B	B
5	B	C	B	C	B	C
6	B	C	C	B	B	C
7	B	B	C	B	C	C
8	C	B	C	B	C	B
9	C	B	B	C	C	B
10	C	C	B	C	B	B
11	B	C	B	C	B	C
12	B	C	C	B	B	C
13	B	B	C	B	C	C
14	C	B	C	B	C	B
15	C	B	B	C	C	B
16	C	C	B	C	B	B
17	B	C	B	C	B	C
18	B	C	C	B	B	C

Note: B = block, C = conduct. Conduction of rectifiers changes during an interval. For example, during interval 2 rectifiers R I, III and V are conducting. Actually, S_3 is less negative during the first half of this period than S_2. Therefore, R I will not conduct materially the first half and R III carries the load. In the second half of interval 2, R I carries and R III is idle.

FIGURE 461-38

THREE-PHASE 12-RECTIFIER SYSTEM



THEORETICAL

MINIMUM VOLTAGE = 96.6 % OF PEAK

RIPPLE VOLTAGE = 100-96.6 = 3.4 %

FIGURE 461-39

THREE-PHASE 12-RECTIFIER SYSTEM

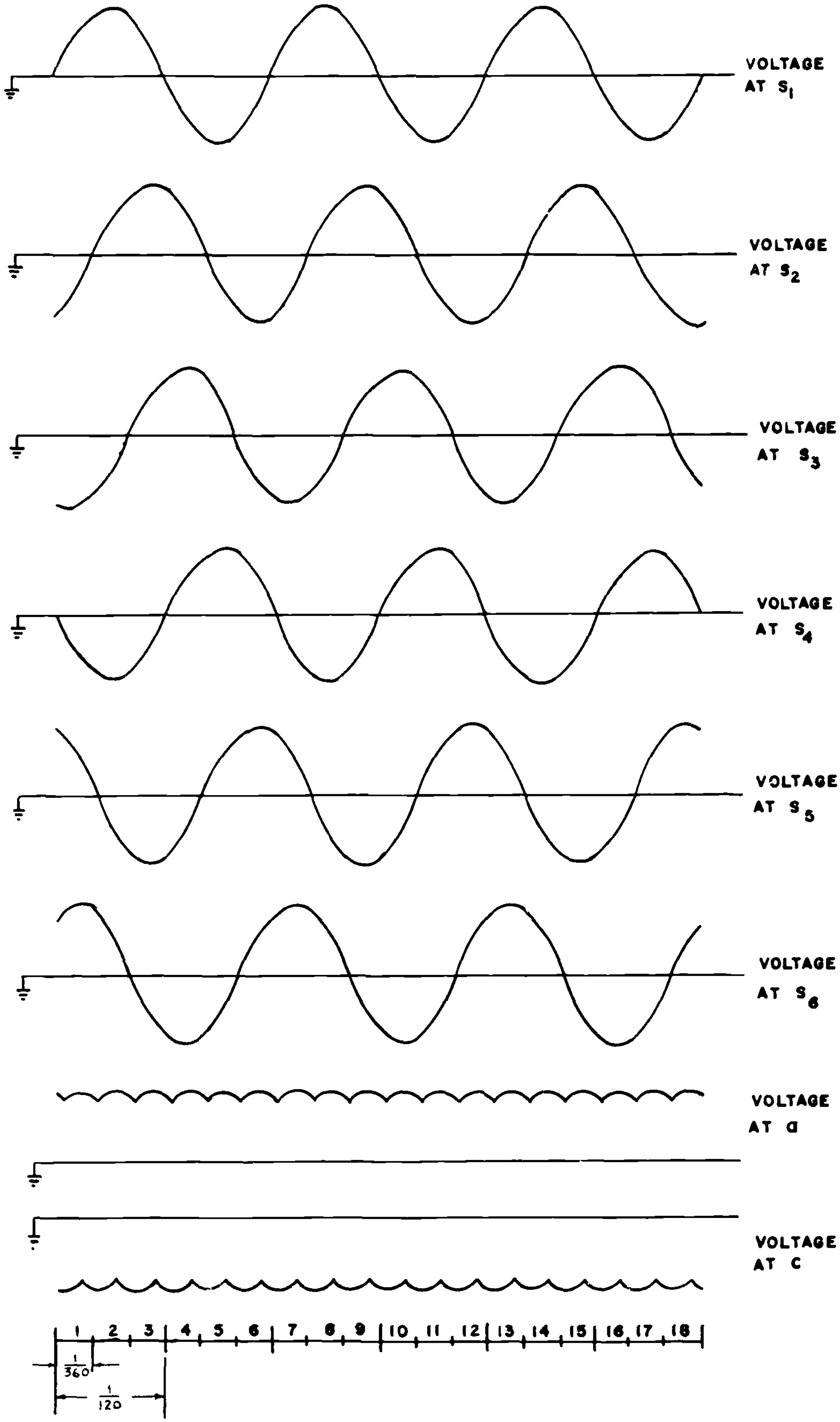
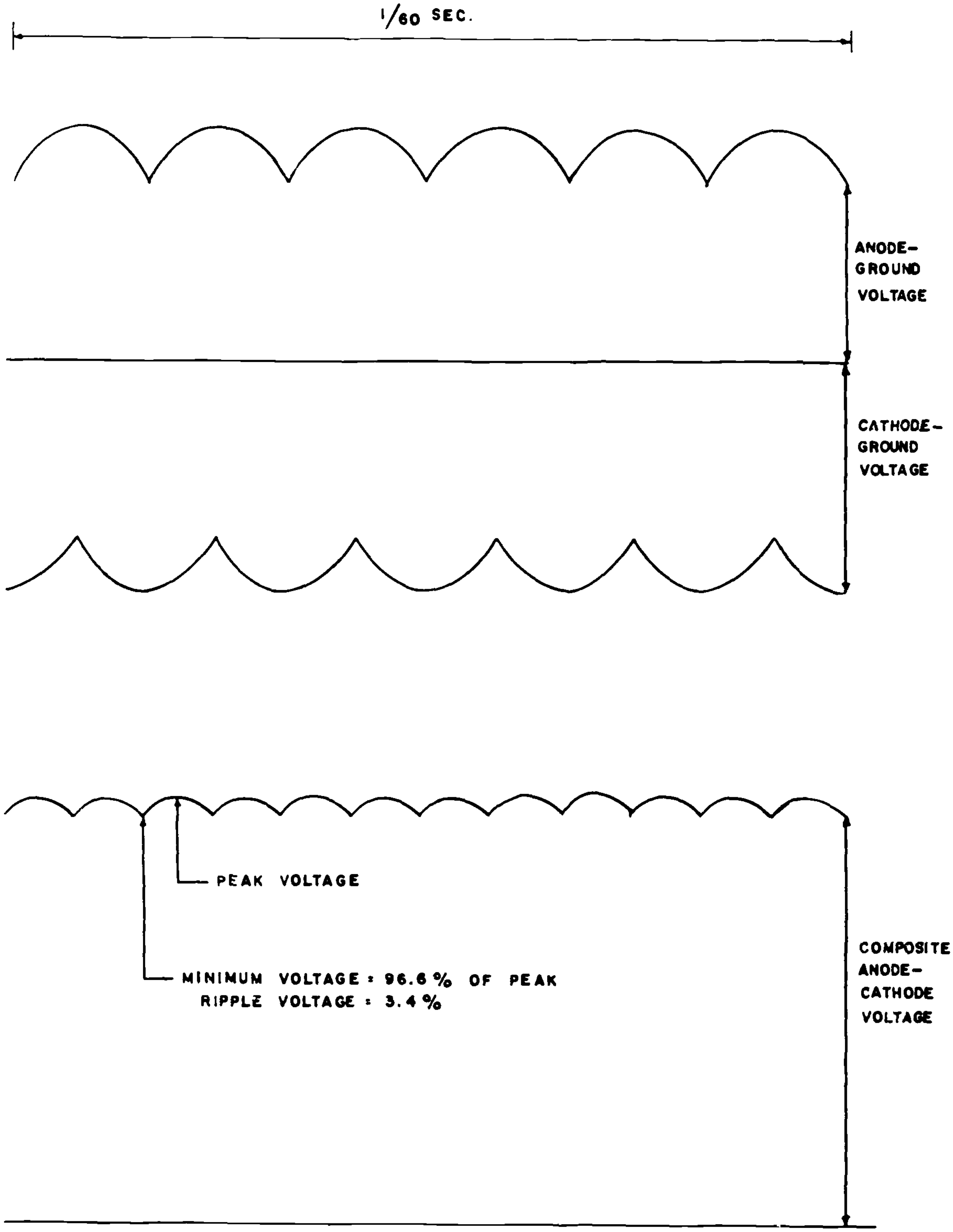


FIGURE 461-40



THEORETICAL VOLTAGE OUTPUT OF
12-RECTIFIER SYSTEM

LECTURE NO. 8

TITLE:	X-Ray Timers
PURPOSE:	To discuss timers used with x-ray equipment and means used to check timer accuracy
TIME:	One hour
VISUAL AIDS:	Blackboard Spring-driven timer Motor-driven synchronous timer Electronic timer
HANDOUTS:	None
REFERENCES:	Ter-Pogossian Physical Aspects of Diagnostic Radiology

X-RAY TIMERS

I. Introduction

The timer is the device which initiates and terminates the x-ray exposure. The timer controls the x-ray contactor which, in turn, controls the voltage to the primary of the high-voltage transformer (Fig. 461-45).

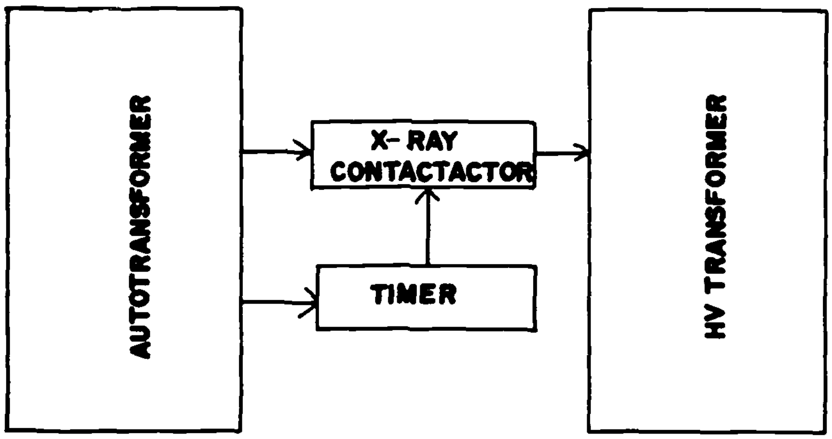


Figure 461-45 Basic timer circuit

II. Spring-driven Timer

A. Setting time on dial automatically winds spring

1. Depressing exposure switch on timer energizes solenoid that operates x-ray contactor

2. Timer unwinds at constant speed to "zero"

   a. Timer contacts open

   b. Exposure terminated

B. Timer range normally from 1/20 to 8 or 12 seconds

1. Accuracy uncertain below 1/4 second

2. Minimum timer setting about 1/20 second

C. Use now confined to older mobile and dental x-ray machines

D. Timer usually connected to x-ray control by electrical 3-conductor cable

III. Synchronous Timer

A. Similar to spring-driven timer except timer movement is controlled by a synchronous motor

1. Requires manually resetting time in most timers. Some timers are of the automatic resetting type.
2. Turning timer switch on initiates exposure through a clutch system.
3. The timer motor runs continuously
4. An arm on the clutch terminates the exposure

B. Exposure times down to 1/20 second are possible.

C. Use is limited

D. Timer range

1. For therapy from 1 second to 55 minutes
2. For industrial radiography from 1 second to 1 hour or more
3. For medical radiography from 1/20 second to 20 seconds
4. Indexed timer settings are used for medical radiography
5. Continuous setting is used for therapy or industrial use

E. Some timers, usually industrial and medical radiographic, have automatic reset

IV. Electronic Timer

A. Exposure time determined by rate of charge or discharge of capacitor in an RC circuit (Fig. 461-46).

1. Time governed by RC time constant of circuit

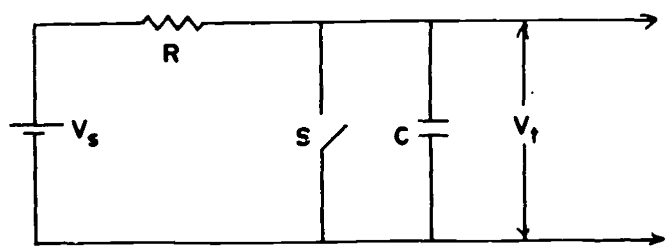


Figure 461-46. Timer (RC) circuit

2. $V_t = V_s \ (1 - e^{-t/RC})$

a. The greater the RC, the longer the exposure time

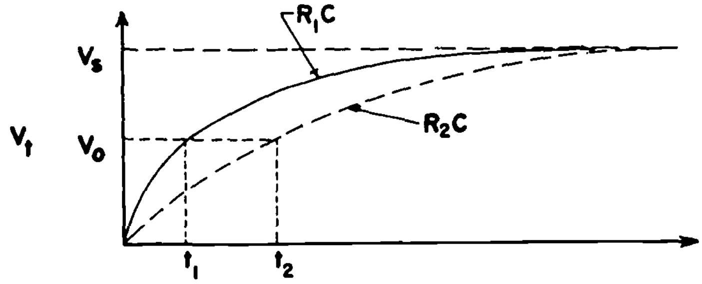


Figure 461-47 Timer RC curves

b. Normally constant C, variable R

B. Timer can be triggered in phase with a.c. line

1. X-ray contactor is opened and closed in phase with a.c. line

2. Therefore it times the electrical (a.c.) impulses

3. This timer is known as an impulse timer

C. Impulse-type timers are reliable down to 1/120 sec. for single phase generators

V. Checking Timer Accuracy

A. Long timer

1. For times greater than several (2 or 3) seconds

a. Use a calibrated stopwatch

b. Cycle counter

B. Short timer

1. Less than 2 or 3 seconds

2. Timer checks include

a. Spinning top (Fig. 461-48)

1) Metal disc with single hole located near periphery

2) Disc mounted on axis of rotation point

b. Rotation (spinning) of disc either manual or by a synchronous motor driven at a constant speed

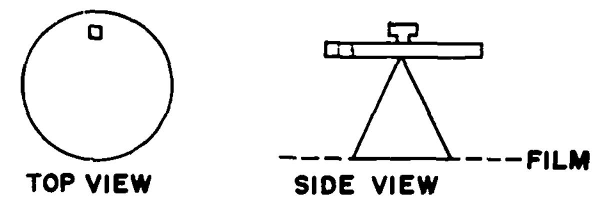


Figure 461-48 Spinning top

c. Film is placed below the disc and an exposure made with the disc rotating

d. With single-phase generators the number of "dots" indicate impulses and exposure time (Fig. 461-49)

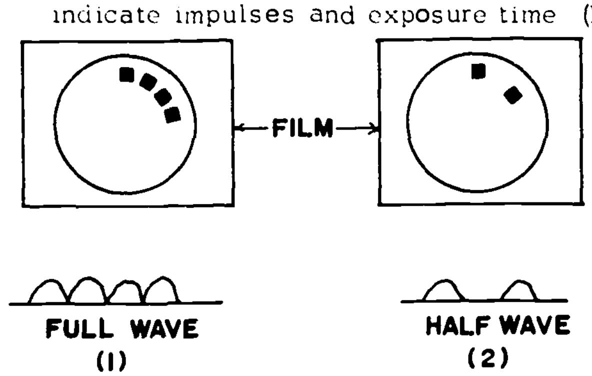


Figure 461-49 Spinning top "dots"

e. In (1) full-wave, (2) half-wave or self-rectified

1) Timer is set for 1/30 sec

2) A radiograph is made with the disc spinning

3) The number of squares on the film indicates the number of impulses

4) The density of the film exposed in the squares indicates the duration of the exposure

5) Knowing the type of rectification, the exposure time can be determined .

f. Not useful for 3-phase or high frequency generators unless the top is driven at known speed

1) "Dots" so close together that continuous exposure exists

3. Additional timer check systems

a. High voltage bleeder (Fig. 461-50)

1) Resistance divider connected in HV circuit at x-ray tube

2) Calibrated oscilloscope used to record impulses

a) Requires memory module for recording impulses

b) Also shows tube voltage waveform

3) Usually 1000 : 1 resistance divider

4) With calibrated time base it can also be used with polyphase and high frequency generators

5) Can also be used with peak-reading voltmeter

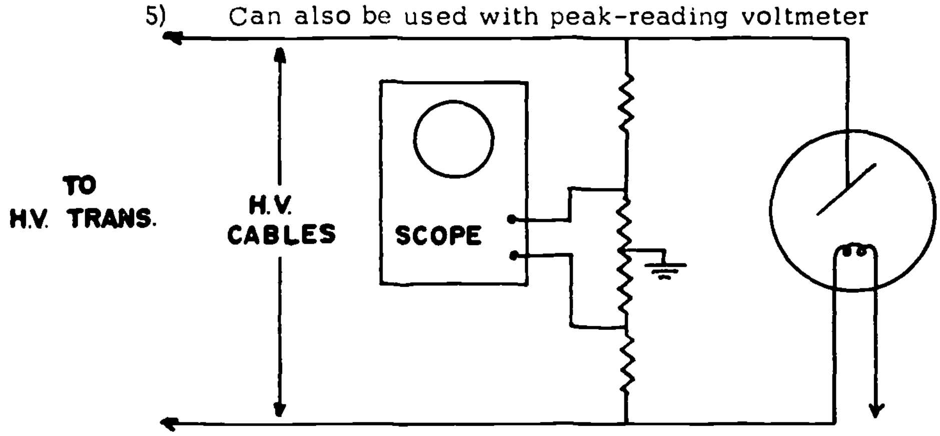


Figure 461-50 High voltage bleeder

6) With vertical scope voltage calibration also indicates peak kilovoltage

c. Solid-state detector (Fig. 461-51)

1) Detector connected to oscilloscope

2) Does not require electrical connection to x-ray unit

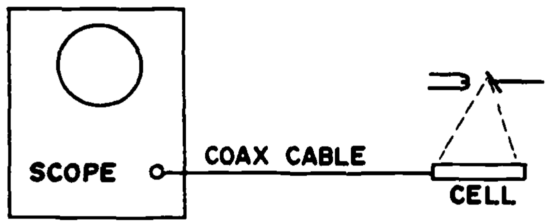


Figure 461-51 Solid state detector

3) Cell response and system capacitance may distort waveform

4) Cell voltage

a) Depends upon type of cell used

b) Depends upon exposure rate at cell

d. Ion chamber

1) Used like solid state detector

a) Requires chamber voltage supply usually > 300 v d.c.

b) Short coax cable necessary to reduce RC constant

C. The phototimer (Fig. 461-52)

1. The radiation transmitted through the object to the film is measured and used to terminate the exposure

2. Small fluorescent screen behind cassette

   a. Light emitted from screen proportional to incident x-ray exposure rate

   b. Light generates current in phototube which controls electronic timer

      1) Usually used to charge capacitor

   c. Charge collected proportional to fluorescent screen exposure which is proportional to film exposure

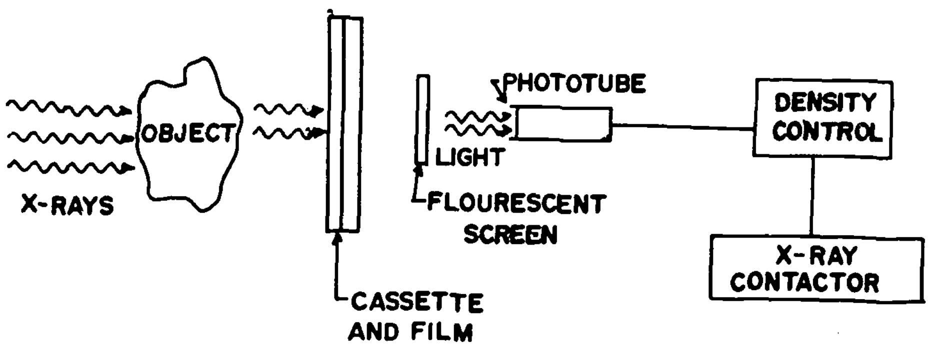


Figure 461-52. Phototimer

LECTURE NO. 9

TITLE: X-ray Tubes

PURPOSE: To discuss the history, design, manufacture and operation of x-ray tubes

TIME: One hour

VISUAL AIDS:
Gas tube
Coolidge Universal tube
Stationary anode tubes--Radiator type: air, water, and oil cooled
Rotating anode tube
Therapy tube

HANDOUTS: 461-6 Tube rating chart

REFERENCES:

Bloom, Hollenbach and Morgan
<u>Medical Radiographic Technic</u>

Miller
<u>Yankee Scientist</u>

Sproull
<u>X-rays in Practice</u>

Machlett
<u>Dynamax Application Data</u>

Machlett
<u>Introduction to Three Phase Rating</u>

X-RAY TUBES

I. Types

A. Gas tube

1. Glass envelope with two or three electrodes (Fig. 461-53)

a. Cathode

b. Anticathode or target

c. Anode

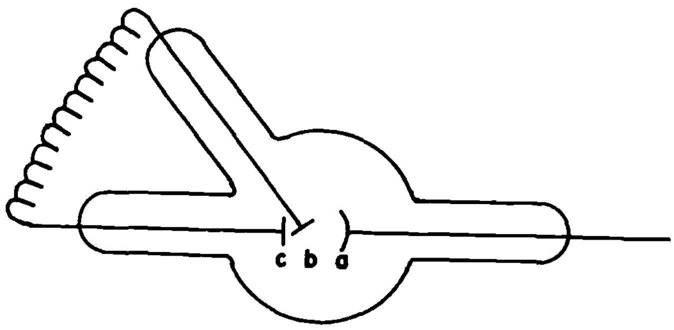


Figure 461-53 Gas X-ray Tube

2. Evacuated to about 10^{-4} mm Hg. Depend for operation on small residual gas in tube

3. Gas pressure determined operating conditions

B. Hot cathode (Coolidge) tube

1. W. D. Coolidge (1912) developed hot cathode x-ray tube

a. Outgrowth of his work on tungsten for use in incandescent lamps

b. Tube consisted of glass envelope, cathode and anode (Fig. 461-54)

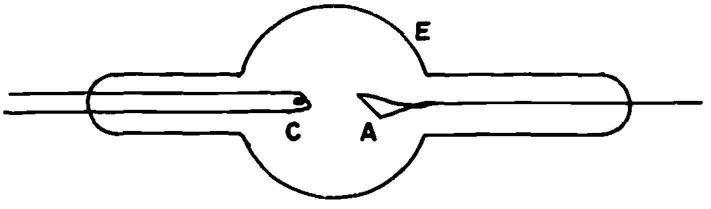


Figure 461-54 Coolidge Tube

c. Tube was highly evacuated

d. Electron emission from filament given by $I = AT^2 \exp(-b/T)$ where I = thermionic current, A and b are constants, and T = absolute temperature

2. Diagnostic tubes, radiographic

a. Small focal spot

b. High current and kilovoltage

c. Short exposure time

3. Diagnostic tubes, fluoroscopic

a. Small focal spot

b. Low current, medium to high kilovoltage

c. Long exposure time

4. Therapy tubes and industrial tubes

a. Large focal spot

b. Low current, high kilovoltage

c. Long exposure time

II. X Ray Tube Design

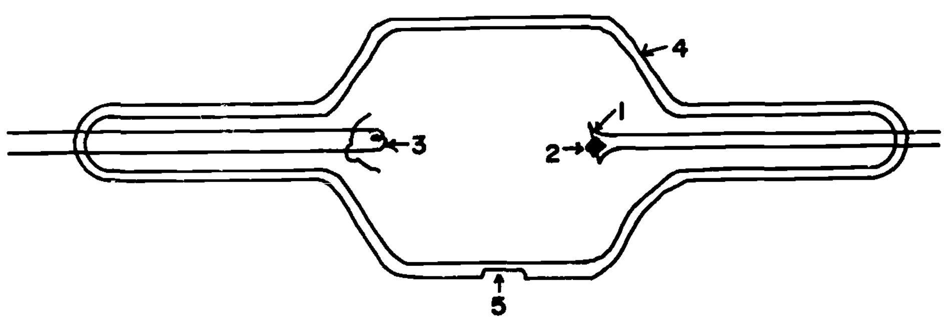


Figure 461-55 Typical Stationary Anode X-Ray Tube

A. Typical stationary anode tube (Fig. 461-55)

1. Anode

2. Target

3. Cathode (filament and cathode cup)

4. Envelope

5. Window

B. Anode design

1. Material requirements
    a. High atomic number
    b. High melting point
    c. Low vapor pressure
    d. Good heat conductivity
2. Tungsten best satisfies requirements
3. Heat dissipation usually limiting factor in target loading
    a. Copper backing
    b. Line focus principle
    c. Rotating anode

C. Cathode design

1. Consists of tungsten filament and focusing cup
2. Shape of filament and cup and location of filament in cup determine focal spot size and shape
3. Filament may be coil or spiral of tungsten
4. One end of filament attached to cup either inside or outside of envelope

D. Envelope

1. Insulator
2. Support for anode and cathode
3. Vacuum seal

E. External insulation

1. Tube housing grounded
2. Insulation between tube and housing
    a. Oil
    b. Gas (Freon, SF - 6)

F. Heat Dissipation

1. Conduction
2. Radiation

3. External cooling
    a. Oil
    b. Water
    c. Fan

III. Tube Ratings
    A. High energy, short time
    B. Low energy, long time
    C. Use of rating charts and cooling curves

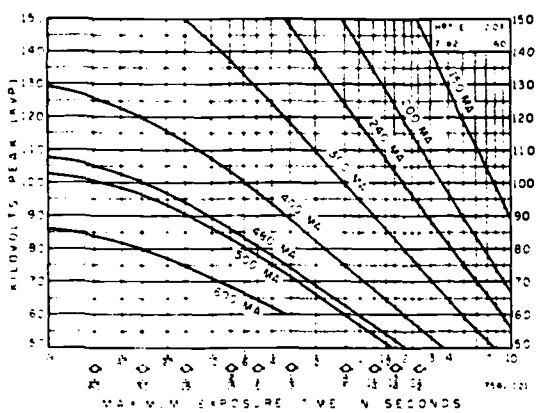
Handout 461-6

TYPICAL TUBE RATING CHARTS*

For Operation on Full-wave Rectified, Single-phase Equipment

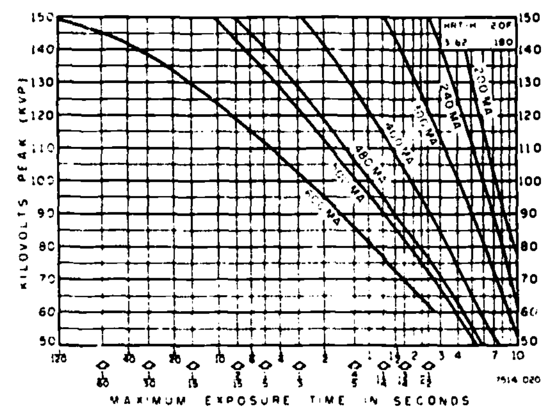
RADIOGRAPHIC RATING CHARTS
17.5 Degree Target Angle

60-Hz Stator Supply

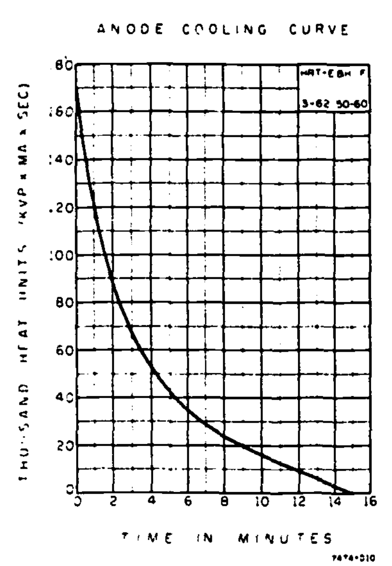


2.0-mm focal spot

180-Hz Stator Supply



2.0-mm focal spot



Anode Cooling Curve

* Taken from General Electric Co. x-ray tube data sheets.

