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X-Cal — A Calibration System for Electrical Measurement Devices Used With Diagnostic X-Ray Units

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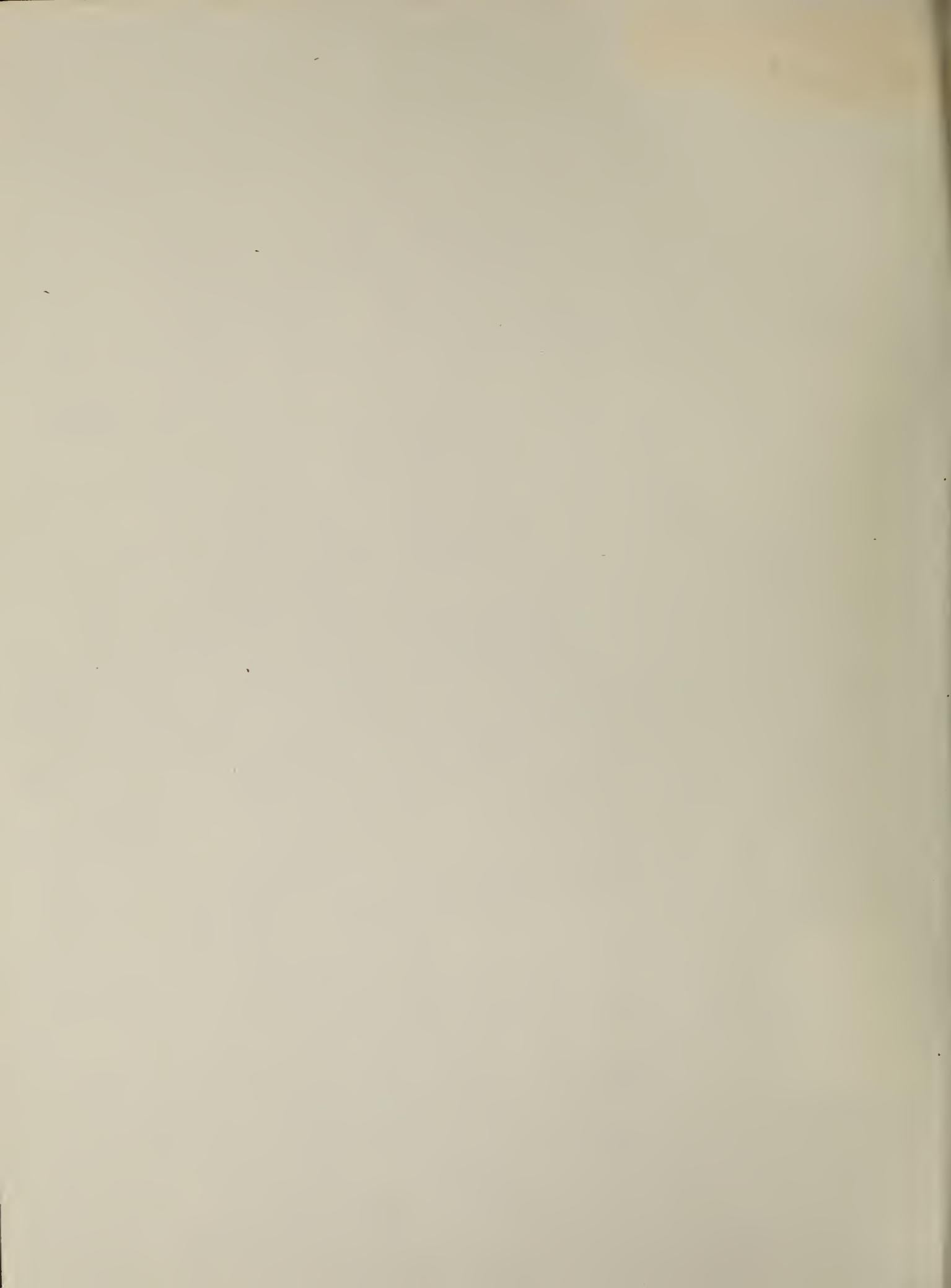National Bureau of Standards

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Abstract

A high-voltage-divider calibration system (designated as X-CAL System) was designed to calibrate the direct and alternating voltage measurement capabilities of commercial high voltage dividers used to characterize diagnostic x-ray units. The system includes capability for determining the frequency response of these dividers and for the calibration of the filament current and anode current measurement features of specific commercially-available devices. The calibration system combines in a single unit a range of capabilities which allows calibration of a device under test to be accomplished with a minimum of set up time. This report describes the rationale for measuring certain parameters of the high voltage dividers. It provides the design details of the X-CAL system and certain sections of this report serve as the operating manual for the system. The report lists the specified accuracies and the ranges of applicable parameters of the various subsystems, describes the five different calibrations which can be performed using the X-CAL system, discusses techniques used in the original calibration of the X-CAL system itself, and contains the basic circuit diagrams for the system.
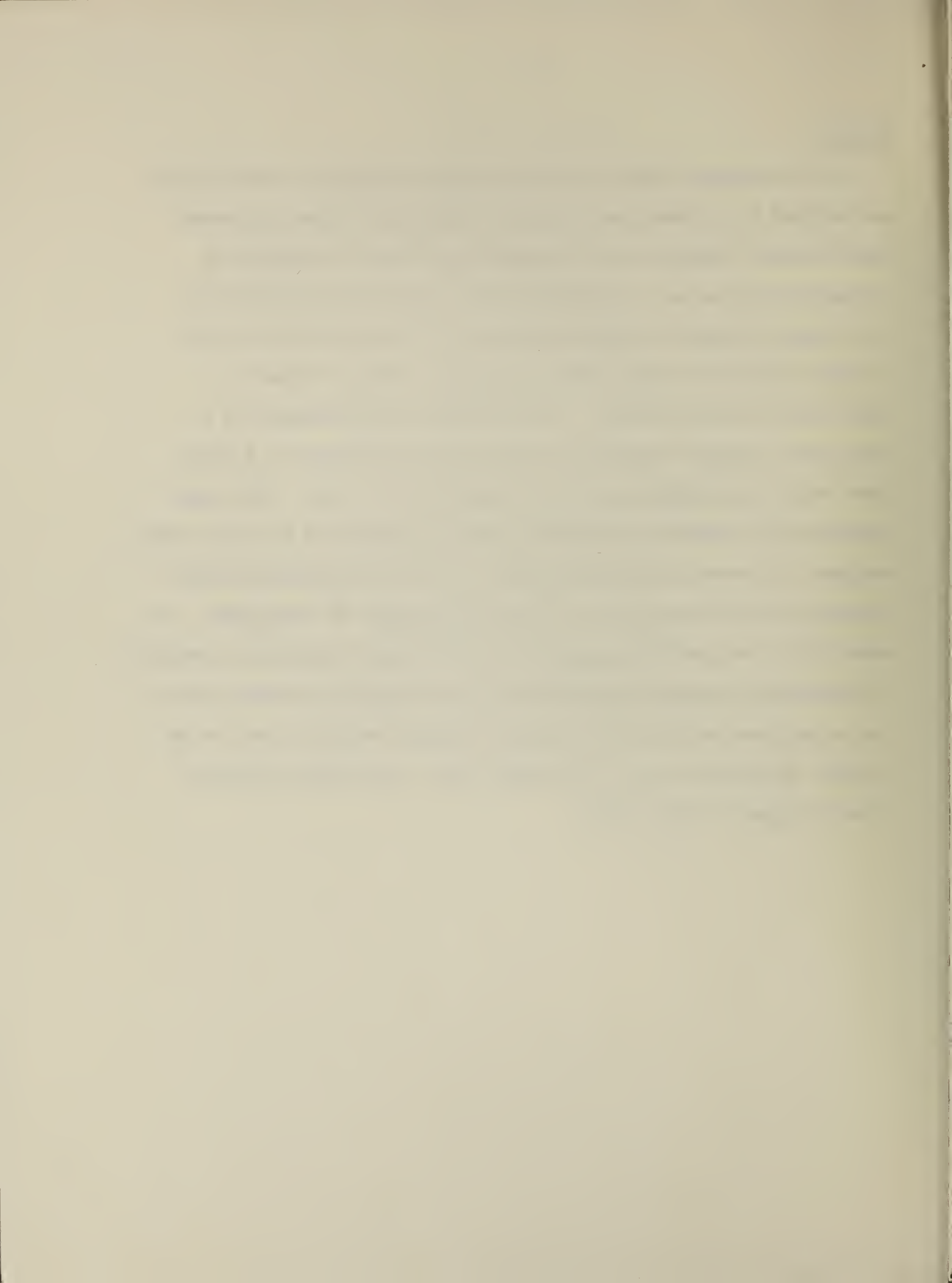
1. Introduction

The X-CAL high voltage divider calibration system was designed to calibrate the direct and alternating voltage measurement capabilities of commercial high voltage dividers used to electrically characterize diagnostic x-ray units. In addition there is capability for determining the frequency response of these dividers. This set of measurements as applied to dividers used to characterize diagnostic x-ray units was developed at NBS and is a part of the calibration services of NBS. The X-CAL system was developed for and with the support of the Calibration Coordination Group (CCG) of the Department of Defense. It will be used to routinely calibrate divider units used in military hospitals as part of a service-wide effort to control radiation exposure. Because of CCG requirements, two test functions have been included in X-CAL for the calibration of special measurement features of one particular device, the Machlett Dynalyzer.[1] These are filament current and anode current measurements. With minor X-CAL system modification, these test functions can be used to calibrate any measurement system offering these capabilities. The calibration system combines in a single unit a range of capabilities which allows calibration of a device under test (DUT) to be accomplished with a minimum of set up time.

This report is intended to give a user, or potential user, a description of the motivation for, the operation of and the design details of the X-CAL system. It is also intended and is written appropriately to serve as an operating manual for the system. Section 2 lists the specified accuracies and the ranges of applicable parameters of the various subsystems. The motivation for the various electrical measurements is described in Section 3. Section 4 describes the five different calibrations which can be performed

using the X-CAL system. System installation is described in Section 5. Detailed operating instructions are given in Section 6. Section 7 discusses techniques used in the original calibration of the X-CAL system itself. Section 8 describes maintenance and recalibration procedures for the X-CAL system. A suggested list of replacement parts is given in Section 9. Section 10 contains the basic circuit diagrams for the system and Section 11 is a list of references.

2. Specifications

The X-CAL calibration system allows five specific calibrations to be performed. These are listed below with statements of accuracies and ranges of applicable parameters.

2.1 Direct Voltage Divider Ratio Measurement

Voltage Range - 0 to ±75 kV.

Accuracy of measurement - ±1%.

2.2 Alternating Voltage Divider Ratio Measurement

Voltage Range - determined by power supply provided by user.

Accuracy of measurement - ±1% using calibrated

standard high-voltage gas-filled capacitor.

2.3 Frequency Response of Divider Ratio

Frequency Range - fixed frequency oscillator (50,

100, 500, 1000, 5000, 10000 Hz) or variable frequency

function generator.

Accuracy of measurement - ±1% for ratios normalized

to dc ratio values.

2.4 Filament Current

Current Range - continuously variable from 0 to

20 amps for a 1 ohm load.

Accuracy of measurement - ±1%.

2.5 Anode Current

Current Range - selectable from 0.05 amp to 2 amp

(0.05, 0.1, 0.5, 1, 2) into a 200 ohm load.

Current Pulse Width - selectable from 0.01 s to 1 s

(0.01, 0.05, 0.1, 0.5, 1) with current pulse controller

limiting average power to 10 watts.

Accuracy of measurement - ±1%. This accuracy statement

is for the current pulses driving the 200 ohm load of a

Machlett Dynalyzer[1] when the peak current value is converted

into the corresponding average current value. The table

of conversion factors is in Section 6.

The measurements described in 2.5 and 2.6 are designed specifically

for a Machlett Dynalyzer[1] system and the specifications apply only to measure-

ments on this system. The adaptation of the X-CAL system for calibration of

other units is detailed in Section 6.8.

2.6 Description of System Modules and Specific Control Functions

The following sections describe the system components which were

specially developed for the X-CAL system. Commercially available items

have been used when possible and the instruction manuals for these

items should be referred to for details of their operation.

2.7 System Control Module Switches

Power - Turns on control module and activates control

circuitry. Other calibration system modules have

independent power switches.

Test Function - Enables appropriate test circuitry and routes

test signals. Five separate test modes may be selected:

DCHV, ACHV, FREQ Res, ANODE I, and FIL I.

A/C - Selects for processing either the anode or cathode
  output signal from the DUT.

Active/Passive - Differentiates between signals generated
  by devices under test which contain active signal processing
  components and passive devices. In the ACTIVE position,
  the signal is routed to the appropriate signal processing
  circuits. When the passive mode is selected, the input
  signal is amplified by an amplifier, the gain of which can
  be selected (by resistor replacement and trim pot adjustment)
  to provide direct readout from the DUT.

Signal - INT/EXT - Determines the source of the low level
  signal used in the frequency response measurements. In
  the INT position, switch selectable discrete frequencies
  are available. For more extensive measurements, the EXT
  position allows use of a separate function generator.

Ratio Trans - HI/LO - Selects either the high
  frequency or low frequency sections of the ratio
  transformer for use in frequency response measurements.

Frequency - Sets the frequency of the internal
  oscillator to one of six values.

Reset - Resets the peak and hold detector used
  in the ACHV measurement circuit.

2.8 Filament Current-Viewing-Resistor Test Module

Pwr - turns on ac supply but does not control the
  ac panel meter.

AC I - Current control

AC Panel Meter - Indicates current in external circuit
  directly. Unless the FIL I test mode is selected, the
  meter display is blanked.

2.9 Anode-Current-Viewing-Resistor Test Unit

Pwr - Energizes main dc supply.

Peak Current - Selects nominal value of peak current

produced in a 200 ohm external load.

Pulse Duration - Selects pulse length. Peak current and

pulse duration circuitry are configured to limit average

power dissipation in a 200 ohm load to 10 W.

Peak Current Meter - Indicates peak current produced

by unit.

3. Theory

It has been estimated that exposure to medical and dental x-rays is

the source of 90 percent of the population dose from man-made sources.[2]

The x-ray dose produced by an x-ray unit depends on x-ray tube construction,

the waveform of the potential difference across the tube, the current

through the tube and the duration of the voltage pulse. In practice the

operator has control of the last three parameters, and of these, the

peak potential difference across the tube is most important. There are

two different techniques used to determine the peak voltage level in

diagnostic x-ray units.[3-12] One is to infer the peak voltage from a

measurement of appropriate parameters of the emitted beam of x-rays. The

other is to perform an electrical measurement of the voltage using

conventional high voltage measurement techniques. The relative advantages

of various measurement methods have been discussed and the consistency of

these measurements (under a limited range of voltage and time parameters

of pulses), when used to measure the same voltage waveform, has been

determined by other workers.[5,11]

Unnecessary radiation exposure can result when the operation of diagnostic x-ray equipment is not well characterized. Direct measurements of x-ray energy spectrum and dose during each exposure are presently impractical. However, one means of controlling radiation exposure is to insure the accuracy of the measurement of electrical quantities associated with diagnostic x-ray units.

The X-CAL unit provides electrical calibration of devices which perform electrical measurements on diagnostic x-ray units. Because high voltage measurements are made in a large number of applications outside the field of diagnostic radiology, the application of standard calibration techniques to x-ray unit high voltage dividers insures the consistency of the calibration of the measurement apparatus to within the specified uncertainty of the measurements among users of high voltage apparatus.

A basic theoretical model[13], which has been used to describe pulse dividers, represents the divider as a matrix relating the input current and voltage to the output current and voltage:

$$\begin{bmatrix} V_{in}(\omega) \\ I_{in}(\omega) \end{bmatrix} = \begin{bmatrix} A_{11}(\omega) & A_{12}(\omega) \\ A_{21}(\omega) & A_{22}(\omega) \end{bmatrix} \cdot \begin{bmatrix} V_0(\omega) \\ I_0(\omega) \end{bmatrix} \tag{1}$$

From Eq. 1, two parameters of the divider are defined. One is the voltage transfer function, $H(\omega)$, which is the ratio of the output voltage to the input voltage when the output current is zero, i.e.,

$$H(\omega) = V_0(\omega)/V_{in}(\omega) \Big|_{I_0(\omega)=0} = 1/A_{11}(\omega). \tag{2}$$

The other is the divider ratio, N, which is defined as

$$N = A_{11}(0) = \lim_{\omega \to 0} A_{11}(\omega). \qquad (3)$$

To apply these equations to the dividers under test, it is useful to consider the circuit in Fig. 3.1. The model is not adequate to predict the exact shape of the frequency response of all the dividers tested, but from this model, many of the significant properties of the device can be inferred. For example, V_o/V is given by

$$V_o/V = \frac{\frac{1}{R_H}\left(\frac{1}{R} + \frac{1}{R_H}\right) + \omega^2 C_H (C + C_H) + j\,\omega\left(\frac{C_H}{R} - \frac{C}{R_H}\right)}{\left(\frac{1}{R} + \frac{1}{R_H}\right)^2 + \omega^2 (C + C_H)^2}. \qquad (4)$$

From 3, the divider ratio is

$$N = \frac{V}{V_o} = \lim_{\omega \to 0} A_{11}(\omega) = (R + R_H)/R. \qquad (5)$$

This equation is the basis for the practice[6] of calibrating this type of pulse divider by determining the resistance ratio.

The expression derived from the equivalent circuit indicates that $A_{11}(\omega)$ is a complex number. In general, all of the matrix elements $A_{ij}(\omega)$ are complex. Measurement systems are designed so that the ratio of the input to the output voltage can be represented as a single real number.
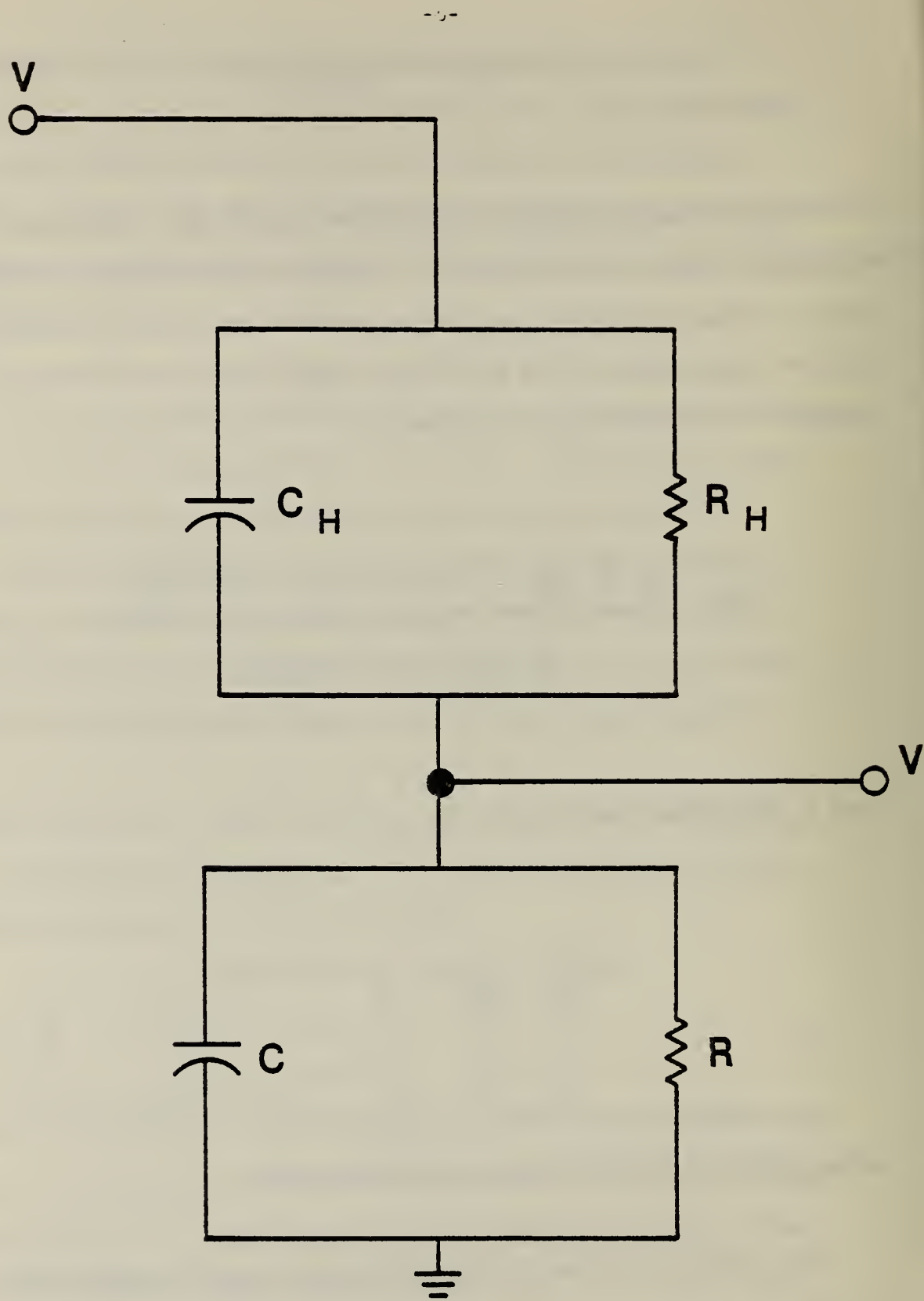
FIGURE 3.1 Approximate lumped parameter equivalent circuit for a high voltage divider.