LECTURE NO. 10

TITLE:	Fluoroscopy
PURPOSE:	To discuss fluoroscopy and the equipment used in industry and medicine
TIME:	One hour
VISUAL AIDS:	Blackboard Demonstration of direct fluoroscopy Demonstration of image intensification
HANDOUTS:	None
REFERENCES:	General Electric *Image Intensification and Recording Principles* Johns and Cunningham *The Physics of Radiology*

FLUOROSCOPY

I. Introduction

A. Fluorescence--light emitted very soon after absorption $\leq 10^{-6}$ sec.

B. Phosphorescence--emission of light considerably later than fluorescence $\geq 10^{-6}$ sec.

C. A fluoroscope consists of

1. X-ray source

2. Fluorescent screen

3. Leaded glass barrier

D. Object to be examined placed in useful beam between x-ray tube and fluorescent screen

1. Shadow image produced on screen

2. Image viewed either directly or indirectly

II. Screens

A. Fluoroscopic

1. ZnCdS--zinc cadmium sulfide

B. Intensifying (film)

1. $CaWO_4$--calcium tungstate

2. Developed by Edison 1896

III. Factors Affecting Fluoroscopic Viewing

A. Retinal physiology (Fig. 461-56)

1. Rods

a. Used for vision in fluoroscopy

b. Only distinguish light and dark

c. Minimum intensity at ~ 5,000 Å

2. Cones

a. Used for vision in well lighted room

b. Gives color vision

c. Minimum intensity at ~ 5,500 Å

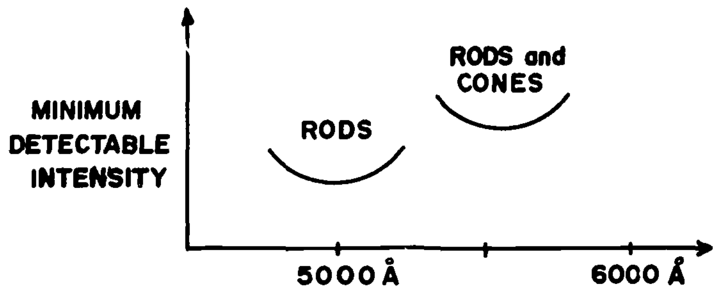


Figure 461-56 Retinal Sensitivity

q 3. Photopic vision (rods and cones)

a. > 0.01 millilambert

4. Scotopic vision (rods)

a. < 0.01 millilambert

B. Dark adaptation

1. Time

a. Tenfold sensitivity increase in 10 minutes

b. One hundred fold sensitivity increase in 18 minutes

c. One thousand fold sensitivity increase in 50 minutes

2. Goggles

a. Red

b. Obtains and maintains dark adaptation of rods

c. Transmits light of wavelength longer than 6,000 Å

IV. Image Intensification

A. Image intensifier tube

1. Input phosphor
2. Photocathode
3. Output phosphor

B. Operation

1. Electronic intensification
2. Minification
3. Electronic control
    a. Contrast
    b. Focus
    c. Brightness
4. Noise

C. Image tube size

1. 5,6,7,8,9,11 inches
2. Refers to size of face

V. Fluoroscopic Imaging Systems

A. Direct viewing

1. Lens and mirror system
2. Low power microscope
3. Viewing output phosphor

B. Fluorography

1. Photography of fluorescent image
2. Lens systems
3. Mirror systems
4. Cineradiography

C. Types of systems

1. Direct viewing
2. TV
3. Direct + TV
4. Direct + TV + cine
5. TV or cine only

VI. Applications

A. Industrial

1. Continuous production line scanning

a. Die castings

b. Food processing

c. Fruit inspection

B. Medical

1. General practice

a. Dynamic diagnosis

b. Foreign body localization

2. Special procedures

a. Catheterization

b. Contrast studies

C. Miscellaneous

1. Shoe fitting

a. No longer considered acceptable

2. Veterinary

LECTURE NO. 11

TITLE:	X-Ray Equipment in Industry
PURPOSE:	To review x-ray equipment used in industry
TIME:	One hour
VISUAL AIDS:	Blackboard Slide projector and slides of typical industrial x-ray installations (obtained from pictures in scientific journals)
HANDOUTS:	None
REFERENCES:	Materials Evaluation (current issues) Halmshaw Physics of Industrial Radiology

X-RAY EQUIPMENT IN INDUSTRY

I. Introduction

X rays are used in industry for the radiography and fluoroscopy of industrial specimens and food stuffs, for thickness gauging, fill height of liquids in light opaque containers and analytical techniques. The x-ray radiographic equipment used is similar to that used in medicine except that supporting structures must be more flexible and eye-pleasing trim is not necessary.

II. Types of Equipment

A. Radiography

1. Similar to medical x-ray therapy equipment
   a. Self-rectified and constant potential most commonly used up to about 400 kVp.
   b. Betatrons and linear accelerators used in the mega-voltage range.
2. Exposure times are often long
   a. Minutes to hours or even continuous operation.
   b. Compromise made between focal spot size and tube current for continuous duty cycle and adequate radiograph sharpness.
3. Equipment may be mobile or crane mounted in a fixed location

B. Fluoroscopy

1. Self-rectified or full-wave rectified generators commonly used
2. Usually involves production line monitoring
3. Equipment normally supplied in shielded enclosure.
4. Both direct viewing (fluoroscopic screen) and image intensification systems are used.

C. Thickness gauging

1. Determining changes in thickness of rolled metal and thickness/moisture content of paper.
2. Equipment normally of self-rectified type
3. Small x-ray beam directed through material to detector.
   a. Detector signal proportional to material thickness
   b. Signal used to control final roller spacing
   c. Second unattenuated beam used as reference.

D. Analytical systems

1. X-ray diffraction, emission spectrometry, etc.
2. Equipment usually operated anode grounded with half-wave or voltage doubling circuits.
   a. 50 to 75 kVp
   b. 25 to 50 mA
3. X-ray generator and tube including controls in single desk-type cabinet
   a. Interchangeable x-ray tubes using various elements as target material
   b. Some units use tubes operating from vacuum pump and have interchangeable targets
4. Radiation protection problems often acute
   a. High intensity, low energy x-ray beam
   b. Thermionic rectifiers, if used, can become source of x rays if rectifiers become "gassy".

E. Height-of-fill systems

1. Equipment is usually of self-rectified type operating at less than 100 kVp.
2. Small x-ray beam directed across can line toward detector
   a. Detector signal proportional to attenuation in can.
   b. Signal "high" if can underfilled, "low" if can overfilled.
   c. Detector signal triggers can reject system.

LECTURE NO. 12

TITLE:	Megavolt Machine Sources of X Rays
PURPOSE:	To review current equipment used to produce high-energy x rays (betatron, synchrotron, linac, Van de Graaff, resonant transformer)
TIME:	One hour
VISUAL AIDS:	Blackboard Slide projector for slides of typical high energy x-ray equipment (taken from scientific journals)
HANDOUTS:	None
REFERENCES:	Johns and Cunningham The Physics of Radiology Lapp and Andrews Nuclear Radiation Physics

MEGAVOLT MACHINE SOURCES OF X-RAYS

I. Introduction

Energy of accelerated electron determines maximum energy of resulting photons.

II. Types of Accelerators

- A. Orbital and linear
- B. Betatron
  1. May be used for x-rays or electrons
  2. Uses magnetic induction
     - a. Electrons take place of secondary transformer winding
     - b. Electrons liberated by heated tungsten filament
       1) Injected into porcelain donut--shaped tube between magnet poles
       2) Electron gun injects electrons
     - c. Magnet excited by 180 Hz voltage
     - d. Changing magnetic flux produces electric field in evacuated donut
     - e. Electrons bent into circular path by magnetic field and accelerated by electric field (Fig. 461-57, 58)

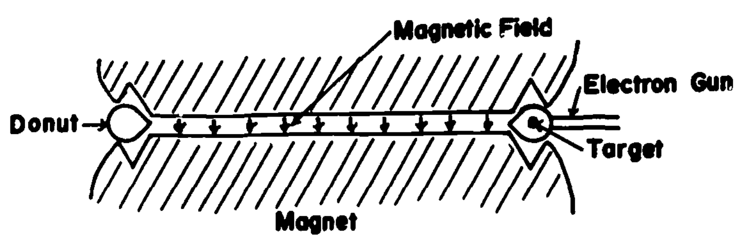


Figure 461-57 Betatron Operation

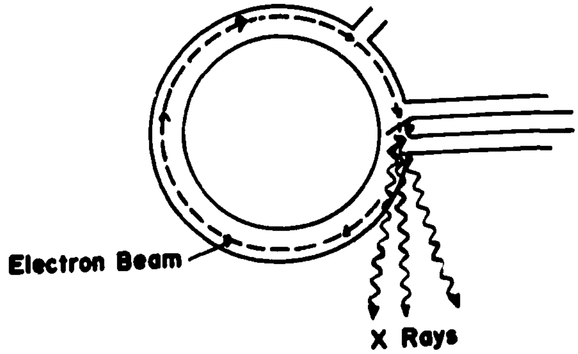


Figure 461-58 Betatron donut

f. Electrons accelerated through 1/4 of a.c. cycle (Fig. 461-59)

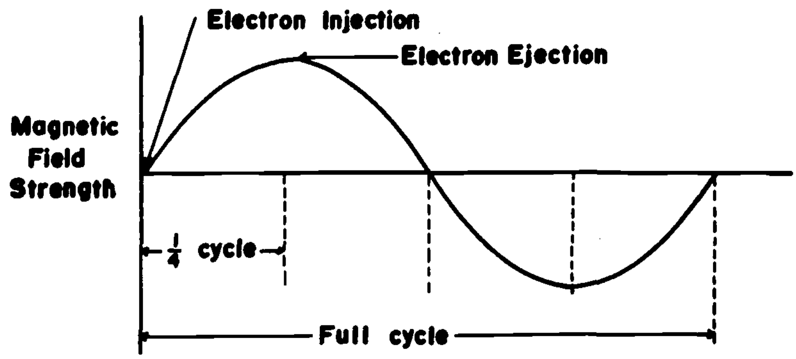


Figure 461-59 Betatron Voltage Cycle

3. Medically 25 MeV with 100 - 200 R/min at 1 meter
   a. Units up to several hundred MeV in use
      1) Research
      2) Electron beam

C. Electron synchrotron
   1. Basically a betatron
   2. Modulate magnetic field at constant RF for greater energies
   3. Electrons accelerated through resonant cavity

D. Van de Graaff generator (Fig. 461-60)
   1. Electrostatic generator. Operates under high insulating gas pressure
   2. Auxilliary voltage source, 5 - 20 kV, sprays electrons onto moving felt belt

3. Electrons transported to metal dome
   a. Based on Faraday's principle that conducting sphere will accept any charge placed on it by internal contact
   b. Applys regardless of magnitude of charge or potential existing since there is no electric field inside the dome
4. Systems used up to 10 MeV
5. High resistance bridge to ground from dome
   a. Accelerating electrodes in x-ray tube attached to bridge
   b. Provide uniform voltage drop across tube
   c. Target at ground potential
6. Output at 2 MeV, 250 μ A, approximately 100 R/minute at one meter

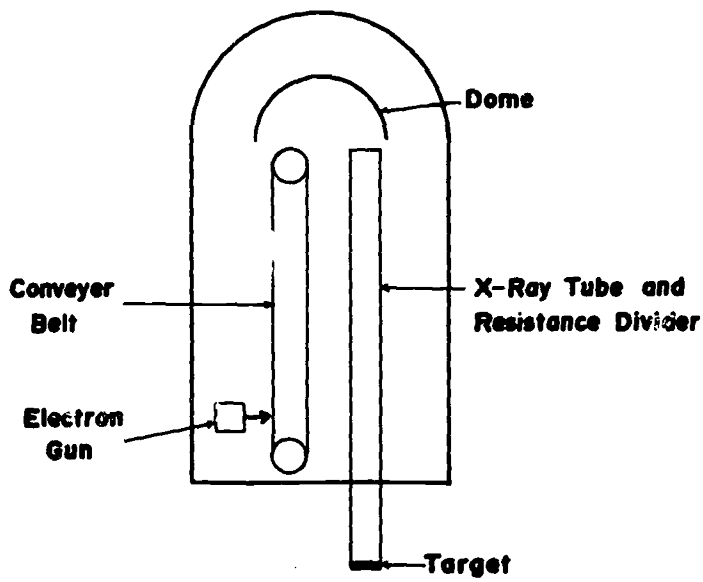


Figure 461-60 Van de Graaff Generator

E. Resonance transformer (Fig. 461-61)

1. One and two MeV
2. Multisection x-ray tube at axis of low frequency resonance transformer
3. Low number of primary turns compared to secondary
4. Secondary coil tuned to its own inductance and distributed capacitance so that, when excited by primary at the resonance frequency of 180 Hz, large secondary voltages are developed
   a. Secondary connected to accelerating electrodes in x-ray tube
   b. Insulated with SF-6
5. Water cooled tungsten tube target
6. Operates self-rectified
7. Output at 2 MeV, 1.5 mA approximately 150 R/minute at one meter

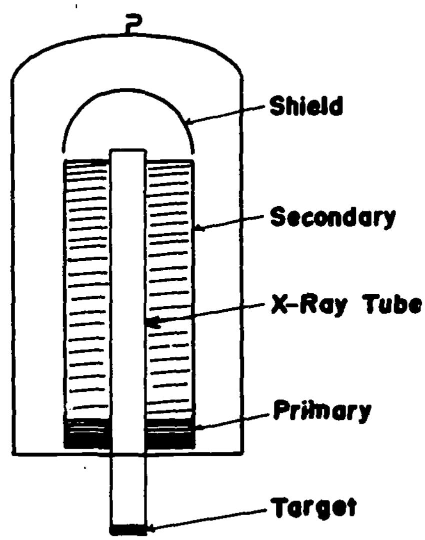


Figure 461-61 Resonance Transformer

F. Microwave linear accelerator

1. Travelling-wave of radio frequency power provided by Klystron power tubes
2. Wave travels within evacuated tube called wave guide
3. Electrons injected into wave guide can be visualized as trapped on crest of moving wave (Fig. 461-62)

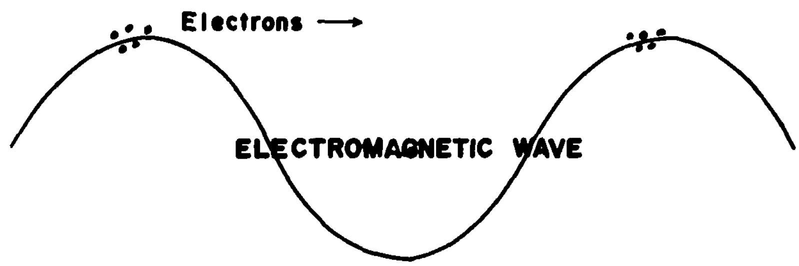


Figure 461-62 Microwave Lineal Voltage

4. Continually receive energy from power tubes as they travel down wave guide
5. Pulsed at about one microsecond

LECTURE NO. 13

TITLE: Biological Effects of Radiation

PURPOSE: To describe the response of a biological system to radiation and the factors effecting response

TIME: One hour

VISUAL AIDS: Blackboard

HANDOUTS: NCRP Report No. 39 (student to purchase)

REFERENCES:

Bacq and Alexander
    The Fundamentals of Radiobiology

Lea
    Actions of Radiations on Living Cells

National Council on Radiation Protection
    Report No. 39 Basic Radiation Protection Criteria

Pizzarello and Witcofski
    Basic Radiation Biology

BIOLOGICAL EFFECTS OF RADIATION

I. Introduction

A. Biological damage known for long time

1. Human injury reported a few months after Roentgen's discovery

2. First case of x-ray induced cancer reported in 1902

3. Lethal effects demonstrated in 1905

B. Radiation effects normally damaging to cell

1. Few rare beneficial mutations

C. Lethal dose, LD_{50} 400-600 rads

1. Only about 1 atom in 10^8 are ionized

2. Corresponds to temperature increase of about $0.001^{\circ}C$

II. Types of Exposure

A. Short-term or acute

1. Total exposure given delivered in short time

2. Usually accidental or unintentional

B. Long-term or protracted

1. Accumulated over long period of time

a. Therapeutic exposures

b. Occupational exposures

III. Types of Effect

A. Somatic - effect is to individual exposed

B. Genetic - effect is to progeny of individual exposed

IV. Pattern of Effects

A. Latent period - time lag between exposure on onset of detectable effects

1. In general the larger the dose the shorter the latent period

2. Short-term exposure - minutes, hours, days, weeks

3. Long-term exposure - years, decades, generations

B. Symptomatic period - effects become observable

1. Histological evidence

a. Microscopic study of tissue structure

1) Lowering blood counts

2) Abnormal mitosis - cell division

3) Chromosome breaks

4) Clumping of chromatin - in cell nucleus

2. Gross effects

a. Macroscopic - seen by unaided eye

1) Loss of appetite

2) Intestinal hemorrhage

3) Nausea

4) Fatigue

5) Loss of hair

6) Erythema

7) Weight loss

8) Sterility

C. Recovery period - repair process (Fig. 461-63)

1. Some damage is irrepairable
2. Some effects cumulative
3. Others recuperate from damage

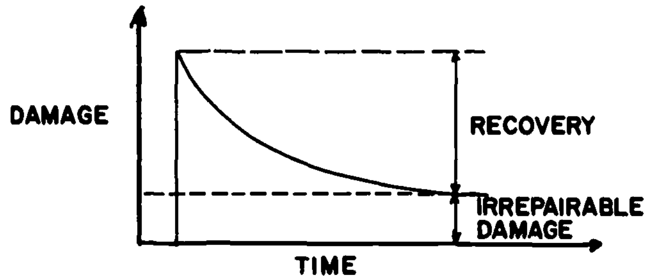


Figure 461-63 Repair Process

V. Short Term Exposure vs Probable Effect

A. Whole body exposure

B. Penetrating radiation

Acute Exposure	Probable Effect
0-25 R	No obvious injury
25-50 R	Possible blood changes but no serious injury
50-100 R	Blood cell changes, some injury, no disability likely
100-200 R	Injury, possible disability
200-400 R	Injury, disability, possible death
400-500 R	Fatal to 50%

VI. Long Term Effects

A. Carcinogenesis

1. Skin cancer - early workers
2. Bone tumors - radium dial pointers
3. Lung cancers - uranium miners
4. Leukemia

B. Life-span shortening (Fig. 461-64)

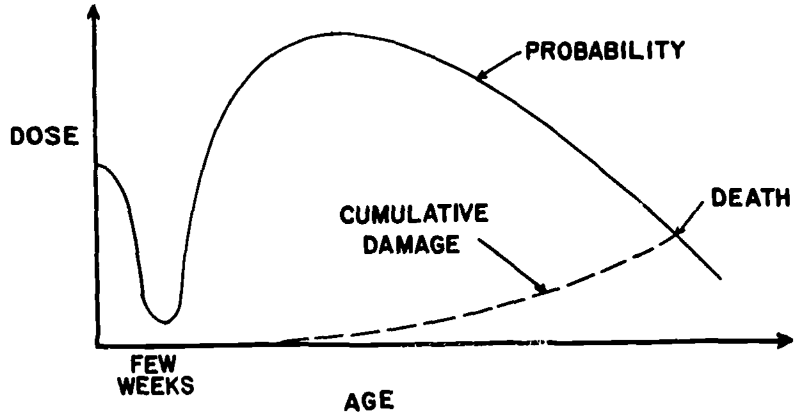


Figure 461-64 Life-span Shortening

C. Genetic mutations

1. Lethal mutations not important
2. Most mutations detrimental

D. Embryological effects

1. Fetus most sensitive during first tri-mester
2. Especially first 6-8 weeks

E. Cataracts

1. Eye not specially sensitive to x-ray
2. Neutrons and alphas have high RBE

VII. Factors Effecting Biological Response

A. Absorbed dose

1. Type of radiation
2. Energy of radiation
3. Material exposed

B. Area exposed

1. Larger area greater effect

C. Dose rate

1. Effect of fractionated exposure less

D. Variability of species

1. For example LD_{50} for rabbit > man > swine

E. Cell and tissue sensitivity

1. Similar tissue → similar histological effect
2. Different cell types → different effects
3. Law of Bergonie and Tribendeau
   a. Sensitivity is proportional to reproductive activity and inversely proportional to differentiation
   b. They postulated:
      1) Those cells that are not dividing (fully differentiated) are radiation resistant
      2) Cells that are dividing are sensitive

Increasing Radiosensitivity ↓

1. Nerve, muscle, bone
2. Liver
3. Blood vessels
4. Skin
5. Gonads
6. Cells lining GI tract
7. Bone marrow (immature blood cells)
8. Lymphoid tissue

VIII. Principles of Radiation Protection

A. Time - exposure $\propto$ t
B. Distance - exposure $\propto$ $1/d^2$
C. Shielding - exposure $\propto$ $e^{-\mu x}$
D. Monitoring - determines efficiency of above 3

SPECIAL PROJECT

TITLE:	Library Projects (including trip through library conducted by library staff)
PURPOSE:	To introduce the student to library research
TIME:	As required to prepare report
MATERIALS:	Reference library dealing with topics in the X-ray field
REFERENCES:	As required for selected topic

Acceptable topics are not limited to those listed here. In addition, the method of assigning the topics, the method of presentation (oral and/or written), the length, and the format are all left to the discretion of the instructor.

LIBRARY PROJECTS

1. THE DISCOVERY OF X-RAY
2. HIGH-VOLTAGE RECTIFICATION
3. SOLID-STATE RECTIFIERS
4. HIGH-VOLTAGE CABLES
5. INSULATING MATERIALS FOR HV EQUIPMENT
6. DEVELOPMENT OF THE COOLIDGE X-RAY TUBE
7. COLD CATHODE PRODUCTION OF X-RAYS
8. HOT CATHODE PRODUCTION OF X-RAYS
9. INCIDENTAL SOURCES OF X-RAYS (TV, etc.)
10. EVOLUTION OF THE DENTAL X-RAY MACHINE
11. X-RAY DIFFRACTION UNITS (Theory of Operation)
12. X-RAY GAGING UNITS (Theory of Operation)
13. REQUIREMENTS OF X-RAY MACHINES FOR VETERINARY USE
14. REQUIREMENTS OF X-RAY MACHINES FOR THERAPY
15. MICRO-ANALYSIS OF BIOLOGICAL SAMPLES WITH X-RAYS
16. INDUSTRIAL APPLICATIONS
17. SPECIAL APPROVED TOPICS

GS-461 MACHINE SOURCES OF X RAY

SECTION II

LABORATORY EXERCISES

LABORATORY NO. 1

TITLE: Introduction to Radiography

PURPOSE: To introduce the student to the principles of radiography.

TIME: Three hours

MATERIALS FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One sheet of 8" x 10" "no screen" X-ray film
One 8" x 10" cardboard film holder
One darkroom station
One 8" x 10" film hanger
One specimen for radiography - (Any small object with some internal structure is acceptable. Exposure factors will have to be adjusted accordingly.)

REFERENCES: Mees and James
<u>Theory of the Photographic Process</u>

Laboratory No. 1

INTRODUCTION TO RADIOGRAPHY

I. INTRODUCTION

The purpose of this experiment is to introduce the student to the principles of radiography. A radiography is a visible record produced by the passage of x rays through an object and recorded on a special type film. The purpose of radiography is to provide a permanent record of a view of the internal structure of an object.

II. EQUIPMENT

A. One Teaching X-Ray Unit

B. One sheet 8 x 10 inch "no screen" x-ray film

C. One 8 x 10 inch cardboard film holder

D. One darkroom station

E. One 8 x 10 inch film hanger

F. Specimen for radiography - one sand dollar (echinarachnius)

III. PROCEDURE

A. Loading the exposure holder

The exposure holder holds the film during the exposure. It is made of cardboard and has a lead sheet on the back side to reduce scatter. After entering the darkroom and achieving adequate dark adaptation, remove the film from storage and load into the holder. Exposure holders for direct radiography are loaded as follows:

1. Open the holder.

2. Pick up the film in its protective paper folder with thumb and forefinger without bending or crimping the film and paper.

3. Lay them in the envelope.

4. Place the large flap over the film.

5. Fold the side flaps and end flap down.

6. Lower the holder cover.

7. Close the latch.

B. Exposing the film

1. Place film under the x-ray tube with the long dimension perpendicular to the tube axis. This is done because the field distribution along the axis perpendicular to the tube axis is nearly symmetrical whereas the field distribution along the tube axis is not symmetrical.

2. Place exposure holder with the side marked "tube side" toward the x-ray tube. This is necessary because of the lead sheet in the back of the exposure holder.

3. Place specimen in the center of the film and use lead numbers or letters to identify your film. The required exposure settings have previously been determined to be 50 kVp, 5 mA, and 2 seconds.

C. Developing the exposed film

1. After exposure, take to darkroom for development. Dark adaptation must again be attained before continuing.

2. Remove film from holder and place in a processing hanger.

3. The steps in loading the hanger are:

a. Hold the film gently between thumb and forefinger and attach the upper right clip of the hanger to the film.

b. Attach the upper left clip.

c. Attach the lower left spring-loaded clip.

d. Attach the lower right spring-loaded clip.

e. Check to be sure the film is taut so that it will not bulge or flap during processing or drying.

4. Place loaded hanger in the developer for manufacturer's recommended development time and temperature. The developer

contains an alkali for softening the emulsion which allows it to permeate and convert the exposed silver halide grains to metallic silver. Common developing times and temperatures are: 70°F -- 4 1/2 minutes; 68°F -- 5 minutes; and 65°F -- 6 minutes.

5. After the required length of time in this developer, place film in water and wash (with constant agitation) for one minute to remove the developing chemicals. Following this place film in the fixer solution for ten minutes. The fixer removes the unexposed silver from the emulsion and contains an acid which hardens the emulsion.

6. Remove film from fixer and place in running water to rinse for 30 minutes. The final rinse removes all traces of processing chemicals from the film.

7. Remove film from water and dry. When dry, remove film from hanger and store in its protective paper covering. The radiograph is now ready for viewing. The radiograph is a negative and is always viewed as such.

D. Viewing the film

1. Place the radiograph on the view box.
2. View the radiograph and observe the internal structure.

LABORATORY NO. 2

TITLE: X-Ray Machine Simulator

PURPOSE: To investigate the operational characteristics of basic x-ray machines

TIME: Six hours

MATERIALS FOR EACH STUDENT GROUP:

One X-Ray Machine Simulator
Fifteen sheets linear graph paper (K & E 46-0703 or equivalent)
One ships curve (K & E 1685-48 or equivalent)
One straight edge

REFERENCES:

Bloom, Hollenback and Morgan
<u>Medical Radiographic Technic</u>

General Electric Technical Publication
<u>High-Tension Generation and Its Use in Radiography</u>

Trout, USPHS Publication No. 1718
<u>An X-Ray Machine Simulator</u>

LABORATORY NO. 2

X-RAY MACHINE SIMULATOR

Object

The object of this laboratory exercise is to determine experimentally the operating characteristics of basic x-ray machine circuits.

Introduction

All x-ray machines from the most simple to the most sophisticated have two common features: the ability to vary both the tube current (I_p) and the tube voltage (E_{hv}) independently, thereby controlling the x-ray output. The tube current is varied indirectly by varying the x-ray tube filament current (I_f). The voltage across the x-ray tube is varied by changing the voltage (E_p) applied to the primary of the high-voltage transformer.

Other circuit characteristics such as the type of rectification and the high-voltage cable capacitance will influence the operation of an x-ray unit. This laboratory exercise will serve to demonstrate the relationship between filament current and tube current, secondary voltage and tube current, and primary voltage and secondary voltage under different conditions of rectification through the use of an X-Ray Machine Simulator. The X-Ray Machine Simulator performs in the same manner as an x-ray machine, but without the production of x rays.

Symbols

Electrical symbols used and their meanings are as follows:

I_p	Tube (plate) current
I_f	Filament current
E_p	High-voltage primary
E_s	High-voltage secondary
E_{hv}	High-voltage across tube
C	Capacitance

CAUTION: IN OPERATING THE SIMULATOR DO NOT EXCEED THE FOLLOWING!

Tube voltage E_{hv} = 200 volts DC

Tube current I_p = 35 mA

Filament current I_f = 1.6 amp

Part No. 1

SELF-RECTIFIED OPERATION

I. Effect of filament current on tube current at a constant high voltage transformer secondary voltage.

A. Assemble the Simulator for self-rectified operation as described below and shown in the circuit diagram.

1. Circuit modules required: Control, inverse reducer, transformer, and tube.

2. Meters required: 0-150 volt AC Primary, 0-300 volt AC secondary, 0-3 A AC filament, 0-50 mA DC tube current and three-inch DC 'scope.

3. Complete set interconnecting wires.

4. Interconnecting wiring:

a. Connect control L1 to inverse reducer L1 (C).

b. Connect inverse reducer L1 (T) to transformer L1.

c. Connect control L2 to transformer L2.

d. Connect control L3 to transformer L3.

e. Connect transformer AC to tube POS.

f. Connect transformer ACC to transformer FCT.

g. Connect transformer FIL 1 to tube FIL 1.

h. Connect transformer FIL 2 to tube FIL 2.

5. Meter connections:

   a. Connect 0-150 volt AC meter to control L1 and control L2.

   b. Connect 0-300 volt AC meter to transformer AC and transformer ACC.

   c. Connect 0-3 A AC meter to tube FIL 2 and tube filament.

   d. Connect 0-50 mA DC meter negative to tube anode and positive to tube POS.

   e. Connect 'scope vertical amplifier red terminal to tube anode (TP) and black terminal to transformer FIL 1.

6. Oscilloscope preliminary setting:

   a. Set vertical and horizontal position controls to mid position.

   b. Set vertical amplifier to DCX 100.

   c. Set horizontal amplifier to DCX 1.

   d. Set sweep generator to INT 5.

7. Preliminary operation

   a. With line and x-ray switches OFF, kV and FIL controls full counterclockwise, insert line plug into 115 volt, 60 Hertz line.

   b. Turn on line switch. The tube filament should glow and the 0-2 ampere filament current meter indicate less than one ampere.

c. Turn on 'scope and wait one minute.

d. Adjust 'scope trace to mid scale vertical and full scale horizontal.

e. Turn on x-ray switch and adjust control for experimental conditions.

8. Operation limitations:

a. NEVER EXCEED 1.6 amperes filament current or 35 milliamperes tube current.

b. NEVER EXCEED 200 volts tube plate voltage.

B. Place the inverse reduced switch in the closed (out) position.

C. Holding the high-voltage transformer secondary voltage (E_s) constant at 150 volts, vary the filament current (I_f) from 1.00 to 1.50 amperes in 0.10 ampere steps.

D. Measure and record:

1. The high-voltage transformer primary voltage (E_p).

2. The tube current (I_p).

E. Record freehand the tube voltage waveforms for $E_s = 150$ volts and $I_f = 1.50$ ampere with the inverse reducer shorted (out) and with the inverse reducer connected (in).

F. On linear paper, plot tube current (I_p) vs filament current (I_f).

II. Effect of high-voltage transformer secondary voltage on tube current at a constant filament current.

A. Holding the filament current (I_f) constant at 1.50 amperes, vary the transformer secondary voltage (E_s) from 0 to 50 volts in 10 volt steps and from 50 to 200 volts in 25 volt steps. Place the inverse reducer switch in the closed (out) position.

B. Measure and record the tube current (I_p).

C. On linear paper, plot tube current (I_p) vs secondary voltage (E_s).

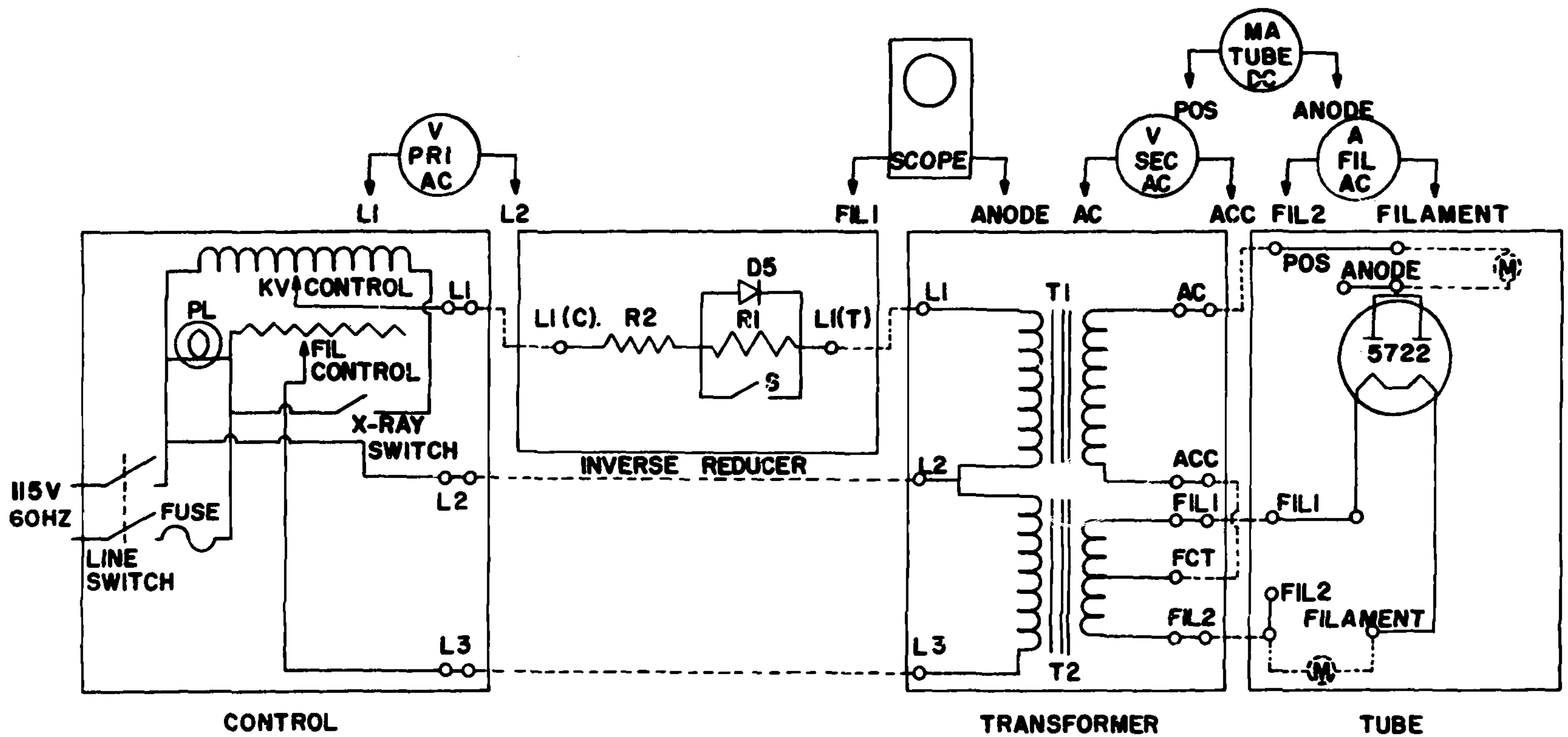
III. Effect of primary voltage on secondary voltage at a constant tube current.

A. Holding the tube current (I_p) constant at 1.00 mA, vary the primary voltage (E_p) from 25 to 100 volts in 25 volt steps. Repeat for tube current of 5 mA. Place the inverse reducer switch in the closed (out) position.

B. At each constant tube current measure and record the secondary voltage (E_s).

C. On linear paper, plot secondary voltage (E_s) vs primary voltage (E_p) for each tube current (I_p).

X-RAY MACHINE SIMULATOR
SELF—RECTIFIED



Part No. 2
HALF-WAVE OPERATION

I. Effect of filament current on tube current at a fixed high-voltage transformer secondary voltage

A. Assemble the Simulator for half-wave operation as described below and shown in the circuit diagram.

1. Circuit modules required: control, transformer, rectifier, capacitor and tube. Note: Remove diodes D1 and D3 from rectifier circuit board.

2. Meters required: 0-150 volt AC primary, 0-300 volt AC secondary, 0-300 volt DC high voltage, 0-3 A AC filament, 0-50 mA DC tube current and three-inch DC 'scope.

3. Complete set interconnecting wires.

4. Interconnecting wiring:

a. Connect control L1 to transformer L1.

b. Connect control L2 to transformer L2.

c. Connect control L3 to transformer L3.

d. Connect transformer AC to rectifier AC.

e. Connect transformer ACC to rectifier ACC.

f. Connect transformer FCT to rectifier negative (-).

g. Connect transformer FIL 1 to tube FIL 1.

h. Connect transformer FIL 2 to tube FIL 2.

i. Connect rectifier positive (+) to tube POS.

j. Connect rectifier negative (-) to capacitor negative (-) and rectifier positive (+) to capacitor positive (+), (C1, C2, or C3).

5. Meter connections:

   a. Connect 0-150 volt AC meter to control L1 and control L2.

   b. Connect 0-300 volt AC meter to transformer AC and transformer ACC.

   c. Connect 0-300 volt DC meter negative to rectifier negative (-) and positive to rectifier positive (+).

   d. Connect 'scope vertical amplifier (red) terminal to rectifier positive (+) and (black) terminal to rectifier negative (-).

   e. Connect 0-3 A AC meter to tube FIL 2 and tube filament.

   f. Connect 0-50 mA DC meter negative to tube anode and positive to tube POS.

6. Oscilloscope preliminary setting:

   a. Set vertical and horizontal position controls to mid position.

   b. Set vertical amplifier to DCX 100.

   c. Set horizontal amplifier to DCX 1.

   d. Set sweep generator to INT 5.

7. Preliminary operation:

   a. With line and x-ray switches OFF, and kV and FIL controls full counterclockwise, insert line plug into 115 volt, 60 Hertz line.

   b. Turn on line switch. The tube filament should glow and the 0-3 ampere filament current meter indicate less than one ampere.

   c. Turn on 'scope and wait one minute.

   d. Adjust 'scope trace to mid scale vertical and full scale horizontal.

   e. Turn on x-ray switch and adjust kV and FIL controls to obtain required experimental conditions.

8. Operating limitations:

   a. NEVER EXCEED 1.6 amperes *filament current* or 35 milliamperes tube current.

   b. NEVER EXCEED 200 volts tube plate voltage.

B. Holding the high-voltage transformer secondary voltage (E_s) constant at 150 volts, vary the filament current (I_f) from 1.00 to 1.50 amperes in 0.10 ampere steps.

C. Measure and record:

1. The high-voltage transformer primary voltage (E_p)

2. The tube voltage (E_{hv})

3. The tube current (I_p) for 0, 0.01, 0.05, or 0.1 mF capacitance

D. Record freehand the tube voltage waveforms for (E_s) = 150 volts and (I_f) = 1.00 ampere with 0, 0.01, 0.05, and 0.1 mF capacitance.

E. Record freehand the tube voltage waveforms for (E_s) = 150 volts and (I_f) = 1.50 amperes with 0, 0.01, 0.05, and 0.1 mF capacitance.

F. On linear paper, plot tube current (I_p) vs filament current (I_f). On a second sheet of linear paper, plot tube voltage (E_{hv}) vs filament current (I_f).

II. Effect of high-voltage transformer secondary voltage on tube current at a constant filament current.

A. Holding the filament current (I_f) constant at 1.50 amperes, vary the transformer secondary voltage (E_s) from 0 to 50 volts in 10 volt steps and from 50 to 200 volts in 25 volt steps.

B. Measure and record:

1. The tube current (I_p)

2. The tube voltage (E_{hv}) for 0, 0.01, 0.05, and 0.1 mF capacitance

C. On linear paper, plot tube current (I_p) vs secondary voltage (E_s).

On a second sheet of linear paper, plot tube voltage (E_{hv}) vs secondary voltage (E_s).

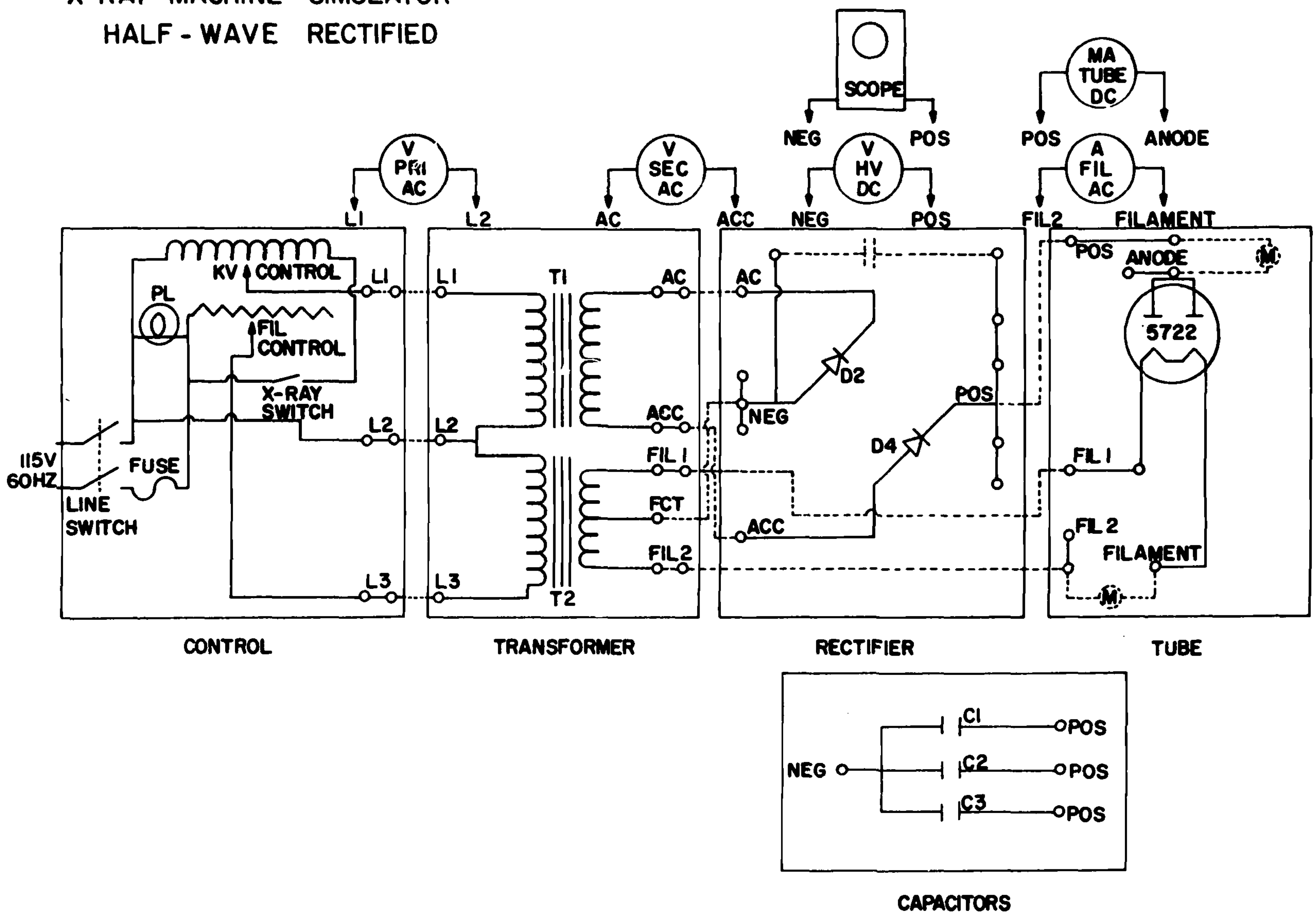
III. Effect of primary voltage (E_p) on secondary voltage (E_s) at a constant tube current.

A. Holding the tube current constant at 1.00 mA, vary the primary voltage (E_p) from 25 to 100 volts in 25 volt steps. Repeat for tube current of 5 mA. Operate with C = 0 mF.

B. At each constant tube current, measure and record the secondary voltage (E_s).

C. On linear paper, plot secondary voltage (E_s) vs primary voltage (E_p) for each tube current (I_p).

X-RAY MACHINE SIMULATOR
HALF-WAVE RECTIFIED



Part No. 3
FULL-WAVE OPERATION

I. Effect of filament current on tube current at a constant high-voltage transformer secondary voltage

A. Assemble the simualtor for full-wave operation as described below and shown in the circuit diagram

1. Circuit modules required: control, transformer, rectifier, capacitors, and tube

2. Meters required: 0-150 volt AC primary, 0-300 volt AC secondary, 0-300 volt DC high voltage, 0-3 A AC filament, 0-50 mA DC tube current and three-inch 'scope

3. Complete set interconnecting wires

4. Interconnecting wiring:

a. Connect control LI to transformer LI.

b. Connect control L2 to transformer L2.

c. Connect control L3 to transformer L3.

d. Connect transformer AC to rectifier AC.

e. Connect transformer ACC to rectifier ACC.

f. Connect transformer FCT to rectifier negative(-).

g. Connect transformer FIL 1 to tube FIL 1.

h. Connect transformer FIL 2 to tube FIL 2.

i. Connect rectifier positive (+) to tube POS.

j. Connect rectifier negative (-) to capacitor negative (-).

k. Connect rectifier positive (+) to capacitor positive (+), (Cl, C2, or C3).

5. Meter connections:

a. Connect 0-150 volt AC meter to control <u>L1</u> and control <u>L2</u>.

b. Connect 0-300 volt AC meter to transformer <u>AC</u> and transformer <u>ACC</u>.

c. Connect 0-300 volt DC meter negative to rectifier negative (-) and positive to rectifier positive (+).

d. Connect 'scope vertical amplifier red terminal to rectifier positive (+) and black terminal to rectifier negative (-).

e. Connect 0-3 A AC meter to tube <u>FIL 2</u> and tube filament.

f. Connect 0-50 mA DC meter negative to tube anode and positive to tube <u>POS</u>.

6. Oscilloscope preliminary setting:

a. Set vertical and horizontal position controls to mid position.

b. Set vertical amplifier to DCX 100.

c. Set horizontal amplifier to DCX 1.

d. Set sweep generator to INT 5.

7. Preliminary operation:

a. With line and x-ray switches OFF, kV and FIL control full counterclockwise, insert line plug into 115 volt, 60 Hertz line.

b. Turn on line switch. The tube filament should glow and the 0-3 ampere filament current meter indicate less than one ampere.

c. Turn on the 'scope. Wait one minute.

d. Adjust 'scope trace to mid scale vertical and full scale horizontal.

e. Turn on x-ray switch and adjust controls to experimental conditions.

8. Operating limitations:

a. NEVER EXCEED 1.6 ampere filament current on 35 mA tube current.

b. NEVER EXCEED 200 volts tube plate voltage.

B. Holding the high-voltage transformer secondary voltage (E_s) constant at 150 volts AC, vary the filament current (I_f) from 1.00 to 1.50 amperes in 0.10 ampere steps.

C. Measure and record:

1. The high-voltage transformer primary voltage (E_p)

2. The tube voltage (E_{hv})

3. The tube current (I_p) for 0, 0.01, 0.05, and 0.1 mF capacitance

D. Record freehand the tube voltage waveforms for E_s = 150 volts and I_f = 1.00 ampere with 0, 0.01, 0.05, and 0.1 mF capacitance.

E. Record freehand the tube voltage waveforms for E_s = 150 volts and I_f = 1.5 amperes with 0, 0.01, 0.05, and 0.1 mF capacitance.

F. On linear paper, plot tube current (I_p) vs filament current (I_f). On a second sheet of linear paper, plot tube voltage (E_{hv}) vs filament current (I_f).

II. Effect of high-voltage transformer secondary voltage (E_s) on tube current (I_p) at a fixed filament current (I_f).

A. Holding the filament current (I_f) constant at 1.50 amperes, vary the transformer secondary voltage (E_s) from 0 to 50 volts in 10 volt steps and from 50 to 200 volts in 25 volt steps.

B. Measure and record:

1. The tube current (I_p)

2. The tube voltage (E_{hv}) for 0, 0.01, 0.05, and 0.1 mF capacitance

C. On linear paper, plot tube current (I_p) vs secondary voltage (E_s). On a second sheet of linear paper, plot tube voltage (E_{hv}) vs secondary voltage (E_s).

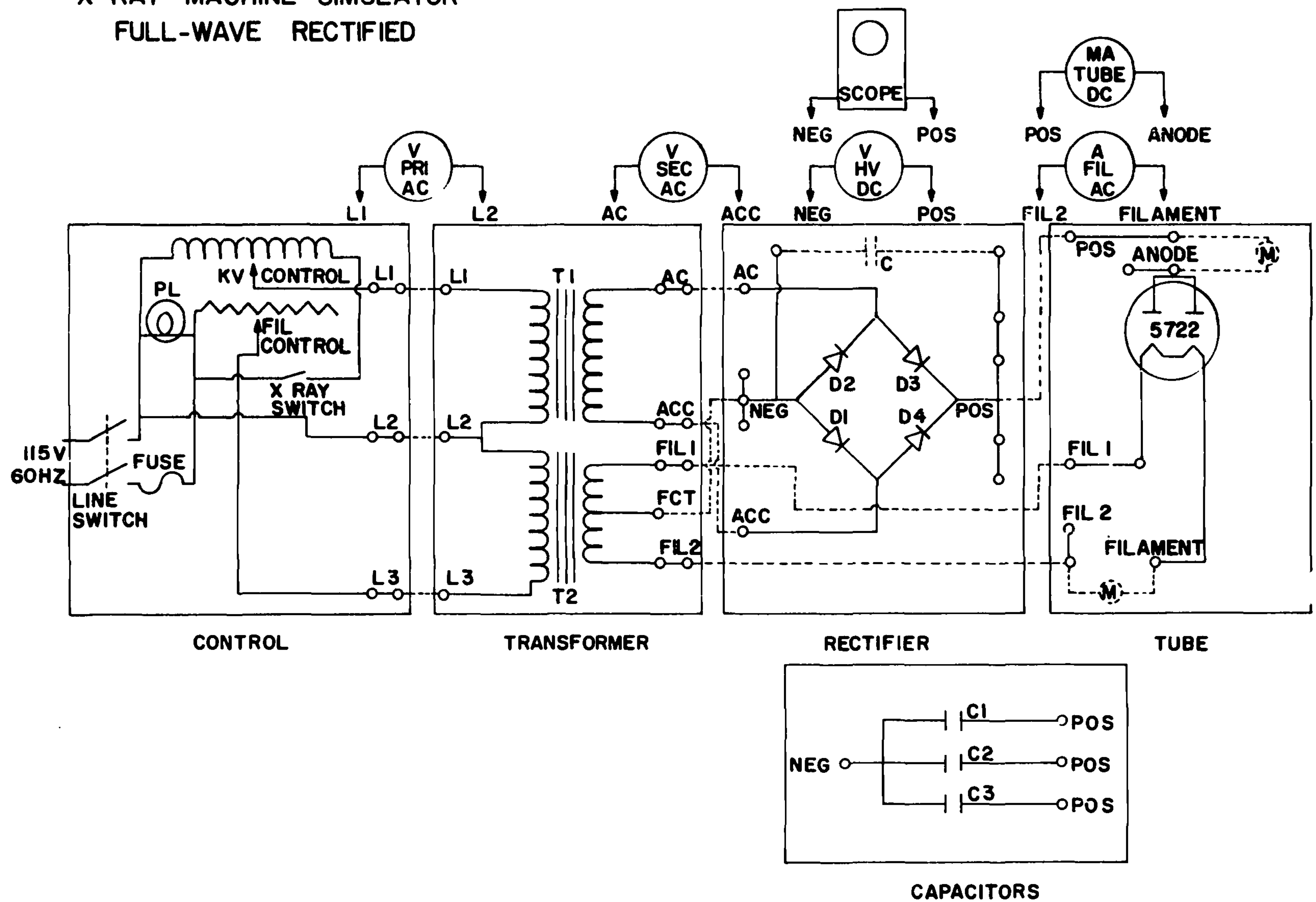
III. Effect of primary voltage (E_p) on secondary voltage (E_s) at a fixed tube current.

A. Holding the tube current constant at 1.00 mA, vary the primary voltage (E_p) from 25 to 100 volts in 25 volt steps. Repeat with a tube current of 10 mA. Operate with $C = 0$ mF.

B. At each constant tube current, measure and record the secondary voltage (E_s).

C. On linear paper, plot secondary voltage (E_s) vs primary voltage (E_p) for each tube current (I_p).

X-RAY MACHINE SIMULATOR
FULL-WAVE RECTIFIED



Part No. 4

NO LOAD TRANSFORMER RATIO

I. Effect of primary voltage on secondary voltage with no load on secondary.

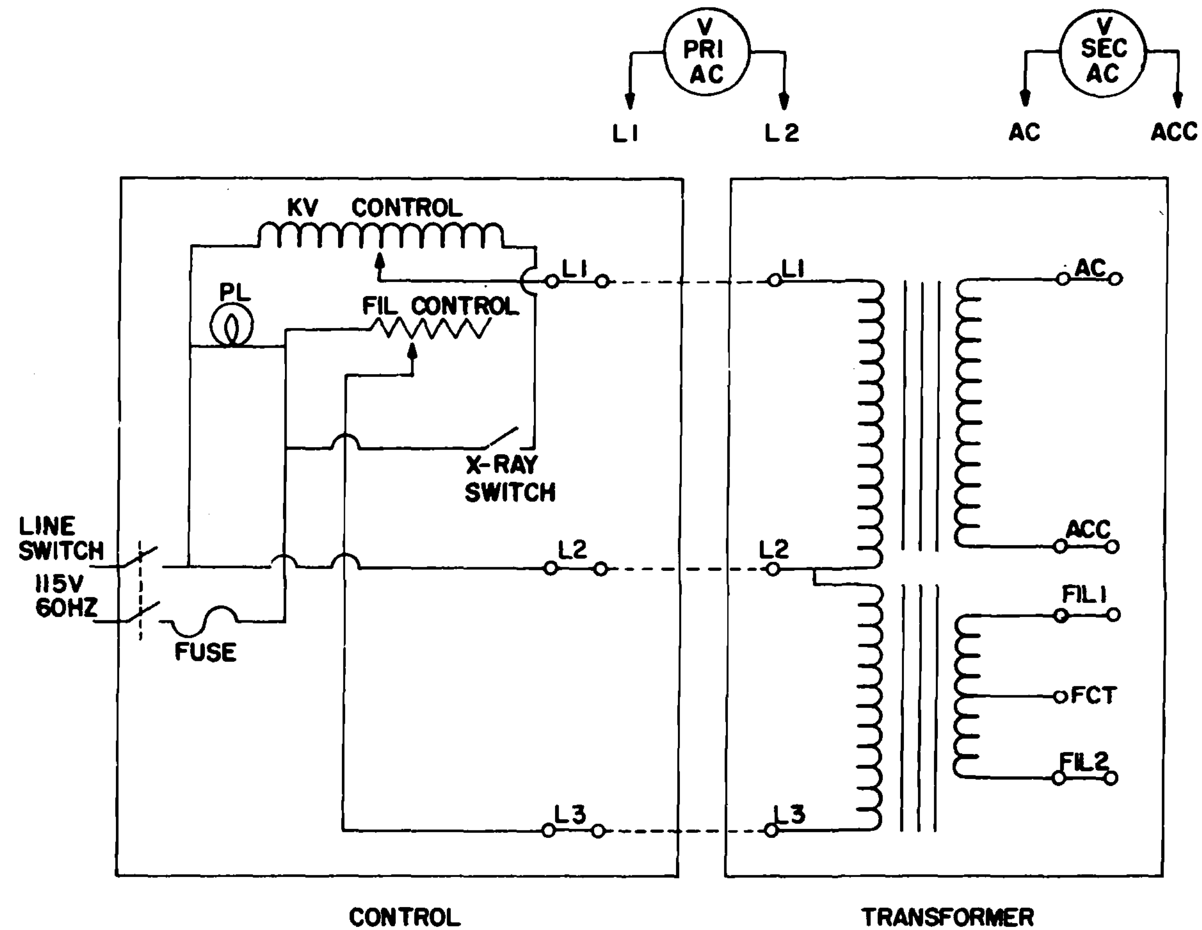
A. Assemble the simulator control and transformer sections for no load operation, as shown on the "No Load" circuit diagram.

B. Vary the primary voltage (E_p) from 25 to 100 volts in 25 volt steps.

C. Measure and record the secondary voltage (E_s).

D. On linear paper, plot secondary voltage (E_s) vs primary voltage (E_p).

X-RAY MACHINE SIMULATOR
NO LOAD



QUESTIONS

A. Discuss the significance of the curves of tube current vs filament current obtained for full-wave, half-wave, and self-rectified operation.

B. Discuss the significance of the curves of tube current vs secondary voltage obtained for full-wave, half-wave, and self-rectified operation.

C. Discuss the significance of the voltage waveshapes obtained.

D. Explain the effect of cable capacitance on tube voltage waveform and the effect of tube current on these waveforms.

E. Briefly discuss the operation of full-wave, half-wave, and self-rectified circuits.

F. Compute the transformer transformation ratio from the data in Section III of Laboratory Part No. 2 and 3. Is the ratio constant? Why?

G. Discuss the operation of an inverse reducer in a self-rectified circuit. How does the inverse reducer effect high voltage design?

H. In Section I of Laboratory Part No. 2 and 3, explain any change in tube voltage with filament current.

Name:________________________
Date:_________________________
Laboratory No. 2 Simulator No:_____

Laboratory Data Sheets

Part No. 1 - Self-Rectified Operation

1, Section D. Effect of filament current on tube current and primary voltage at a constant high voltage transformer secondary voltage (E_s = 150 volts).

I_f	I_p	E_p
1.00		
1.10		
1.20		
1.30		
1.40		
1.50		

1, Section E. Tube voltage waveforms with and without the inverse reducer (E_s = 150 volts, I_f = 1.50 amperes).

Inverse Reducer Shorted — Inverse Reducer Connected

____________________ _______________________'scope base line

II, Section B. Effect of high-voltage transformer secondary voltage on tube current at a constant filament current (I_f = 1.50 amperes).

E_s	I_p
10	____
20	____
30	____
40	____
50	____
75	____
100	____
125	____
150	____
175	____
200	____

III, Section B. Effect of primary voltage on secondary voltage at a constant tube current.

	$I_p = 1.0$ mA	$I_p = 5.0$ mA
E_p	E_s	E_s
25	____	____
50	____	____
75	____	____
100	____	____

Name:____________________
Date:____________________
Simulator No.:________________

Part No. 2 - Half-Wave Operation

I, Section C. Effect of filament current on tube current, primary voltage and tube voltage at a constant high voltage transformer secondary voltage (E_s = 150 volts).

	Capacitance											
	0 mF			0.01 mF			0.05 mF			0.1 mF		
I_f	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}
1.00												
1.10												
1.20												
1.30												
1.40												
1.50												

I, Section D. Tube voltage waveforms for a filament current I_f = 1.00 ampere and secondary voltage E_s = 150 volts.

C = 0 mF 0.01 mF 0.05 mF 0.1 mF

________ ________ ________ ________'scope base line

I, Section E. Tube voltage waveforms for a filament current I_f = 1.50 ampere and a secondary voltage E_s = 150 volts.

C = 0 mF 0.01 mF 0.05 mF 0.1 mF

________ ________ ________ ________'scope base line

II, Section B. Effect of high voltage transformer secondary voltage on tube current and tube voltage at a constant filament current (I_f = 1.50 amperes).

	Capacitance							
	0 mF		0.01 mF		0.05 mF		0.1 mF	
E_s	I_p	E_{hv}	I_p	E_{hv}	I_p	E_{hv}	I_p	E_{hv}
10								
20								
30								
40								
50								
75								
100								
125								
150								
175								
200								

III, Section B. Effect of primary voltage on secondary voltage at a constant tube current (C = 0 mF).

	I_p = 1.0 mA	I_p = 5.0 mA
E_p	E_s	E_s
25		
50		
75		
100		

Name: ____________________

Date: ____________________

Simulator No.: ______________

Part No. 3 - Full-Wave Operation

I, Section C. Effect of filament current on tube current, primary voltage and tube voltage at a constant high voltage transformer secondary voltage (E_s = 150 volts).

	Capacitance											
	0 mF			0.01 mF			0.05 mF			0.1 mF		
I_f	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}
1.00	___	___	___	___	___	___	___	___	___	___	___	___
1.10	___	___	___	___	___	___	___	___	___	___	___	___
1.20	___	___	___	___	___	___	___	___	___	___	___	___
1.30	___	___	___	___	___	___	___	___	___	___	___	___
1.40	___	___	___	___	___	___	___	___	___	___	___	___
1.50	___	___	___	___	___	___	___	___	___	___	___	___

I, Section D. Tube voltage waveforms for a filament current I_f = 1.00 ampere and a secondary voltage E_s = 150 volts.

C = 0 mF 0.01 mF 0.05 mF 0.1 mF

________ ________ ________ ________ 'scope base line

I, Section E. Tube voltage waveforms for a filament current, I_f = 1.50 amperes and a secondary voltage E_s = 150 volts.

C =	0 mF	0.01 mF	0.05 mF	0.1 mF
	____	____	____	____ 'scope base line

II, Section B. Effect of high-voltage transformer secondary voltage on tube current and tube voltage at a constant filament current (I_f = 1.50 amperes).

	Capacitance							
	0 mF		0.01 mF		0.05 mF		0.1 mF	
E_s	I_p	E_{hv}	I_p	E_{hv}	I_p	E_{hv}	I_p	E_{hv}
10	___	___	___	___	___	___	___	___
20	___	___	___	___	___	___	___	___
30	___	___	___	___	___	___	___	___
40	___	___	___	___	___	___	___	___
50	___	___	___	___	___	___	___	___
75	___	___	___	___	___	___	___	___
100	___	___	___	___	___	___	___	___
125	___	___	___	___	___	___	___	___
150	___	___	___	___	___	___	___	___
175	___	___	___	___	___	___	___	___
200	___	___	___	___	___	___	___	___

III, Section B. Effect of primary voltage on secondary voltage at a fixed tube current.

	I_p = 1.0 mA	I_p = 10 mA
E_p	E_s	E_s
25		
50		
75		
100		

Name:____________________

Date:____________________

Simulator No:_______________

Part No. 4 - No Load Transformer Ratio

I, Section C. Effect of primary voltage on secondary voltage with no load on secondary.