The divider ratio, as defined here, has that property and is the quantity

which has traditionally been used in the description of dividers used

to measure the voltage in diagnostic x-ray units. For the divider

ratio to be a valid quantity, however, it is necessary that $|A_{11}(\omega)|$

not differ significantly from N over the frequency range of interest.

It can be seen from Eq. 4 that if

$$RC = R_H C_H,$$

i.e., if the divider is compensated, then $A_{11}(\omega)$ is frequency independent

and the divider ratio will be real. For a variety of reasons, e.g., inadequacy

of the model by not accounting for stray capacitances, construction errors, etc.,

the compensation in actual dividers is not exact. All dividers, therefore, have

a quadrature component large enough to be measured.

Using the X-CAL system, the divider ratio [Eq. (3)] is measured by

applying high voltages between 25 kV and 75 kV. This corresponds

to x-ray tube voltages of 50 kV to 150 kV. The test is carried out with

direct voltage so that it is also necessary to demonstrate that the divider

has the appropriate frequency response.

The frequency dependence of the ratio can be determined using the circuit shown in Fig. 3.2. The inductive voltage divider shown is a seven decade device, the division ratio of which is characterized by an uncertainty of order one part per million of the full scale reading. It should be emphasized that to measure a voltage ratio of 10^4:1--a common ratio for dividers used with x-ray units--with an uncertainty of a few percent of the value of the ratio, requires that the inductive divider be accurate to a few parts per million of full scale.

Oscillator voltages are usually less than 10 V rms, so the output from the resistor divider is of order 10^{-3} V. The voltmeter is a two-phase or vector instrument used in the differential input mode. Typically, the input impedance of each channel in these voltmeters is 10^8 Ω shunted by no more than 20 pF. To the measurement accuracy required, this input impedance is sufficiently large so that the measuring device causes an insignificant perturbation on the remainder of the circuit.

A two-phase voltmeter is useful because the quantity measured, $1/A_{11}(\omega)$, is complex, i.e., Eq. 4 can be expressed in the form

$$\frac{V_o}{V_{in}} = \frac{1}{A_{11}(\omega)} = \alpha + j\beta .$$ (6)

If the inductive divider is adjusted so that the in-phase component of the differential voltage is zero, the value of α can then be read directly from the inductive divider. The magnitude of the quadrature component
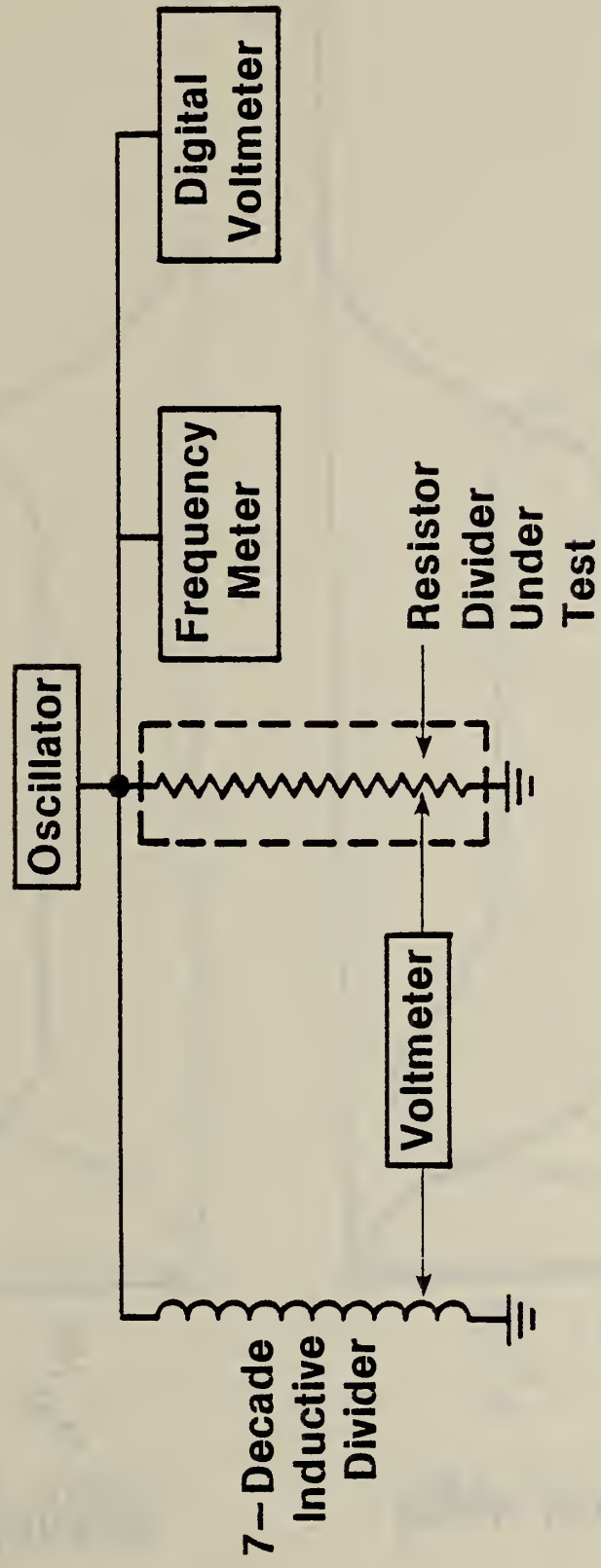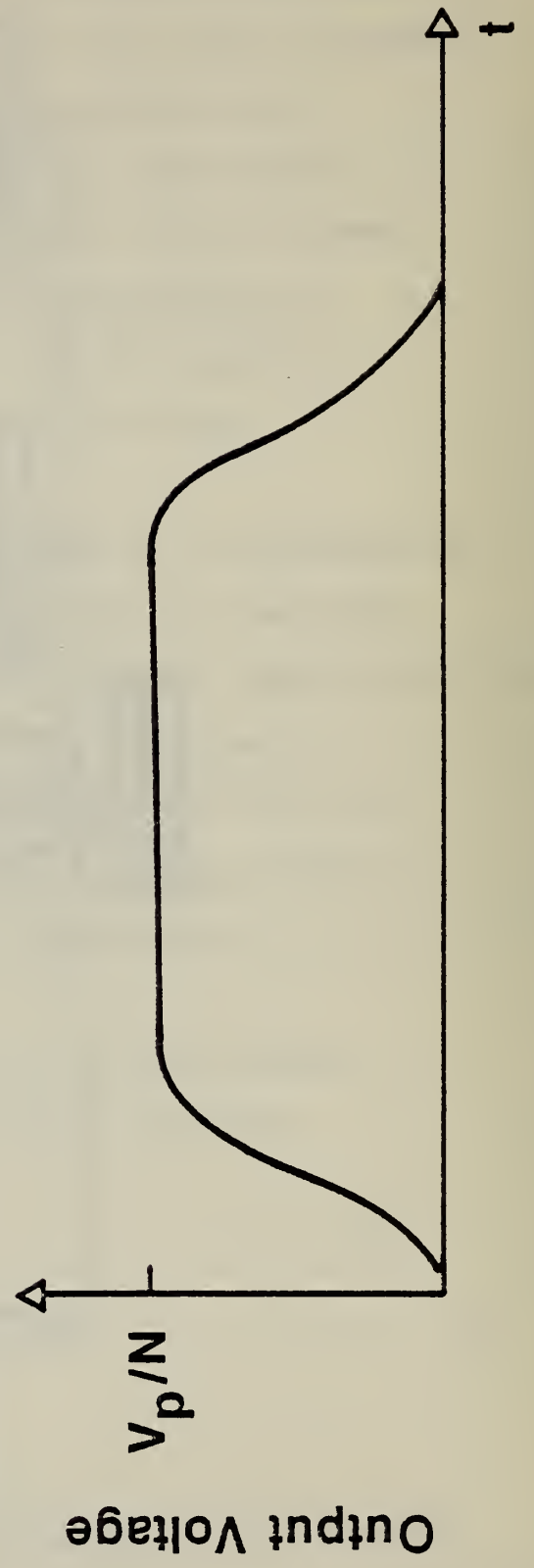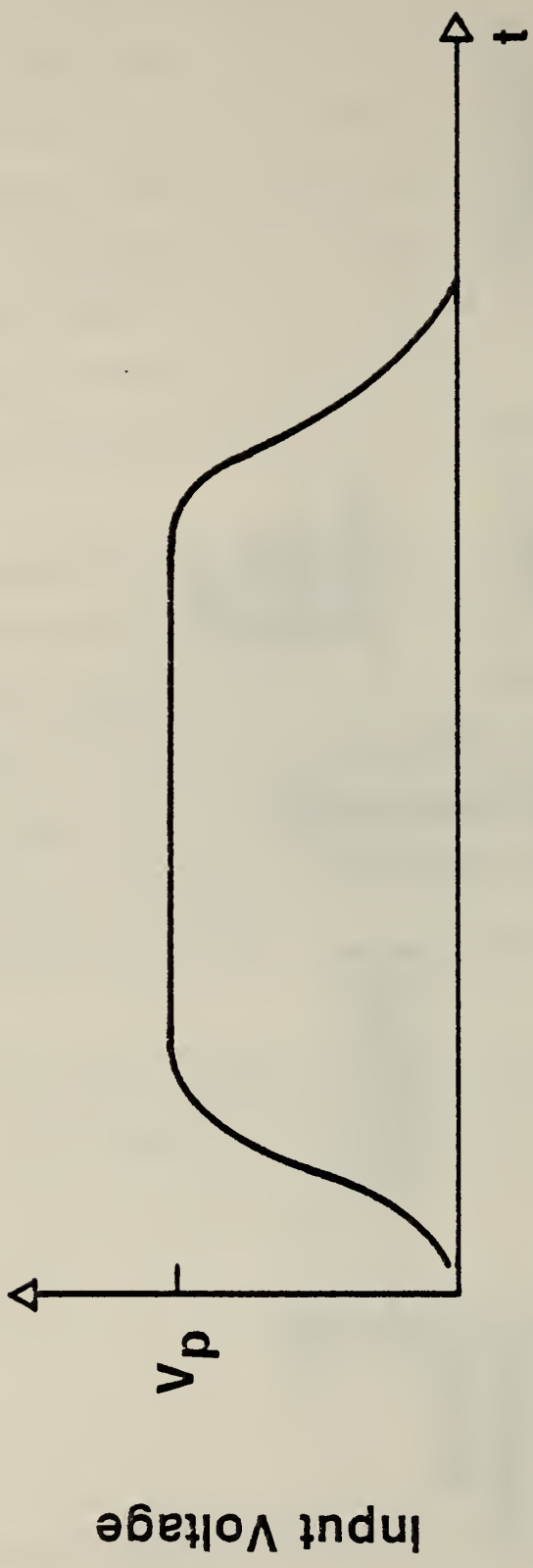
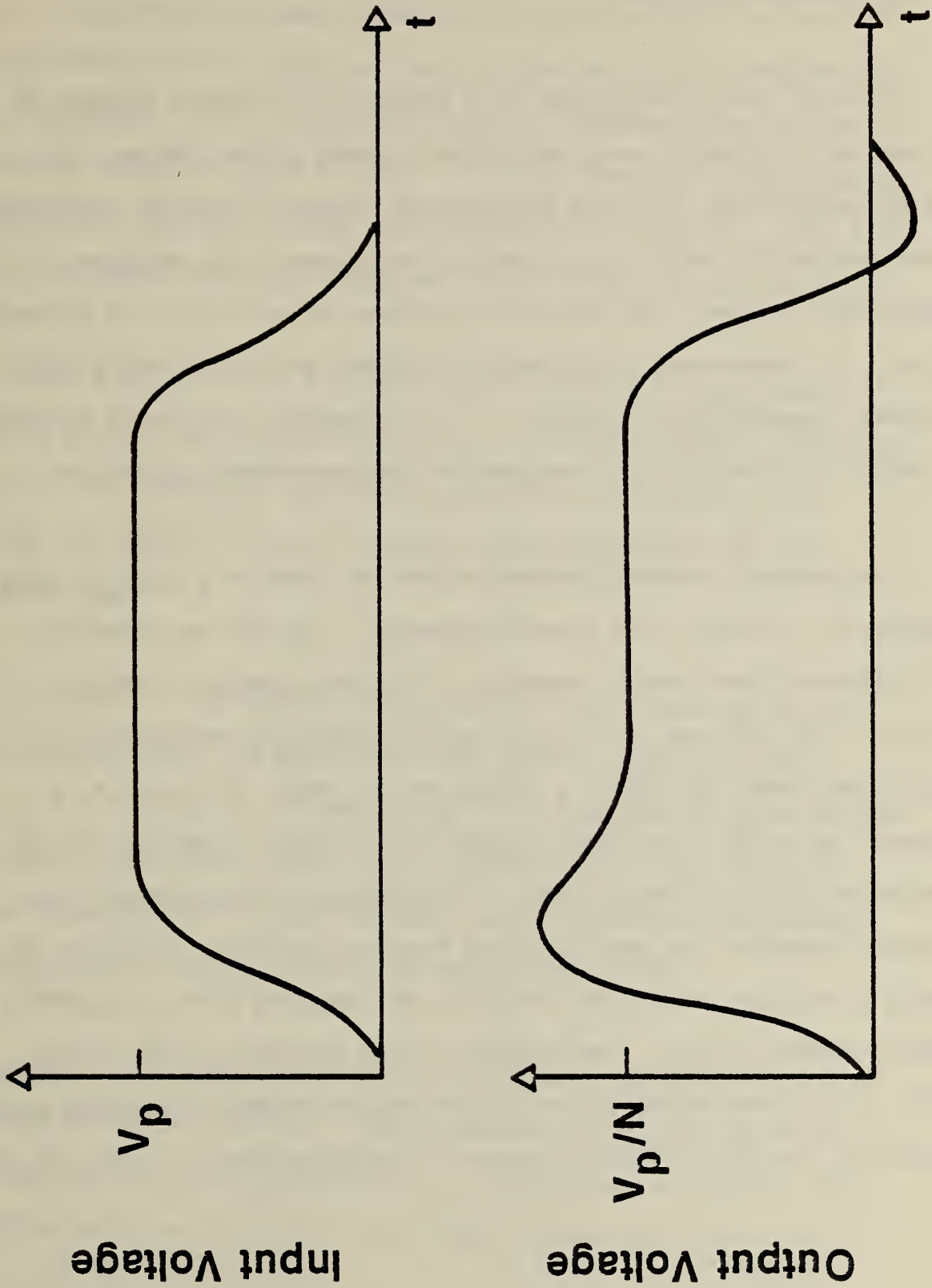FIGURE 3.2 Test circuit for determining frequency response of a divider.

FIGURE 3.4 Time response characteristics of a divider with poor high frequency response.

is read from the voltmeter.

As shown above, the voltage ratio obtained for dividers intended to
be used with diagnostic x-ray units often depends on the frequency of
the applied voltage. By using the measured frequency response, approximate
measurement errors can be calculated for any assumed input waveform. It is
anticipated, however, that few users would want to calculate, and mathematically
correct for, measurement errors because dividers with sufficiently-small
frequency dependence are available. It is, therefore, relatively convenient
to obtain a divider which is designed for the measurement application.

The measured frequency dependence data can serve as a guide to judge the
adequacy of a divider for a given measurement. This can be understood
by considering some specific examples. The first example is shown in
Fig. 3.3. In this case the voltage ratio is frequency independent and
the divider output voltage is a replica of the input. In Fig. 3.4,
however, the ratio of the input voltage to the output is smaller at high
frequencies than at direct voltage. The magnitude and duration of the
overshoot depend on the details of the frequency response. This type of
waveform can cause particular difficulty when measured with an electronic peak-
detect-and-hold circuit. The overshoot at the beginning of the pulse--
which in this case is due to the divider and not present in the high voltage
pulse--can lead to a significant error in the determination of the peak voltage.

To avoid this difficulty, some dividers are designed so that the ratio of the input voltage to the output voltage is larger at high frequencies than at low frequencies. With this design the pulse waveforms shown in Fig. 3.5 are obtained. From the model in Fig. 1 it can be seen that this situation results if the capacitance in the low voltage arm is increased. This also leads to a non-zero quadrature component of the voltage transfer function.

In both Figs. 3.4 and 3.5 it can be seen that the divider output eventually attains its expected value, i.e., it eventually has a magnitude of V_p/N. It is, therefore, possible to obtain the true value of the kV_p using this divider if care is taken to make measurements at the appropriate time.

By contrast, if the entire voltage pulse is short compared to the divider response time, the output would be similar to the case shown in Fig. 3.6. Although it is expected that this situation is rare, dividers with response times longer than a few milliseconds have been observed. This fact,coupled with the short exposure times available on multiphase x-ray units, could lead to significant measurement errors.

One final consequence of a frequency-dependent voltage ratio is summarized in Figs. 3.7 and 3.8. These examples illustrate the results if the voltage ratio at low frequencies, e.g., 50-500 Hz, is different from the divider ratio, which is the value of the voltage ratio under direct