E_p	E_s
25	______
50	______
75	______
100	______

Laboratory No. 2

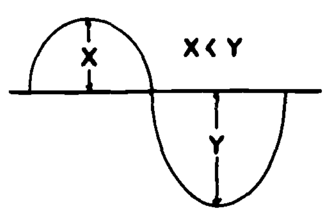
TYPICAL DATA

Part 1, Section I. D. I_p and E_p vs I_f at constant E_s = 150 volts, self-rectified.

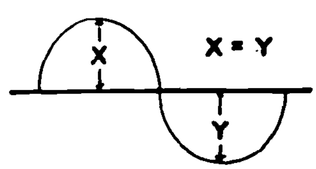
I_f - amp	I_p - mA	E_p - volts
1.00	0	68
1.10	0	63
1.20	0	68
1.30	1	68
1.40	3	68
1.50	10	70

Section I. E. Voltage waveforms, E_s = 150 volts, I_f = 1.50 amperes, self-rectified.

INVERSE REDUCER SHORTED



INVERSE REDUCER CONNECTED



Part 1. Section II. B. I_p vs E_s at constant I_f = 1.50 amperes, self-rectified.

E_s - volts	I_p - mA
10	2
20	5
30	7
40	8
50	9
75	10
100	10
125	10
150	11
175	11
200	11

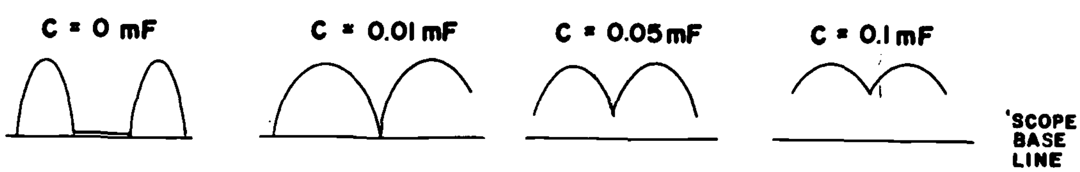
Section II. C. E_p vs E_s at constant I_p, self-rectified.

	I_p = 1.0 mA	I_p = 5 mA
E_p - volts	E_s - volts	E_s - volts
25	54	50
50	108	105
75	163	159
100	218	214

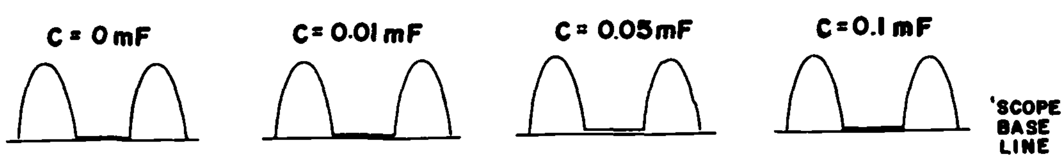
Part 2, Section I. C. I_p, E_p and E_{hv} vs I_f for constant E_s = 150 volts, half-wave rectified.

	Capacitance - mF											
	0			0.01			0.05			0.10		
I_f	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}
1.00	0	68	63	0	68	79	0	68	140	0	68	170
1.10	0	68	63	0	68	71	0	68	135	0	68	168
1.20	0	68	63	0	68	63	0	68	110	0	68	147
1.30	1	68	63	1	68	63	1	68	67	1	68	89
1.40	4	68	63	4	68	63	4	68	63	4	68	64
1.50	10	70	63	10	70	63	10	70	63	10	70	63

Section I. D. Voltage waveforms, E_s = 150 volts, I_f = 1.00 ampere, half-wave rectified.



Section I. E. Voltage waveforms, E_s = 150 volts, I_f = 1.50 amperes, half-wave rectified.



Part 2, Section II. B. I_p and E_{hv} vs E_s for constant $I_f = 1.50$ amperes, half-wave rectified.

E_s - volts	I_p - mA	E_{hv} - volts
10	2	3
20	4	6
30	7	9
40	8	13
50	9	17
75	10	28
100	10	39
125	10	52
150	10	62
175	11	72
200	11	85

Note: Capacitance has no effect on I_p or E_{hv}

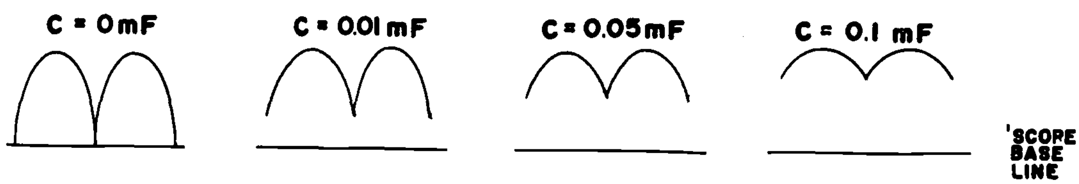
Section III. B. E_s vs E_p for constant $C = 0$ and I_p, half- wave rectified.

	$I_p = 1.0$ mA	$I_p = 5$ mA
E_p - volts	E_s - volts	E_s - volts
25	54	50
50	108	105
75	163	159
100	218	214

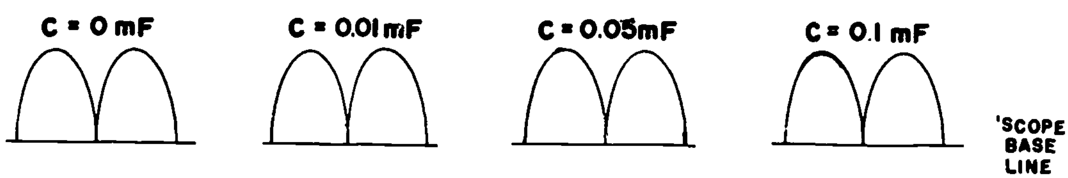
Part 3, Section I. C. I_p, E_p and E_{hv} vs I_f for constant E_s = 150 volts, full-wave rectified.

	Capacitance - mF											
	0			0.01			0.05			0.10		
I_f	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}	I_p	E_p	E_{hv}
1.00	0	68	130	0	68	141	0	68	178	0	68	191
1.10	0	68	130	0	68	138	0	68	174	0	68	189
1.20	0	68	130	0	68	132	0	68	164	0	68	180
1.30	2	68	130	2	68	130	2	68	138	2	68	153
1.40	7	68	130	7	68	130	7	68	130	7	68	130
1.50	20	71	130	20	71	130	20	71	130	20	71	130

Section I. D. Voltage waveforms, E_s = 150 volts, I_f = 1.00 ampere, full-wave rectified.



Section I. E. Voltage waveforms, E_s = 150 volts, I_f = 1.50 amperes, full-wave rectified.



Part 3, Section II. B. I_p and E_{hv} vs E_s for constant I_f = 1.50 amperes, full-wave rectified.

E_s - volts	I_p - mA	E_{hv} - volts
10	4	7
20	10	15
30	13	22
40	15	31
50	16	40
75	17	63
100	18	86
125	18	105
150	19	130
175	19	153
200	20	178

Note: Capacitance has no effect on I_p or E_{hv}.

Section III. B. E_s vs E_p for constant C = 0 and I_p, full-wave rectified.

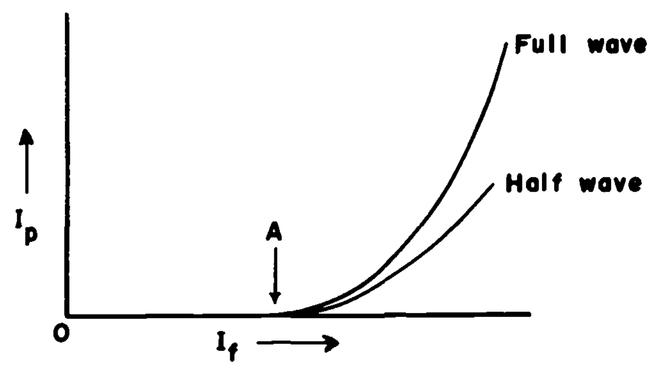
	I_p = 1.0 mA	I_p = 10 mA
E_p - volts	E_s - volts	E_s - volts
25	54	50
50	108	105
75	164	159
100	217	215

Part 4, Section I. C. E_p vs E_s, no load transformer ratio.

E_p - volts	E_s - volts
25	55
50	109
75	164
100	218

Answers to Questions

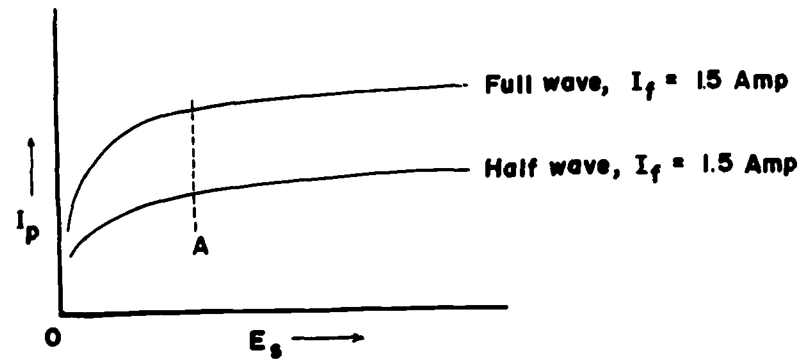
A.



From 0 to A no electrons are emitted from the filament, hence no tube current. After reaching A, electrons are emitted by the filament and the tube current increases by $I = AT \exp(-b/T)$, where T = filament temperature in degrees Kelvin and $A = 60.2$, $b = 52{,}400$ for tungsten.

For the same filament current (I_f), the full-wave tube current (I_p) is two times the half-wave or self-rectified tube current since the tube conducts during both half cycles for full-wave rectification and during one-half cycle for half-wave or self rectification.

B.



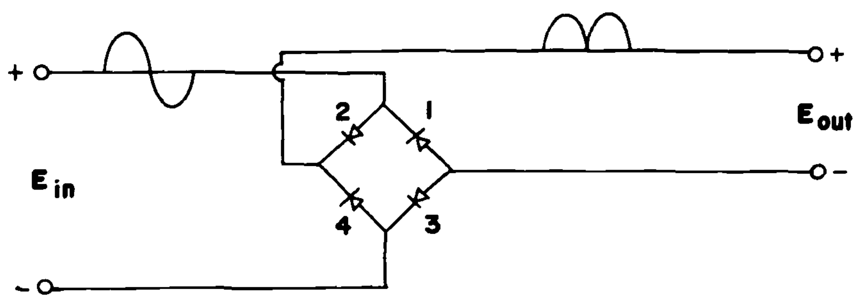
The shape of the curve from 0 to A is the result of space charge effects. Beyond A the curve levels off due to voltage saturation, the tube is operating emission limited, and the electrons taken at a constant rate nearly independent of the voltage. The full-wave rectified tube current (I_p) is approximately twice the half-wave or self-rectified tube current.

C. The voltage waveshapes with no capacitance are essentially sinusoidal. With full-wave rectification both halves of the voltage wave are above the 'scope base line showing that the tube can conduct during both halves of the cycle. With half-wave rectification the tube conducts during half the cycle and the voltage "zero" during the second half of the cycle. In self-rectification, the tube acts as the rectifier and, as with half-wave rectification, the tube conducts only during half the voltage cycle. With self-rectification, the inverse half cycle peak is greater than the useful half cycle peak when the inverse reducer is not used. When the inverse reducer is used, the inverse and useful half cycles have the same amplitude.

D. With low tube currents the high voltage cable capacitance smooths the voltage waveform. The greater the capacitance (cable length), the greater the smoothing effect. The peak value of the voltage waveform does not change with increasing cable capacitance but the effective value of the voltage does increase.

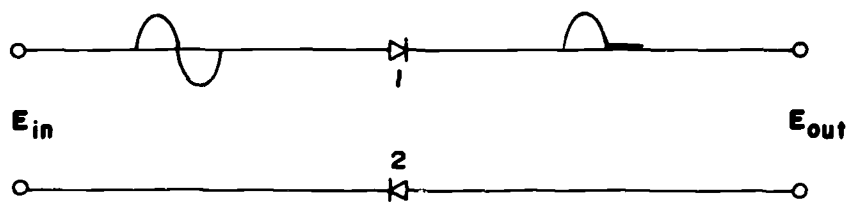
With high tube currents, the high voltage cable capacitance has little or no effect on the voltage waveform due to the more rapid discharge of the cable capacitance.

E. Full-wave rectification



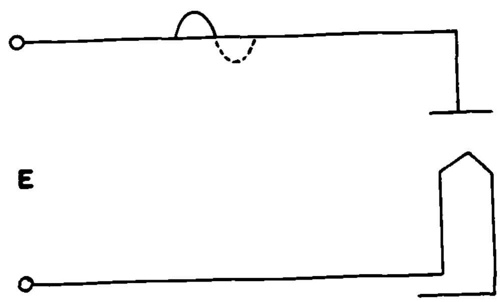
On the positive half cycle, rectifiers 2 and 3 conduct. On the negative half cycle, rectifiers 1 and 4 conduct.

Half-wave rectification



On the positive half cycle, rectifiers 1 and 2 conduct. On the negative half cycle, they do not conduct.

Self-rectification

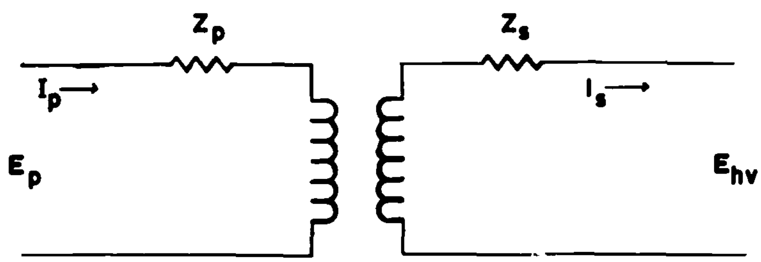


The tube acts as the rectifier and conducts during the positive half cycle and does not conduct during the negative half cycle.

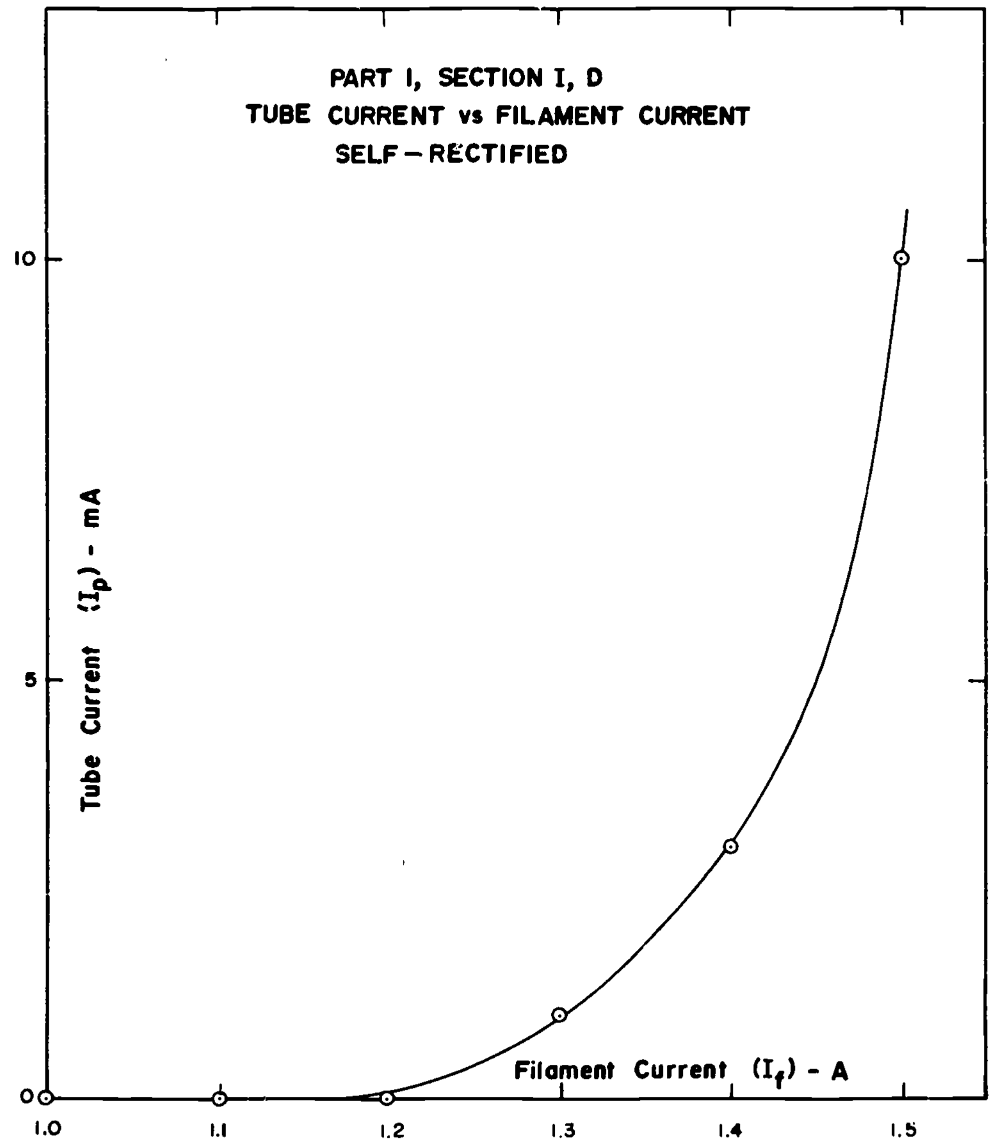
F. At a tube current of 1 mA, the average transformation ratio is 2.17 (E_{out}/E_{in}) and at 10 mA, the average transformation ratio is 2.09. The slight increase in transformation ratio with decreased secondary loading is due to losses in the high voltage secondary.

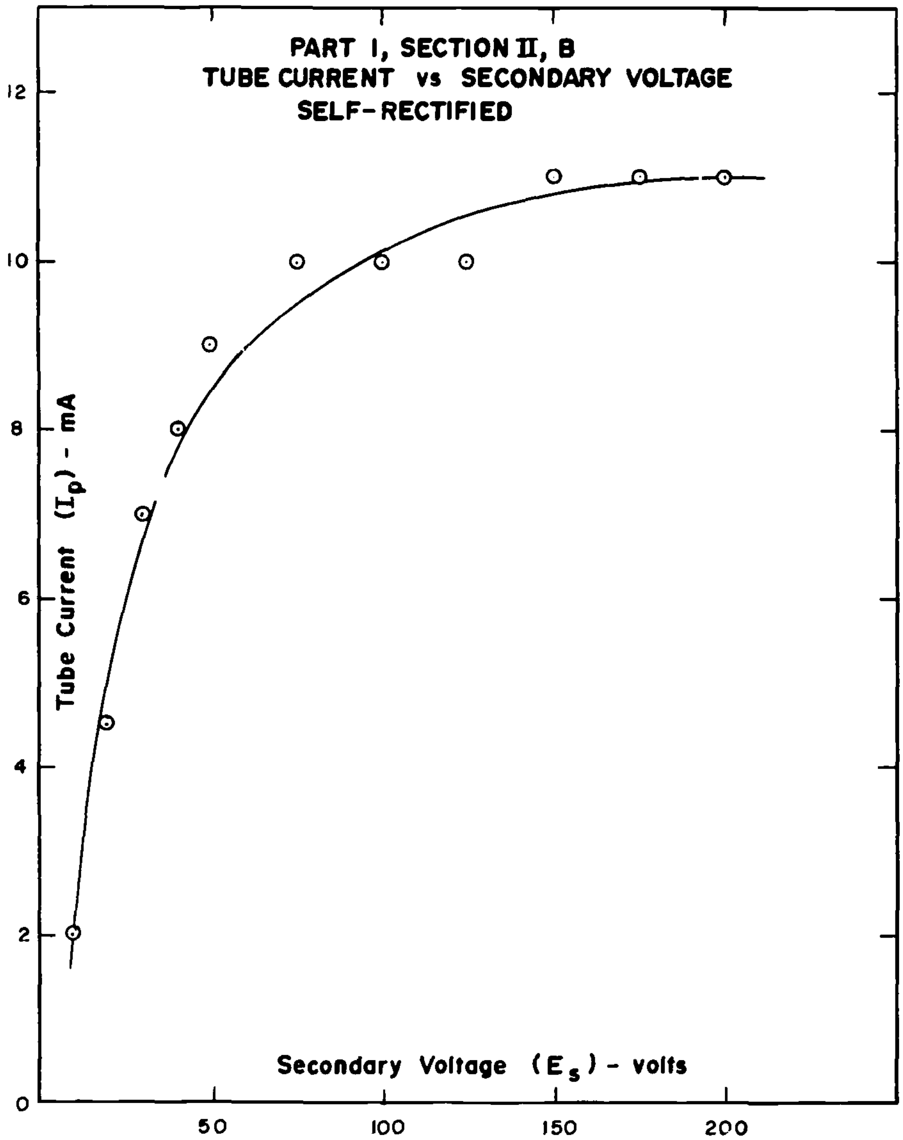
G. The inverse reducer places a load in the primary circuit during the half cycle that the tube is not conducting. During the useful half cycle, the rectifier conducts shorting out the load resistor. During the inverse half cycle the rectifier does not conduct and the primary current flows through the load resistor producing a voltage drop across the resistor and therefore reducing the voltage across the high-voltage transformer; consequently, the voltage across the high-voltage transformer secondary and the X-ray tube. If the inverse reducer were not used, the high voltage insulation would have to be designed for the maximum voltage obtained in the inverse half cycle rather than that obtained in the useful half cycle.

H.

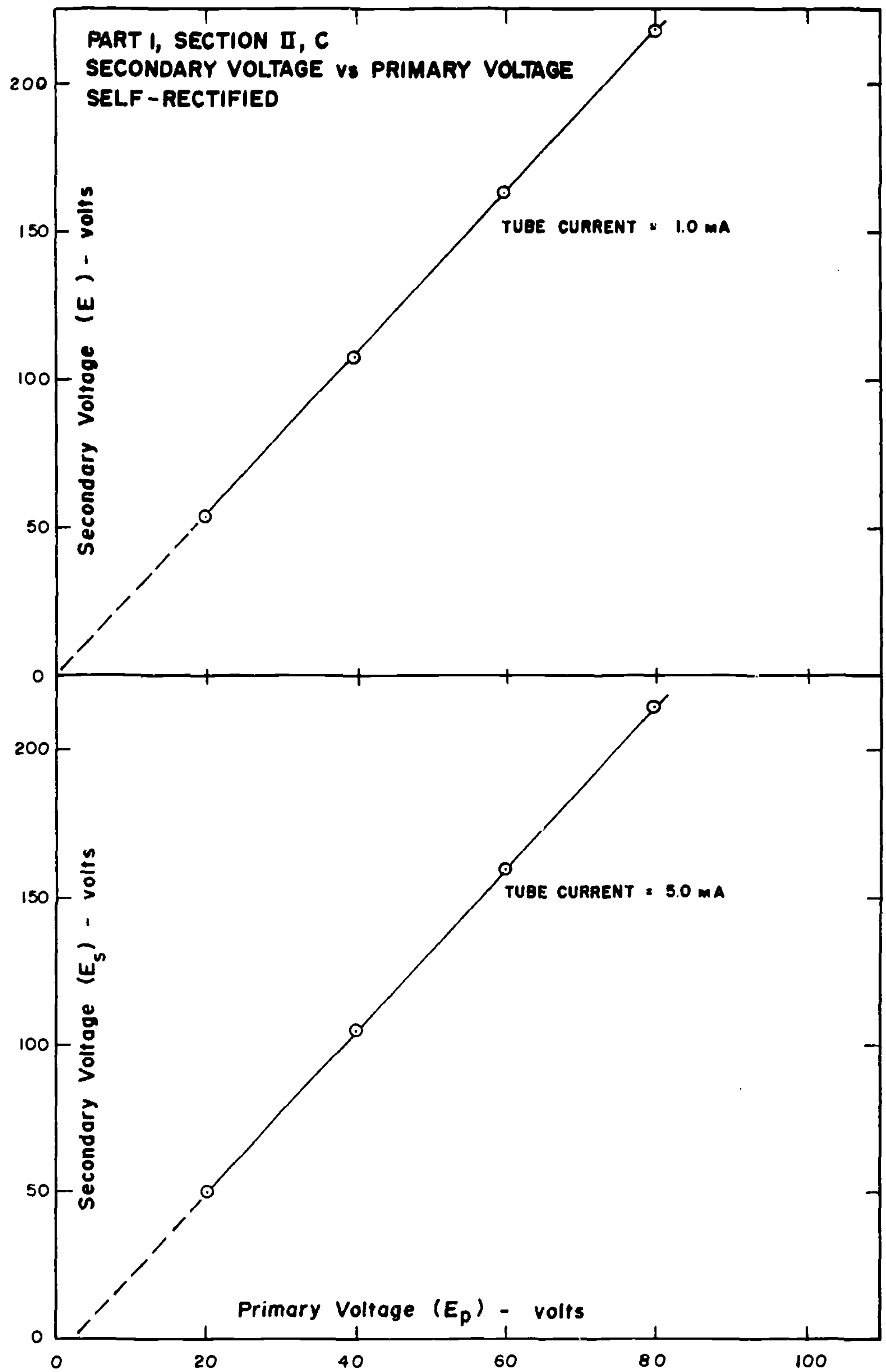


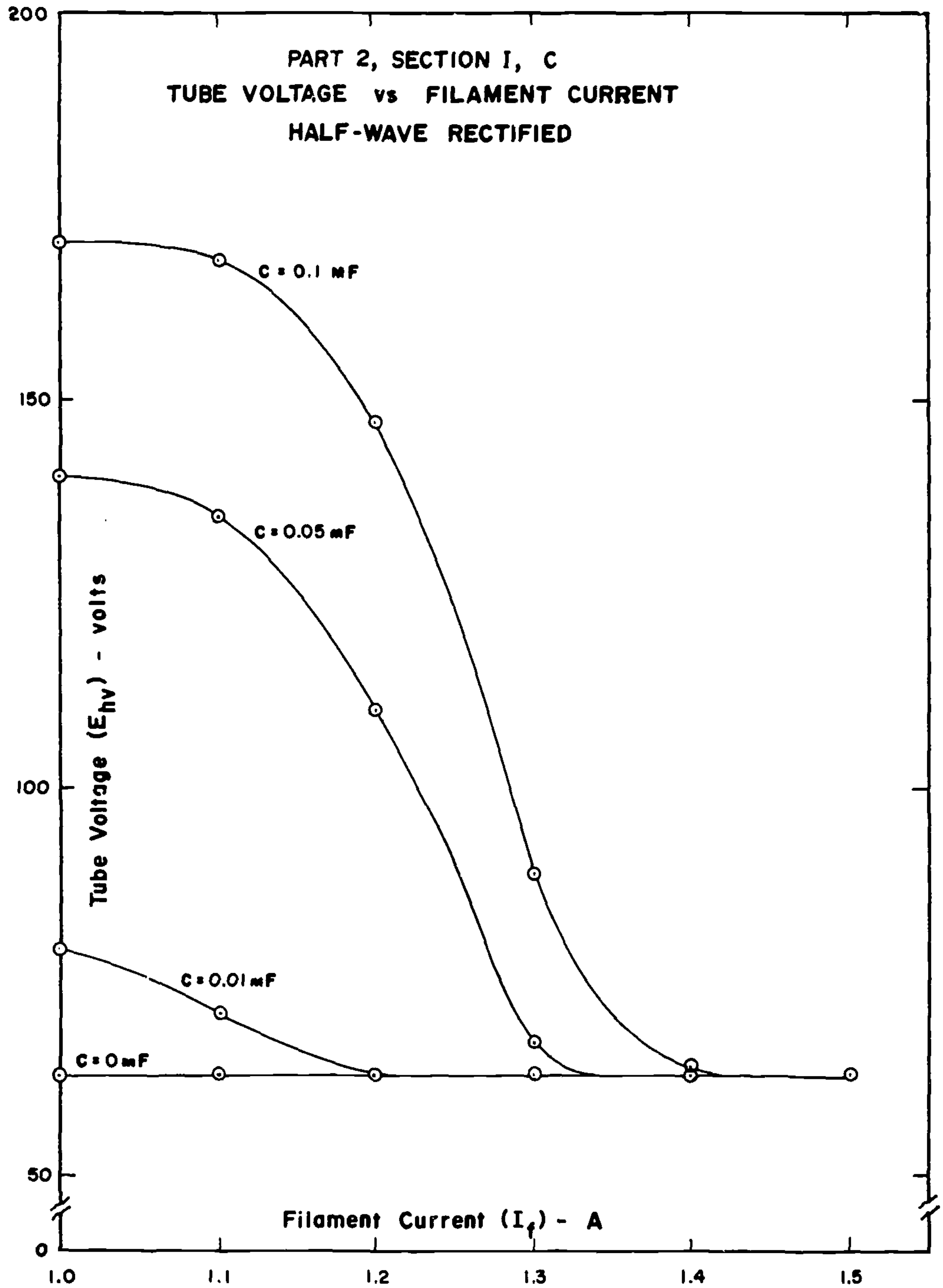
As the filament current, and hence the tube current, increases the tube voltage (E_{hv}) will decrease due to loading in the secondary ($\overline{E} = \overline{V} + \overline{IZ}$). In order to hold E_{hv} constant, the primary voltage E_p must be increased by an amount equal to the increased losses in the secondary and the increased losses in the primary due to the increased primary current.


PART I, SECTION I, D
TUBE CURRENT vs FILAMENT CURRENT
SELF-RECTIFIED
Tube Current (I_p) - mA
Filament Current (I_f) - A
10
5
0
1.0
1.1
1.2
1.3
1.4
1.5

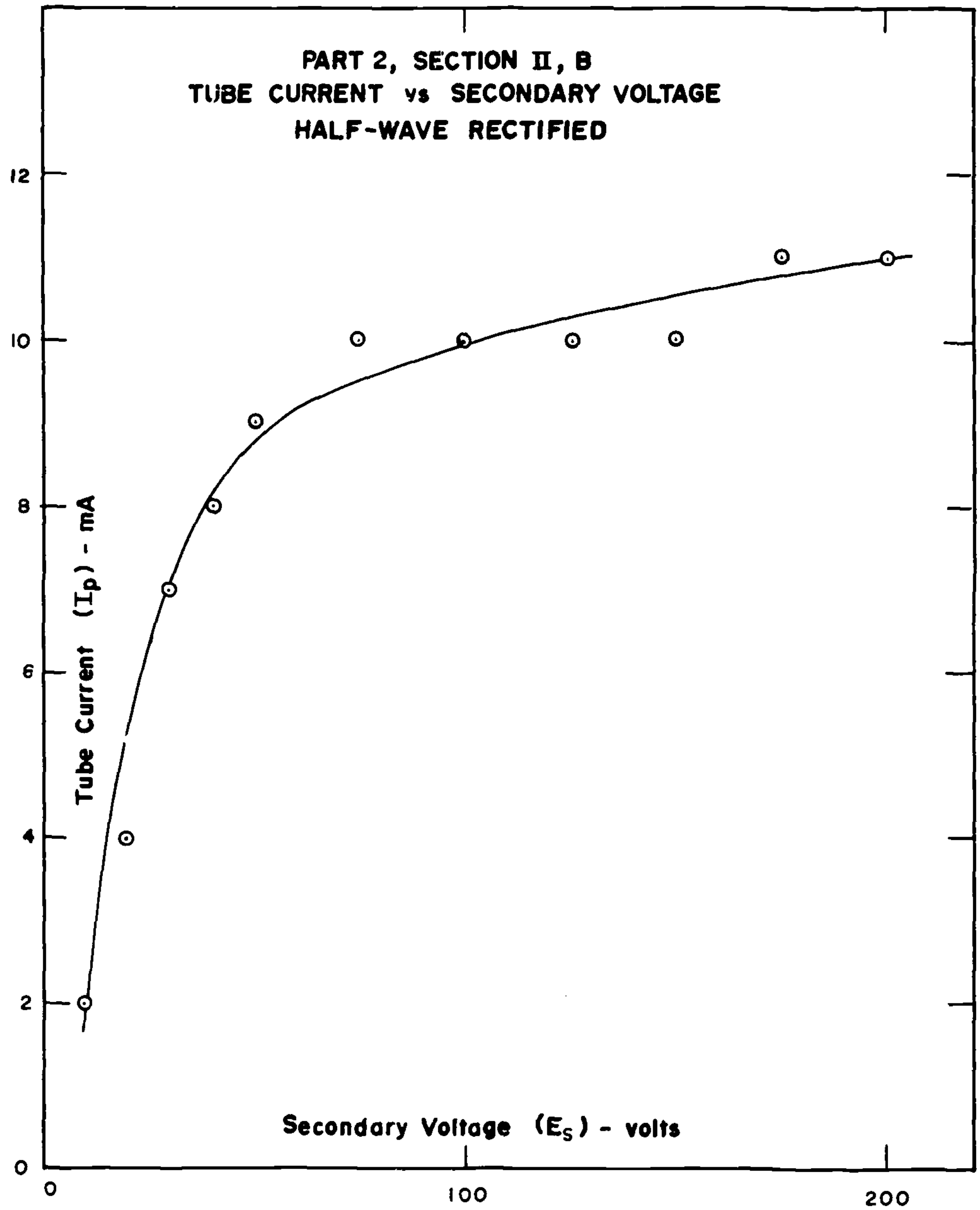


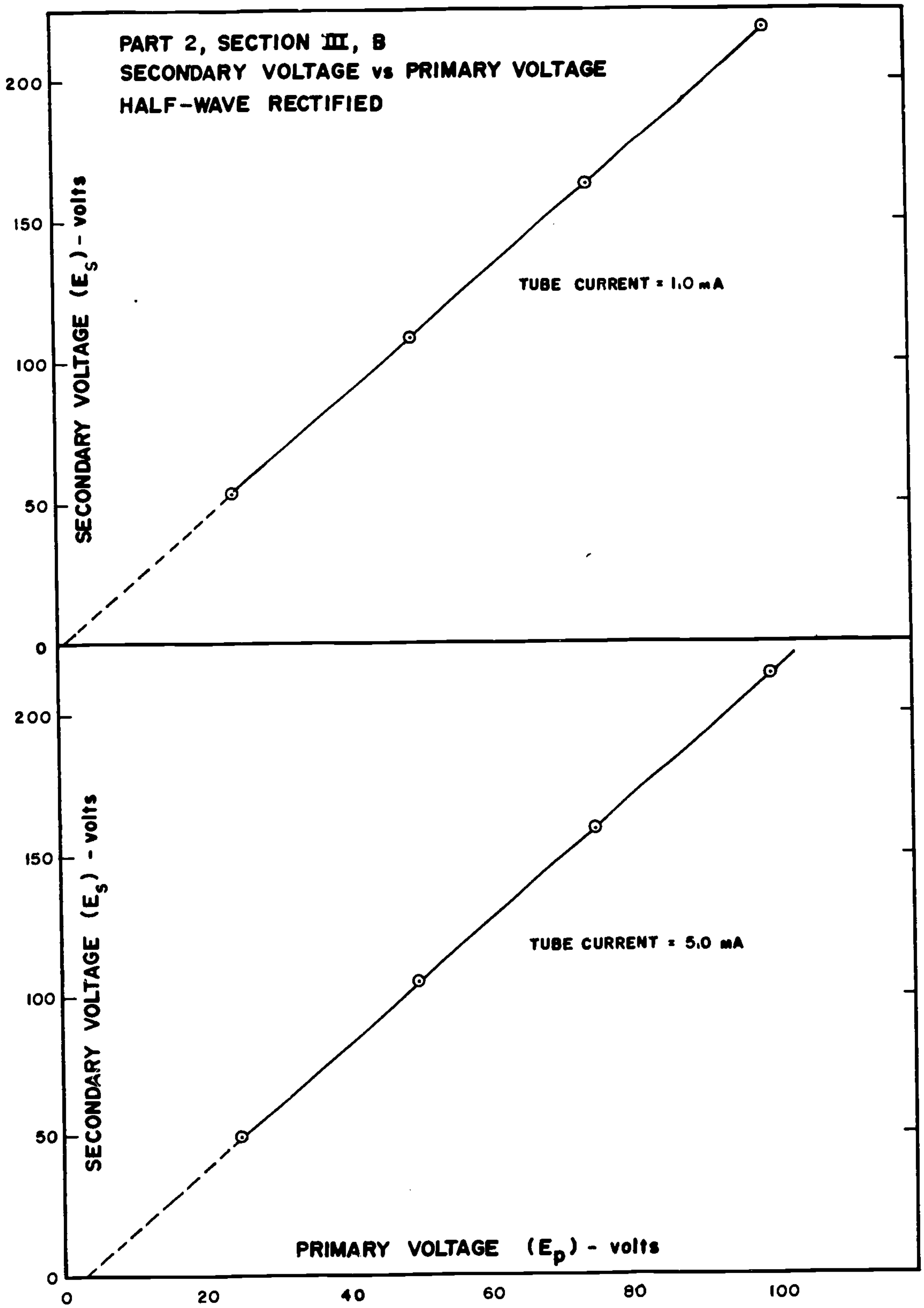
PART I, SECTION II, B
TUBE CURRENT vs SECONDARY VOLTAGE
SELF-RECTIFIED
Tube Current (I_p) - mA
Secondary Voltage (E_s) - volts
0
2
4
6
8
10
12
50
100
150
200

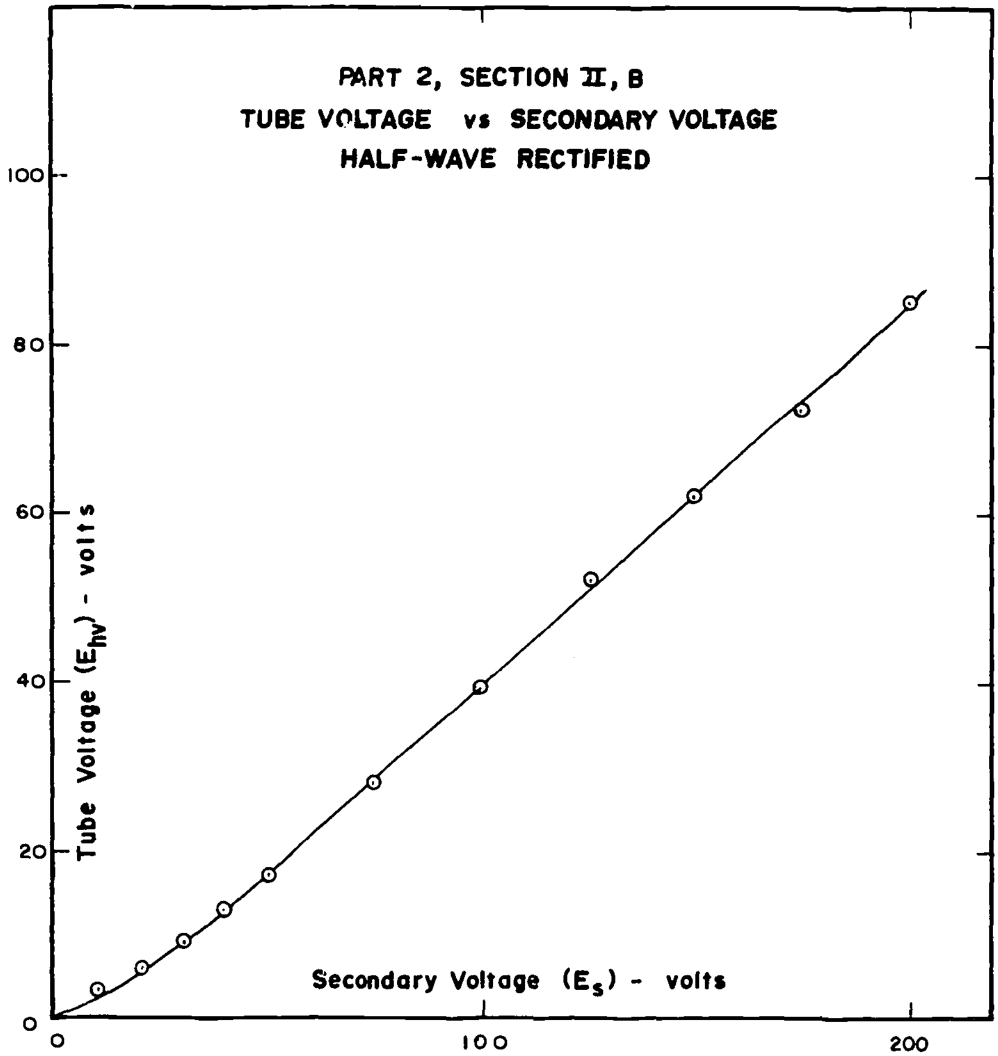

PART I, SECTION II, C
SECONDARY VOLTAGE vs PRIMARY VOLTAGE
SELF-RECTIFIED
TUBE CURRENT = 1.0 mA
Secondary Voltage (E) - volts
TUBE CURRENT = 5.0 mA
Secondary Voltage (E_s) - volts
Primary Voltage (E_p) - volts
0
50
100
150
200
0
20
40
60
80
100

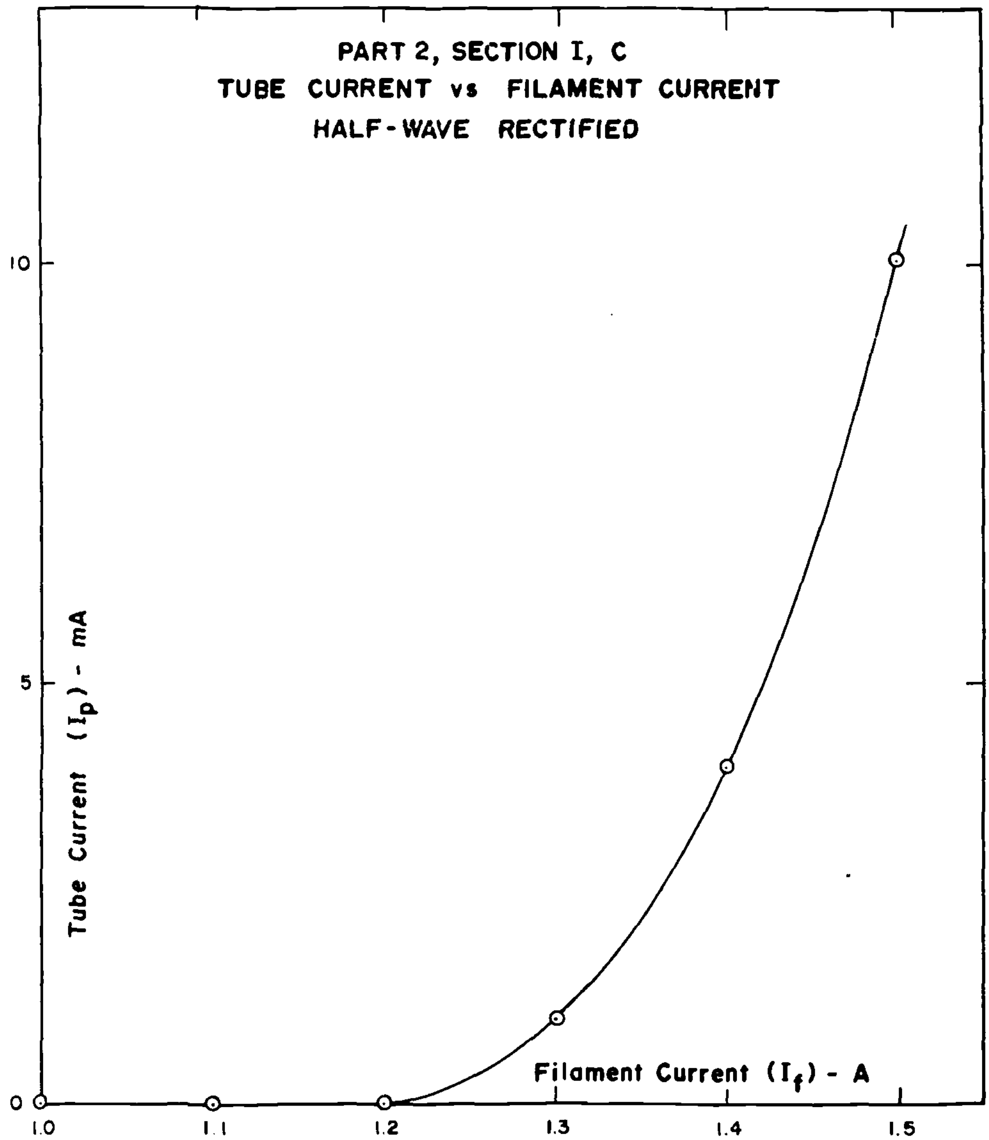


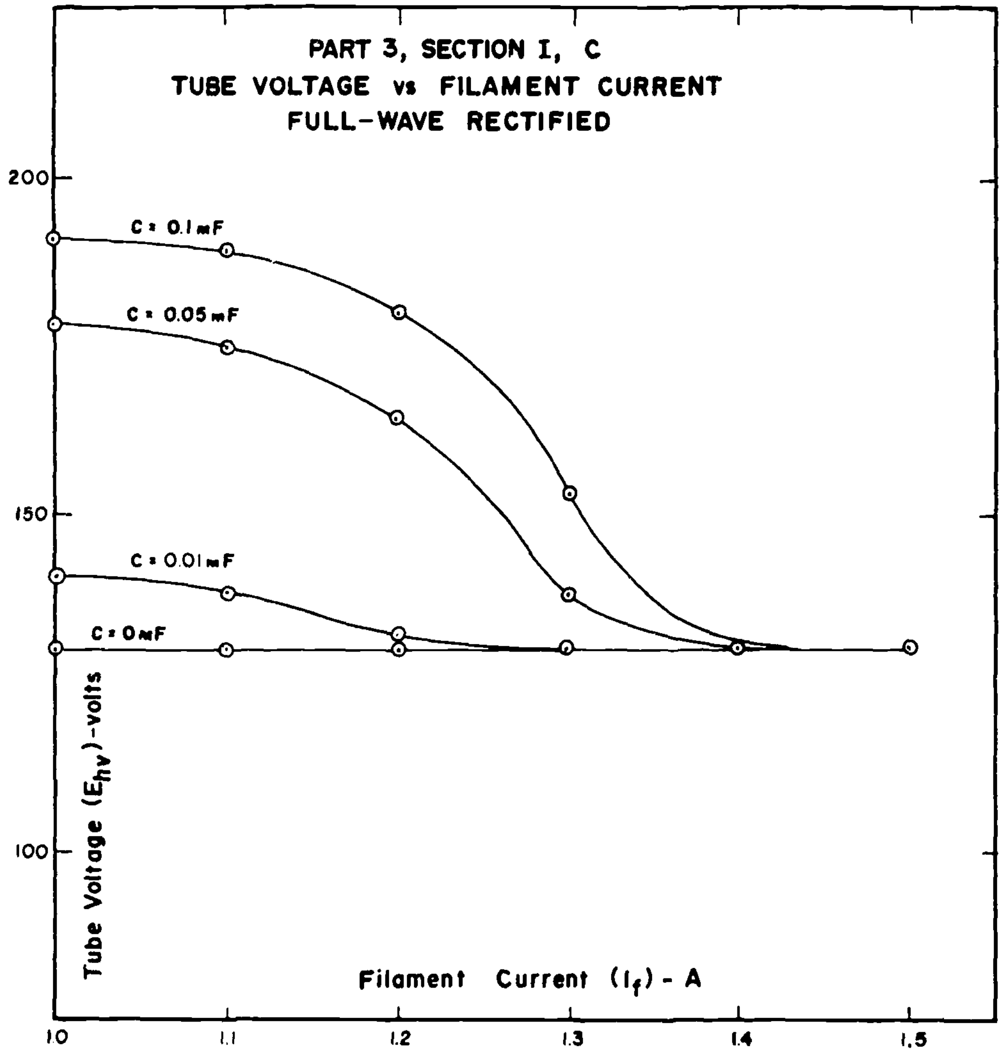
PART 2, SECTION I, C
TUBE VOLTAGE vs FILAMENT CURRENT
HALF-WAVE RECTIFIED
C = 0.1 mF
C = 0.05 mF
C = 0.01 mF
C = 0 mF
Tube Voltage (E_{hv}) - volts
Filament Current (I_f) - A
200
150
100
50
0
1.0
1.1
1.2
1.3
1.4
1.5


PART 2, SECTION II, B
TUBE CURRENT vs SECONDARY VOLTAGE
HALF-WAVE RECTIFIED
Tube Current (I_p) - mA
Secondary Voltage (E_S) - volts
0
2
4
6
8
10
12
0
100
200

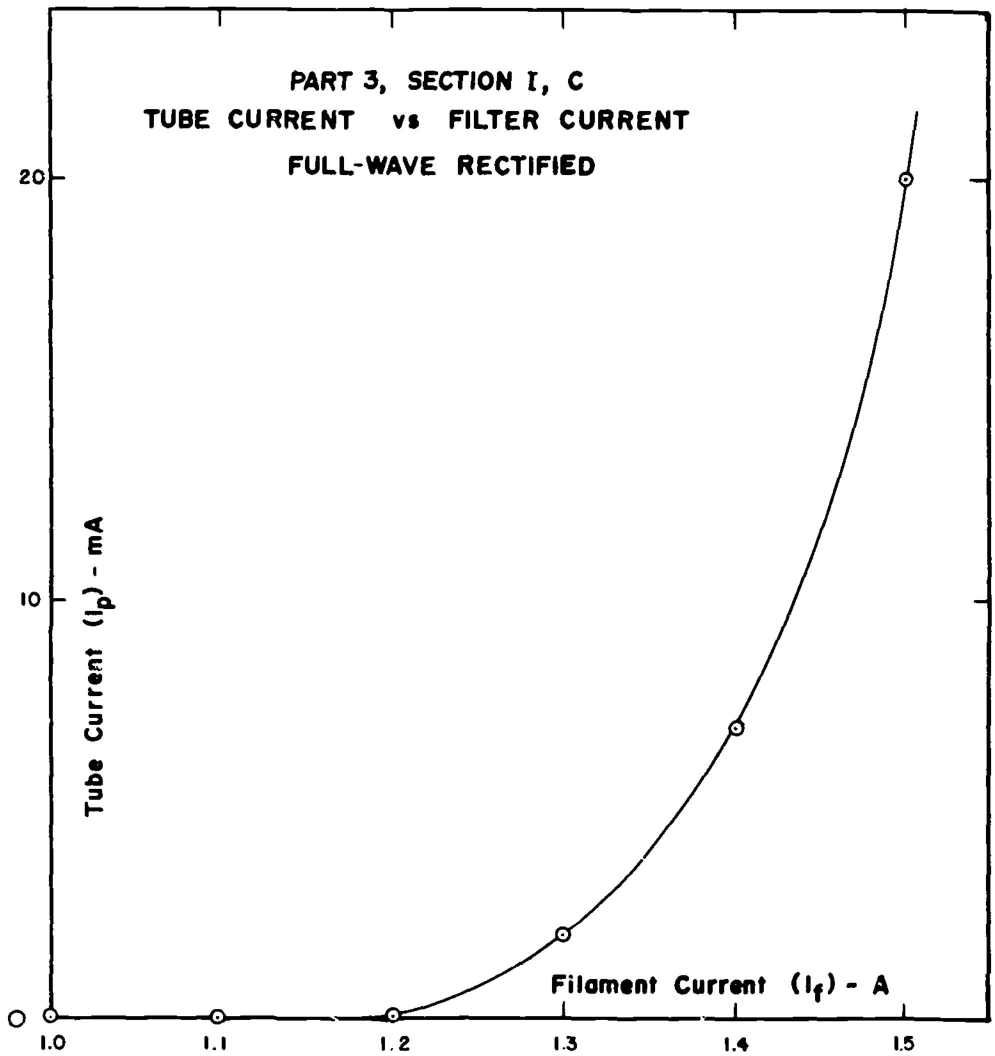

PART 2, SECTION III, B
SECONDARY VOLTAGE vs PRIMARY VOLTAGE
HALF-WAVE RECTIFIED
SECONDARY VOLTAGE (E_s) - volts
TUBE CURRENT = 1.0 mA
0
50
100
150
200
SECONDARY VOLTAGE (E_s) - volts
TUBE CURRENT = 5.0 mA
PRIMARY VOLTAGE (E_p) - volts
0
50
100
150
200
0
20
40
60
80
100

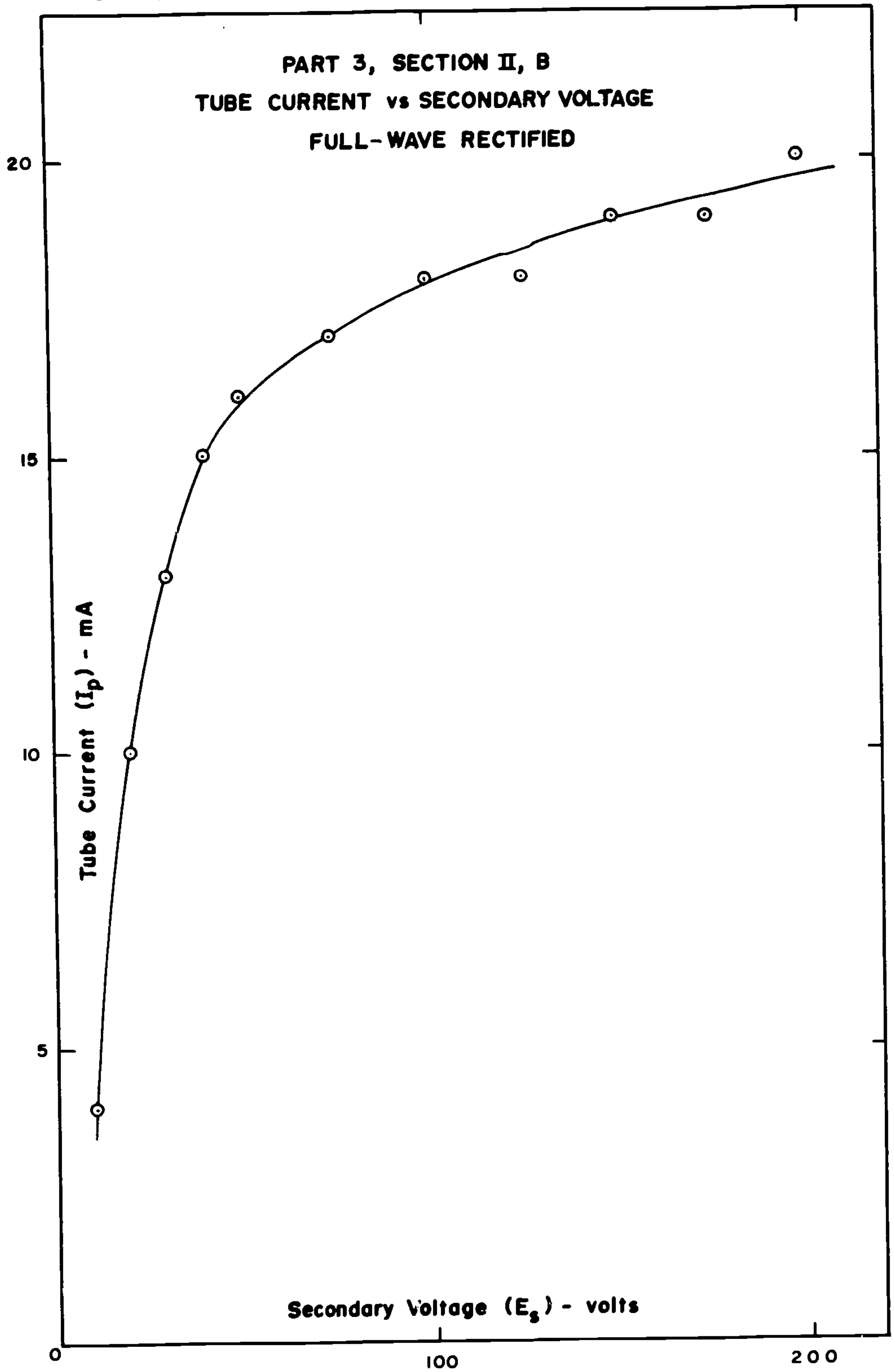

PART 2, SECTION II, B
TUBE VOLTAGE vs SECONDARY VOLTAGE
HALF-WAVE RECTIFIED
Tube Voltage (E_{hv}) - volts
Secondary Voltage (E_s) - volts
0
20
40
60
80
100
0
100
200

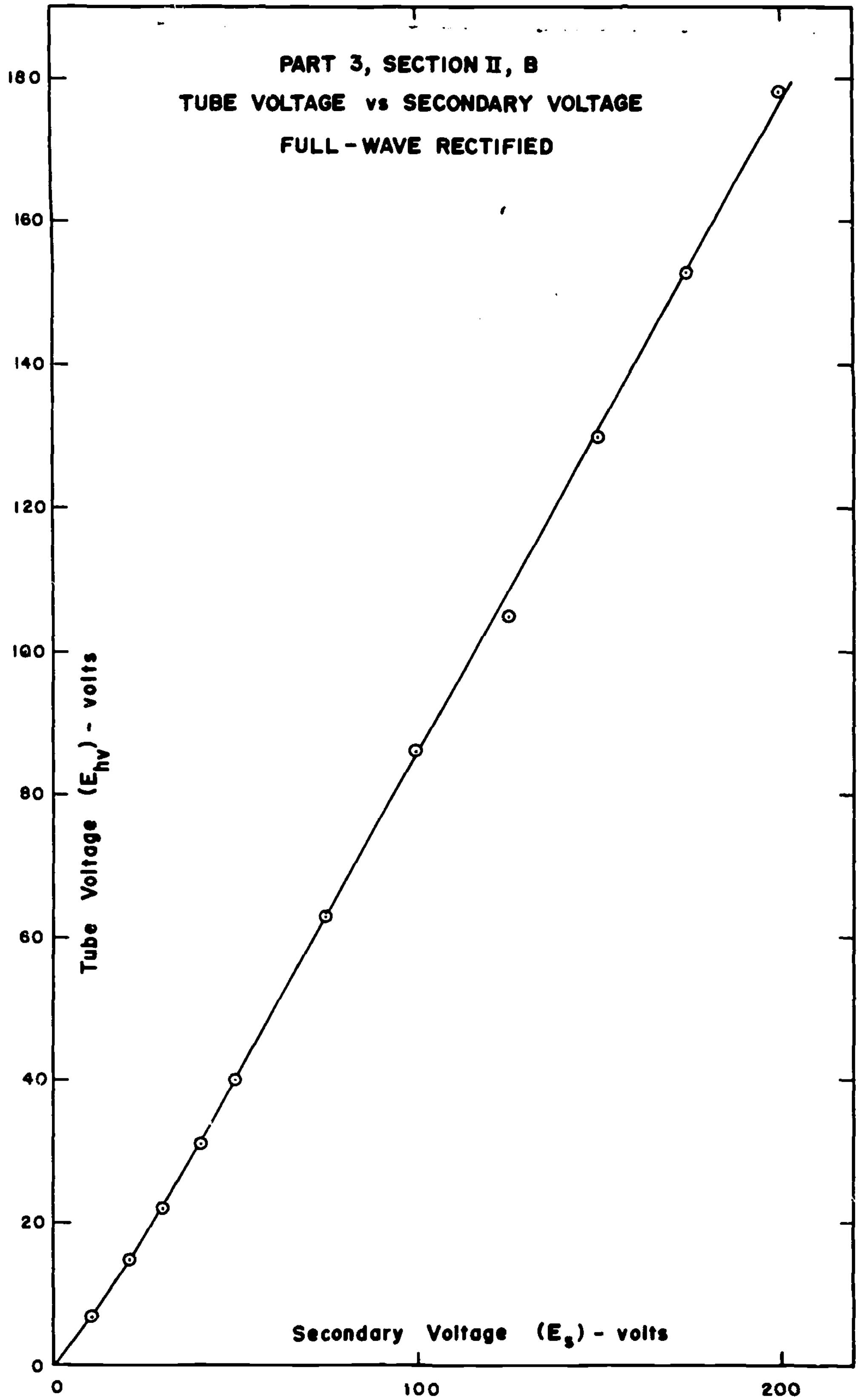

PART 2, SECTION I, C
TUBE CURRENT vs FILAMENT CURRENT
HALF-WAVE RECTIFIED
Tube Current (I_p) - mA
Filament Current (I_f) - A
10
5
0
1.0
1.1
1.2
1.3
1.4
1.5