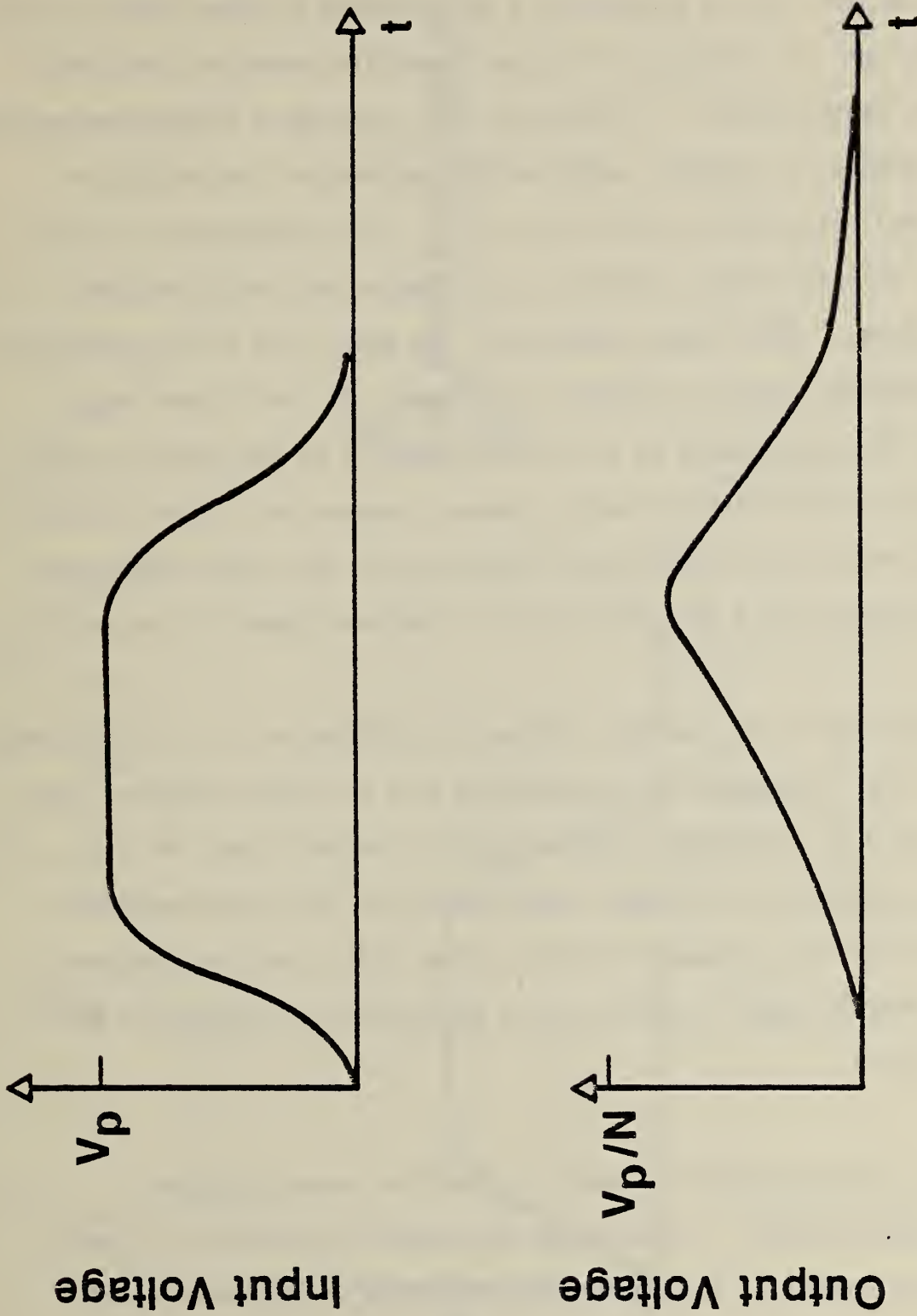Input Voltage

V_p

Output Voltage

V_p/N
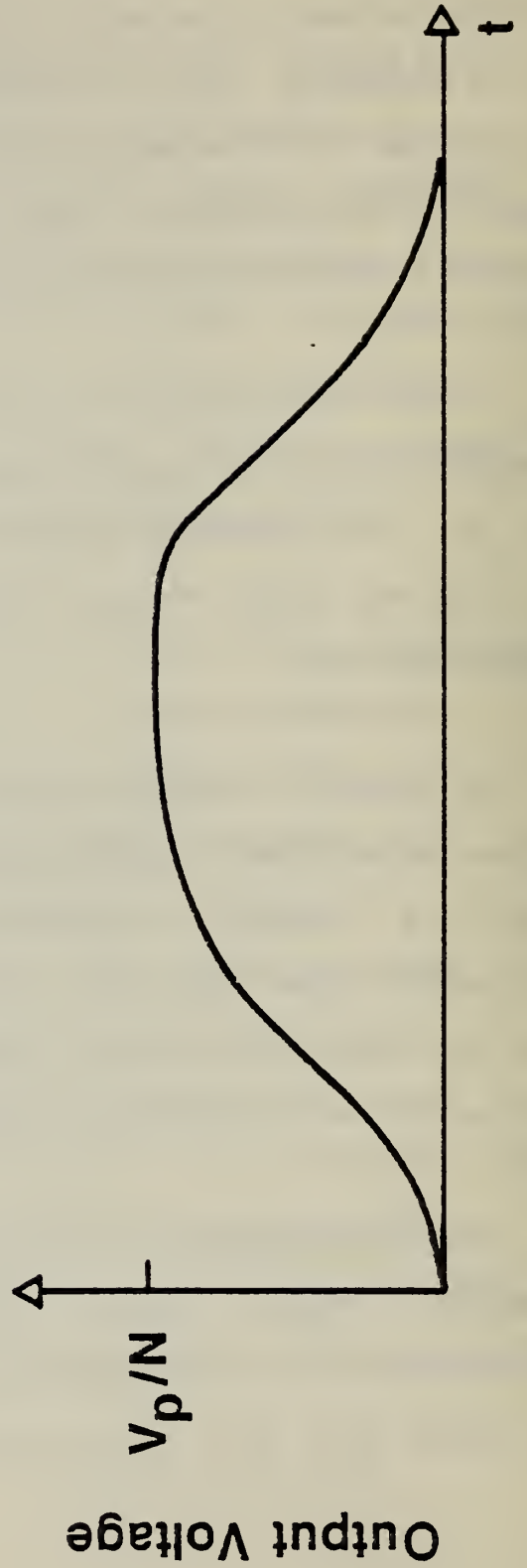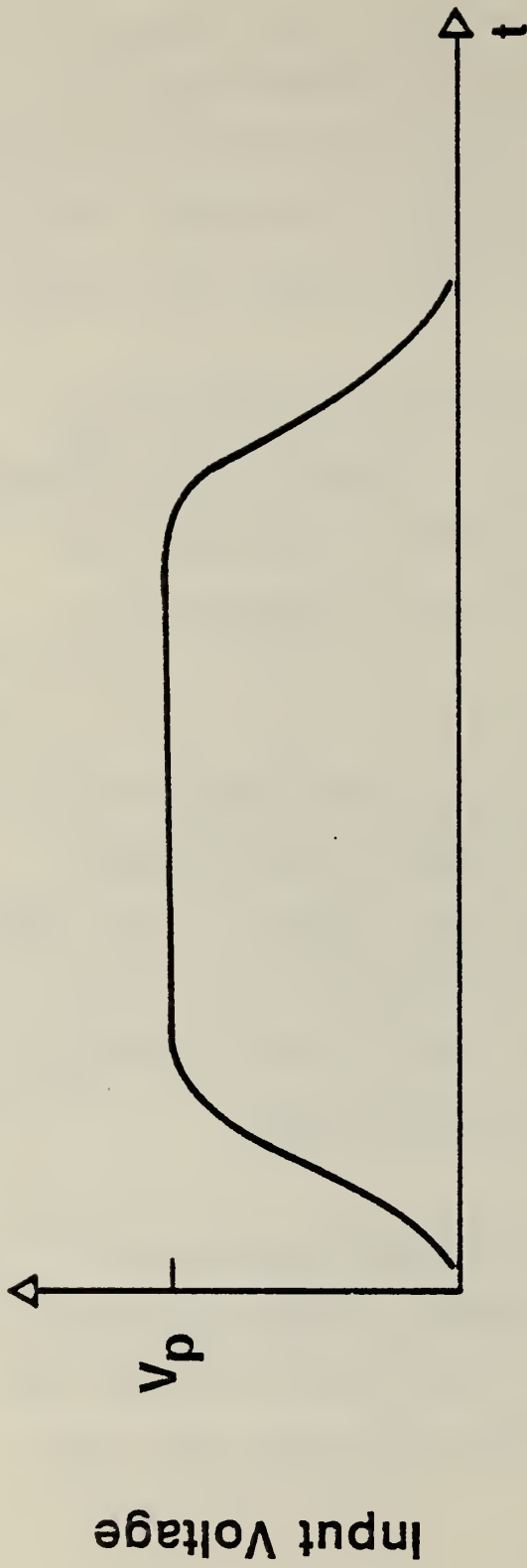
FIGURE 3.6 Time response characteristics of a divider with a response time long relative to input pulse duration.

voltage. The resulting error depends on whether the high voltage pulse
applied to the x-ray is produced by a unit powered by three phase or single
phase voltage. In the case of a three phase pulse waveform, the error
could be insignificant. To illustrate this, consider a three phase waveform which
can be modeled as a smooth, approximately rectangular, pulse with an
added, small sinusoidal ripple (Fig. 3.7). It is assumed that the pulse
duration is sufficiently long that only steady-state conditions need
be considered. Under these assumptions, the peak value of the rectangular
pulse component would be correctly reproduced. At the divider output,
however, the ripple would be a different fraction of the peak value than
it would be at the divider input. However, because the ripple is usually a small
fraction of the high voltage pulse, the error in the ripple measurement
may contribute only a very small error to the measurement of the pulse.

The situation is, however, substantially different for a single phase
unit. If it is assumed that the waveform is a full wave rectified sine
wave (Fig. 3.8), elementary Fourier analysis indicates that the low
frequency components contribute significantly to the voltage waveform.
Therefore, if it is assumed that the divider ratio, which is measured
under direct voltage, is valid in this application, a substantial error
could result.

The current through the tube is pulsed and roughly follows
the voltage waveform. A traditional measurement technique is to apply
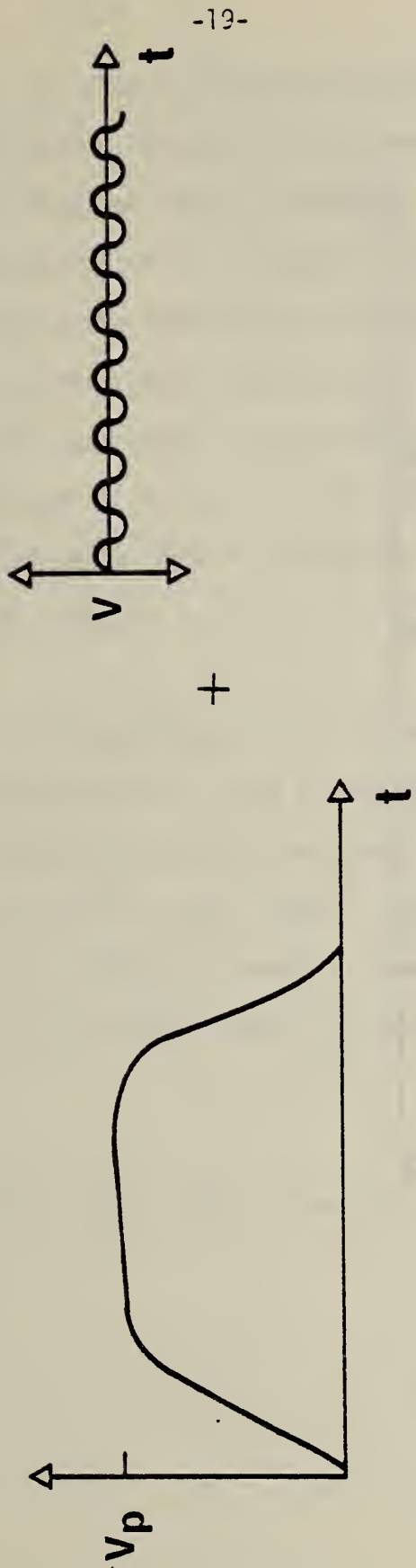the pulsed current to a resistor and measure the voltage drop across
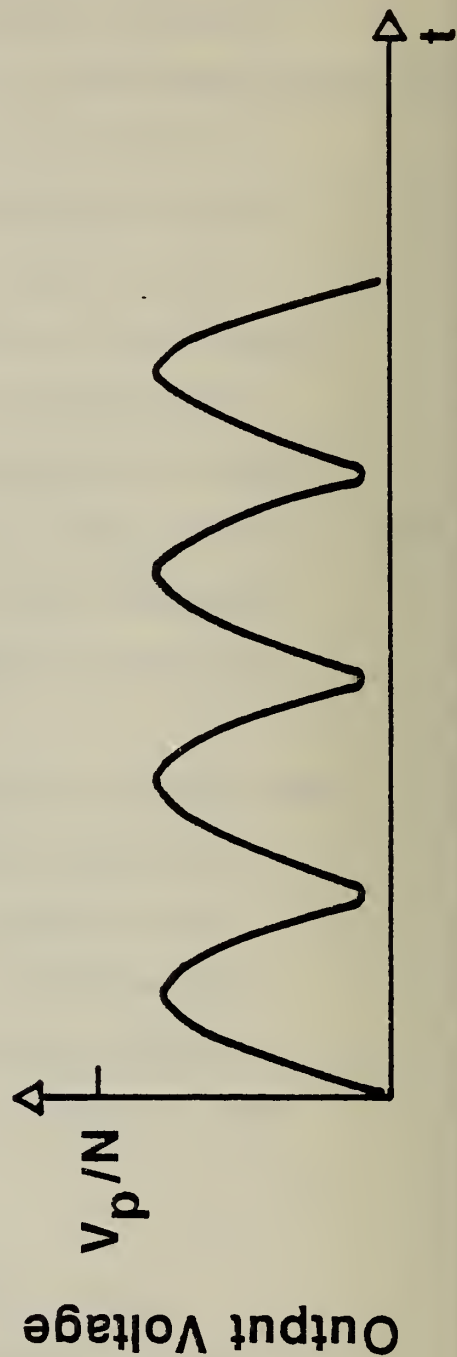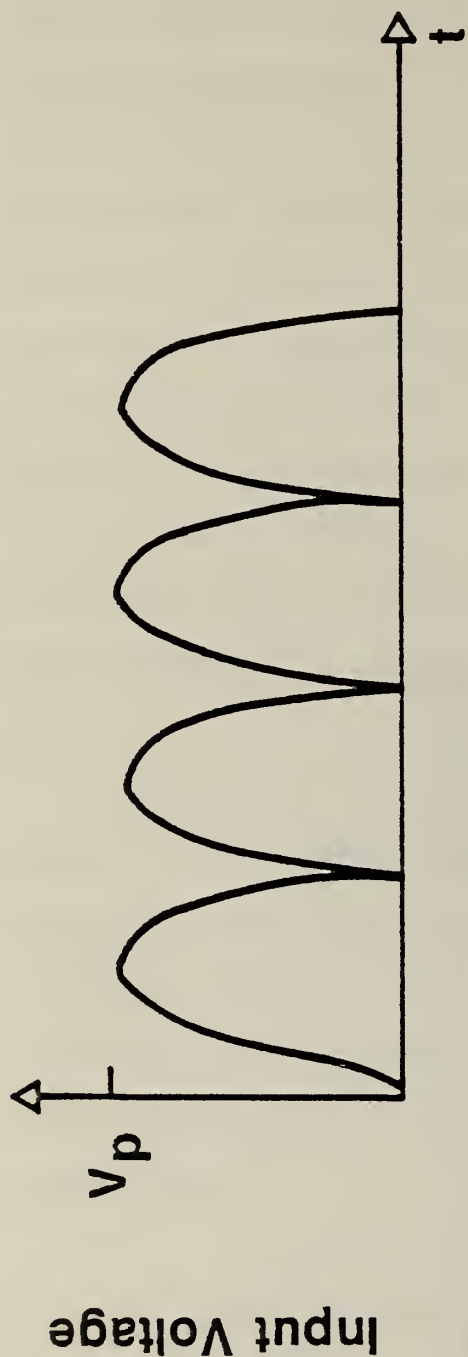
FIGURE 3.7   Representation of a multiphase waveform as an approximately rectangular pulse with small superimposed ripple.

the resistor. That technique was chosen in this application because the impedance of the current-viewing resistor is independent of frequency to the accuracy, and over the frequency range, required. The voltage across this resistor is monitored using a peak-detect-and-hold circuit so the measuring circuit displays the magnitude of the peak current. The circuit is designed to calibrate measurement systems having an input impedance of approximately 200 Ω and which do not require that the current-carrying line be grounded to the device under test. A possible modification of the X-CAL which would permit calibration of pulse transformers is suggested in Section 6.

The filament current is a steady-state, 60-Hz current with a magnitude up to 20 A. The measurement approach is to use a very accurate current transformer having a well-characterized resistive burden to provide a voltage signal which is proportional to the filament current. This voltage is then measured using a digital voltmeter. The system is designed to display the rms value of the filament current.

4. System Description

4.1 The X-CAL calibration system allows five specific calibrations to be performed. These are:

4.1.1 Direct Voltage Divider Ratio Calibration

4.1.2 Alternating Voltage Divider Ratio Calibration

4.1.3 Frequency Dependence of the Divider Ratio

4.1.4 Filament Current

4.1.5 Anode Current.

Each of these functions is discussed in more detail in the following sections.

4.2 Direct Voltage Divider Ratio Calibration

The electrical system used in this calibration is illustrated
schematically in Fig. 4.1. A direct voltage, variable from 0 to ±75 kV, is
applied to a Park divider[14] and to the device under test. The low side
of the Park divider is active as indicated in Fig. 4.1. The active low
side configuration offers a significant advantage over passive low sides
in that deleterious effects such as loading due to the indicating instrument
are virtually eliminated. In this configuration, the voltages indicated
by the calibration system and the device under test may be compared
directly if the device under test has a self-contained readout capability.
If not, the calibration unit contains a low side system which may be
operated in either a passive or active mode to provide a digital display
of the output voltage from the device under test.

4.3 Alternating Voltage Divider Ratio Calibration

The measurement technique employed in this calibration is shown in
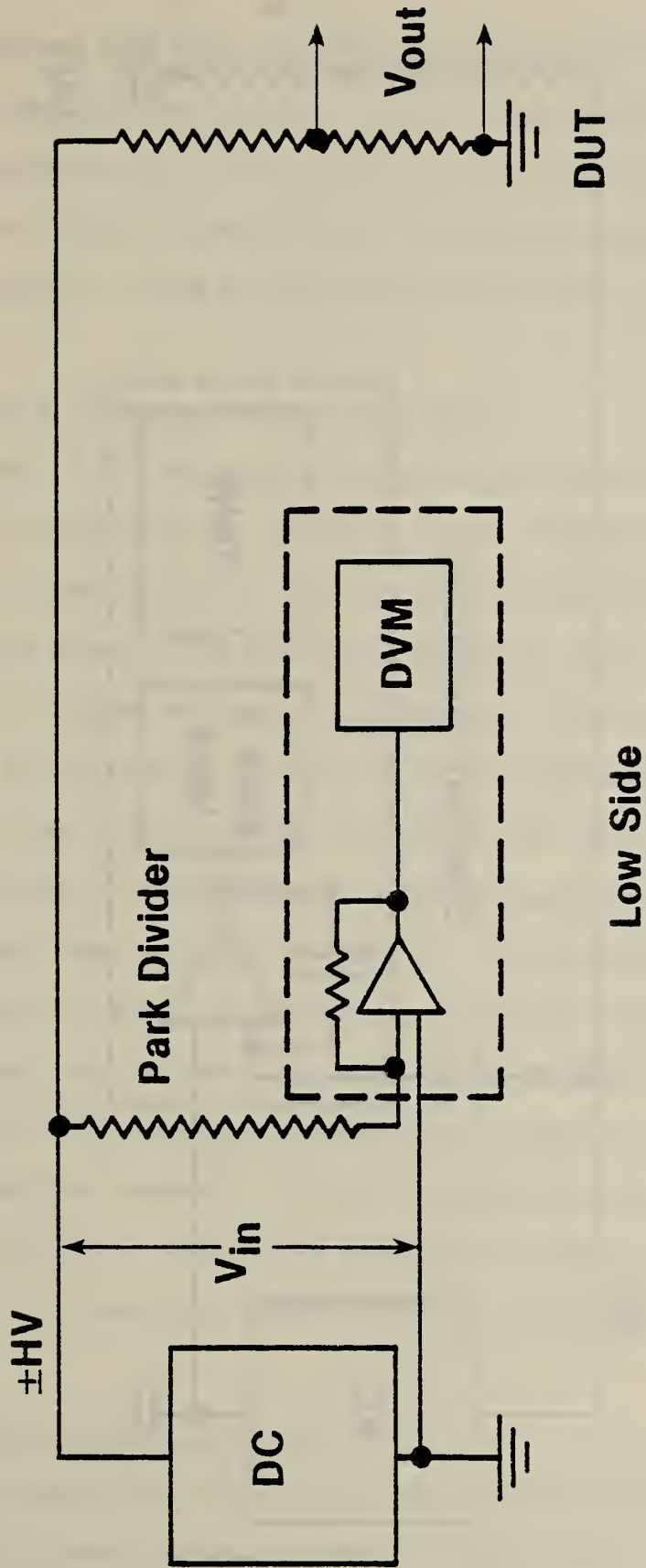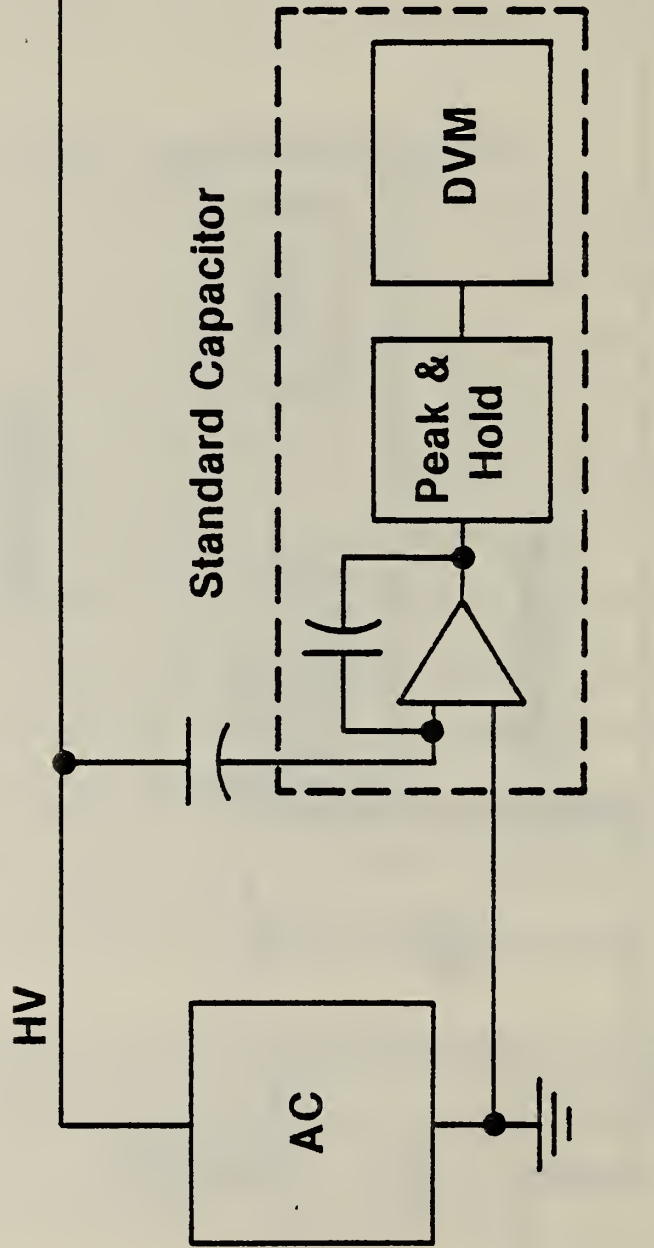Fig. 4.2. The ac power supply (provided by user) applies an alternating

FIGURE 4.1 Test circuit for determining the dc ratio of a divider under test (DUT).

voltage to a standard capacitor (provided as part of the X-CAL system) which
again incorporates an active low side. In this measurement, the low side
voltage is introduced into a peak and hold circuit, which acquires and
holds the maximum voltage impressed upon it during the measurement
period. This voltage is read and displayed by a digital voltmeter.