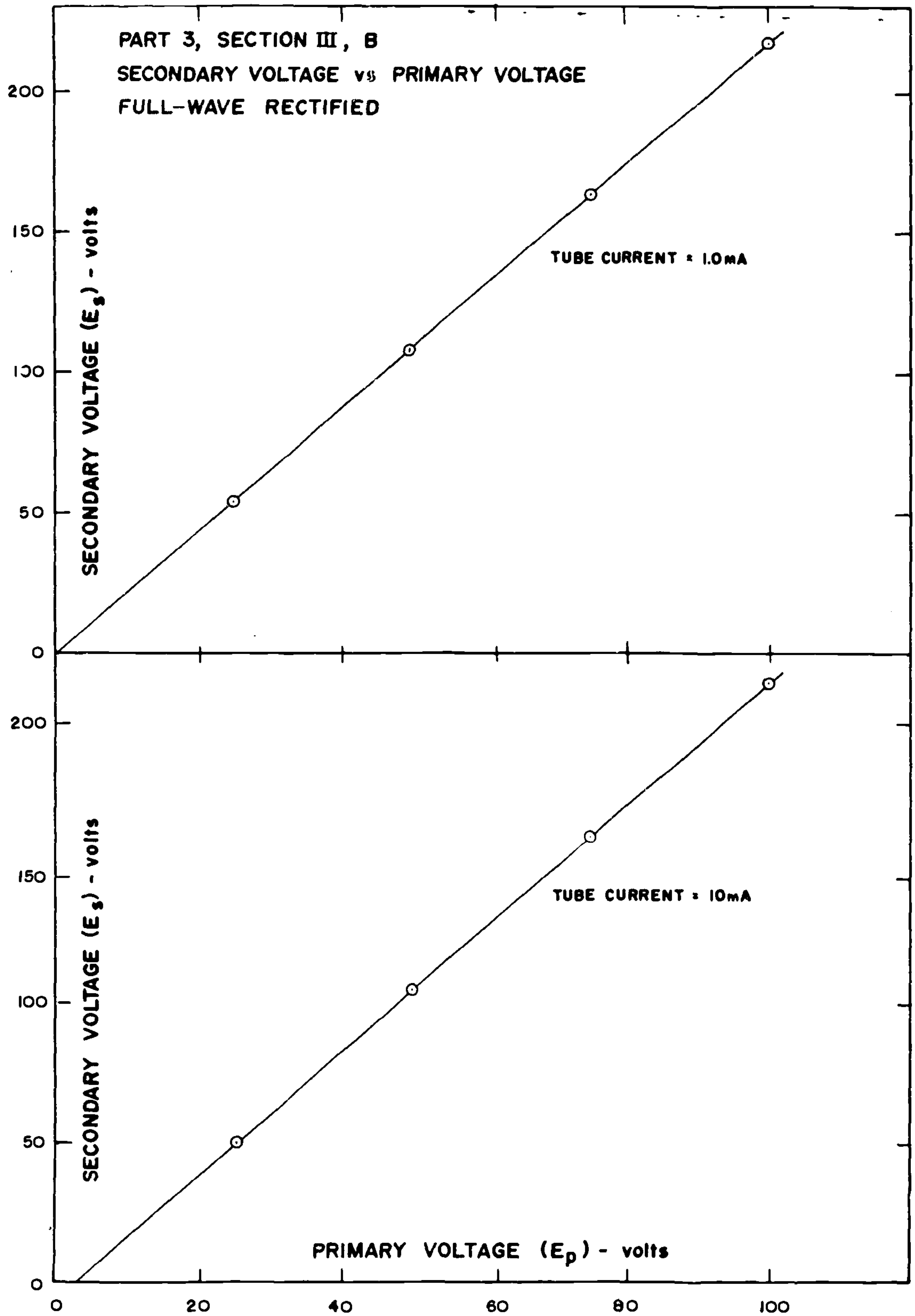


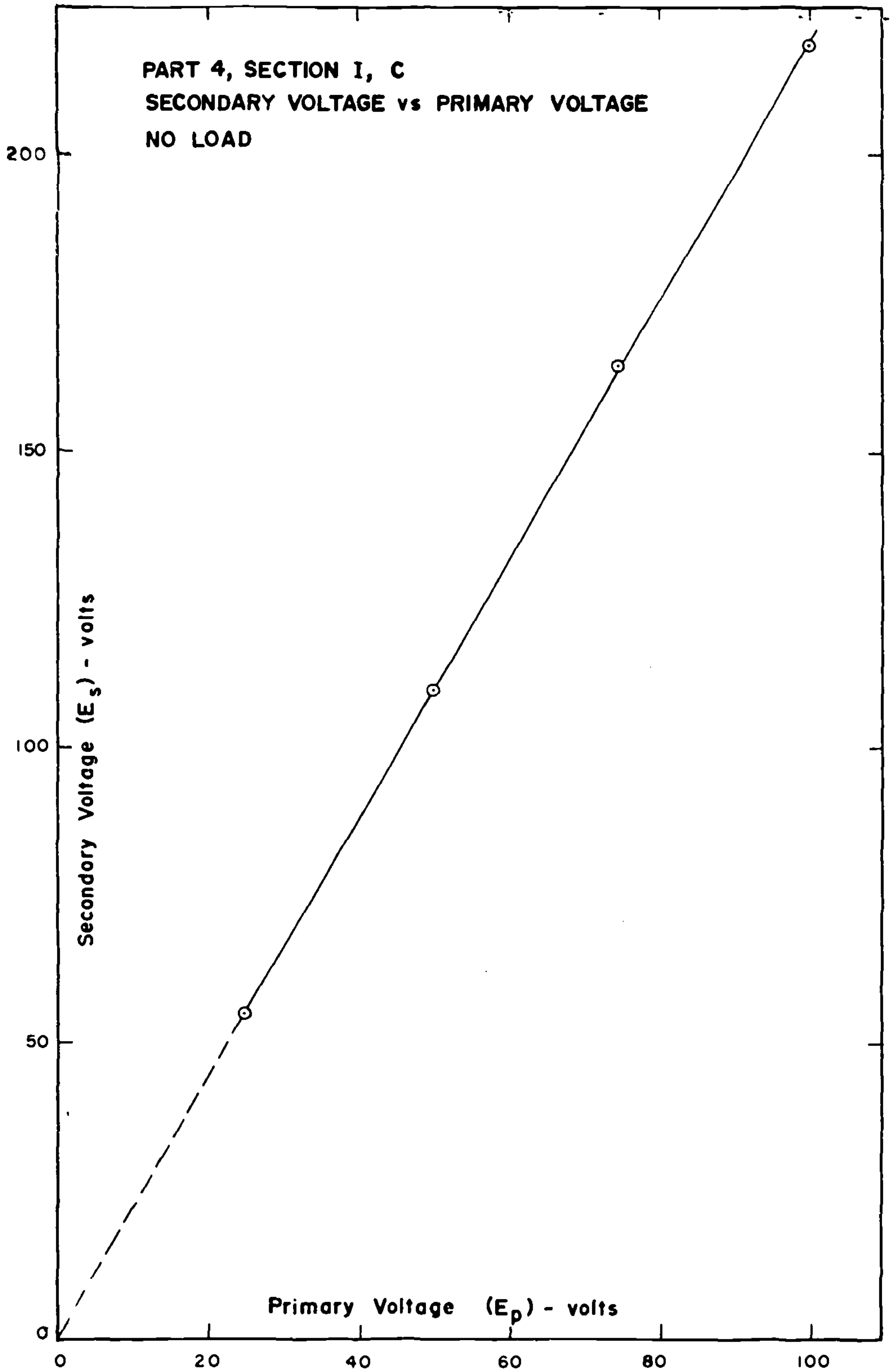
PART 3, SECTION I, C
TUBE VOLTAGE vs FILAMENT CURRENT
FULL-WAVE RECTIFIED
200
150
100
C = 0.1 mF
C = 0.05 mF
C = 0.01 mF
C = 0 mF
Tube Voltage (E_{hv}) - volts
Filament Current (I_f) - A
1.0
1.1
1.2
1.3
1.4
1.5


PART 3, SECTION I, C
TUBE CURRENT vs FILTER CURRENT
FULL-WAVE RECTIFIED
20
10
0
Tube Current (I_p) - mA
Filament Current (I_f) - A
1.0
1.1
1.2
1.3
1.4
1.5


PART 3, SECTION II, B
TUBE CURRENT vs SECONDARY VOLTAGE
FULL-WAVE RECTIFIED
Tube Current (I_p) - mA
Secondary Voltage (E_s) - volts
0
5
10
15
20
100
200


PART 3, SECTION II, B
TUBE VOLTAGE vs SECONDARY VOLTAGE
FULL-WAVE RECTIFIED
Tube Voltage (E_{hv}) - volts
Secondary Voltage (E_s) - volts
0
20
40
60
80
100
120
140
160
180
0
100
200


PART 3, SECTION III, B
SECONDARY VOLTAGE vs PRIMARY VOLTAGE
FULL-WAVE RECTIFIED
TUBE CURRENT = 1.0mA
SECONDARY VOLTAGE (E_s) - volts
200
150
100
50
0
TUBE CURRENT = 10mA
SECONDARY VOLTAGE (E_s) - volts
PRIMARY VOLTAGE (E_p) - volts
0
20
40
60
80
100



PART 4, SECTION I, C
SECONDARY VOLTAGE vs PRIMARY VOLTAGE
NO LOAD
Secondary Voltage (E_s) - volts
Primary Voltage (E_p) - volts
0
50
100
150
200
0
20
40
60
80
100

LABORATORY NO. 3

TITLE: X-Ray Machine Circuitry

PURPOSE: To study the basic circuitry and components found in a simple x-ray machine.

TIME: Six hours

MATERIALS FOR EACH STUDENT GROUP:

One Demonstration Teaching Unit
One power line monitor
One vacuum tube voltmeter
One Victoreen model 444 survey meter
One stepless autotransformer (0 - 130 V)

REFERENCES:

Ter-Pogossian
The Physical Aspects of Diagnostic Radiology

Laboratory No. 3

X-RAY MACHINE CIRCUITRY

I. INTRODUCTION

The purpose of this laboratory is to investigate the circuitry and components of a basic x-ray machine.

II. EQUIPMENT

A. Demonstration Teaching Unit

B. Power line monitor

C. VTVM

D. Victoreen 444 Survey Meter

E. Stepless autotransformer (0-130 V)

III. PROCEDURE

A. Basic X-ray Machine Circuit

Wire a basic x-ray machine circuit (self-rectified without inverse reducer) and describe each of the following components and their function:

1. Line switch and circuit breaker
2. Voltage compensator and voltmeter
3. kVp selector
4. X-ray contactor
5. High-tension transformer
6. X-ray tube

7. Milliammeter

8. X-ray tube filament transformer

9. mA control

10. Timing circuit

B. Voltage Compensator

1. Connect x-ray machine control section to Variac controlled outlet.

2. Set line-in voltage to 117 volts and set compensator voltmeter on red line. With kVp selector on tap 1, measure line-out voltage.

3. Change line-in to 113 volts and measure line-out voltage. Do not change compensator setting from step 2.

4. Repeat step 3 with line-in at 121 volts.

5. Repeat steps 2, 3, and 4 but adjust compensator to red line.

6. Remove power cord from Variac control and connect directly to wall outlet.

C. kVp Selector Voltages

1. Set compensator on red line.

2. Measure the line-out voltages for each kVp selector tap setting from 1 to 12.

D. X-ray Tube Filament Voltages

1. Connect the circuit for self-rectified operation without inverse reducer.

2. Measure the voltage extremes applied to the filament transformer

primary and the resulting voltages applied to the filament of the x-ray tube.

E. Comparison of Output when Operated Self rectified, With and Without Inverse Reducer. (Circuit set-up as in part B. above)

1. Set compensator on red line.

2. Set kVp selector on tap 5.

3. Set timer on 30 seconds and activate circuit.

4. Adjust tube current to 2 mA.

5. Determine the relative output of the x-ray beam with a Victoreen 444 survey meter.

6. Wire inverse suppressor into circuit.

7. Repeat steps 1 through 5.

F. Comparison of Output when Operated Half-wave Rectified and Full-wave Rectified.

1. Bypass inverse suppressor and wire in rectifiers 1, 2, 3, and 4 for full-wave rectified operation.

2. Set kVp selector to tap 6.

3. Set timer to 30 seconds and activate circuit.

4. Adjust tube current to 2 mA and be sure compensator is on red line.

5. Determine relative output.

6. Wire in rectifiers 1 and 2 for half-wave rectified operation.

7. Repeat steps 2 through 6.

G. High-voltage Transformer Regulation

1. Wire circuit for half-wave rectified operation.

2. Set kVp selector on tap 4.

3. Using voltage divider provided on generator section, measure the voltage (peak-to-peak) across the x-ray tube as mA is varied from 2 to 6. (Assume the ratio of tube voltage to divider voltage is 1,000).

4. Report the regulation as a per cent of the initial kVp. (Note: Monitor the voltage to the primary of the high-voltage transformer to be sure that it is essentially constant as the mA is varied).

Laboratory No. 3

TYPICAL DATA

III. B. Voltage compensator

Line in	Line out	Compensator
113	44	Tap 1 - red line
117	46	Tap 1
121	47	Tap 1
121	44	Tap 5 - red line
117	44	Tap 3 - red line
113	44	Tap 1 - red line

III. C. kVp selector voltage

kVp Tap	Voltage
1	41
2	47
3	53
4	59
5	64
6	69
7	75
8	81
9	87
10	91
11	96
12	101

III. D. X-ray tube filament voltage .

Primary Voltage	Secondary Voltage
87 (minimum)	2.5
112.5 (minimum)	3.8

III. E. Output with and without inverse reducer, self-rectified operation.

Inverse Reducer In	Inverse Reducer out
2.4 R/h	2.4 R/h

III. F. Output with half- and full-wave rectified operation.

Half-wave Rectifed	Full-wave Rectified
6 R/h	6 R/h

III. G. High-voltage transformer regulation

Tube Current-mA	kVp
2	5.1
3	4.6
4	4.0
5	3.6
6	3.1

LABORATORY NO. 4

TITLE: X-Ray Machine Output

PURPOSE: To familiarize the student with the use of the condenser R-meter to measure x-ray exposure and to study the influence of distance, filtration, tube current, and kilovoltage on exposure rate.

TIME: Three hours

MATERIALS FOR EACH STUDENT GROUP:

- One Teaching X-Ray Unit
- One Condenser R-Meter with 25-R medium energy chamber
- One 1 mm Al filter
- One chamber holder
- One barometer
- One thermometer
- Two sheets linear graph paper, K & E 46-0703 or equivalent
- One sheet two by one cycle log-log graph paper K & E 40-7083 or equivalent
- One ships curve, K & E 1685-48 or equivalent
- One straight edge

REFERENCES:

Attix, Roesch, Tochilin
Radiation Dosimetry

Johns
Physics of Radiology

Victoreen Instrument Co.
Condenser R-Meter Instruction Manual

Trout
A Teaching X-Ray Unit U.S.P.H.S. Publication 1859

Laboratory No. 4

X-RAY MACHINE OUTPUT

I. INTRODUCTION

The purpose of this laboratory is to:

A. Familiarize the student with the use of the condenser R-meter to measure X-ray exposure,

B. Investigate the validity of the inverse square law,

C. Study the effects of tube current on exposure rate for two conditions of filtration, at a fixed kilovoltage and source-chamber distance,

D. Study the effects of kilovoltage on exposure rate for two conditions of filtration, at a fixed tube current and source-chamber distance.

II. EQUIPMENT

A. Teaching X-ray Unit

B. Condenser R-meter with 25 R medium energy chamber

C. 1 mm aluminum filter

D. Chamber holder

E. Barometer

F. Thermometer

III. PROCEDURE

A. Use of the Condenser R-meter to Measure X-ray Exposure

1. Read condenser R-meter instruction manual.

2. Record model and serial numbers for reader and chamber.

3. Record barometric pressure and temperature and determine correction factor.

4. Practice charging and discharging the chamber.

B. Effect of Tube Current on Exposure Rate

1. Measure the exposure rate at 1, 3 and 5 mA for 70 kVp with inherent filtration. Use a source-chamber distance (SCD) of 30 cm and select exposure times to obtain mid-scale readings (between 1/3 and 2/3 of full scale).

2. Repeat step one with 1 mm Al added filtration.

3. Correct the readings for temperature and pressure.

4. Plot corrected exposure rate versus tube current on linear graph paper. (Use same sheet of paper for both curves)

C. Effect of Kilovoltage on Exposure Rate

1. Measure the exposure rate at 40,50,60,70,80,90 and 100 kVp at 3 mA with inherent filtration. Use a SCD of 30 cm and select exposure times to obtain mid-scale readings.

2. Repeat step one with 1 mm Al added filtration.

3. Correct the readings for temperature and pressure.

4. Plot corrected exposure rate versus tube voltage on linear graph paper. (Use same sheet of paper for both curves)

D. Effect of Distance on Exposure Rate

1. Measure the exposure rate at 20, 25, 30, 40 and 50 cm

SCD at 70 kVp and 3 mA with inherent filtration. Select exposure time to obtain mid-scale readings.

2. Correct the readings for temperature and pressure.

3. Plot corrected exposure rate versus distance on log-log graph paper.

IV. QUESTIONS

A. Find the slope of your curve of exposure rate versus distance plotted on log-log graph paper. How does your value compare with that of the inverse square law?

B. Under what conditions does the inverse square law fail?

C. Explain why the exposure rate is a linear function of tube current.

D. What is the effect of filtration on exposure rate at a fixed kVp and SCD? Is this effect altered by changing the tube current? Explain.

E. What is the effect of filtration on exposure rate at a fixed tube current and SCD? Is his effect altered by changing the kilovoltage? Explain.

Laboratory No. 4

TYPICAL DATA

III. A. $P = 763.2$ mm Hg

$T = 24.5^{\circ}C$

$$K_{TP} = \frac{T + 273}{295}\left(\frac{760}{P}\right) = \frac{297.5}{295}\left(\frac{760}{763.2}\right)$$

$$K_{TP} = 1.005$$

B. Effect of tube current on exposure rate

(1) kVp = 70; d = 30 cm; inherent filtration

mA	Exposure	Exposure Time	Exposure Rate	Corrected Rate
1.0	12.0 R	90 sec	8.0 R/min	8.04 R/min
3.0	11.7 R	30 sec	23.4 R/min	23.5 R/min
5.0	13.0 R	20 sec	39.0 R/min	39.2 R/min

(2) kVp = 70; d = 30 cm; 1 mm Al added filtration

mA	Exposure	Exposure Time	Exposure Rate	Corrected Rate
1.0	12.0 R	180 sec	4.0 R/min	4.02 R/min
3.0	11.4 R	60 sec	11.4 R/min	11.47 R/min
5.0	9.6 R	30 sec	19.8 R/min	19.9 R/min

C. Effect of kilovoltage on exposure rate

1. 3 mA; d = 30 cm; inherent filtration

kVp	Exposure Rate
40	12 R/min
50	18.2 R/min
60	23.8 R/min
70	29.4 R/min
80	34.2 R/min
90	39.3 R/min
100	44.7 R/min

2. 3 mA; d = 30 cm; 1 mm Al added filtration

kVp	Exposure Rate
40	3.28 R/min
50	6.10 R/min
60	9.30 R/min
70	12.3 R/min
80	15.7 R/min
90	19.3 R/min
100	22.6 R/min

D. Effect of distance on exposure rate

1. 70 kVp; 3 mA; inherent filtration

SCD	Exposure Rate
20 cm	56.0 R/min
25 cm	34.2 R/min
30 cm	23.6 R/min
40 cm	13.5 R/min
50 cm	9.0 R/min

IV. ANSWERS TO QUESTIONS

A. The slope of the curve of exposure rate versus distance on log-log paper was found to be -2. This is exactly the value one would expect if the inverse square law were to hold since

$$R = \frac{C}{d^2}$$

where: R = exposure rate

C = constant

d = distance

$$\ln R = \ln C - \ln d^2 = \ln C - 2 \ln d$$

$$\frac{\Delta \ln R}{\Delta \ln d} = -2 = \text{theoretical slope}$$

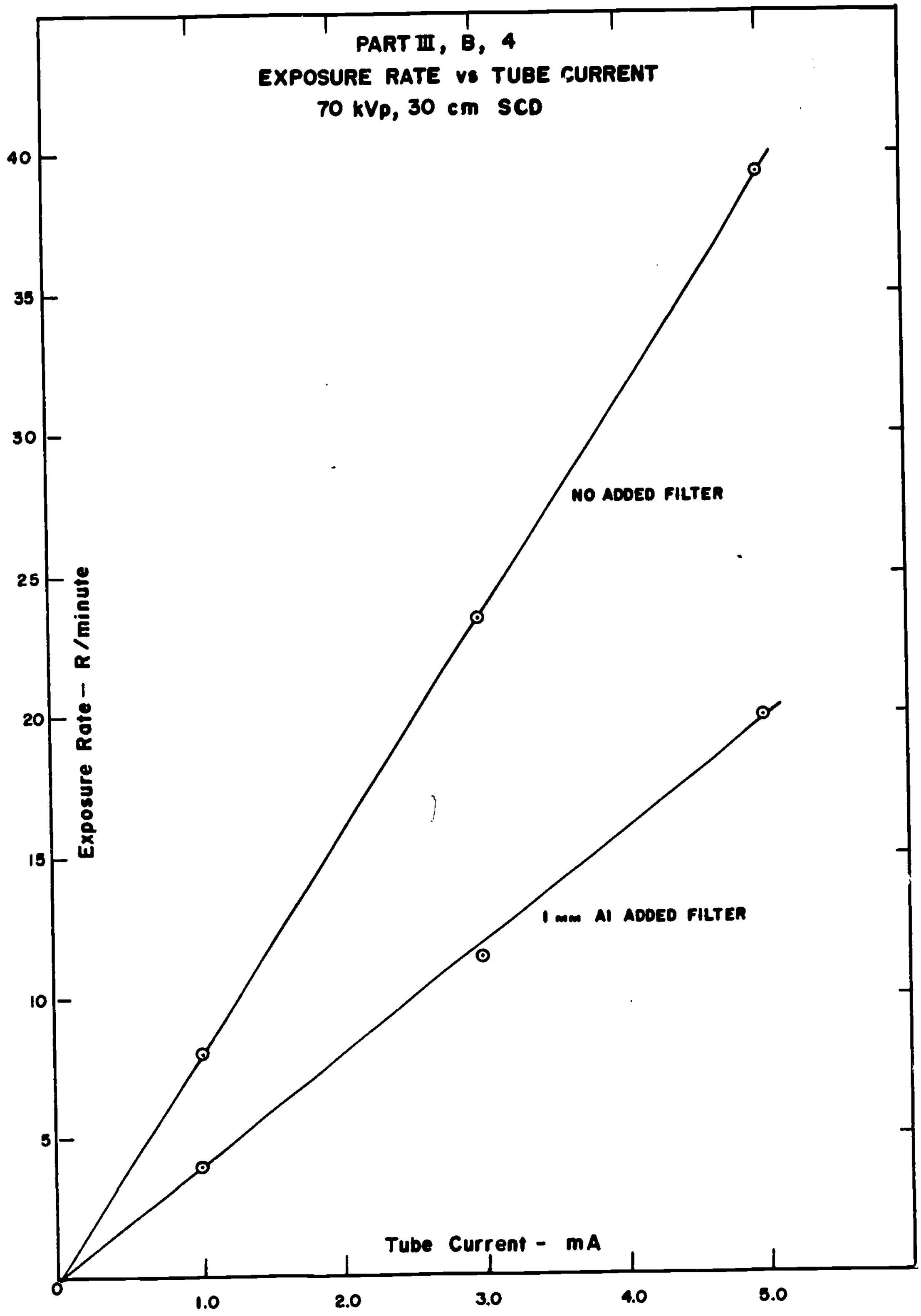
Thus one would have to say that our value is in very good agreement with the theoretical.

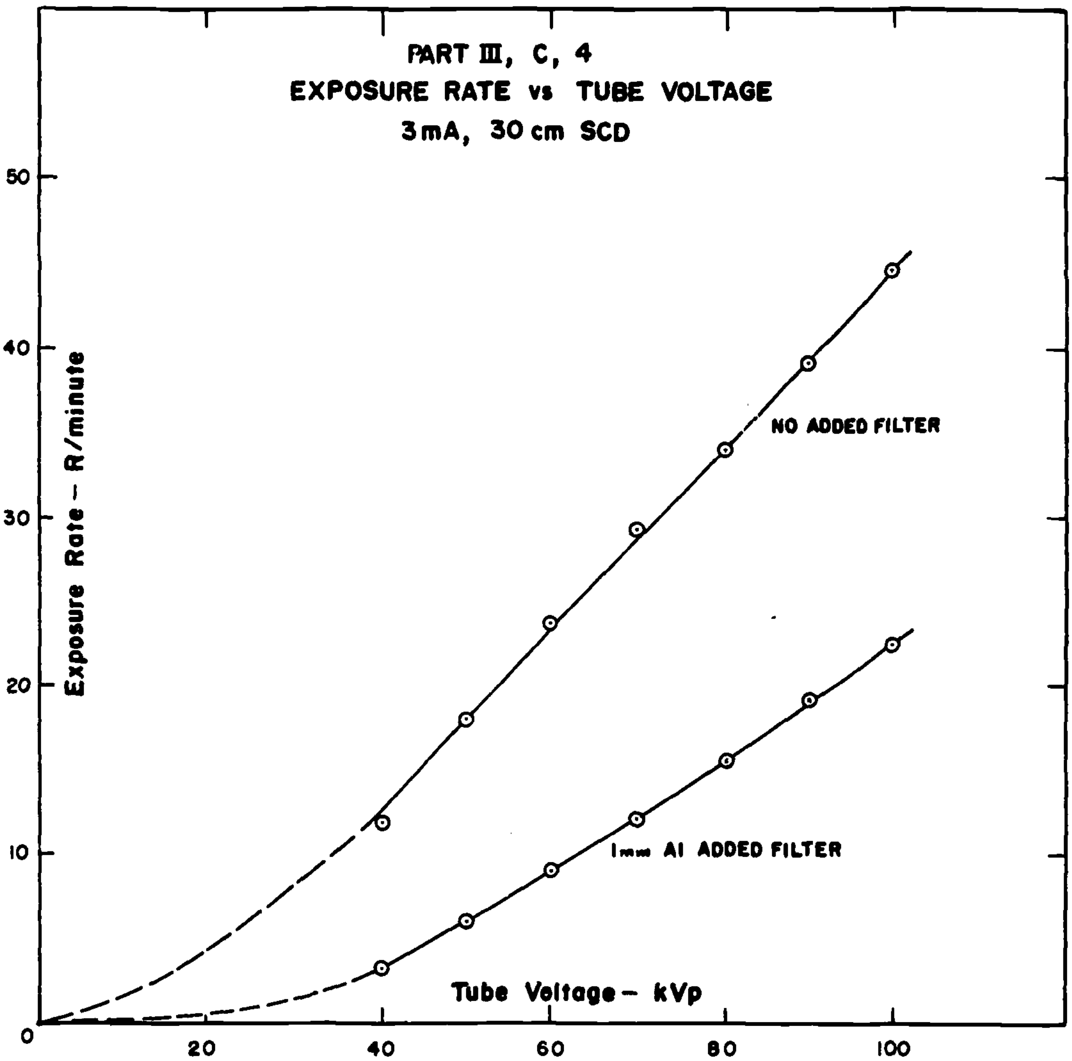
B. The inverse square law will fail if the source from which the irradiation is being emitted is not a point source. As long as the source does not deviate too much from a point, the inverse square law will be very closely approximated. Other factors that will cause deviation from the inverse square law are air absorption and scattered radiation reaching the measuring chamber.

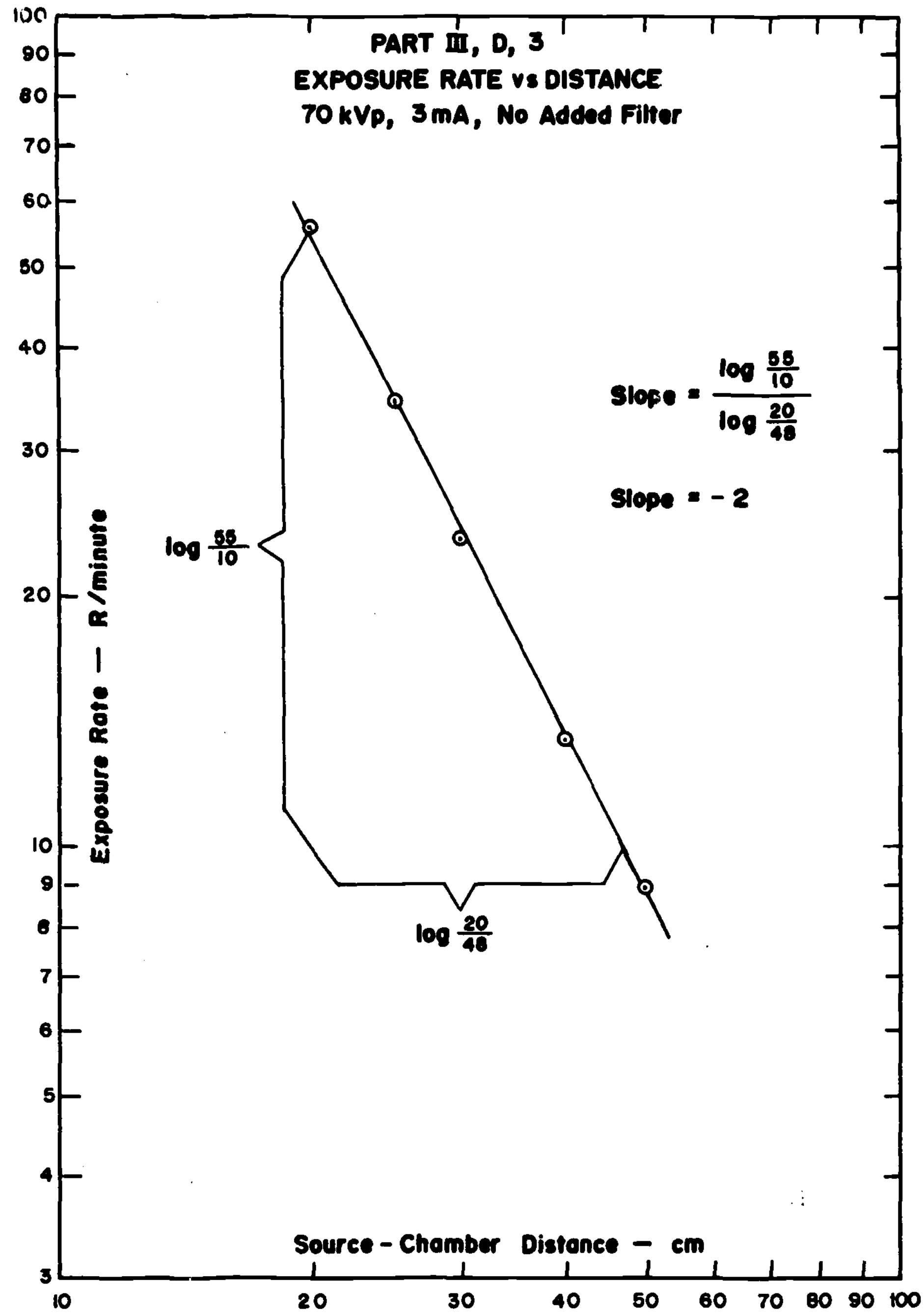
C. As the tube current is increased, the number of electrons emitted from the cathode are increased and hence the number of x rays produced will be increased. Since the tube voltage is being kept constant, the basic shape of the energy spectrum will not be altered, just the number of x rays produced at each energy will be increased by the same factor. This increase in x rays, which is directly proportional to the tube current, will cause the exposure rate to increase in a linear manner for constant kVp. Thus the exposure rate will be directly proportional (and hence linear) to the tube current.