4.4 Frequency Response of the Divider Ratio

A measurement of the frequency response of the divider ratio over the
frequency range 50-10,000 Hz can provide a direct indication of the physical
condition of a divider and can be used to predict the response of the
divider to voltage pulses. The electrical schematic of the technique used in
this measurement is shown in Fig. 4.3. A source of alternating voltage provides
a signal to the device under test and to a ratio transformer. A well-defined
fraction of the input voltage may be selected by the ratio transformer. A
phase sensitive detector, operated as a vector voltmeter, measures the
difference between input voltages "A" and "B". If the ratio transformer
is adjusted to provide a null indication on the vector voltmeter, the reading
of the ratio transformer is equal to the in-phase component of the divider
ratio. There will also be a quadrature voltage, since the divider has both
resistive and reactive components, and this quadrature voltage is read directly
from the vector voltmeter. These readings may be combined with the input
voltage to provide a normalized divider ratio as described in Section 6.

4.5 Filament Current Calibration

The Machlett Dynalyzer[1] provides the user with the capability
of measuring the filament current of the x-ray tube in the x-ray unit
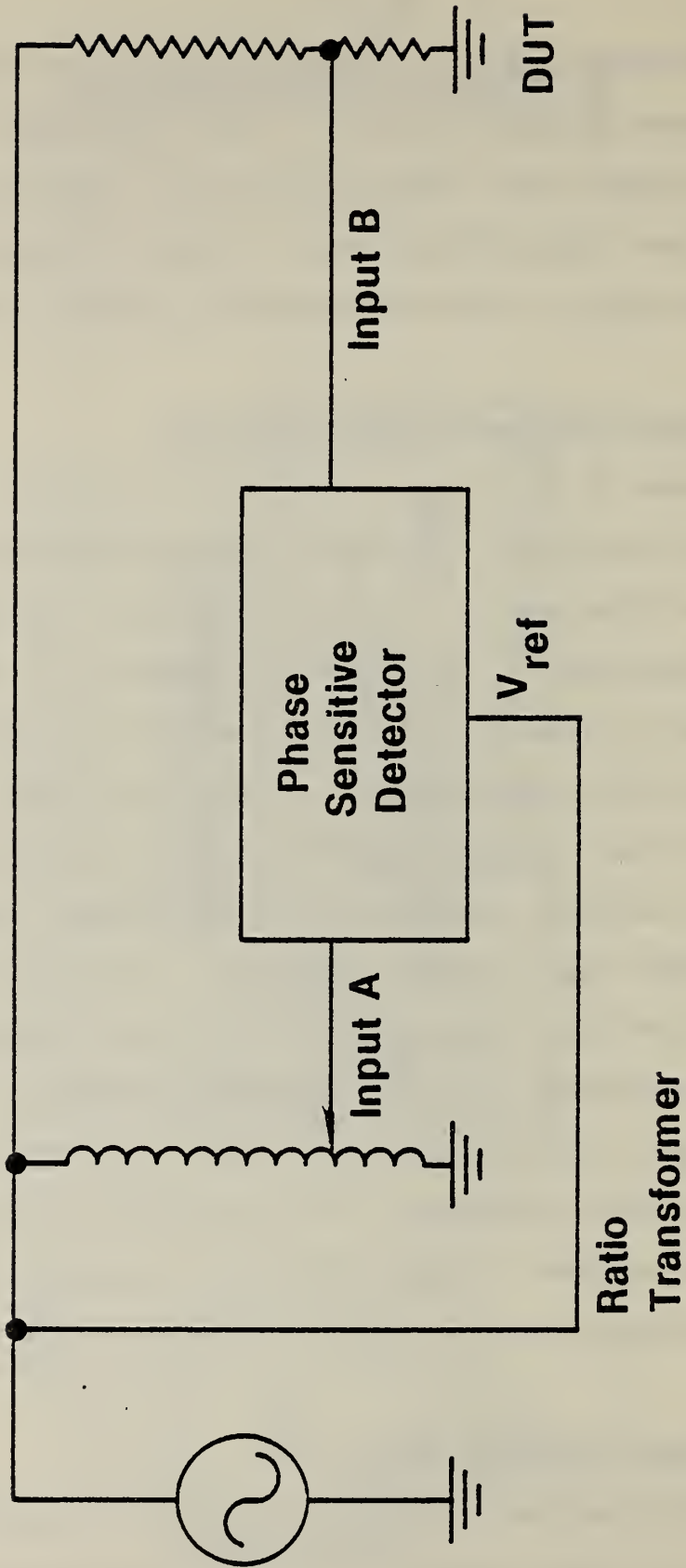
under test. The X-CAL system may be used to calibrate the filament current
measuring system as is indicated in Fig. 4.4. An alternating current, variable
between 0 and 20 amperes, passes through a current viewing resistor
(nominally 1Ω). The current value measured by the commercial system can
be compared to that determined by the precision instrument current
transformer which is a part of the X-CAL unit.

4.6 Anode Current Measurement Calibration

The X-CAL system provides a current pulse (variable up to 2 amperes)
which may be used to calibrate a Machlett Dynalyzer[1] unit as illustrated
in Fig. 4.5. The pulse generator, when triggered, drives current through the
nominal 200-ohm load of the device under test. The current waveform, which is
not intended to duplicate an actual x-ray machine current pulse, is approximately
rectangular. There is some droop to the pulse with the maximum current
occurring immediately after triggering. The maximum value of the current
is determined by amplifying the voltage drop across a current viewing resistor
(CVR) and applying this voltage to a peak and hold circuit which captures
the maximum voltage level (corresponding to maximum current). The commercial
unit measures the average value of the current pulse so a conversion factor
relating the peak current value and the average current has been determined
for the pulser in the X-CAL unit driving the nominal 200 ohm load of Machlett
Dynalyzer[1] to allow direct comparison of the two readings.

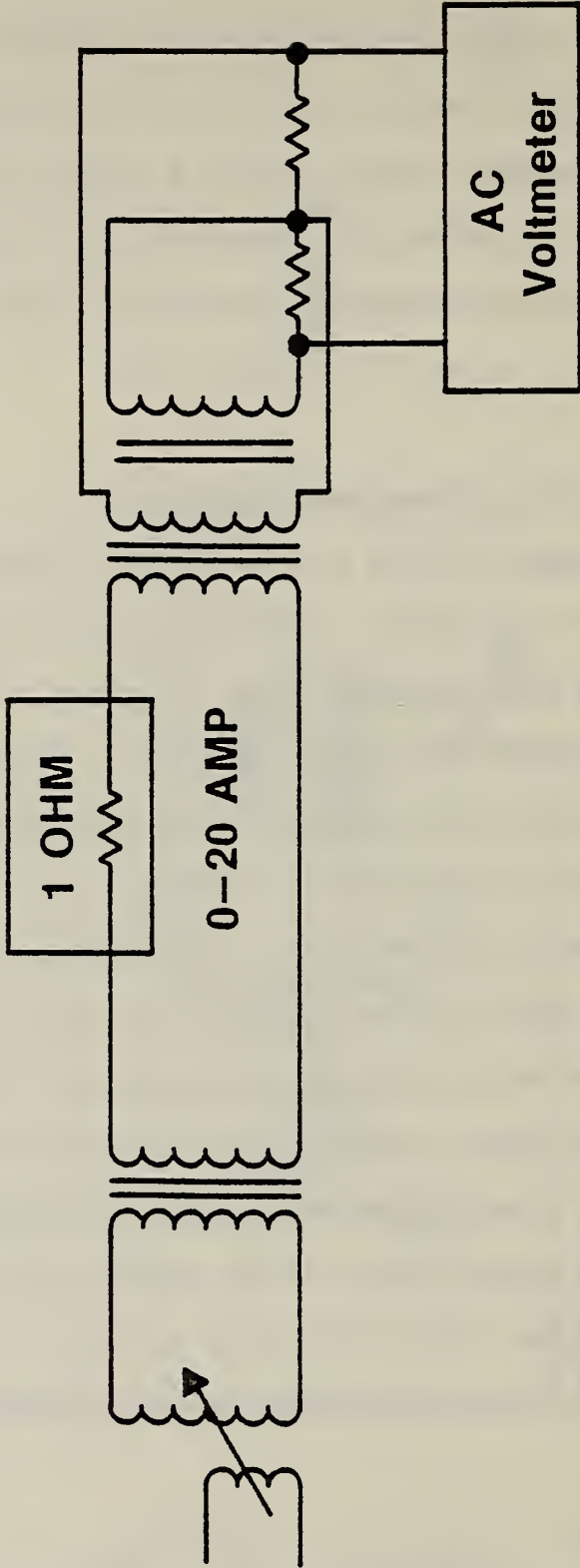### 5. Installation

The X-CAL system consists of two enclosed racks of electric instruments,
connecting cables and a standard capacitor. A necessary component of
the system is a Park resistor, which is to be provided by the user.

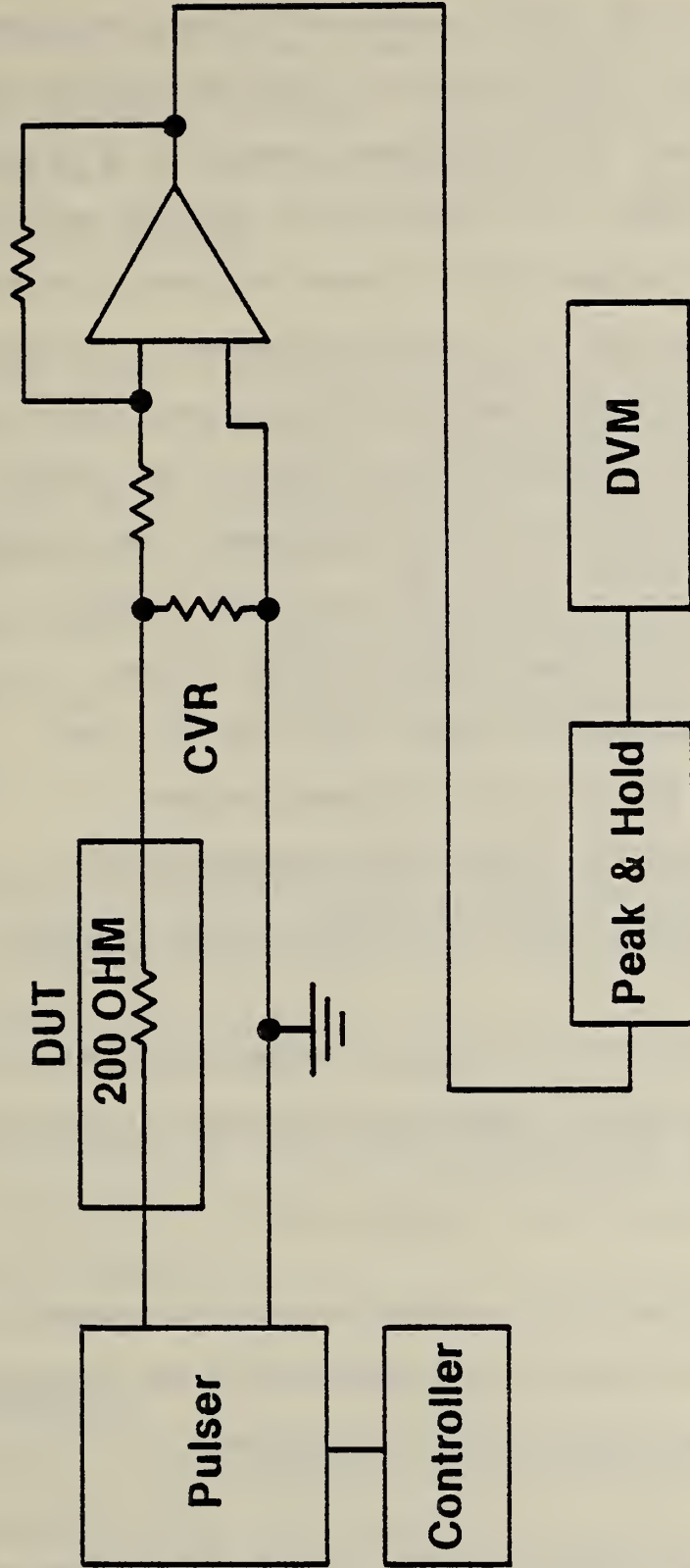AC Voltmeter

DUT

1 OHM

0-20 AMP

FIGURE 4.5 Test circuit for assessing the accuracy of the anode current measuring capability of the divider system under test.

Upon receipt of the system, uncrate all cartons and inspect the contents for damage. The high-voltage transformer assembly should be removed from its case. This transformer assembly is to be mounted in the high voltage cabinet. This installation should be such that the outlet for the high voltage cable is toward the rear of the cabinet. Be careful not to damage the x-ray connectors located on the front panels of the high voltage cabinet when installing the transformer assembly. After the transformer assembly has been placed in the cabinet, it should be filled with oil according to the manufacturer's specifications.

> CAUTION: Avoid introducing any foreign material
> into the transformer assembly during filling.
> When the assembly has been filled with oil, the
> high voltage cable may be inserted and then
> connected to the corona shield attached to the
> x-ray connector used for the high voltage dc tests.

The main electronics rack should be inspected to make sure that all cables are in place and all plugs securely inserted in their corresponding sockets.

Coaxial cables should be connected between the appropriate input and output terminals of the ratio transformer and the corresponding bulkhead feedthrough mounted on the bulkhead panel.

The high voltage cabinet should be located in a secure area in accordance with the users' safety regulations. Interconnecting cables allow approximately 7 m between the main cabinet and the high voltage cabinet.

Output cables (anode and cathode) should be connected to the corresponding input and output connectors. The HV-interlock cable and the control cable between the high voltage control unit and the transformer assembly should also be connected.

A good grounding system is necessary to insure proper system operation as well as for safety reasons. A ground strap should be run to the grounding terminal on the transformer assembly, the high voltage cabinet and between the two cabinets. In addition, the ground terminals on the high voltage control unit and the current pulser should be connected to the rack ground which is then attached to a reliable ground in the users laboratory.

The best technique for ascertaining that the system is functioning properly is to calibrate an x-ray divider unit. Detailed operating instructions are given in Section 6.

Conditioning procedures for the dc high voltage supply are given by the manufacturer and should be followed whenever the high voltage tank is drained and refilled with oil.

6. Operating Instructions

6.1 The following sections describe in detail how the measurements leading to the calibration of an x-ray divider are to be done. In each case, the user should become more adept at making measurements as he gains experience. Local operating procedures may be generated, providing the integrity of the measurements are not compromised. Local safety rules regarding high voltages should be followed. The high voltage supply

provided with the system generates lethal voltage and current levels and
should be treated accordingly. Cables connecting x-ray dividers to the
high voltage cabinet may retain considerable charge after high voltage
tests are completed and the judicious use of a grounding stick is highly
recommended.

6.2 Dividers with Display Units

The instructions in the following sections assume the divider under
test is one which has a display unit as an integral part of the system.
For dividers not meeting this requirement, refer to Section 6.8.

6.3 High Voltage (DC) Divider Ratio

The test configuration is shown in Fig. 6.1. The high voltage
cable is connected to the device under test (either anode or cathode)
and then passed through the divider unit to a Park divider. It should be
noted that x-ray divider units are designed to be inserted between the x-ray
machine power supply (transformer) and the x-ray tube itself. The high voltage
divider assembly (shown as a resistor divider in Figs. 4.1-4.3) is connected
internally to the high voltage cable. All high voltage connections are made
by using standard x-ray high voltage cables and connectors which results in
a configuration with no exposed high voltage. In Fig. 6.1 and following
figures in this section, connections involving high voltage cables are shown
symbolically as originating from the top of the divider unit under test. The
measurement mode should be set to DCHV and the output from the Park resistor connected
to PARK on the input bulkhead panel. With the system turned on and allowed to
stabilize for 15-20 minutes, a reading of zero (±1-2 mV) should be observed on
the digital readout on "x-ray". The high voltage polarity appropriate for the
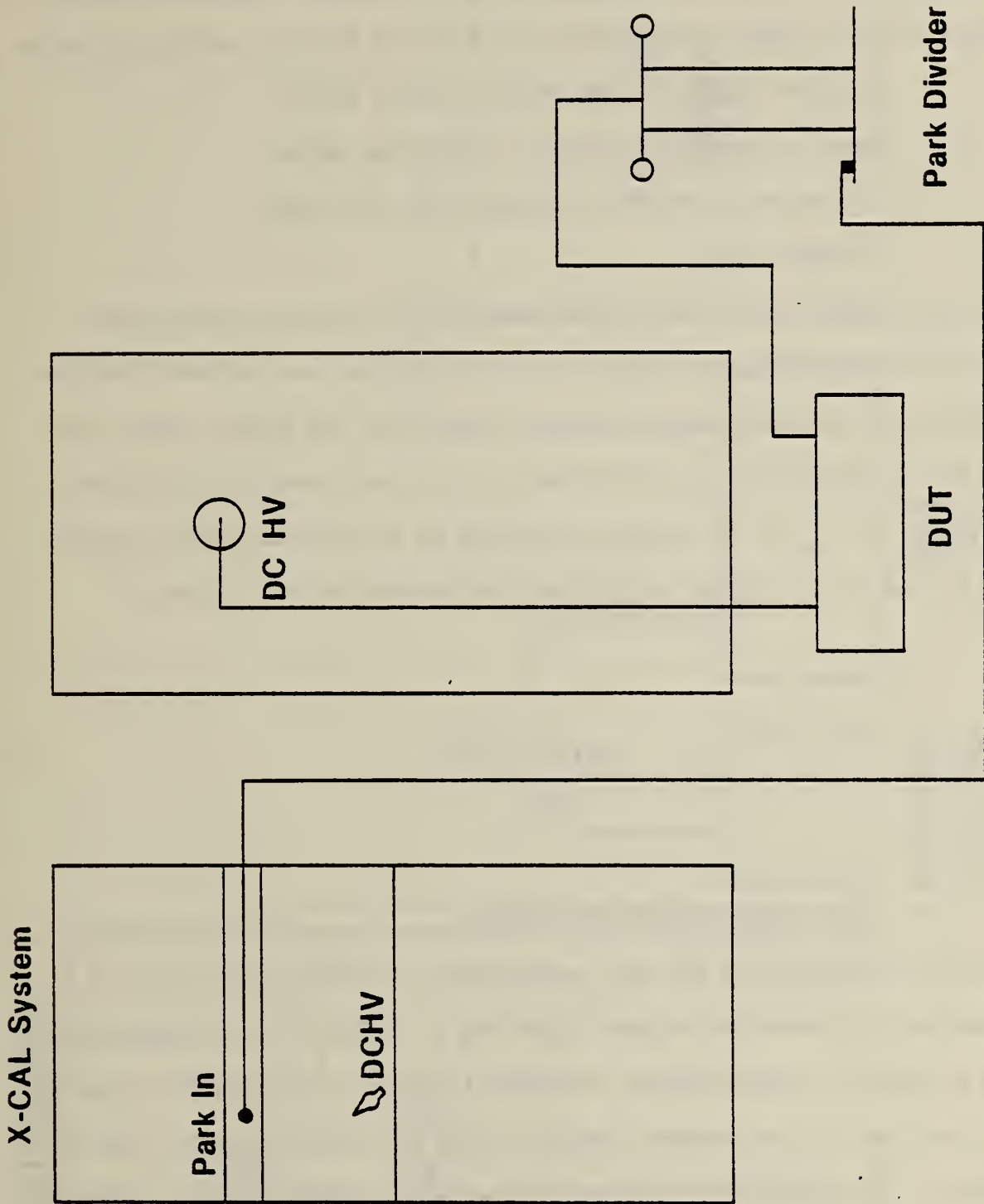
FIGURE 6.1 X-CAL system configuration for dc ratio measurements.

test should be selected. Measurements over the desired range may now be made.
Reconnection of the high voltage leads and a change in high voltage supply
polarity is all that is required to go from one divider section to another.

CAUTION: OBSERVE HIGH VOLTAGE SAFETY RULES!

Refer to the manufacturers instruction manual

for proper operating procedures for the high

voltage supply.