D. When filtration is added at a fixed kVp and SCD, the exposure rate is decreased by a certain fraction. As the tube current is increased, the exposure rate is decreased by this same fraction when the Al filter is added. The reason for this is that the filter removes a certain fraction of the x rays (predominantly lower energy) from the spectrum. As the tube current is increased and the tube voltage kept constant only the relative intensity of the spectrum will be increased and the filtration will remove the same fraction regardless of intensity. Thus the exposure rate will be decreased by the same fraction when a filter is added regardless of tube current.

E. When filtration is added at a fixed tube current and SCD, the exposure rate is reduced. This effect is altered by changing the kVp. As can be seen from the graph of tube voltage versus exposure rate, the change is greater at lower kVp than at the higher kVp. The reason for this is that with a constant tube current the total intensity will be a constant and for the lower kVp the spectrum will contain a large number of low energy x rays. The Al filter will absorb a great fraction of this soft radiation. However, as the kVp is increased, the effective energy is increased and hence the spectrum is shifted in the higher energy direction. There will be less soft radiation and thus a smaller fraction of the total intensity will be absorbed by the Al filter and the exposure rate will not be decreased by as much.


PART III, B, 4
EXPOSURE RATE vs TUBE CURRENT
70 kVp, 30 cm SCD
NO ADDED FILTER
1 mm Al ADDED FILTER
Exposure Rate — R/minute
Tube Current - mA
40
35
30
25
20
15
10
5
0
1.0
2.0
3.0
4.0
5.0


PART III, C, 4
EXPOSURE RATE vs TUBE VOLTAGE
3 mA, 30 cm SCD
Exposure Rate – R/minute
Tube Voltage – kVp
NO ADDED FILTER
1mm Al ADDED FILTER
0
10
20
30
40
50
20
40
60
80
100


PART III, D, 3
EXPOSURE RATE vs DISTANCE
70 kVp, 3 mA, No Added Filter
Slope = $\frac{\log \frac{55}{10}}{\log \frac{20}{48}}$
Slope = - 2
log $\frac{55}{10}$
log $\frac{20}{48}$
Exposure Rate — R/minute
Source - Chamber Distance — cm
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
10
20
30
40
50
60
70
80
90
100

LABORATORY NO. 5

TITLE: Use of Dental, Therapeutic, Industrial and Medical Radiographic X-Ray Equipment

PURPOSE: To familiarize the student with the use of various types of x-ray equipment

TIME: Six hours

MATERIALS FOR EACH STUDENT GROUP:

One GE 100 Dental Unit
One GE 100 Mobile Radiographic Unit
One GE DXS-350 Radiographic Unit
One GE Maximar 100 Superficial Therapy Unit
One GE Maxitron 300 Therapy Unit
One Victoreen Condenser R-meter with 1 R, 25 R and 100 R medium energy chambers
One Victoreen Roentgen Ratemeter with model 602 probe
One Victoreen model 444 survey meter
Three sheets linear graph paper, K & E 46-0703 or equivalent
One ships curve, K & E 1685-48 or equivalent
One straight edge

REFERENCES: Operating Instructions for X-ray Machines

Laboratory No. 5

USE OF DENTAL, THERAPEUTIC, INDUSTRIAL, AND MEDICAL RADIOGRAPHIC X-RAY EQUIPMENT

I. INTRODUCTION

The purpose of this laboratory is to familiarize the student with the use of various types of x-ray equipment.

II. EQUIPMENT

A. GE 100 II Dental Unit

B. GE 100 II Mobile Radiographic Unit

C. GE DXS-350 Radiographic Unit

D. GE Maximar 100 Superficial Therapy Unit

E. GE Maxitron 300 Therapy Unit

F. Victoreen Condenser R-meter with 1 R, 25 R, and 100 R medium-energy chambers

G. Victoreen Roentgen Ratemeter with model 602 probe

H. Victoreen Model 444 Survey Meter

III. PROCEDURE

Instruction manuals will be placed with each piece of equipment. Read the operating instructions paying particular attention to the rated duty cycle of the unit. Outline the procedure you intend to follow in order to obtain the requested data and have your outline approved by an instructor before you operate any of the x-ray units.

A. GE 100 II Dental Unit

Calculate and then measure the x-ray beam size at the end of each of the following cones:

1. 8" pointer
2. 8" open
3. 12" open
4. 16" open

Show all calculations and measurements.

B. GE 100 II Mobile Radiographic Unit

Plot the x-ray exposure per mAs as a function of kVp using the Condenser R-meter and the following settings:

no added filtration	40 kVp
"	50 kVp
"	60 kVp
"	70 kVp
"	80 kVp
"	90 kVp
"	100 kVp

C. GE DXS-350 Radiographic Unit

Using the Victoreen 444 Survey Meter, measure the exposure corresponding to the following radiographic techniques:

22 cm-PA chest: 72" - 80 kVp - 10 mAs
12 cm-lateral jaw: 30" - 64 kVp - 5 mAs
24 cm-oblique colon: 40" - 90 kVp - 60 mAs
20 cm AP lumbar spine: 40" - 76 kVp - 100 mAs
12 cm foot: 40" - 94 kVp - 200 mAs

D. GE DXS-350 Radiographic Unit

Using the Condenser R-meter, derive a plot of exposure per mAs versus mA. Obtain data at each of the following mA stations:

Small Focal Spot	Large Focal Spot
25	100
50	200
100	300

E. GE Maximar 100 Superficial Therapy Unit

Using the Roentgen Rate Meter, derive a plot of the exposure per mA-minute versus mm of Al added filtration. Obtain data for all combinations of the following settings:

40 kVp	0.25 mm Al added
70 kVp	0.50 mm Al added
100 kVp	1.00 mm Al added
	2.00 mm Al added
	3.00 mm Al added

F. GE Maxitron 300 Therapy Unit

Using the Condenser R-meter, determine exposure per mA-minute at 100 cm SCD for each of the following HVL's:

0.25 mm Al
1.00 mm Al
3.00 mm Al
1.00 mm Cu
2.00 mm Cu
3.00 mm Cu

Adjust and record the kVp and mA used for each HVL station.

Laboratory No. 5

TYPICAL DATA

III. A. GE 100 II Dental Unit

Equipment: Fluorescent screen and meter stick

Setting: 50 kVp, 10 mA, 2 sec. exposures

1. 8" Pointer Cone

Measured field dia. = 2.625"

w = 11/16", l = 2", h = 8"

$$x = \frac{(8)\ (11/16)}{2} = \frac{44}{16} = 2.75''$$

Calculated field dia. = 2.75"

2. 8" Open Cone

Measured dia. = 2.875"

w = 11/16", l = 2", h = 8"

Calculated dia. = 2.75"

3. 12" Open Cone

Measured dia. = 2.875"

w = 7/16", l = 2", h = 12"

$$x = \frac{(12)\ (7/16)}{2} = 42/16$$

Calculated dia. = 2.62"

4. 16" Open Cone

Measured dia. = 2.875

w = 3/8", l = 2", h = 16"

$$x = \frac{(16)\ (3/8)}{2} = \frac{24}{8}$$

Calculated dia. = 3"

B. GE 100 II Mobile Radiographic

Equipment: Condenser R-meter No. 1588

1 R Chamber

Settings: 15 mA, inherent filtration, 40" SCD

kVp	Exposure Time	mAs	Exposure	Exp./mAs
40	4 sec	60	0.195 R	3.25 mR/mAs
50	4 sec	60	0.460 R	7.66 mR/mAs
60	4 sec	60	0.760 R	12.70 mR/mAs
70	3 sec	45	0.770 R	17.10 mR/mAs
80	2 sec	30	0.750 R	25.0 mR/mAs
90	1 sec	15	0.480 R	32.0 mR/mAs
100	1/2 sec	7.5	0.292 R	39.0 mR/mAs

C. GE DXS-350 Radiographic Unit

Equipment: Victoreen Model 444 Survey Meter

Settings: 50 mA, inherent filtration

mAs	kVp	Time	Exposure	FCD
10	80	0.2 sec	15.9 mR	80"
5	64	0.1 sec	5.1 mR	80"
60	90	1.2 sec	117.0 mR	80"
100	76	2.0 sec	140.0 mR	80"
200	94	4.0 sec	283.0 mR	94"

By use of inverse square law, exposures at following distances were obtained

$$R_2 = \frac{R_1 d_1^{\,2}}{d_2^{\,2}}$$

mAs	kVp	FCD	Exposure	Exp. Rate	
10	80	72"	0.0196 R	0.098 R/sec	22 cm - PA chest
5	64	30"	0.036 R	0.36 R/sec	12 cm - lateral jaw
60	90	40"	0.468 R	0.390 R/sec	24 cm - oblique colon
100	76	40"	0.560 R	0.280 R/sec	20 cm - AP lumbar spine
200	94	40"	1.58 R	0.395 R/sec	12 cm - foot

D. GE DXS 350 Radiographic Unit

Equipment: Victoreen Condenser R-meter No. 1588
Ring Stand, 25 R chamber

Setting: SCD = 20", kVp = 100

Small Focal Spot:

mA	Exp. Time	mAs	Exposure	Exp./mAs
25s	5 sec	125	4.20 R	0.0336 R/mAs
50s	5 sec	250	7.99 R	0.0320 R/mAs
100s	2 sec	200	6.10 R	0.0305 R/mAs

Large Focal Spot:

mA	Exp. Time	mAs	Exposure	Exp./mAs
100L	5 sec	500	14.2 R	0.0284 R/mAs
200L	2 sec	400	11.4 R	0.0285 R/mAs
300L	1/2 sec	150	5.0 R	0.0334 R/mAs

E. GE Maximar 100 Superficial Therapy Unit

Equipment: Roentgen Rate Meter
Probe Model 602 (x 10)
30 cm SCD

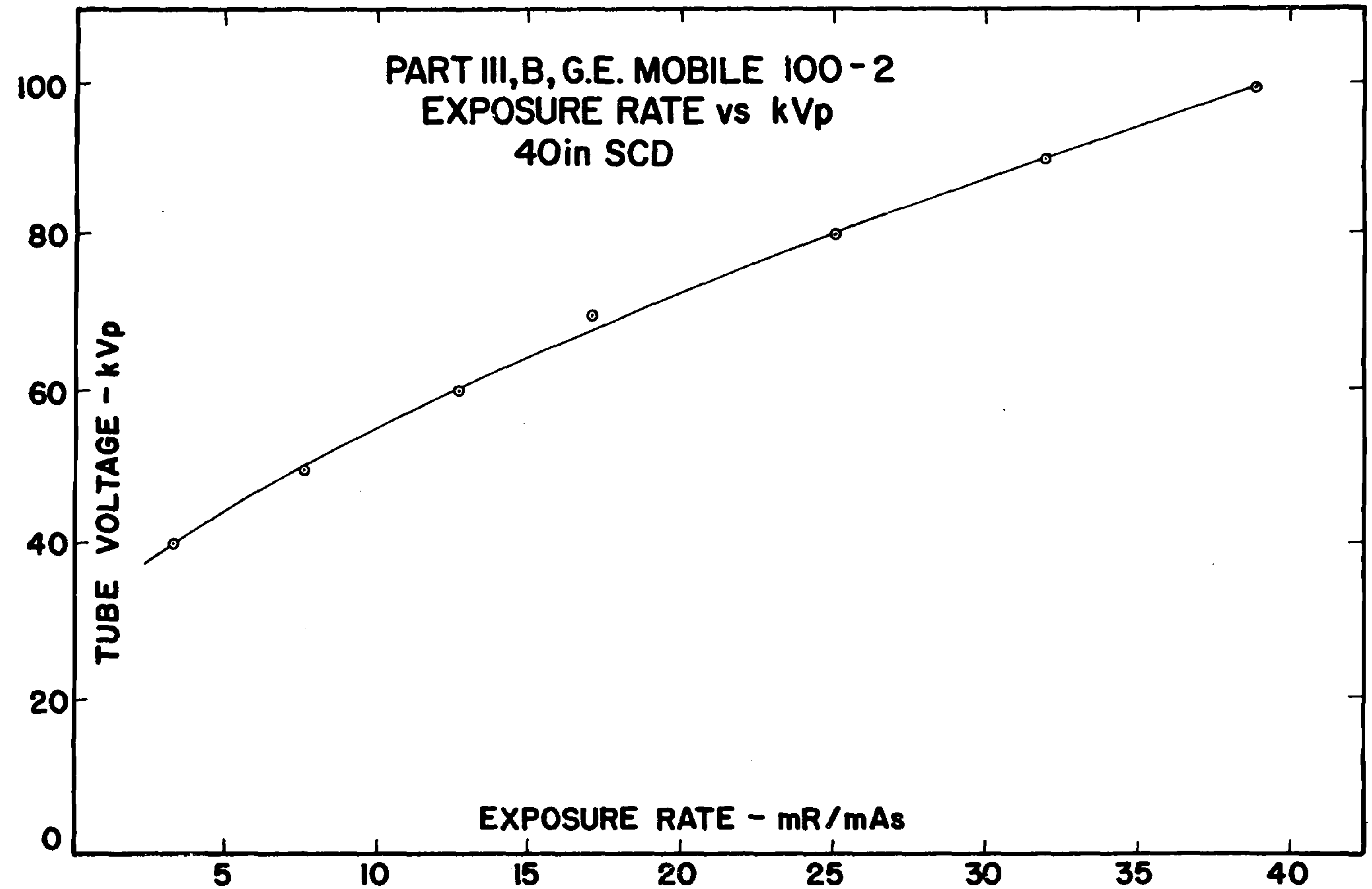
mA	kVp 40 (R/min)	kVp 70 (R/min)	kVp 100 (R/min)	mm Al added	kVp 40 (R/mA-min)	kVp 70 (R/mA-min)	kVp 100 (R/mA-min)
5	13.0	38.0	62	0.275	2.6	7.6	12.4
5	9.5	27.5	46	0.425	1.9	5.5	9.2
5	3.0	12.6	24	0.96	0.6	2.52	4.8
5	0.7	6.0	13.7	2.04	0.14	1.2	2.74
5	0.7	4.6	10.4	3.00	0.14	0.92	2.08

F. GE Maxitron 300 Therapy Unit

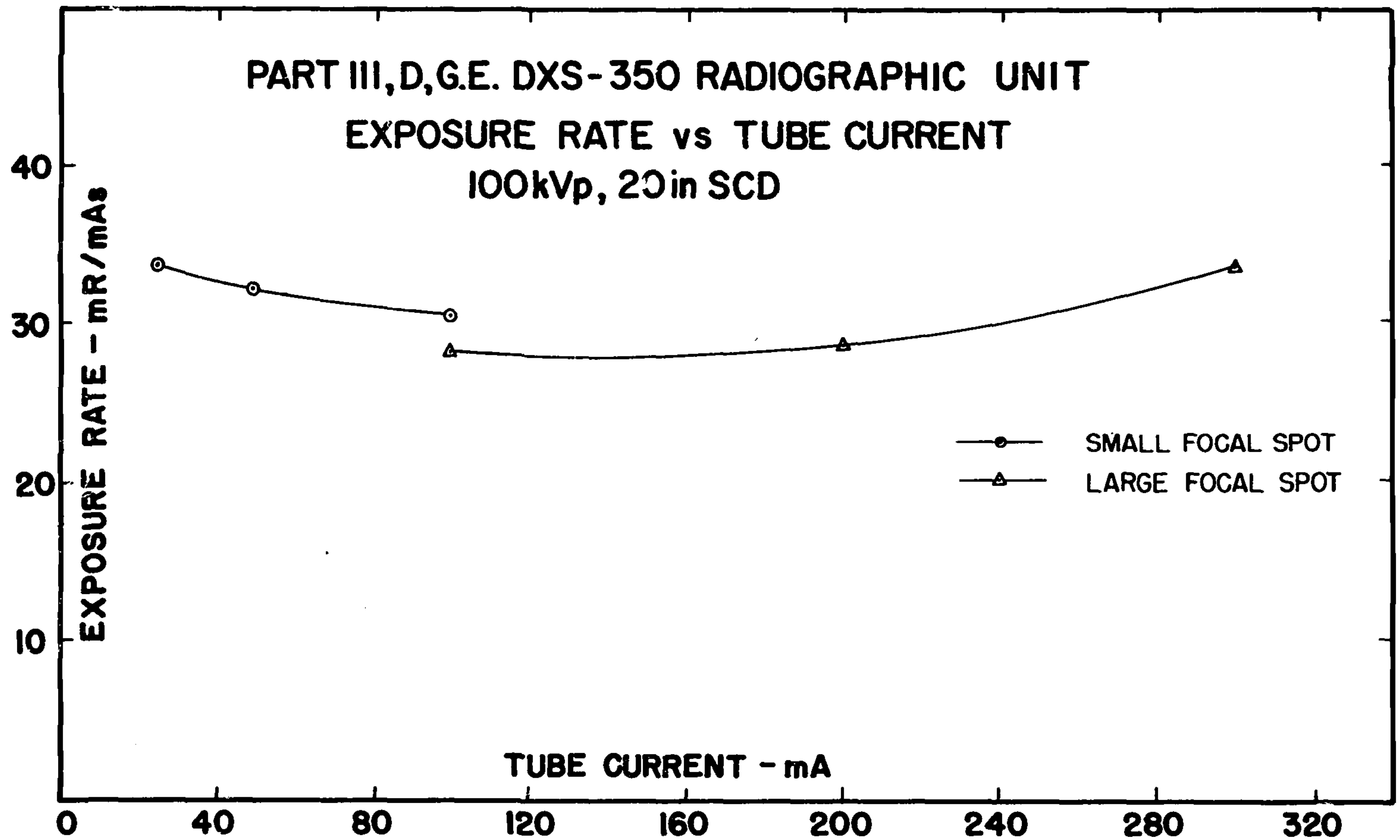
Equipment: Condenser R-meter No. 1588, 100 R chamber

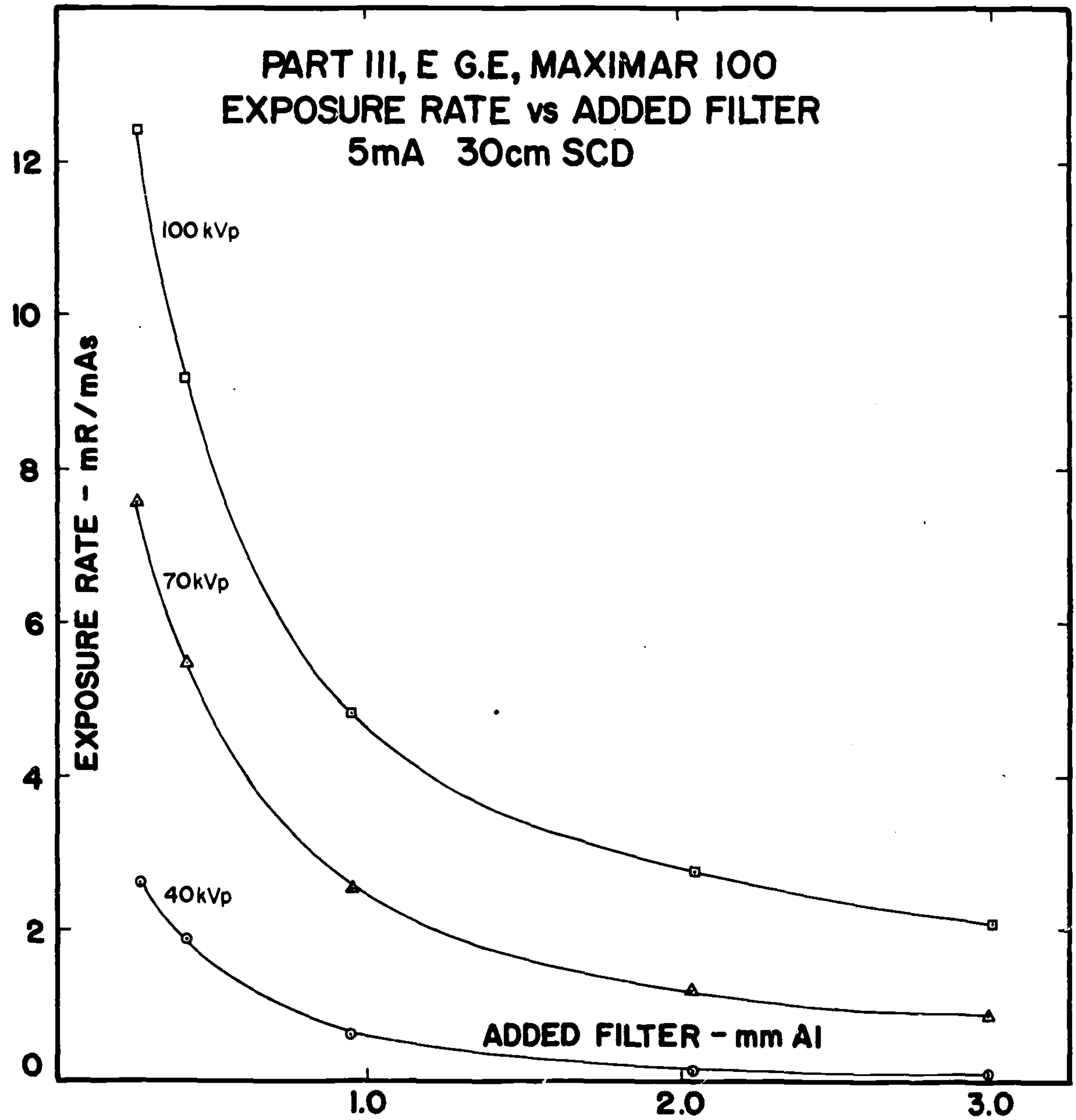
Settings: SCD 100 cm, 20 mA

HVL	kVp	Exp. Time	mA-min	Exp.	R/mA-min
0.25 mm Al	100	1/2 min	10	24 R	2.4
1.00 mm Al	100	1 min	20	28	1.4
3.00 mm Al	140	2 min	40	59	14.75
1.00 mm Cu	200	2 min	40	31	0.775
2.00 mm Cu	300	2 min	40	69	1.725
4.00 mm Cu	300	2 min	40	23	0.575



PART III, B, G.E. MOBILE 100-2
EXPOSURE RATE vs kVp
40in SCD
TUBE VOLTAGE - kVp
EXPOSURE RATE - mR/mAs
100
80
60
40
20
0
5
10
15
20
25
30
35
40


PART III, D, G.E. DXS-350 RADIOGRAPHIC UNIT
EXPOSURE RATE vs TUBE CURRENT
100kVp, 20in SCD
EXPOSURE RATE - mR/mAs
TUBE CURRENT - mA
SMALL FOCAL SPOT
LARGE FOCAL SPOT
0
40
80
120
160
200
240
280
320
10
20
30
40


PART III, E G.E, MAXIMAR 100
EXPOSURE RATE vs ADDED FILTER
5mA 30cm SCD
100 kVp
70 kVp
40 kVp
EXPOSURE RATE - mR/mAs
ADDED FILTER - mm Al
0
2
4
6
8
10
12
1.0
2.0
3.0

LABORATORY NO. 6

TITLE: X-Ray Timers

PURPOSE: To investigate techniques used to check the accuracy of impulse and synchronous timers.

TIME: Six hours

MATERIALS FOR EACH STUDENT GROUP:

One G.E. 100 Dental X-ray Unit
One G.E. Maxitron 300 Therapy Unit
One G.E. Maximar 100 Therapy Unit
One G.E. DXS-350 Radiographic Unit
One Victoreen Condenser R-meter with 25 R model 70-5 and 250 R model 651 chambers
One chamber stand
One stopwatch
One spinning top
One G.E. Dual High Voltage Bleeder
One solid-state x-ray detector
One Tektronix model 546 Dual Trace Oscilloscope with memory module
One 8 x 10 inch sheet Kodak Blue Brand x-ray film
One 8 x 10 inch Par Speed screen cassette
One sheet linear graph paper, K & E 46-0703 or equivalent
One straight edge

REFERENCES: X-ray equipment operating directions

X-RAY TIMERS

I. Introduction

The purpose of this laboratory exercise is to investigate techniques used to check the accuracy of impulse timers and the time delay of synchronous timers.

II. Equipment

A. One G.E. 100 Dental Unit

B. One G.E. Maxitron 300 Therapy Unit

C. One G.E. Maximar 100 Superficial Therapy Unit

D. One G.E. DXS-350 Radiographic Unit

E. One Victoreen Condenser R-meter with 25 R medium energy chamber (model 70-5) and 250 R low energy chamber (model 651)

F. One stopwatch

G. One spinning top

H. One G.E. Dual High Voltage Bleeder

I. One solid-state x-ray detector

J. One Tektronix Model 546 Dual Trace Oscilloscope with memory module

K. One 8 x 10 inch cassette with Par Speed screens

L. One sheet 8 x 10 inch Blue Brand film

III. Procedure

A. G.E. 100 Dental Unit

1. Load an 8x10 inch Par Speed screen cassette with an 8x10 inch sheet of Blue Brand film. Place a piece of 1/16 - 1/8 inch thick lead on the dental stand and place the cassette on the lead. Block off 3/4 of the cassette with leaded vinyl. Center the x-ray tube head over the unblocked portion of the cassette with a 12 inch source-film distance and no cone attached to the tube head. Set the x-ray machine controls for operation at 50 kVp and 10 mA.

2. Place the spinning top on the unblocked portion of the cassette and spin the top. From the control location behind the protective barrier make a 1 impulse exposure when the top is rotating at about 1 rps. In a similar manner, on the other 3/4 of the film, make exposures of 10, 18, and 30 impulses. Start the film through the automatic film processor.

Impulses	Spinning Top "Dots"
1	________________
10	________________
18	________________
30	________________

B. Maxitron 300

1. Timer Accuracy

a. Warm up the x-ray machine following the warm-up procedure posted at the control.

b. Set up the x-ray machine as follows:

Technic Selector	0.5 cu
kVp	140
mA	20

c. Set the timer for 1 minute. Turn on x ray and check the timer accuracy with the stopwatch.

Timer Setting-sec.	Stopwatch-sec.
60	______

2. Delay Time

a. Set up the x-ray machine and make measurements as follows:

Technic Selector	0.5 cu
kVp	140
mA	20
SCD	50 cm
Field	10x10 cm
Instrument	R-meter
Chamber	25 R

Exposure Time-sec.	Uncorrected Exposure-R
40	______
20	______

b. Plot exposure vs time on linear graph paper. The intercept of this line on the extrapolated to the time axis will give the delay time.

C. Maximar 100

1. Timer Accuracy

a. Set up the x-ray machine for operation at 70 kVp and 5 mA.

b. Set the timer for 1 minute. Turn on x ray and check the timer accuracy with the stopwatch.

Timer Setting-sec.	Stopwatch-sec.
60	__________

2. Delay Time

a. Set up the x-ray machine and make measurements as follows:

Filtration	Inherent
kVp	70
mA	5
Cone	5x30 cm
SCD	30 cm
Instrument	R-meter
Chamber	250 R

Exposure Time-sec.	Uncorrected Exposure-R
10	__________
5	__________

b. Plot exposure vs time and determine the delay time.

D. DXS-350

1. The timer accuracy will be checked by observing the voltage waveform on an oscilloscope and counting the number of pulses. The oscilloscope is connected to a high voltage bleeder which has been connected in the high voltage circuit.

2. Turn on the oscilloscope and adjust for memory operation, channel 1 inverted, and mode switch on add.

3. Set up the x-ray machine for operation at 60 kVp, 50 mA with the adjustable collimator closed. Make exposures at the timer settings shown below. Record the number of voltage pulses observed. Change the time base of the 'scope as required.

Timer Setting	Impulses
1/120 sec	________
1/60 sec	________
1/40 sec	________
1/30 sec	________
1/20 sec	________
1/10 sec	________

4. Disconnect the probe leads from the oscilloscope. Place the solid-state x-ray detector on the collimator face and adjust the collimator so that the field size equals the detector size. Connect the detector to the 'scope channel 1 input. Set the 'scope mode selector for channel 1, normal.

5. Set up the x-ray machine for operation as in D.3. Record the number of voltage pulses observed.

Timer Setting	Impulses
1/120 sec	________
1/40 sec	________
1/20 sec	________
1/10 sec	________

IV. Questions

A. Does the timer setting correspond to the actual exposure time in Parts III A and III D? Explain.

B. Explain how the spinning top is used to check timer accuracy. What are some of the limitations in its use?

C. Calculate the delay time of the synchronons timers (Parts III.B. and III.C.). How does this compare with the value obtained graphically?