A direct comparison of the voltage recorded by the device under test
and the input voltage as given by the Park divider may be made from the
readings of the individual displays of the X-CAL and device under test.
The X-CAL system has been calibrated to be direct reading with a Park
divider. If V_{in} is the voltage indicated by the standard Park divider
and V_x the x-ray divider indication, the divider ratio is given by

$$Ratio = \frac{V_{in}}{V_x} \quad . \tag{7}$$

6.4 High Voltage (AC) Divider Ratio

The test configuration for this measurement is shown in Fig. 6.2.
A source of alternating voltage (supplied by the user) is connected to
the divider in a pass-through configuration and to the standard capacitor.
The low side of the standard capacitor goes to the CAP input of the X-CAL
system. The measurement function on the X-CAL system is ACHV. Pressing
the reset button on the main chassis reduces the X-CAL readout to zero
and enables the peak and hold circuit. When the ac supply is activated,
either in a continuous or pulsed mode, the peak and hold circuit will
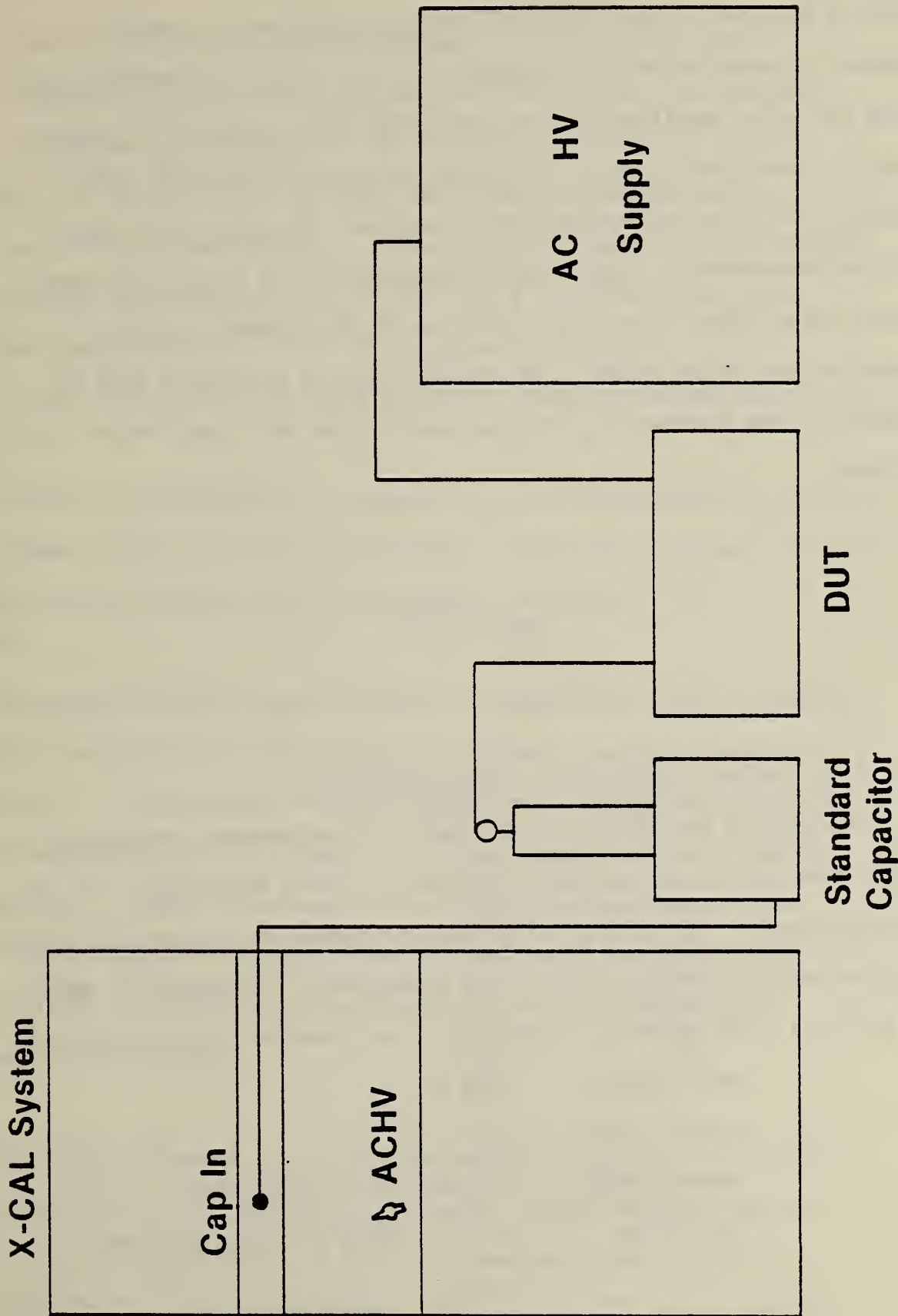
FIGURE 6.2 X-CAL system configuration for ac ratio measurements.

acquire the peak voltage which will then be displayed on the DPM.
Because of droop in the peak and hold circuit, it will be necessary to
read the meter immediately after energizing the ac supply if a pulsed
mode of operation is used. The system has been calibrated to read
directly with the standard capacitor supplied. As with the dc high
voltage measurement, proper safety procedures should be followed when
using the ac supply. Make sure the case of the standard capacitor is
connected to system ground. The divider ratio is calculated from the
reading of the standard V_{in} and the reading from the x-ray divider V_x as
follows

$$\text{Ratio} = \frac{V_{in}}{V_x} \quad . \tag{8}$$

6.5 Frequency Dependence of the Divider Ratio

The purpose for making a measurement of the frequency response of
the divider has been discussed in Section 3. These measurements are the
most involved of the various calibration procedures but become straightforward
with increasing user experience. The experimental arrangement is shown
in Fig. 6.3. The switches on the control unit should be set as follows:

        test function   - FREQ RES
        signal source   - INT
        anode/cathode   - Divider section under test
        ratio tran   - HI or LO (both positions will be
                           used).

A coaxial cable may be connected between the front panel "ref" coaxial connector on the vector voltmeter and the input of the frequency counter if the exact frequencies of the internal oscillator are to be recorded. The function generator provides a continuously variable signal and if this signal source is to be used, the signal source selector on the control unit should be set to "EXT" and a cable connected from the signal generator to the "EXT" input on the feedthru panel. The output level of the signal generator should be adjusted to approximately 5 V rms.

A digital voltmeter with ac response flat to 10 kHz should be connected to the chosen input of the ratio transformer. The 0.35 f section is the "HI" frequency section and 2.5 f the "LO" frequency section.

The operation of the vector voltmeter is summarized in this section. This device measures the voltage difference between two input signals "A" and "B". If the divider and ratio transformers were purely resistive, then all voltages and currents would be in phase and a simple voltmeter would suffice. Indeed, there would be no frequency dependence of the ratio. This, however, is not the case and because of the stray capacitance in the divider, there will be some relative phase shift between the voltages in the circuits.

The vector voltmeter is initially adjusted so that one of the input signals, say "A", is in phase with a reference signal derived from the signal source. When operated in the difference mode, the difference of the two inputs "A" - "B" is displayed. Since "A" and "B" are in general not in phase, their difference is determined in terms of two components. One is in phase with "A", and the other in quadrature.
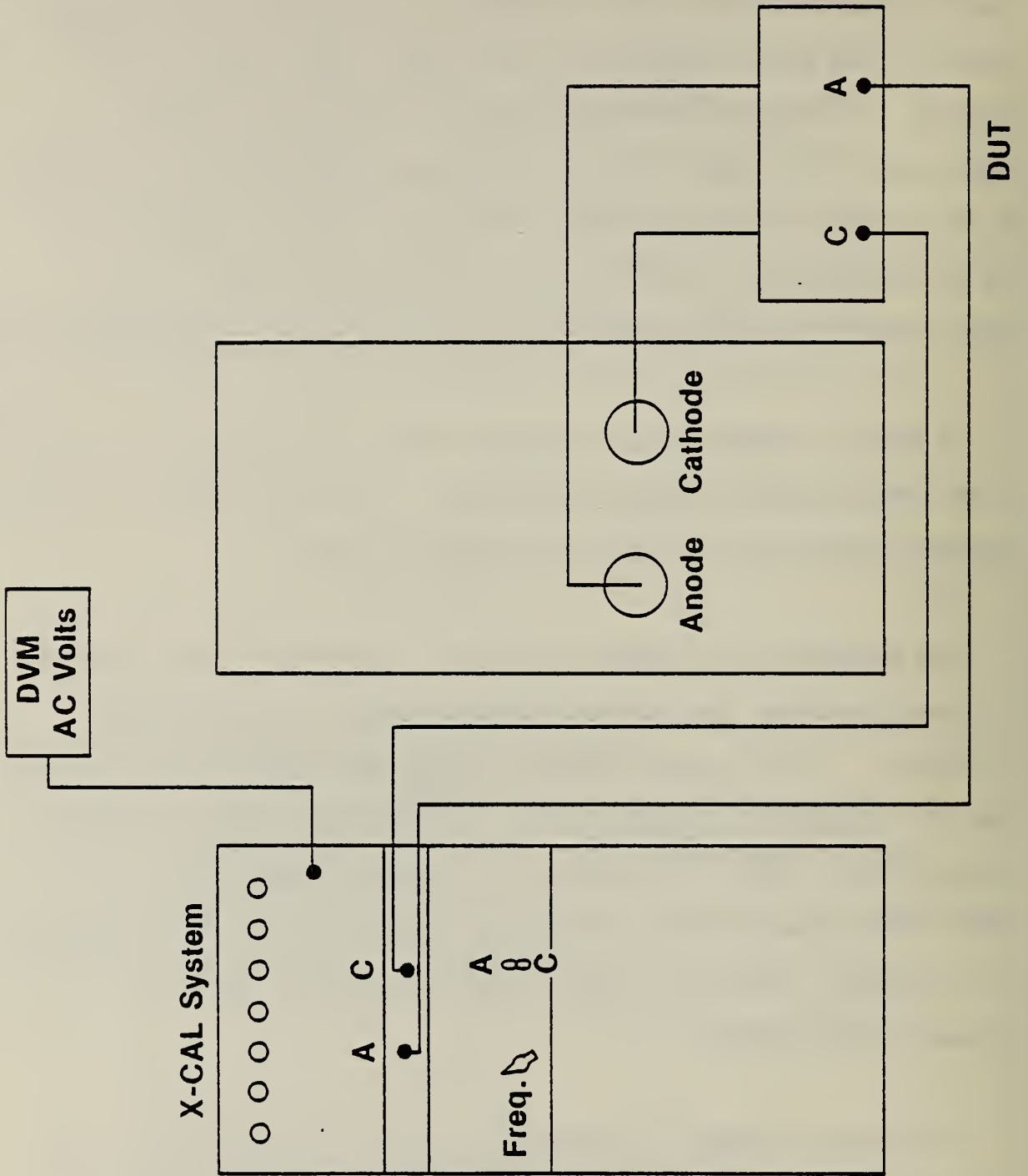
After the initial adjustment of phase, the ratio transformer is
varied until the in phase component of "A" - "B" is zero. At this
point, the measurement of the ratio for a given frequency is complete.
The quantity α defined in Section 3 is the reading of the ratio transformer.
The quantity β also defined in Section 3 is just the ratio of the quadrature
voltage V_{quad} to the input voltage determined by the DVM, V_{in}:

$$\beta = \frac{V_{quad}}{V_{in}} \ . \tag{9}$$

It should be noted that there are corrections to be made to the α and β values
for 5- and 10-kHz signals. These corrections are for the ratio transformer
and are of the order of 3% for the 10-kHz ratios. The additive corrections
$d\alpha$ and $d\beta$ which are taken from the data sheet supplied for the ratio transform
should be applied to the uncorrected values α and β obtained according to the
procedure described above. The divider ratio may then be simply calculated as

$$\text{Ratio} = \frac{1}{\sqrt{\alpha^2 + \beta^2}} = \frac{V_{in}}{V_{out}} \ . \tag{10}$$

The initial adjustment of the vector voltmeter is done in the
following way. The initial control positions on the vector voltmeter
are:

SIGNAL

Input Mode	-	Flat
	-	Float
	-	A
Sensitivity	-	100 mV
High Pass	-	Switches out
Low Pass	-	Switches out

Reference

Phase	-	0 deg.
Mode	-	f
		ext

In Phase

Zero Offset	-	0.0
Time Constant	-	0.1 Hz
Output Expand	-	x1
Prefilter	-	0.15 s

Quadrature

Zero Offset	-	0
Time Constant	-	0.1 Hz
Output Expand	-	x1
Prefilter	-	0.1 s
Outputs	-	in - phase
		Quad

The ratio transformer should be set to 0.0001 (for a 10^4 to 1 divider).
At this point both the in phase and quadrature meters should deflect. The phase
control should be adjusted to make the quadrature reading zero. The
"full scale sensitivity" and the "output expand" switches for the quadrature
component can be changed to give an extremely sensitive indication of
proper adjustment.   For the 50-Hz measurement, some "beating" between
the 50-Hz signal and the ac line frequency (60 Hz) may be present as
evidenced by an oscillation of both the in-phase and the quadrature
meters. The user should adjust the instrument so that the indicator
excursions are centered on zero.

The A, A-B switch should now be placed in the A-B position.
Again, both in-phase and quadrature indicators should deflect. Now, the
ratio transformer, should be adjusted to make the in-phase reading zero.
This can be done very precisely by increasing meter sensitivity during
the nulling adjustments. When this process is complete, the ratio
transformer setting and the quadrature voltage should be recorded. Now,
the frequency may be changed, the initial adjustments made and the
measurement process repeated.

A complete set of measurements should be done using both the 0.35 f
and 2.5 f sections of the ratio transformer. The mid-frequency measurements
for both sections should be the same. The 50-Hz value should be taken
from the 2.5 f data and all others from the 0.35 f data. A useful presentation
of the results of the frequency response measurement may be obtained by
normalizing the frequency dependent ratio to the dc ratio measured at low
voltages ($\sim$ 500 V).

6.6 Filament Current

The Machlett Dynalyzer[1] indicates the filament current flowing to the x-ray tube by measuring the voltage across a 1-ohm current viewing resistor. When the X-CAL system is configured as indicated in Fig. 6.4, this current reading may be compared to that obtained in the X-CAL system from a precision current transformer. The current may be adjusted up to 20 amperes and readings compared directly. In this measurement, the function switch should be in the "fil I" position.

> CAUTION: Do not enable the anode current pulser
> when the system is configured for cathode testing.
> Damage to the DUT could result if the pulser
> used for anode current testing is discharged
> through the filament current viewing resistor.

6.7 Anode Current

The anode current in an x-ray tube is normally pulsed and the X-CAL system contains a dc pulser to provide a rectangular pulse which provides peak currents from 0.05 amp to 2 amp. The function switch should be in the "anode I" position and the system connected as shown in Fig. 6.5.

> CAUTION: Do not enable the anode current
> pulser when the system is configured
> for cathode testing. Damage to the DUT
> could result if the pulser used for
> anode current testing is discharged through
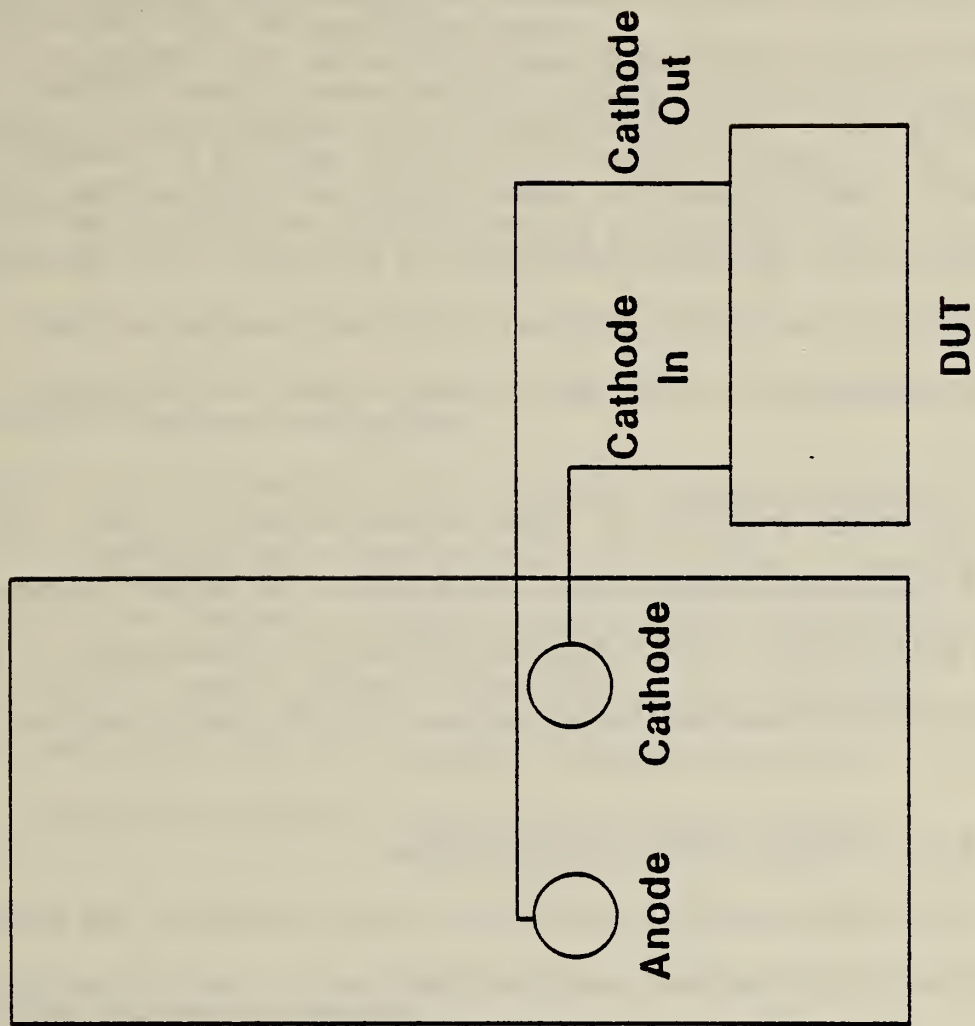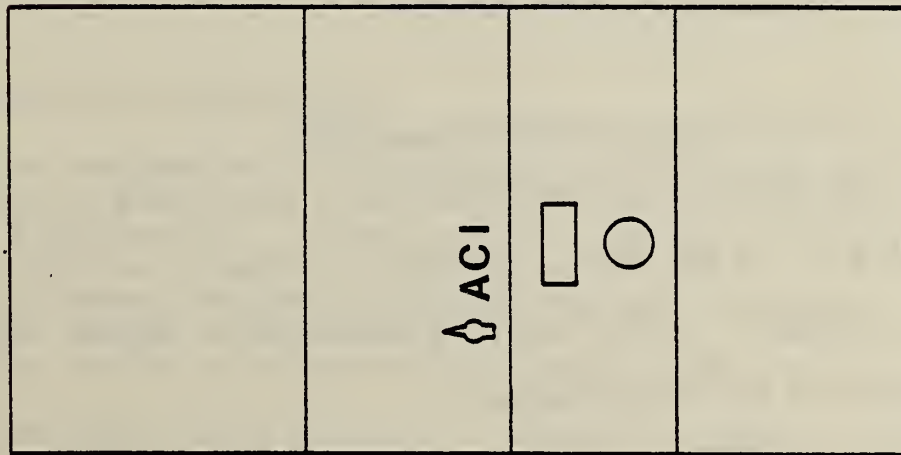> the filament current viewing resistor.

FIGURE 6.4   X-CAL system configuration for filament current calibration measurement.

The current pulser is manually triggered with the duty cycle being controlled such that average power dissipation in a 200 ohm load does not exceed 10 watts. The trigger switch on the pulser unit is lighted when the system is ready for pulsing. When the system is pulsed, the indicator in the X-CAL unit will show the peak current in the pulse. For the Dynalyzer[1] system (divider unit and digital display) which reads average current, a conversion factor between peak current and average current into 200 ohms is given in Table 6.1

The delays involved for higher current pulses are long. For example, with a 2 amp peak current pulse, the minimum time between pulses is 80 s for a pulse width of 1 s. Pressing the trigger button when it is not lighted cannot cause additional pulses. The DUT should be reset between pulses.

6.8 Dividers without Display Units

For dividers with no display units only certain of the procedures described in the sections above are applicable. The following sections indicate the proper procedure for these devices.

The X-CAL system may be used as a comparison system for other dividers and current measurement systems.

6.8.1 Direct Voltage Divider Measurements

The calibration system and divider under test should be configured as in Fig. 6.1. If the DUT has no internal readout, a suitable indicator should be provided. In this case, the comparison is between the standard and the DUT plus the chosen readout.

6.8.2 Alternating High Voltage Measurements

To compare the DUT under alternating high voltage with the calibration system, the arrangement is as shown in Fig. 6.2. Here the output of the DUT is compared directly with the standard reading provided by the X-CAL system.

6.8.3 Frequency Response Measurements

The procedure to be followed in determining the frequency response of the DUT is just that detailed in Section 6.10 - 6.15. What is measured in this procedure is the frequency response of the divider in combination with the cable nominally used to connect the divider to its associated readout system. Because of this, the frequency response measurement should be done by using this cable to connect the DUT to the X-CAL system.

6.8.4 Filament Current Measurements

The variable supply used as a current source for the filament current calibrator is designed to drive a 1-ohm load. Other loads may be used with the proviso that the output current be limited to 20 amperes or less.

6.8.5 Anode Current Measurements

The dc pulser incorporated in the anode-current calibration unit is to be used with a 200-ohm load. If this unit is to be used to evaluate the performance of current measuring devices having input impedances less than 200 ohms, series resistance should be added to the circuit to make the effective load at least 200 ohms. It should be remembered that

the calibration system indicates peak current in the external load. The

conversion between the peak current indicated by the calibration system

and the average current determined by the DUT listed in Table 6.1 are

for units with nominal 200 ohm loads only. Anode current

measuring systems which indicate peak current may be compared directly

with the calibration system. The anode current pulser unit cannot be

used with systems which require that one side of the current path be

connected to ground at the unit under test.

7. Calibration Information

Calibration procedures employed in establishing the stated accuracies

for the X-CAL system are summarized in the following sections.

The direct high voltage measurement uses as a standard a user-

provided Park resistor. A calibration of the active low side was made by

using NBS standards and a NBS Park divider. Divider ratios may normally

be determined to ±0.1% levels of uncertainty, so the stated uncertainty of

the calibration system of 1.0% is conservative.

The alternating high voltage measurements were calibrated by direct

comparison of the X-CAL system and NBS standards. Both steady state
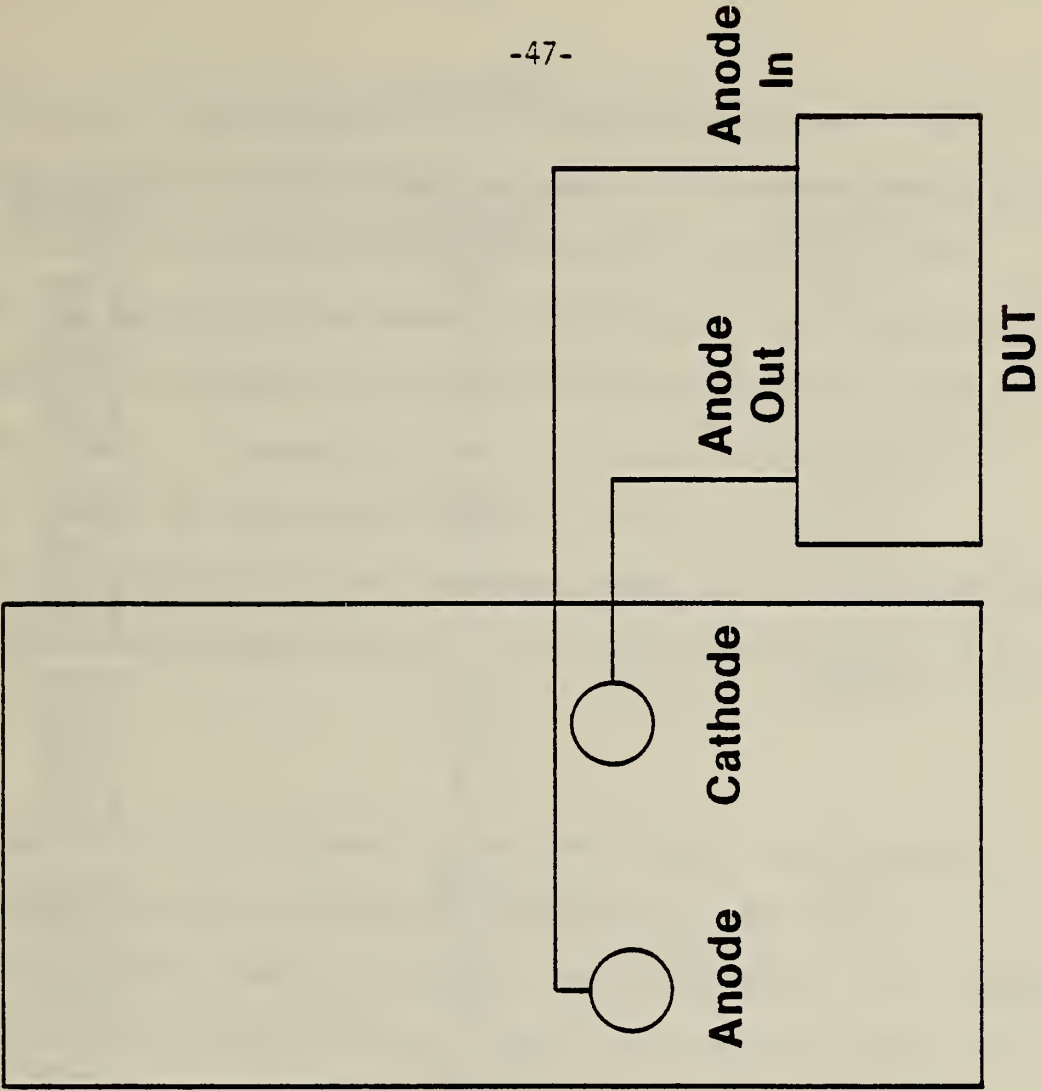
and pulsed voltage levels were utilized.
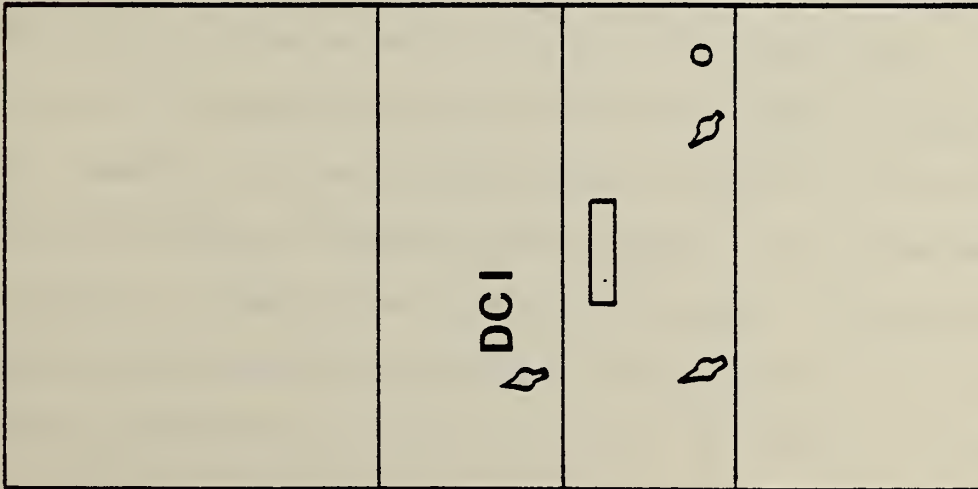
FIGURE 6.5 X-CAL system configuration for anode current calibration measurement.

Table 6.1

Peak Current (amperes)	Pulse Width seconds	$\dfrac{I \text{ average}}{I \text{ peak}}$
0.060	0.01	0.985
	0.05	0.985
	0.1	0.980
	0.5	0.965
	1.0	0.960
0.116	0.01	0.975
	0.05	0.975
	0.1	0.975
	0.5	0.970
	1.0	0.969
0.602	0.01	0.980
	0.05	0.960
	0.1	0.940
	0.5	0.915
	1.0	0.910
1.20	0.01	0.960
	0.05	0.942
	0.1	0.910
	0.5	0.880
	1.0	0.876
1.83	0.01	0.967
	0.05	0.895
	0.1	0.866
	0.5	0.875
	1.0	0.819

Accuracies of measurements of the frequency dependence of the divider ratio are determined primarily by the ratio transformer accuracy. Vendors of these units maintain standards directly traceable to NBS standards. In addition to the vendor's certificate of accuracy, specific measurements of corrections to the divider ratio were made for 5-kHz and 10-kHz signals. A summary of these corrections is provided in Section 6. Since the measurement technique involves a nulling procedure, the actual uncertainty in a measurement and the reproducibility of such measurements depends largely on the laboratory techniques of the user.

The accuracy of the filament current measurements was determined using a precision current transformer constructed by NBS personnel and precision current viewing resistors. Proper operation of the filament current module was verified by direct comparison of module readings with a direct reading 0.1% ac ammeter.

The anode current measurement requires a comparison between the peak current as indicated by the calibration system and the average current over the pulse duration when discharged into a known load, in this case 200 ohm. The calibration procedure involved two separate measurements. The voltage drop caused by a current flowing through a precision non-inductive resistor was amplified and sampled by a peak and hold detector. This measurement yields a value for the peak current in the current pulse. The accuracy of this peak reading was determined by observing the voltage across the current viewing resistor with a calibrated fast digitizing scope. By numerically calculating the

average current of the current pulse for different peak currents and
pulse widths a direct relation between peak current and average current
was determined. Table 6.1 summarizes the results of this calibration
procedure.

8. Maintenance and Calibration

There is no routine maintenance required for the X-CAL system.
Because of the developmental nature of the system, no explicit procedures
for troubleshooting system failures are available. Loss of a particular
test function would suggest investigation of the active circuitry involved
using conventional voltage checks and signal tracing.

Since the X-CAL system is designed to be used to calibrate x-ray
dividers in a comparator mode at the 1% accuracy level, a properly
equipped standards lab may routinely check the accuracy of certain units
of the system.

The DCHV test uses as a standard for comparison a Park resistor and an
active low side with a digital display. By using a second Park divider
and associated readout, the X-CAL system may be adjusted to be direct
reading. This adjustment is made by means of TRIM I, located on the
low side board in the system control module. This board contains three
separate active low sides and associated calibration adjustments. TRIM
I adjusts the Park divider low side, TRIM II the capacitive divider
low side and TRIM III the low side used with passive x-ray dividers.
Also on the low side board are pairs of trim pots used for zero offset
adjustments. The calibration trim pots are nearest the board and are
labeled I, II and III.

The ACHV calibration adjustment TRIM II should only be adjusted if a suitable ac divider system is available.

A third active low side is provided for use with passive dividers. The gain of this system may be adjusted to make the output of a given divider direct reading.

The filament current module uses a current transformer with a precision resistor burden and should maintain accuracy for an extended period barring component failure.

The anode current unit was calibrated using a digitizing scope and would require a similar unit for recalibration. It is suggested that appropriate NBS personnel be contacted for consultation in the event this unit is suspected to be malfunctioning.

Other X-CAL modules are commercially manufactured and the vendors instruction manuals should be used in the event of failure of these units.

9. Parts List

No extensive parts lists have been developed for the X-CAL system since no exotic components were used in the system design and most replacement parts required are available from various vendors. It is suggested that spares be acquired for the active components listed below since lead times for procuring most semiconductors are long.

List of Selected Active Devices

Device No.	Vendor[1]
OP-2	Precision Monolithics
OP-16	Precision Monolithics
4085	Burr-Brown
556	Signetics
TL-083	Texas Instruments
8038	Intersil
Misc. TTL	Texas Instruments

10. Circuit Diagrams

The following set of figures are circuit diagrams for system modules and intermodule cabling. All component values are indicated on the diagrams.
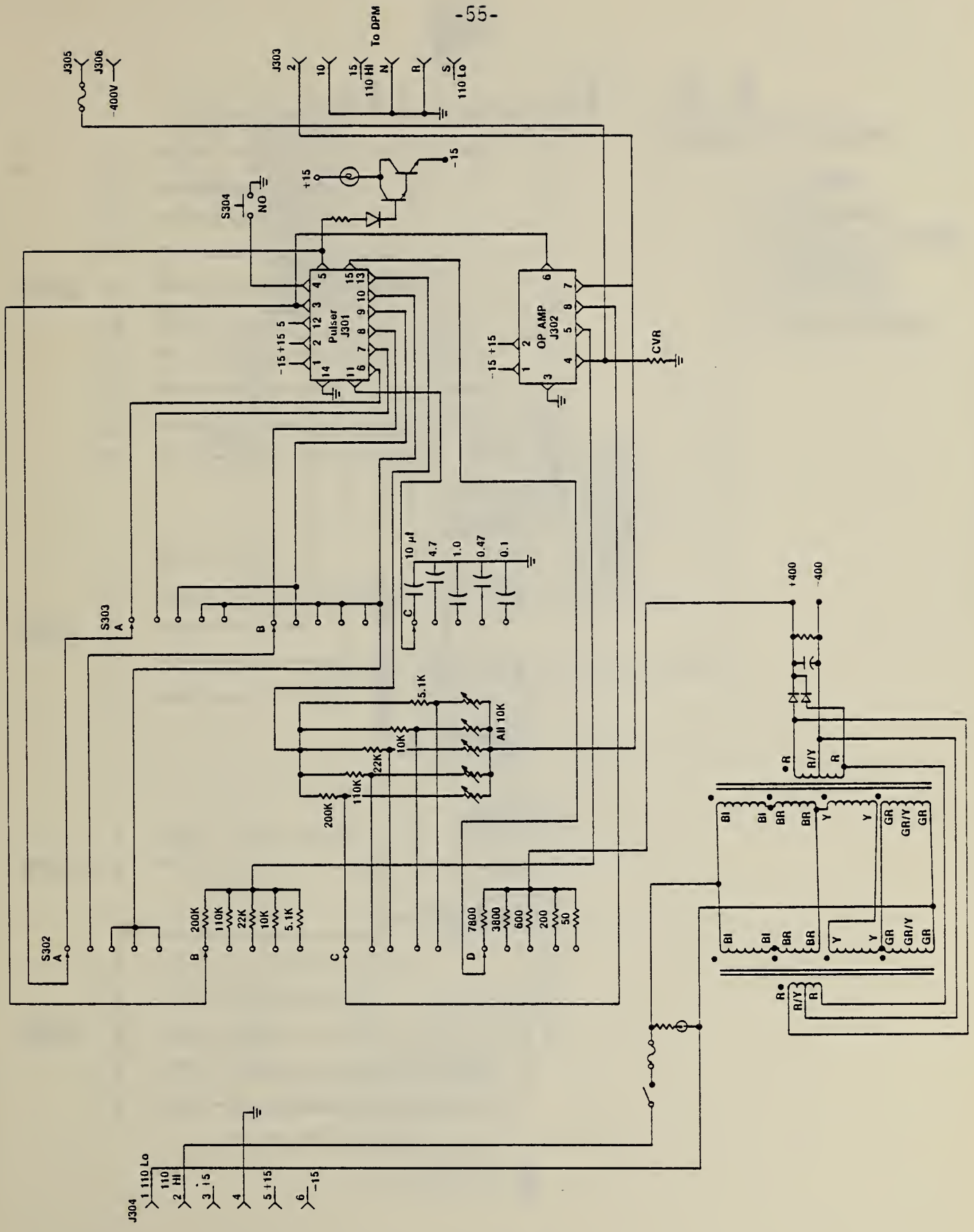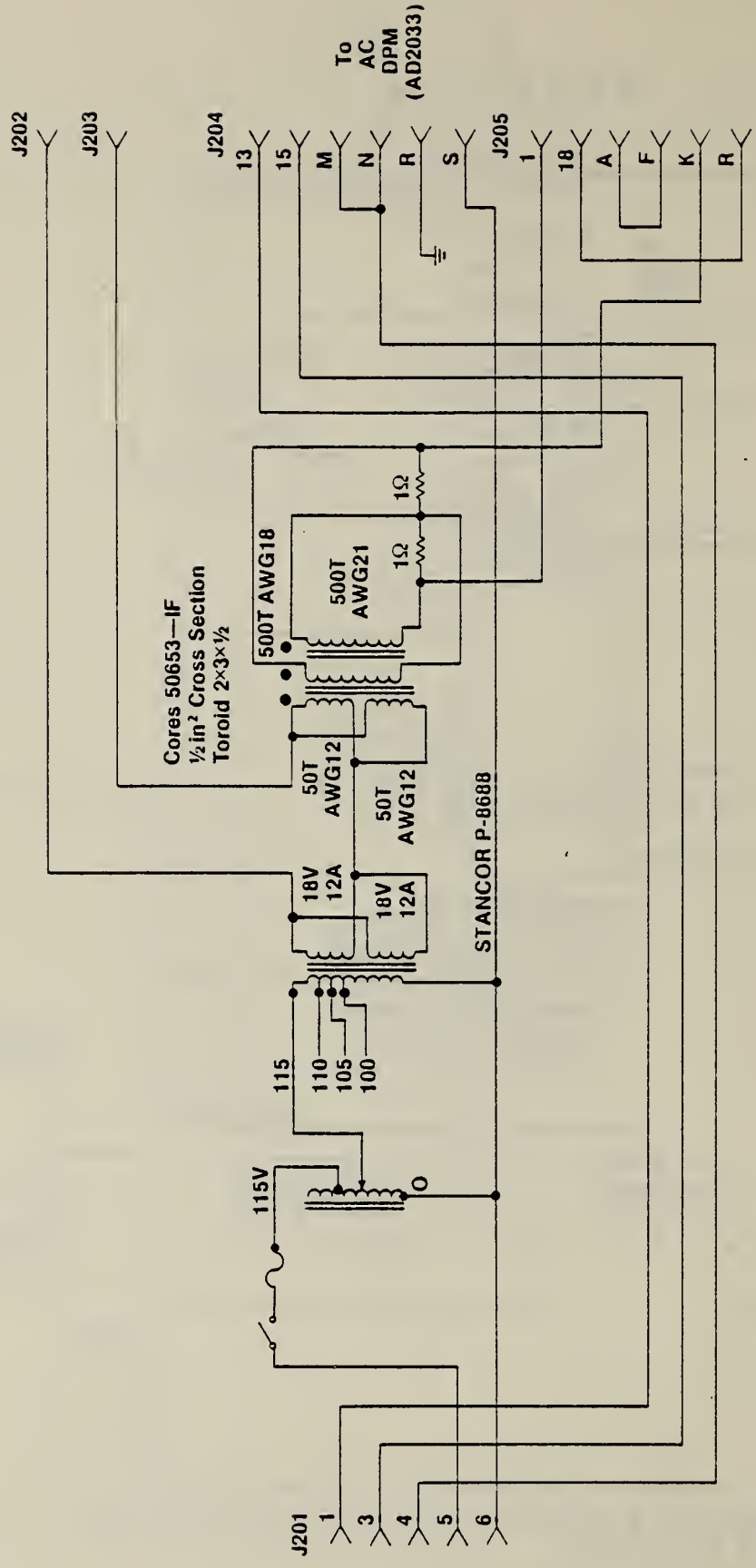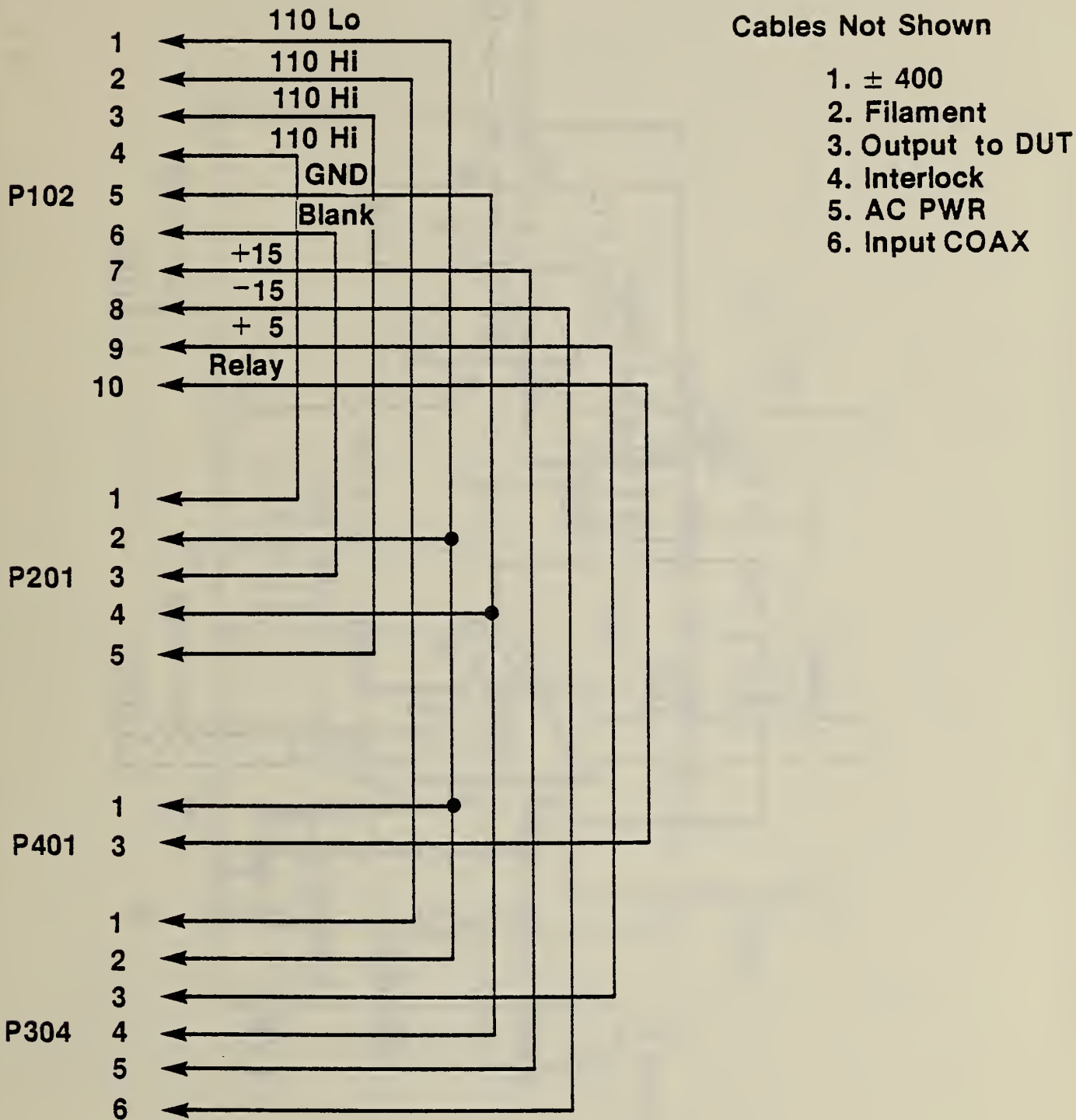
FIGURE 10.2 Circuit diagram for anode pulser module.