D. What x-ray machine operating factors account for the observed delay time (Parts III.B. and III.C.)?

E. What information in addition to timer accuracy can be obtained from the waveforms in Part III.D.?

Laboratory No. 6

TYPICAL DATA

III. A. 2. G.E. Dental 100

Timer Setting - Impulses	Spinning Top "Dots"
1	1
10	10
18	18
30	30

III. B. G.E. Maxitron 300

1. Timer accuracy

Timer Setting - sec	Stopwatch Time - sec
60	60.1

2. Delay Time

Timer Setting - sec	Exposure - R
40	14.1
20	7.0

Delay Time 0.5 sec.

III. C. G.E. Maximar 100

1. Timer accuracy

Timer Setting - sec	Stopwatch Time - sec
60	60.0

2. Delay Time

Timer Setting - sec	Exposure - R
10	133
5	67

Delay Time - 0

III. D. G.E. DXS-350

3. Timer accuracy using HV Bleeder

Timer Setting - sec	Impulses
1/120	1
1/60	2
1/40	3
1/30	4
1/20	6
1/10	12

5. Timer accuracy using solid state detector

Timer Setting - sec	Impulses
1/120	1
1/40	3
1/20	6
1/10	12

IV. Answers to Questions

A. Yes. For the single-phase self-rectified dental unit you get one impulse ("dot") for each 1/60 second impulse timer setting. For the full-wave rectified DXS-350 you get one impulse for every 1/120 second timer setting.

B. A spinning top is a metal disc, pivoted at its center, with a small square hole located near its periphery. The top spins about its pivot point. With single-phase pulsating x-ray sources, the x ray is produced in "pulses" (one 1/120 second pulse every 1/60 second for self- or half-wave equipment, two 1/120 second pluses every 1/60 second for full-wave equipment) so that each x-ray pulse produces a "dot" on the x-ray film. It cannot be used for long (seconds) exposure times or with three-phase, constant potential or high-frequency generators.

C. The equation for a straight line is $y = ax + b$. Let y = time and x = exposure.

1. Maxitron 300

$40 = 14.1\,a + b$

$20 = 7.0\,a + b$

$b = 20 - 7a$

$a = 2.82$

$b = 0.3$

When $x = 0$, $y = 0.3$

Delay = 0.3 sec compared to graphical 0.5 sec

2. Maximar 100

$10 = 133\,a + b$	$10 = 133\,a + 5 - 67\,a$
$5 = 67\,a + b$	$5 = 66\,a$
$b = 5 - 67\,a$	$a = 0.075$
$a = 0.075$	$b = 5 - 5.03$
$b = -0.03$	

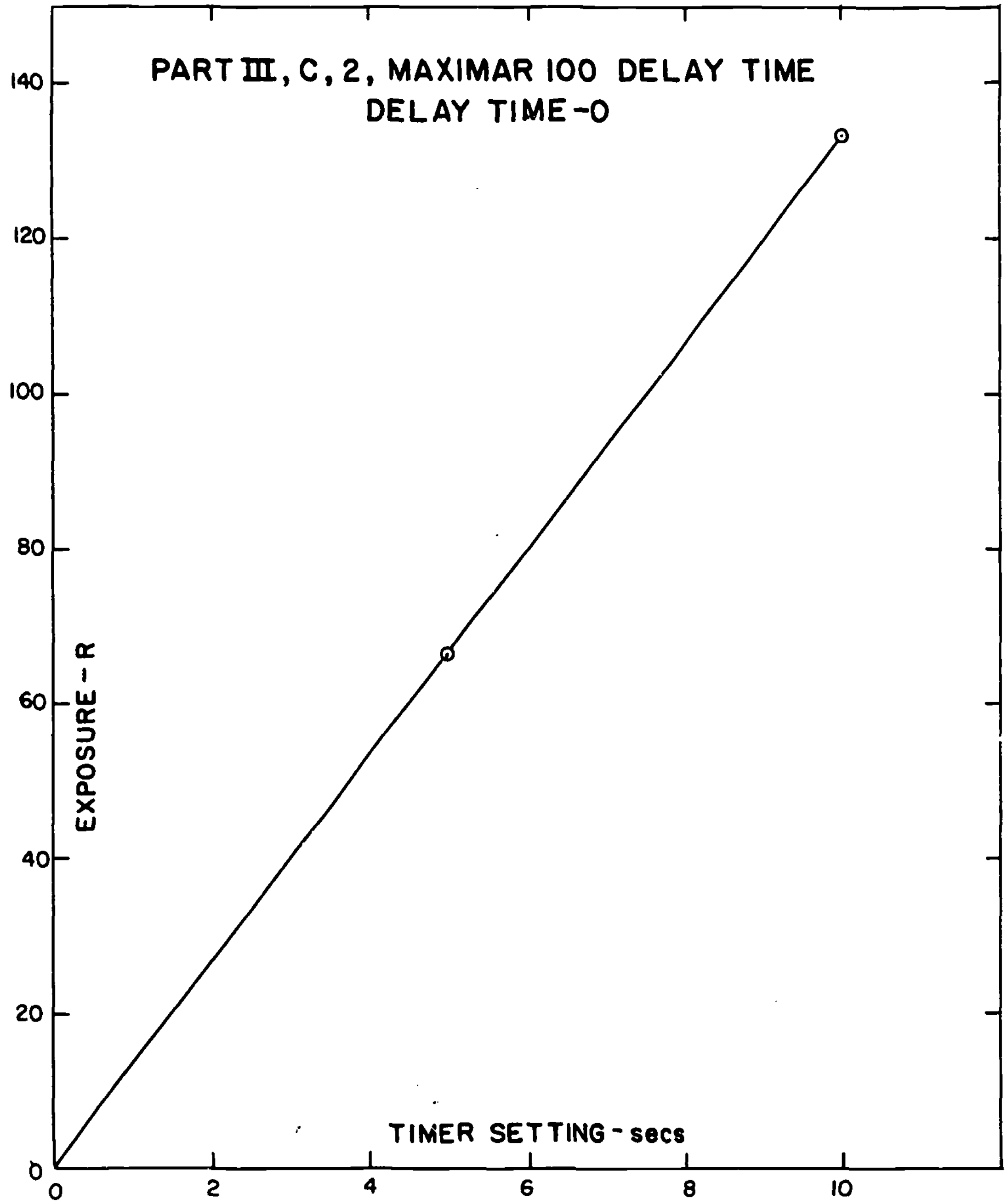
When $x = 0$, $y = -0.03$

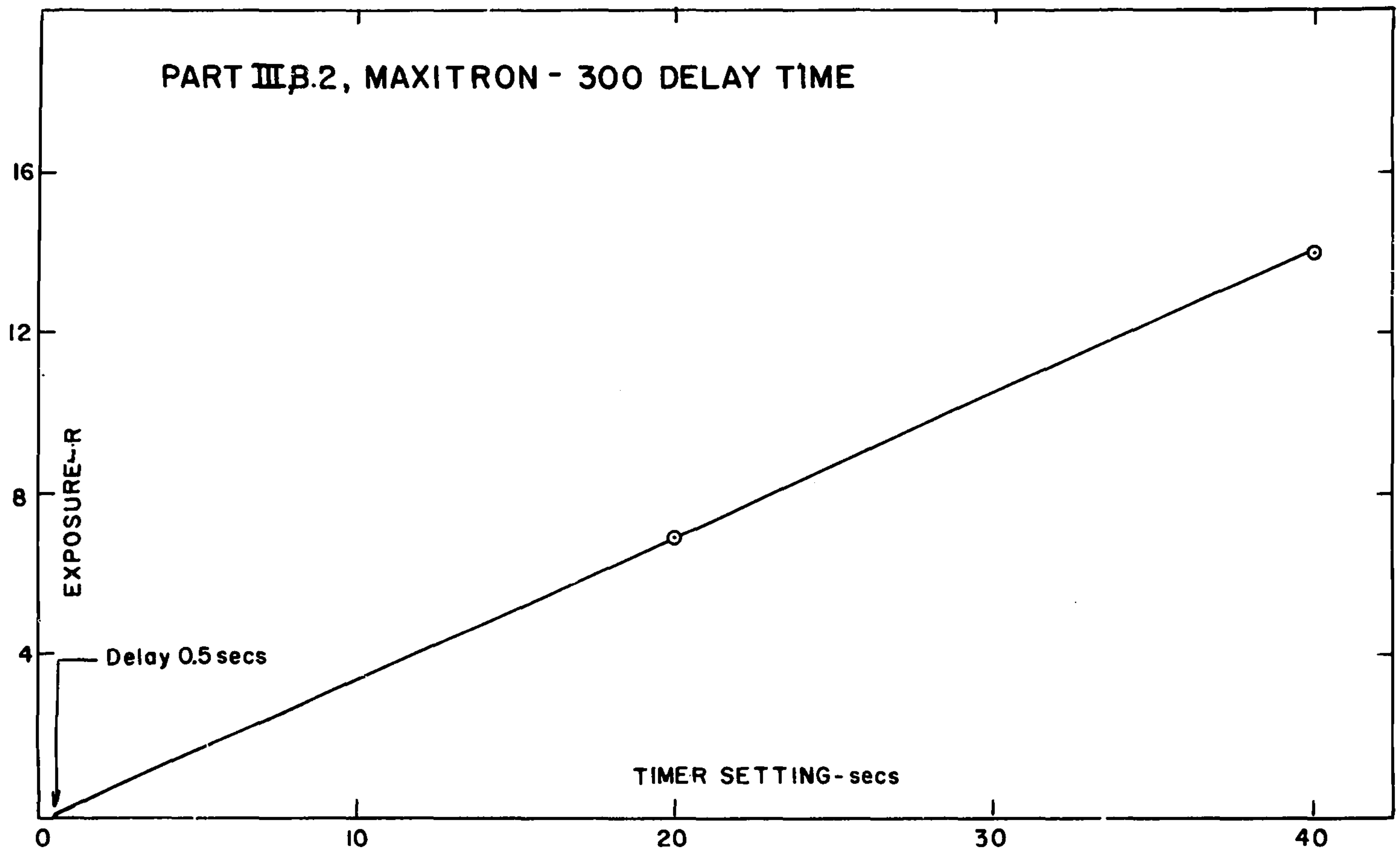
Delay = -0.03 sec compared to graphical 0 sec

D. The delay in the Maxitron 300 is due to circuit delay between initiation of the exposure and build-up of kVp and mA to their operating values. There is no significant delay in the 60 Hz, self-rectified Maximar 100.

E. Additional information includes

1. HV Bleeder
    a. Voltage waveforms
    b. Peak kilovoltage (with calibrated 'scope)
2. Solid-state detector
    a. X-ray output waveform


PART III, C, 2, MAXIMAR 100 DELAY TIME
DELAY TIME-0
EXPOSURE - R
TIMER SETTING - secs
140
120
100
80
60
40
20
0
0
2
4
6
8
10


PART III.B.2, MAXITRON - 300 DELAY TIME
EXPOSURE-R
TIMER SETTING-secs
Delay 0.5 secs
16
12
8
4
0
10
20
30
40

GS-461 MACHINE SOURCES OF X RAY

SECTION III

EXAMINATIONS

Name ________________________________

GS 461

Test No. 1

Part I--Circle the phrase or phrases which correctly complete(s) the statement or answers the question. (5 points each)

1. High-voltage cable capacitance in full-wave rectified x-ray equipment while maintaining a constant peak kilovoltage will cause the average kilovoltage to . . . .

   a. increase
   b. decrease
   c. remain the same
   d. become unstable
   e. arc to ground

2. Transformers are used in a typical x-ray machine circuit to . . . .

   a. increase voltage
   b. decrease voltage
   c. control voltage
   d. provide electronic isolation
   e. alter the frequency

3. In the basic x-ray machine circuit discussed in class, if the x-ray tube was operating at 150 kVp, the peak potential difference between the primary and secondary <u>of the filament transformer</u> would be approximately . .

   a. 75 volts
   b. 750 volts
   c. 7,500 volts
   d. 75,000 volts
   e. none of the above

4. Electrons rather than protons are used for the production of x rays because . . . .

   a. they have less charge
   b. they move with a greater velocity for a given energy
   c. have less mass
   d. are more abundant
   e. are easily liberated from an element

5. An inverse reducer used in a self-rectified x-ray machine . . . .

a. reduces the inverse voltage on the x-ray tube
b. eliminates inverse conduction in the x-ray tube
c. reduces the peak inverse voltage on the high-voltage transformer
d. is more important at high mA than at low mA operation

6. Electromagnetic radiation . . . .

a. travels at the speed of light
b. travels through a vacuum in a straight line
c. is affected by electric and magnetic fields
d. has particulate properties
e. all of the above

7. The line voltage compensator in an x-ray circuit . . . .

a. is used to provide uniform input voltage to the autotransformer
b. maintains a constant high-voltage transformer primary voltage
c. is used only with full-wave rectified equipment
d. automatically selects the tube current
e. is electrically located between the x-ray contactor and the high voltage transformer

8. X rays are produced in an x-ray tube target . . . .

a. by the deceleration of electrons impinging on the target
b. by the ejection of a proton or neutron from a target nucleus
c. by the ejection of an orbital electron from a target atom
d. by capture of an electron in the target atom nucleus
e. by ejection from the target of a free electron

9. The maximum energy of x-ray photons produced in an x-ray tube target depends upon . . . .

a. the target material
b. the target thickness
c. the x-ray tube current
d. the peak kilovoltage
e. all of the above

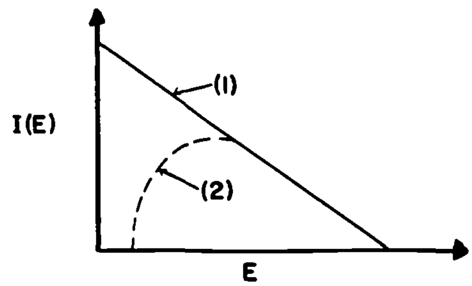
10. Doubling the x-ray tube current will . . . .

a. double the x-ray output
b. halve the x-ray output
c. have no effect on x-ray output

Part II--(20 points each question)

1. A beam of monoenergetic electrons with a kenetic energy of 100 keV strike a thick gold (Z = 79) target.

   a. Sketch the continuous x-ray spectrum of intensity vs energy (1) as produced in the target and (2) as it appears outside the x-ray tube. Explain any difference in the two spectra.
   Answer:



Attenuation in the target and in the wall of the x-ray tube will limit the minimum photon energy. Results in curve (2) rather than curve (1) appearing outside the x-ray tube.

b. Calculate the fraction of the electron energy which is converted into heat.

Answer:

$$Q = 1 - F = 1 - (10^{-6})(79)(100)$$
$$= 1 - .0079$$
$$= .9921$$

c. Calculate the wavelength and frequency corresponding to the highest energy photons produced.

Answer:

$$\lambda = \frac{12.4}{E} = \frac{12.4}{100} = 0.124\ \text{Å}$$

$$\nu = \frac{E}{h} = \frac{(100,000)\ (1.6 \times 10^{-12})}{6.625 \times 10^{-27}} = 24.2 \times 10^{18}\ \text{Hz}$$

or

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^{10}}{.124 \times 10^{-8}} = 24.2 \times 10^{18}\ \text{Hz}$$

2. An x-ray machine is operating at 100 mA and 66 kVp. The high voltage transformer primary voltage is 90 volts. The regulation at 100 mA is 6 kVp.

   a. Calculate the turns ratio of the transformer.

      Answer:

$$\frac{N_s}{N_p} = \frac{E_s}{E_p} = \frac{66,000 + 6000}{90} = \frac{72,000}{90} = \frac{800}{1}$$

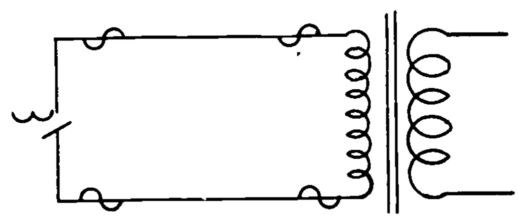
   b. What primary voltage would be required to provide 93 kVp at 50 mA?

      Answer:

$$E_p = \frac{N_p E_s}{N_s} = \frac{1}{800}\ (93,000 + 3000) = \frac{96,000}{800} = 120\ \text{V}$$

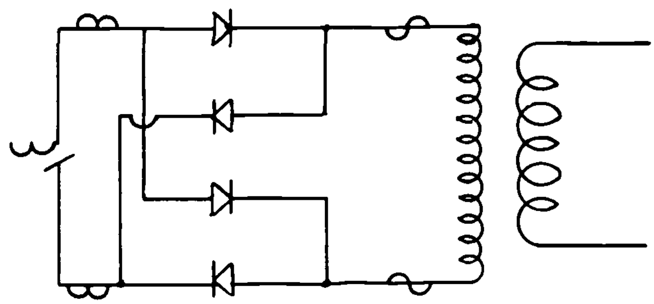
3. a. Draw the diagram of a self-rectified high voltage x-ray circuit with x-ray tube connected to the output (show only high voltage transformer and x-ray tube). Sketch the voltage waveform output from the high voltage transformer and input to the x-ray tube.

Answer:



b. Draw the diagram of a full-wave rectifier with an x-ray tube connected to the output (draw only the rectifiers and tube). Sketch the voltage waveform input to the rectifiers and output at the x-ray tube.

Answer:



Name________________________

GS-461

Final Examination

Part I. - TRUE or FALSE. Write a T on the line in front of the statement if <u>all</u> parts of it are true. Write F if any part of the statement is false. Value - 2 points each.

__F__ 1. The inverse-square law describes the absorption of x rays in air.

__F__ 2. Higher x-ray tube target operating temperatures may be safe when an inverse reducer is used.

__T__ 3. Leukemia would be an example of a long-term biological effect of radiation.

__F__ 4. The fraction of the total volume of an atom occupied by matter is approximately 10^{-5}.

__T__ 5. An x-ray photon differs from a gamma ray photon only in its origin.

__F__ 6. In an x-ray machine with fixed filtration and kVp, the percentage of radiation removed from the useful beam by the filter increases as the tube current increases.

__F__ 7. Only tungsten targets are used in x-ray tubes.

__T__ 8. The cathode assembly in an x-ray tube includes the filament and cathode cup.

__F__ 9. The x-ray tube envelope must provide filtration equivalent to 0.5 millimeter of aluminum.

__F__ 10. X rays were discovered by Dr. W. D. Coolidge.

Part II -Definitions. Briefly define, in the space provided, the following.

Value - 3 points each.

1. Heat Unit

Answer:

Arbitrary unit = kVp x mA x sec. Used to indicate "heat" of x-ray tube anode (either heat input or heat storage)

2. Transformer Regulation

Answer:

Voltage loss in HV transformer due to transformer impedance

3. Genetic Effect of Radiation

Answer:

The effect on ones prodgeny

4. Somatic Effect of Radiation

Answer:

The effect on the individual exposed

5. Nuclear Force

Answer:

Short range force that holds nucleus together

6. Cculomb Force

Answer:

Repulsive force between like charges in atom

7. Rectifier

Answer:

Device which permits current flow in one direction only

8. Characteristic Radiation

Answer:
Radiation produced by ejection of orbital electron and resulting filling of shells. Characteristic of atom.

9. Impulse Timer

Answer:
Timer that starts exposure at start (zero voltage) of + voltage cycle and terminates exposure at zero voltage. Used on single-phase units.

10. mAs

Answer:
Tube current in mA times time in seconds

Part III - Multiple choice. CIRCLE the ONE correct answer.

Value - 3 points each.

1. With correct timer operation, a spinning top exposure made with a timer setting of 1/10 second using a self-rectified generator should indicate:

a. 5 impulses

b. 6 impulses

c. 10 impulses

d. 12 impulses

e. 20 impulses

2. Electrons lose their energy in the x-ray tube target primarily by:

   a. elastic scattering

   b. production of x ray

   c. nuclear absorption

   d. photoelectric and Compton effects

   e. ionization and excitation

3. Bremsstrahlung refers to:

   a. radiation emitted upon breaking a nucleus

   b. a process of nuclear de-excitation

   c. electromagnetic radiations from decelerated electrons

   d. streams of electrons approaching the nucleus of a target atom

   e. the mass to energy conversion

4. Three-phase generators are more efficient than single-phase generators in the production of x rays because:

   a. they are less expensive to operate and install

   b. they have fewer parts

   c. they require more power to operate

   d. they provide near constant potential to the x-ray tube

   e. None of the above

5. In any x-ray generator operated at low tube current, increasing the capacitance in the high-voltage circuit will:

   a. cause the average kilovoltage to increase

   b. suppress inverse tube conduction

   c. have no effect on system operation

   d. decrease the x-ray output

   e. increase the x-ray tube filament current

6. In the basic self-rectified x-ray machine circuit discussed in class, if the x-ray tube was operating at 100 kVp the peak potential difference between the primary and secondary <u>of the filament transformer</u> would be approximately:

   a. 50 volts

   b. 500 volts

   c. 5,000 volts

   d. 50,000 volts

   e. 100,000 volts

7. The <u>maximum</u> energy of x-ray photons produced in an x-ray tube target depends upon:

   a. the anode-cathode spacing

   b. the peak kilovoltage

   c. the x-ray tube current

   d. the type of rectification

   e. the transformer frequency

8. Changing the rectification of an x-ray machine from full-wave to half-wave while holding the kVp and filament current constant would:

a. decrease mA by a factor of 2

b. increase mA by a factor of 2

c. have no effect on mA

d. increase the maximum tube loading by a factor of 2

e. decrease the maximum tube loading by a factor of 2

9. Maximum x-ray tube loading can be increased by:

a. using a rotating anode

b. changing the focal spot shape from square to circular

c. decreasing the x-ray tube current

d. decreasing the focal spot area

e. using a tube with two focal spots

Part IV - Value for each question is shown in parenthesis. Answer each question in the space provided.

(3) 1. What are two classifications of megavolt x-ray machines? Name one type of machine in each classification.

<u>Answer:</u>

1. Orbital - betatron, synchrotron,

2. Linear - Linac, Van de Graaf, resonant transformer

(5) 2. List all of the transformers used in a basic x-ray machine and describe the function(s) of each.

Answer:

1. Autotransformer - provide HV primary control, constant input volts, other circuit supply units.
2. HV transformer - step-up voltage to x-ray tube.
3. Filament transformer - step-down to power x-ray tube filament

(4) 3. List four desirable characteristics of an x-ray tube target.

Answer:

1. High Z
2. High melting point
3. Low vapor pressure
4. Good heat conductor

(2) 4. Explain what is meant by the dual nature of electromagnetic radiation.

Answer:

Some actions explained by wave theory, others only by quantum theory.

(4) 5. How does the exposure rate from an x-ray machine vary with:

a. milliamperage

Answer:

$\propto$ mA

b. kilovoltage

Answer:

$\propto kVp^n$

c. distance

Answer:

$$\propto \frac{1}{d^2}$$

d. filtration

Answer:

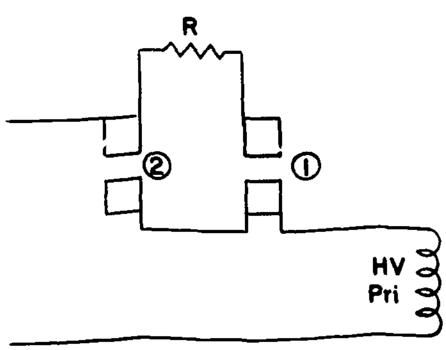
$$\propto e^{-\mu x}$$

(2) 6. Why are rotating anode tubes generally not used in therapy and industrial x-ray machines?

Answer:
Not needed for tubes operated at relatively "low" mA for "long" times with "large" focal spots.

(4) 7. Draw a circuit diagram of a surge resistor and associated x-ray contactor and briefly describe its purpose.

Answer:



Contacts (1) close first closing HV primary through R. Contacts (2) close next shorting out R used to apply V in steps to reduce initial surges.

(5) 8. A high-voltage bleeder (resistance divider) and oscilloscope readout system was used to check the timer on a full-wave rectified x-ray unit. The timer was set for 1/10 second and the oscilloscope trace clearly showed 6 pulses. What conclusions would you draw from these results?

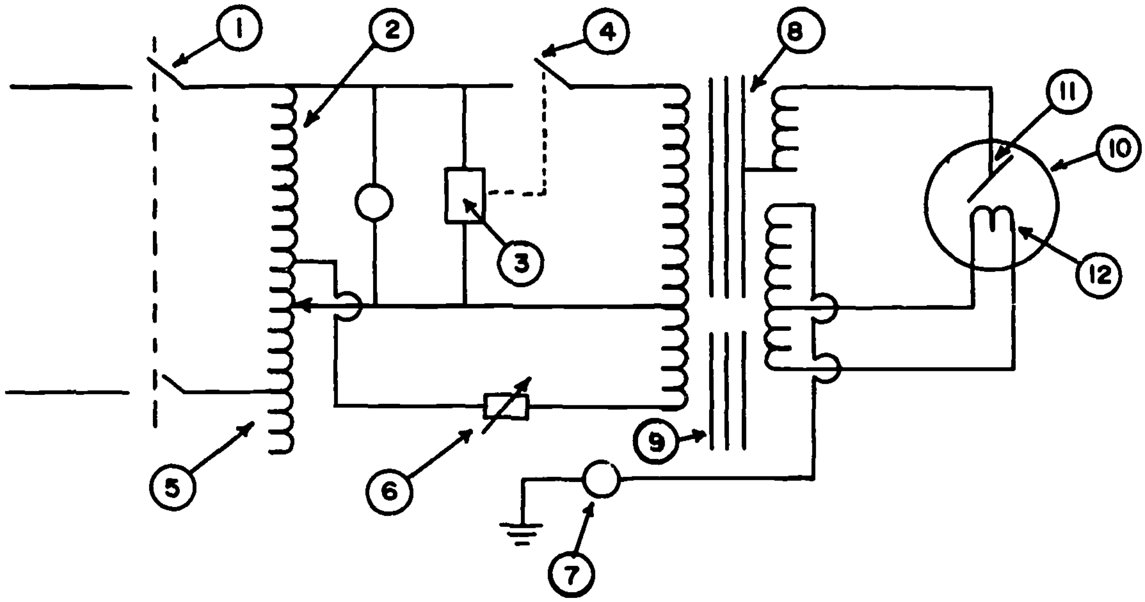
Answer:

Should be 12 pulses

1. Timer in error
2. Unit operating half-wave

10.

(20) 9. Identify each of the circuit components marked on the following circuit diagram:



Answer:

1. Line switch and circuit breaker
2. Autotransformer
3. Timer
4. X-ray contactor
5. Voltage compensator
6. Filament control
7. mA meter
8. HV transformer
9. Filament transformer
10. X-ray tube envelope
11. X-ray tube anode
12. X-ray tube cathode or filament

(4) 10. A beam of monoenergetic electrons with a kinetic energy of 50 keV strike a thick tungsten (z = 74) target.

a. Calculate the fraction of the electron energy which is converted into heat.

Answer:

$$Q = 1 - F = 1 - (10^{-6})\ (50)\ (74)$$

$$= 1 - 3700 \times 10^{-6}$$

$$= 1 - .0037$$

$$= .9963$$

b. Calculate the wave length corresponding to the highest energy photons produced.

Answer:

$$\lambda = \frac{12.4}{E} = \frac{12.4}{50} = 0.248\ \text{Å}$$

(4) 11. An x-ray machine is operating at 200 mA and 80 kVp. The high-voltage transformer primary voltage is 180 volts. The regulation at 200 mA is 12 kVp.

a. Calculate the turns ratio of the transformer.

Answer:

$$\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{80{,}000 + 12{,}000}{180} = \frac{92{,}000}{180} = \frac{512}{1}$$

b. What primary voltage would be required to provide 100 kVp at 100 mA?

Answer:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

$$V_p = \frac{N_p V_s}{N_s} = \frac{1\,(100{,}000 + 6{,}000)}{512}$$

$$= \frac{106{,}000}{512} = 207 \text{ V}$$

Appendix A

Equipment List

The following is a list of equipment needed for each student laboratory group. Major equipment items would, of course, be used by all laboratory groups. Equipment not generally commercially available and fabricated in the X-Ray Science and Engineering or University shops is detailed at the end of this appendix.

Number Required	Item
1	Victoreen model 444 survey meter
1	Victoreen model 510 Roentgen Ratemeter
1	Victoreen model 602 Ratemeter probe
1	Victoreen model 570 Condenser R-meter
1	Victoreen model 227 1R chamber
1	Victoreen model 70-5 25R chamber
1	Victoreen model 131 100R chamber
1	Victoreen model 651 250R chamber
1	Probe and chamber holder
1	Teaching X-Ray Unit (see USPHS Publication No. 1859)
1	General Electric GE-100 Dental X-Ray Unit
1	General Electric Mobile 100-15 X-Ray Unit
1	General Electric DXS-350 radiographic x-ray unit
1	General Electric Maximar 100 Superficial Therapy Unit
1	General Electric Maxitron 300 Deep Therapy Unit
1	X-ray film processing station (see Appendix A of GS-462 course outline)
1	Sheet Kodak No Screen x-ray film (8" x 10")
1	Sheet Kodak Blue Brand x-ray film (8" x 10")
1	Cardboard film holder (8" x 10")
1	Medium speed screen cassette (8" x 10")
1	Kodak M-5 dual speed X-OMAT automatic x-ray film processor

Number Required	Item
1	Film hanger (8" x 10")
1	Film dryer
1	Radiographic speciman (sand dollar)
1	X-Ray Machine Simulator (see USPHS Publication No. 1718)
1	Power line monitor
1	Vacuum tube voltmeter
1	Continuously variable auto transformer (0-130 volts)
1	Mercury barometer
1	Mercury thermometer
1	Stopwatch
1	Spinning top
1	General Electric Dual Type High Voltage Bleeder
1	Tektronix model 546 dual trace oscilloscope with memory module
1	Demonstration X-Ray Machine. This teaching aid was constructed by and the subject of an M.S. thesis by a student in the Radiological Health Fellowship program at Oregon State University and consists of all of the components of a basic 73 kVp x-ray machine mounted on the back of three vertical panels with the machine circuit drawn on the front of the panels. Plug-in type patch cords permit circuit connections providing self-rectified, half-wave and full-wave rectified operation. A step down transformer at the high-voltage transformer primary limits the maximum tube voltage to 20 kVp.

Appendix B

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