STANCOR P-8688

Cores 50653—IF
½ in² Cross Section
Toroid 2×3×½

To
AC
DPM
(AD2033)

FIGURE 10.4 Intermodule cabling.
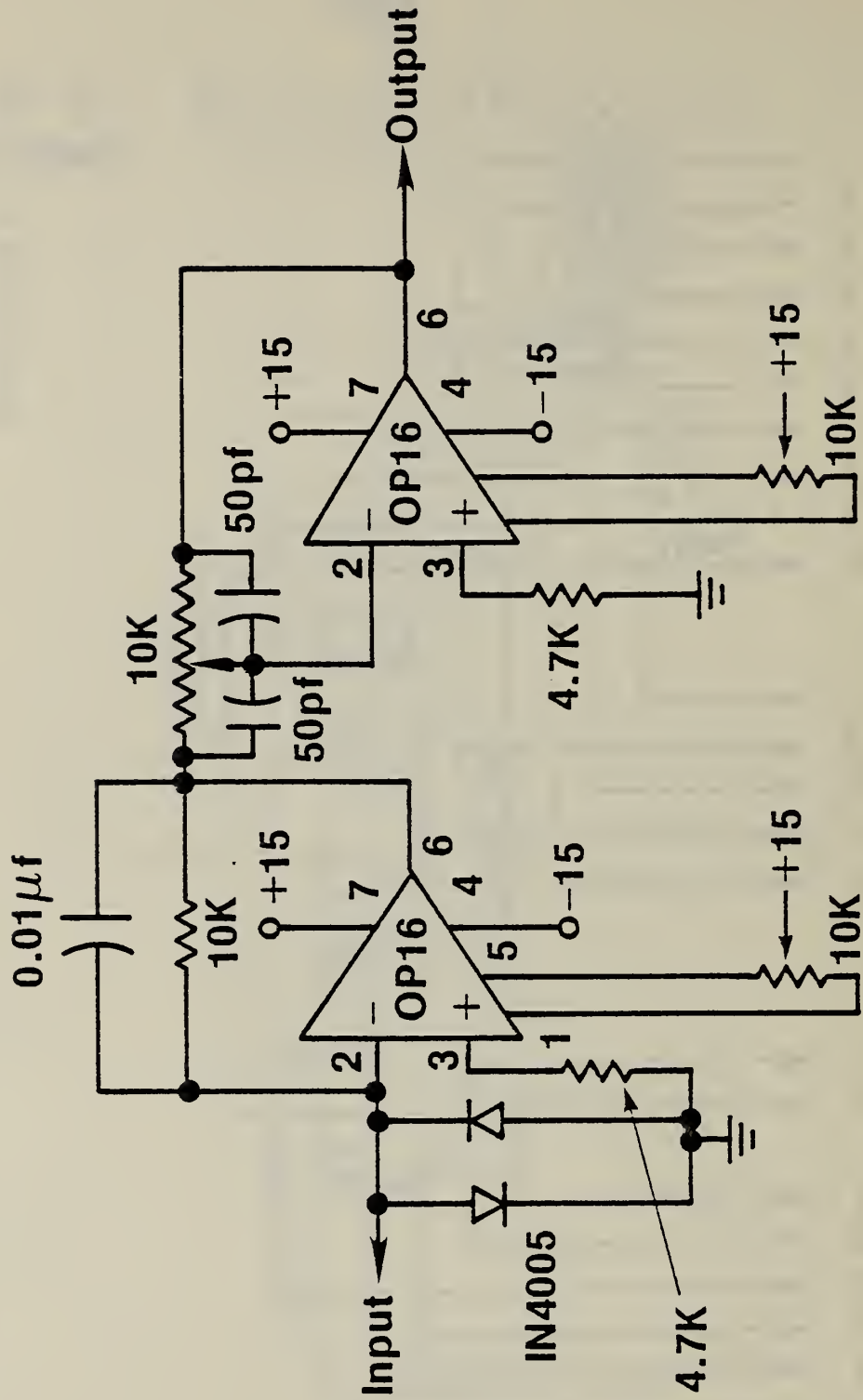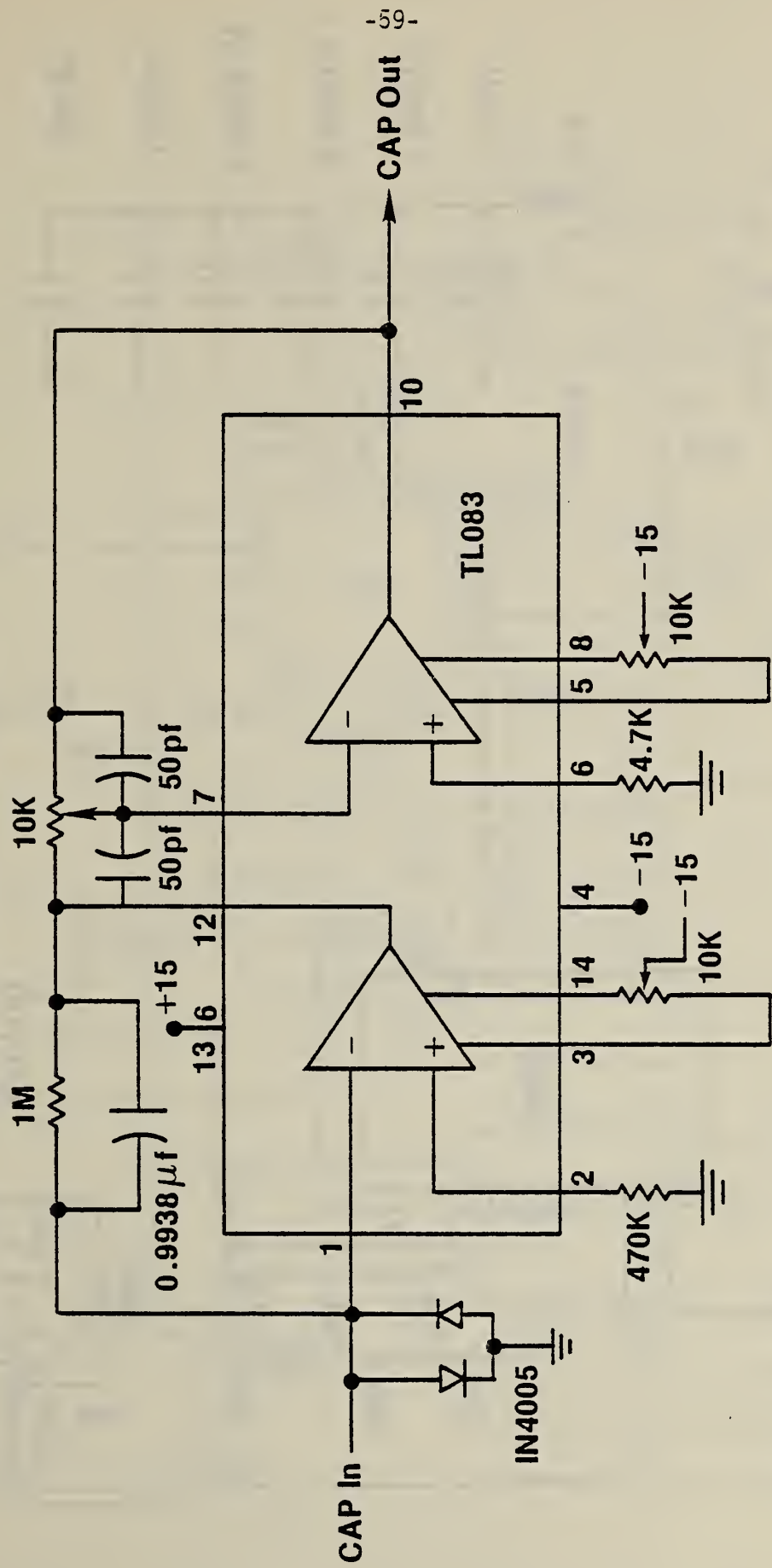
FIGURE 10.6 Circuit diagram for active low side (capacitor divider).
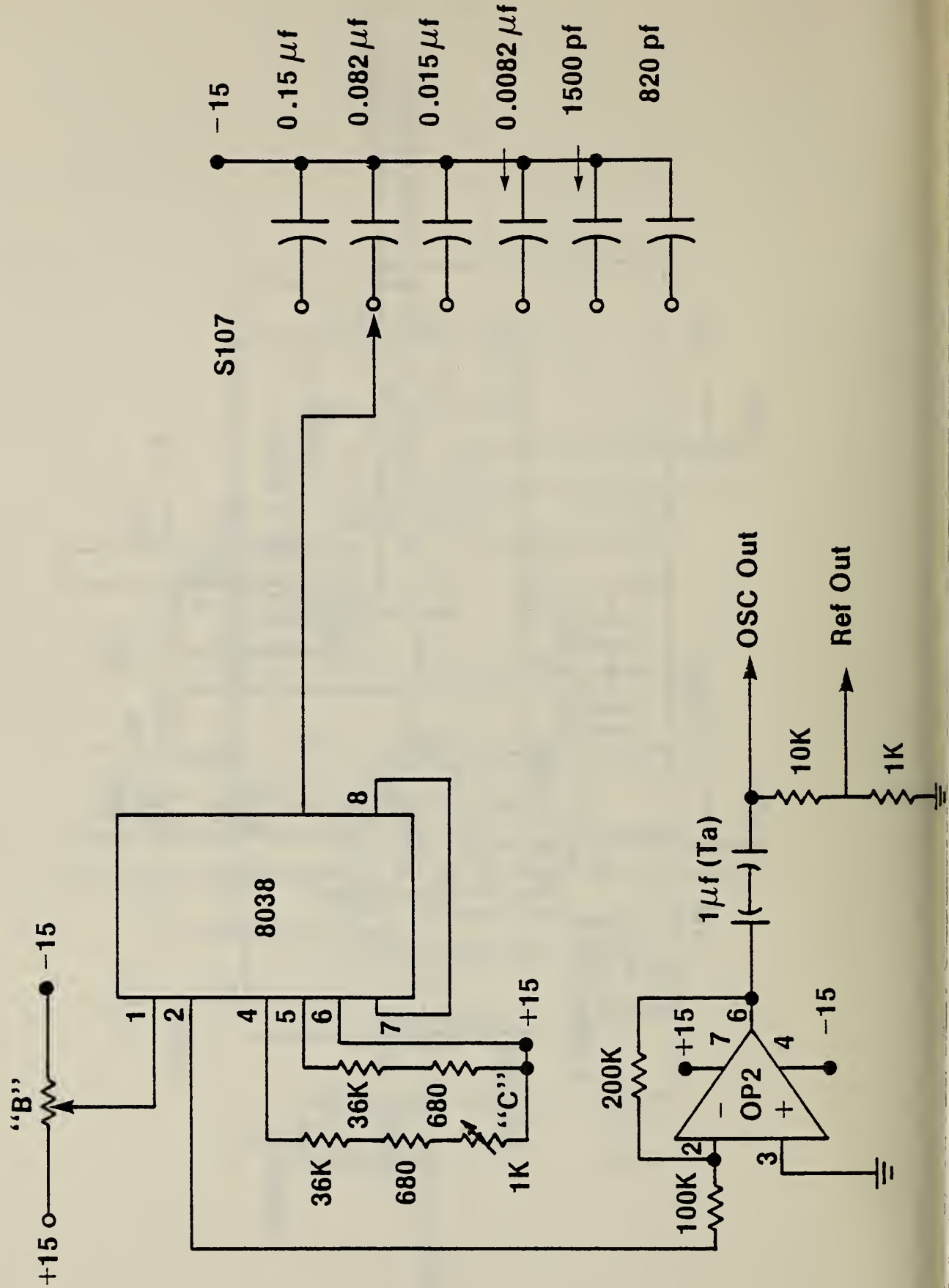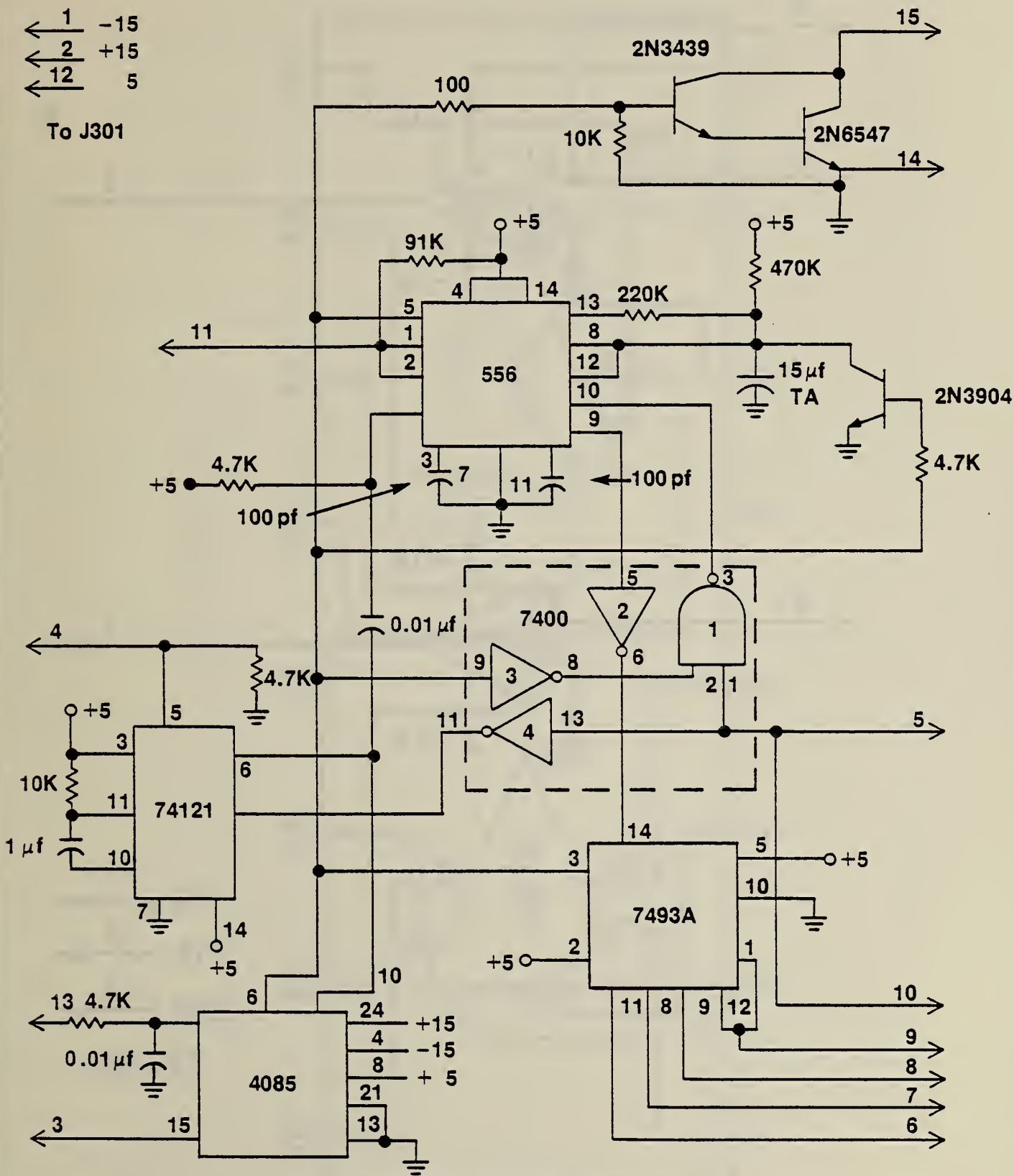
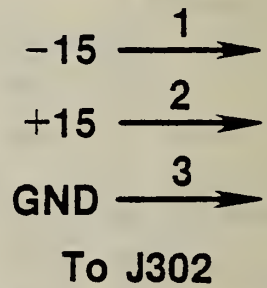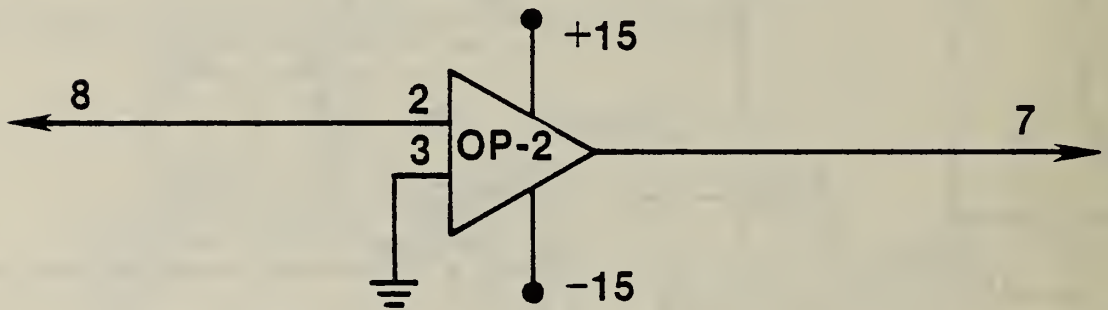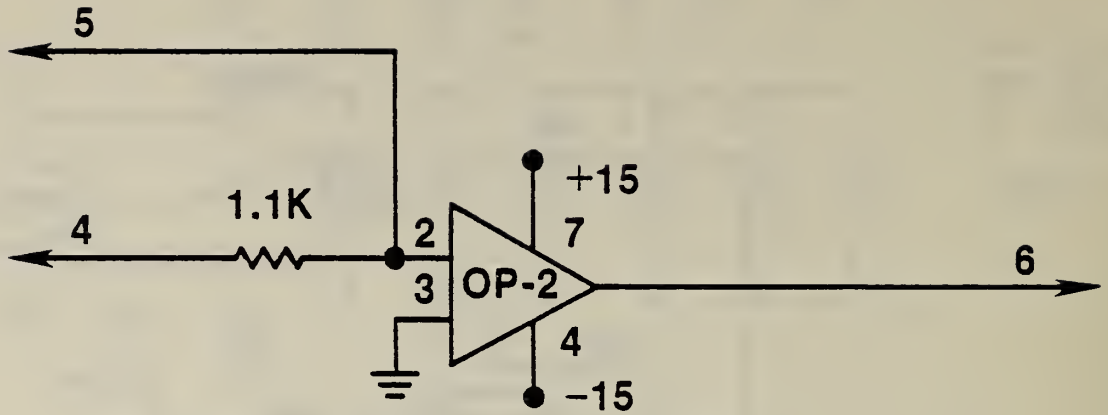FIGURE 10.8 Circuit diagram for anode pulser controller.

FIGURE 10.9 Circuit diagram for gain and calibration stages for
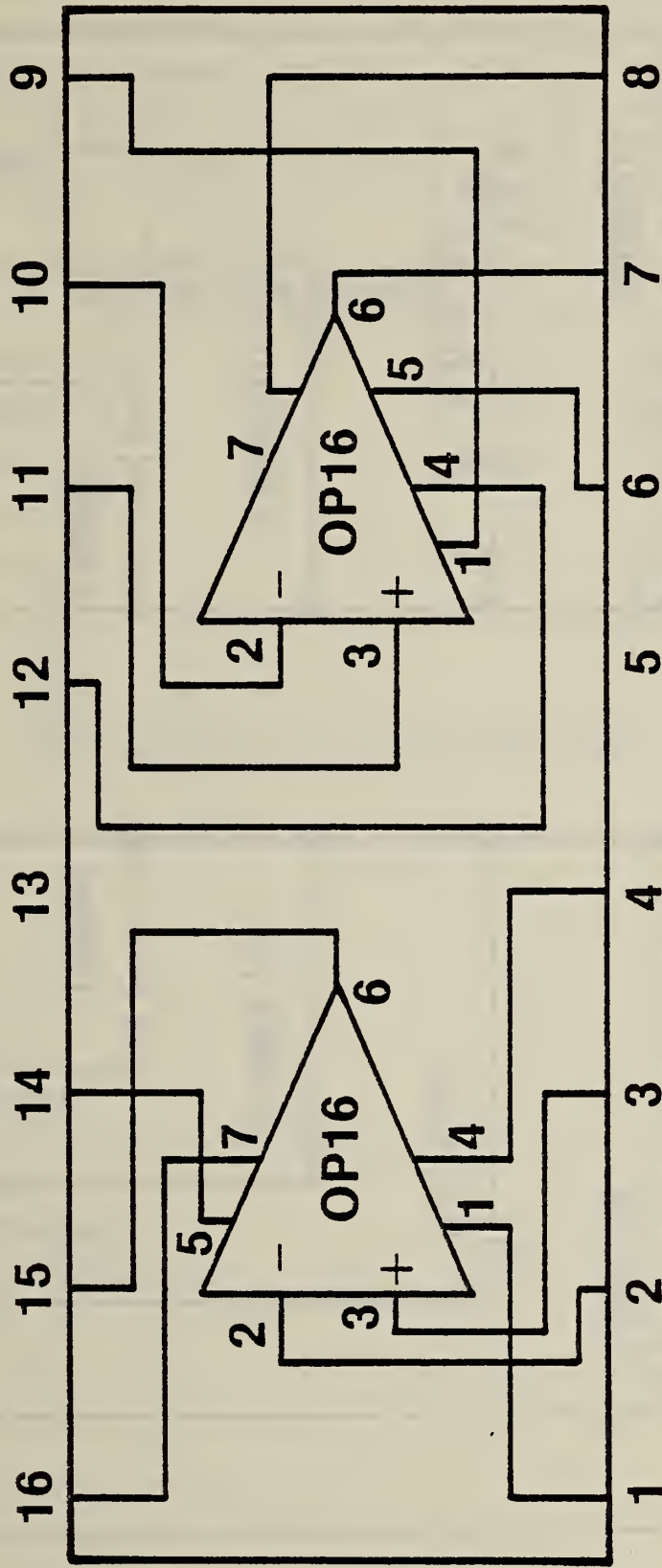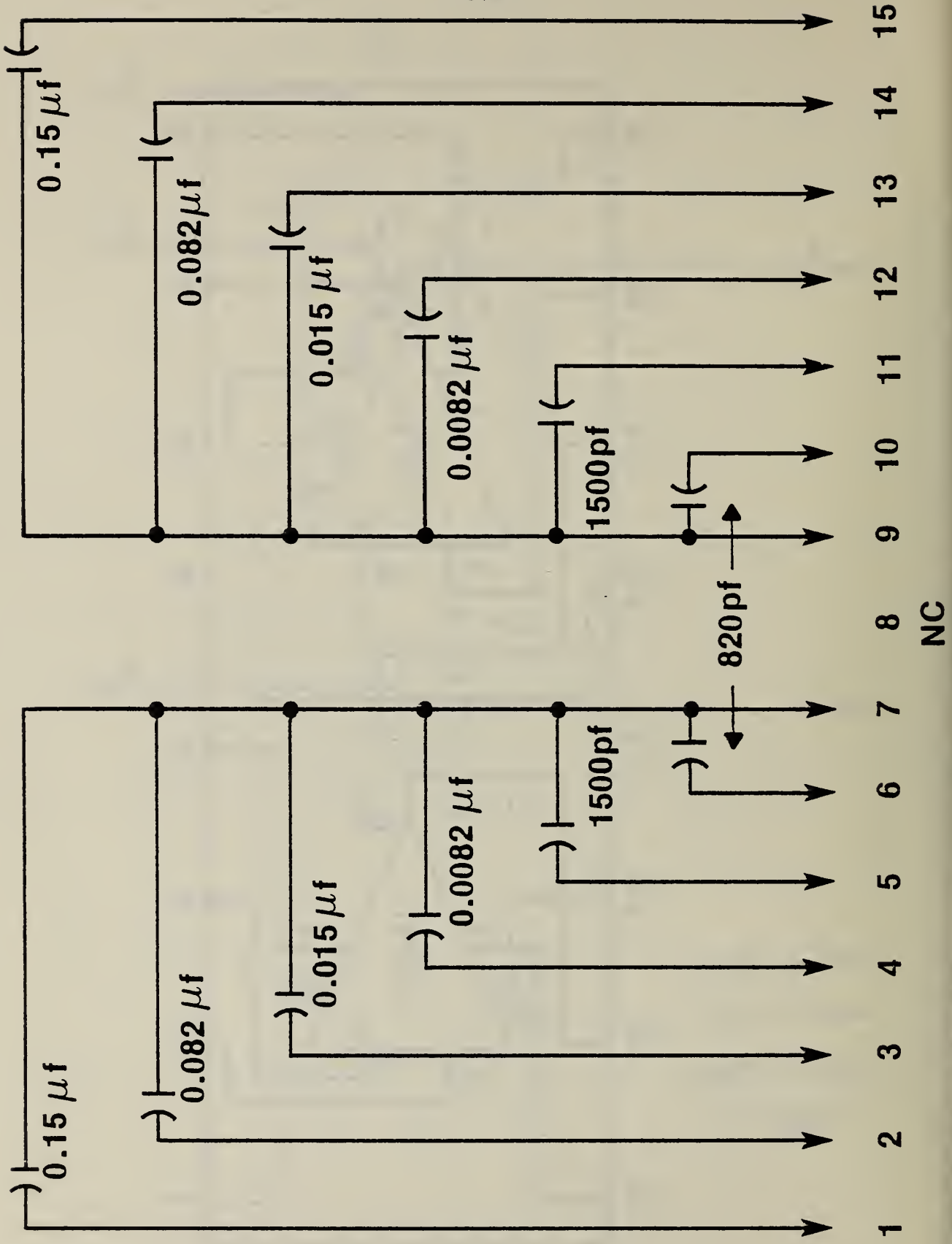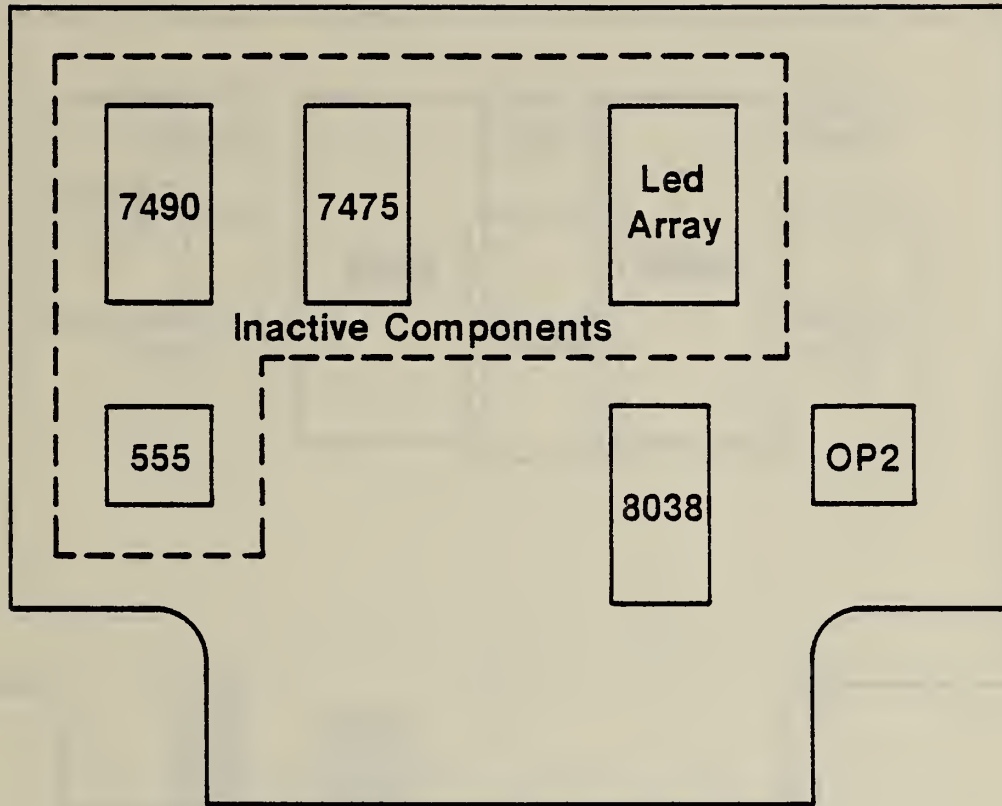anode pulser peak-detect-and-hold circuitry.

FIGURE 10.10 Circuit diagram for dual OP-16 to 16 pin DIP package adapter.

Pins

1   +15
2   −15
3   GND
4   + 5
5   OSC Sel
6
7   Output
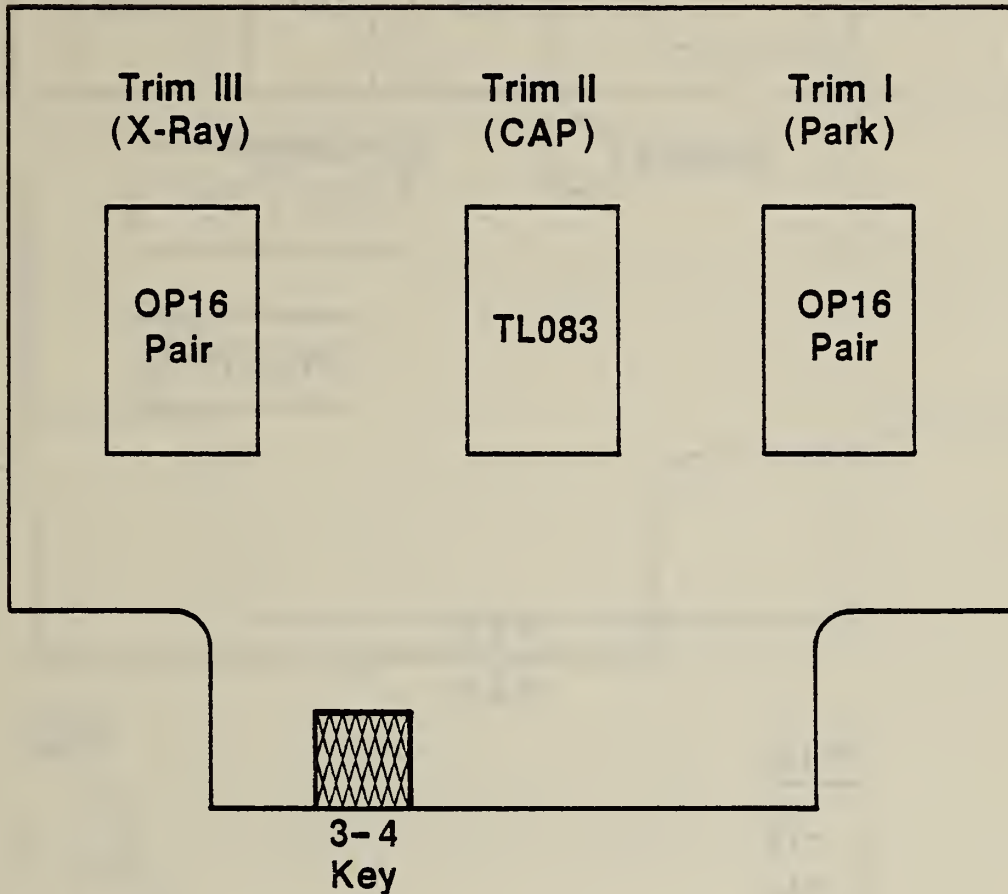8   Ref Output
9
10 ⎫
   ⎬ Key
11 ⎭
12
13
14
15

FIGURE 10.12 Major parts layout for fixed frequency oscillator board.

Front
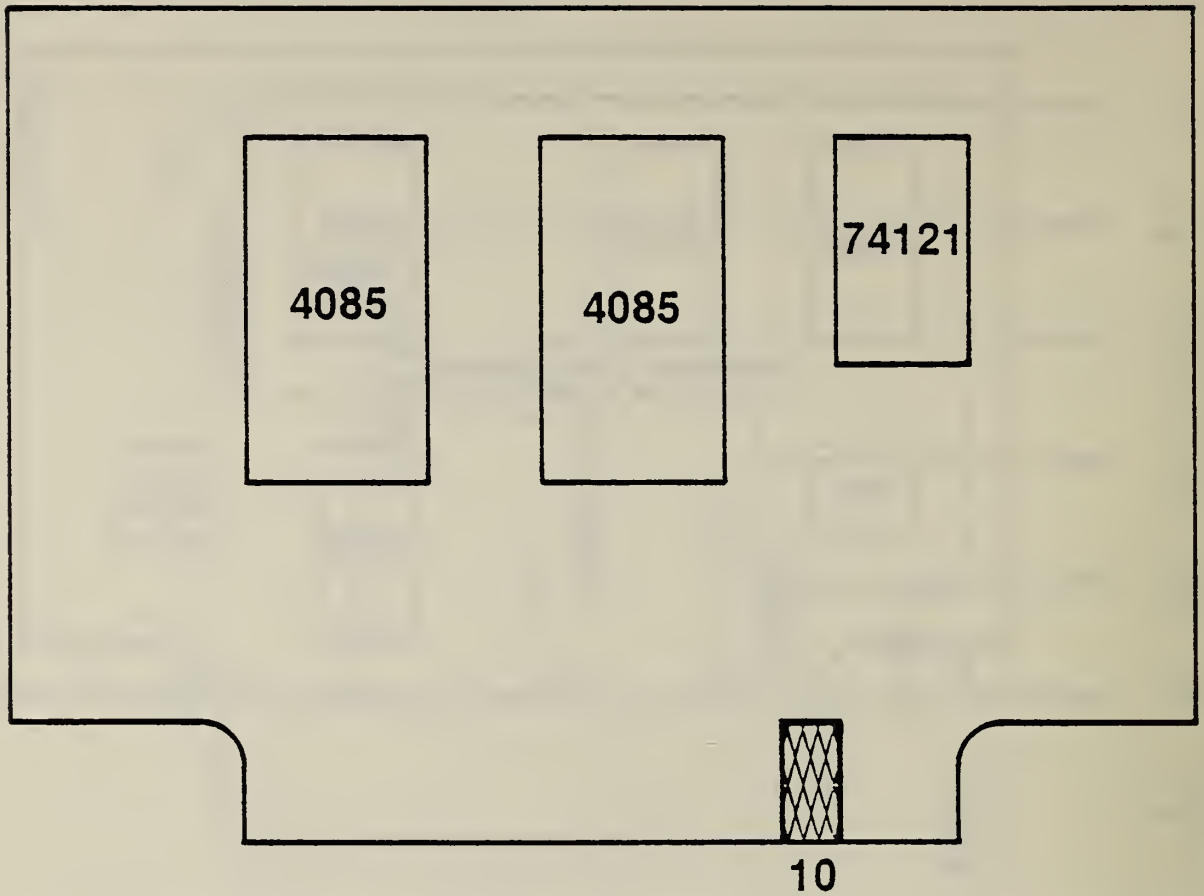
PINS

1 +15
2 −15
3 GND
4 + 5
5 P&H A In (From X-Ray Div. Low Side)
6 P&H A Out
7 P&H B In (From Cap Div. Low Side)
8 P&H B Out
9 Reset (No to GND)
10 Key

FIGURE 10.13 Major parts layout for peak-detect-and-hold board.

Trim III
(X-Ray)

Trim II
(CAP)

Trim I
(Park)

OP16
Pair

TL083

OP16
Pair

3–4
Key

Pins

1	+15
2	−15
3 } Key	
4 }	
5	GND
6	Input From X-Ray Div.
7	
8	Active Input
9	Active Output
10	Cap Div. Output
11	Cap Div. Input
12	Park Div. Output
13	Park Div. Input
14	X-Ray Div. Output
15	

FIGURE 10.14 Major parts layout for active downside board.
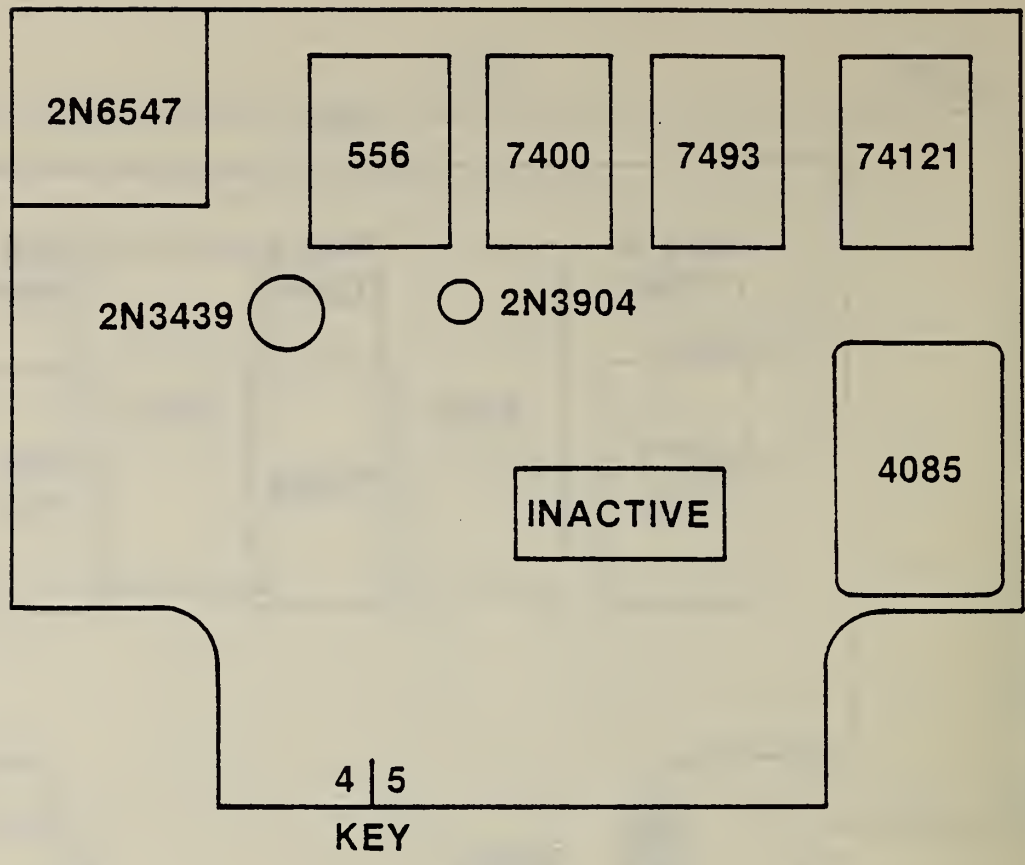
PINS

1 −15
2 +15
3 TO CALIBRATION OP AMP
4 TO S 304
5 TO S 302
6 TO S 303
7 "
8 "
9 "
10 "
11 TO S 303
12 +5
13 FROM CVR OP AMP
14 GND
15 TO S 302

FIGURE 10.15 Major parts layout for anode pulser controller board.

```
┌──────────────────────────────────────────────┐
│   ┌─────────┬─────────┐                        │
│   │   OP2   │   OP2   │                        │
│   └─────────┴─────────┘                        │
│                                    ┌───────────┘
└───────┐                      ┌─────┘
        │                      │
        └──────────────────────┘
```
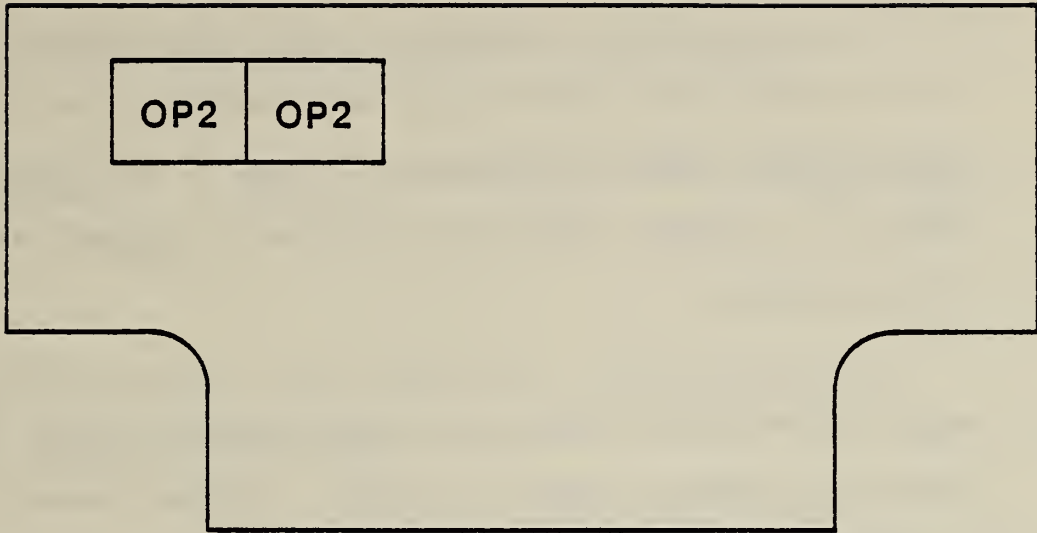
PINS

1 −15
2 +15
3   GND
4   FROM CVR
5   TO S 302
6   TO PEAK AND HOLD
7   TO DPM
8   FROM PEAK AND HOLD
9
10
11
12 ⎱
13 ⎰ KEY
14
15

FIGURE 10.16 Major parts layout for anode pulser gain and calibration board.

11. References

1. Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

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      low side resistor.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The X-CAL high-voltage-divider calibration system was designed to calibrate the direct and alternating voltage measurement capabilities of commercial high voltage dividers used to characterize diagnostic x-ray units. In addition, there is capability for determining the frequency response of these dividers and for the calibration of the filament current and anode current measurement features of specific commercially-available devices. The calibration system combines in a single unit a range of capabilities which allows calibration of a device under test to be accomplished with a minimum of set up time. This report gives a description of the motivation for, the operation of and the design details of the X-CAL system. It lists the specified accuracies and the ranges of applicable parameters of the various subsystems, describes the five different calibrations which can be performed using the X-CAL system, discusses techniques used in the original calibration of the X-CAL system itself, and contains the basic circuit diagrams for the system.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Calibration; diagnostic x-rays; electrical measurements; health; radiation; radiation safety; safety; x-rays.

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