Reference
NBS
PUBLICATIONS

NBSIR 84-2973

An Automatic AC/DC Thermal Voltage Converter and AC Voltage Calibration System

K. J. Lentner, D. R. Flach, and B. A. Bell

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Gaithersburg, MD 20899

August 1984

Final Report

Issued November 1984

Sponsored in part by:

Department of Defense
bration Coordination Group

QC
100
.U56
84-2973
1984

NBSIR 84-2973

AN AUTOMATIC AC/DC THERMAL VOLTAGE CONVERTER AND AC VOLTAGE CALIBRATION SYSTEM

K. J. Lentner, D. R. Flach, and B. A. Bell

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Gaithersburg, MD 20899

August 1984

Final Report

Issued November 1984

Sponsored in part by:
U.S. Department of Defense
Calibration Coordination Group

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

FOREWORD

The development of the system described in this report was partially funded by the U.S. Department of Defense Calibration Coordination Group (DoD/CCG). Members of the DC and LF Committee were from the U.S. Air Force Aerospace Guidance and Metrology Center, Newark Air Force Station, Newark, OH 43055; the U.S. Army TMDE Support Group, Redstone Arsenal, Huntsville, Alabama 35809; and the U.S. Navy Metrology Engineering Center, Naval Weapons Center (Seal Beach), Pomona, California 91766.

The DoD/CCG project number assigned was CCG 79-125, and work was performed under NBS cost center 7220463.

In order to adequately describe the system discussed in this report, commercial equipment and instruments are identified by manufacturer's name and model number. 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.

CONTENTS

Page

Foreword. iii

LIST OF TABLES v

LIST OF FIGURES v

Abstract. 1

1. INTRODUCTION. 1

2. TECHNICAL APPROACH. 2

2.1 System Hardware. 2
2.2 AC/DC Difference Test Procedure 3
2.3 Other System Capabilities. 9

2.3.1 AC Voltage Calibrations 9
2.3.2 Stability Tests 13
2.3.3 TE Tests. 13

3. MEASUREMENT RESULTS AND UNCERTAINTIES 17

4. CONCLUSIONS 21

5. ACKNOWLEDGEMENTS. 22

6. REFERENCES. 22

APPENDIX A. System Equipment List. 23

APPENDIX B. Major Programs 25

APPENDIX C. Typical Software Documentation 28

LIST OF TABLES

Page

Table 1. 3-V TVC ac/dc difference (ppm). 20

Table 2. 10-V TVC ac/dc difference (ppm) 20

Table 3. 50-V ac/dc difference (ppm) 21

Table 4. ATS software summary. 27

LIST OF FIGURES

Figure 1. System block diagram 4

Figure 2. Automatic TVC and AC Voltage Calibration System. 5

Figure 3. Present measurement procedure for obtaining average values of TVC emfs that compensates for drifts and obtains nearly simultaneous values for the mean value. . 10

Figure 4. System block diagram when used to calibrate an external ac source 12

Figure 5. Plots from stability testing program 14

Figure 6. Plot from n test curve fitting program 15

Figure 7. Plot from dc reversal difference program 18

Figure 8. Plot from TE thermal response time program 19

AN AUTOMATIC AC/DC THERMAL VOLTAGE CONVERTER AND AC VOLTAGE CALIBRATION SYSTEM

K. J. Lentner, D. R. Flach, and B. A. Bell

ABSTRACT

An automatic ac/dc difference calibration system is described which uses direct measurement of thermoelement emfs. In addition to ac/dc difference testing, the system can be used to measure some important characteristics of thermoelements, as well as to calibrate ac voltage calibrators and precision voltmeters. The system operates over a frequency range from 20 Hz to 100 kHz, covering the voltage range from 0.5 V to 1 kV. For all voltages the total measurement uncertainties expected (including the uncertainty of the specific reference thermal converters used) were 50 parts per million (ppm) at frequencies from 20 Hz to 20 kHz, inclusive, and 100 ppm at higher frequencies up to 100 kHz. The results of initial intercomparisons between the new system and the manual NBS calibration system, using single-range, coaxial-type, thermal voltage converters as transfer standards, are reported. The results show that the agreement between the two systems is better than the uncertainties originally expected, since the intercomparison of ac/dc differences differed by no more than 15 ppm.

Keywords: ac/dc difference; ac voltage measurement; automation; calibration; metrology; thermal voltage converter.

1. INTRODUCTION

Until recently, techniques for performing precision ac/dc difference measurements generally made use of manual testing methods which utilize photo-cell preamplifiers and light-beam galvanometers as votage detectors, in conjunction with manually balanced voltage comparators [1,2] . Careful attention to the reduction of systematic and random uncertainties in measurement methods, thermoelements (TEs), and thermal voltage converters (TVCs) has resulted in sufficient confidence in test data to allow results to be reported with total uncertainties at the 10-100-ppm level (or better, in special cases) over wide voltage and frequency ranges [3,4]. These manual test methods, however, are very time consuming and subject to errors due to operator fatigue and lack of skill. More recent work [5,6] overcame some of the deficiencies of manual test methods. However, the referenced systems still require the use of a TE voltage comparator which is not available commercially. Because of its special design, the comparator adds to a system's cost and complexity.

Stringent requirements are placed on the measurement system to resolve low-level voltages (about 10 nV), and to overcome the effects of large temperature coefficients and dc reversal differences of the TEs, as well as instabilities of the voltage sources. However, with the advent of stable and

---

[1] Numbers in brackets refer to the literature references listed at the end of this report.

accurate analog voltage amplification techniques in combination with digital electronics, digital voltmeters are available with sufficient stability, linearity, resolution, and accuracy to meet the requirements of automated ac/dc difference measurements. Programmable ac and dc voltage sources also are available which lend themselves to adaption for automatic testing. Advances in analog/digital interfaces have improved the ease with which computers can be used to control these instruments.

The system to be described in this report was designed to overcome the deficiencies of present test methods by taking advantage of the technological advances described above. Specifically, some objectives were to: 1) utilize a desktop computer; 2) use commercially available programmable instruments whenever possible; 3) eliminate as much operator intervention as possible in order that testing could be done completely automatically at one fixed voltage range of the test unit; 4) eliminate the additional cost and complexity of using a TE voltage comparator; 5) use test procedures which assure that the test TE's output emf is held as constant as possible; 6) eliminate the effects of operator fatigue and lack of skill; and 7) achieve about the same level of uncertainty as is presently possible for general purpose ac/dc difference manual testing methods.

The system operates over a frequency range from 20 Hz to 100 kHz, covering the voltage range from 0.5 V to 1 kV. For all voltages the goal was to achieve total measurement uncertainties (including the uncertainty of the reference TVCs used) of 50 ppm at frequencies from 20 Hz to 20 kHz, inclusive, and 100 ppm at higher frequencies up to 100 kHz. In addition to performing ac/dc difference tests, the system can be used to calibrate ac voltage calibrators or precision ac voltmeters. Furthermore, as will be discussed later, automatic measurements of a TE's dc reversal difference, response time, and the value of the exponent "n" in the expression relating a TE's heater current and output emf can also be made.

2. TECHNICAL APPROACH

2.1 System Hardware

The new system differs from most present techniques for ac/dc difference measurements in that no TE voltage comparator is used. Eliminating the comparator places additional requirements upon the stability of the system's ac and dc voltage sources, the digital voltmeter (DVM) which measures a TE's output emf, and the switches which select a TE voltage to be measured by the DVM. The hardware development problem of obtaining low-thermal-emf-switches which could be automatically controlled was solved during previous work [5]. Manually operated low-thermal-emf-switches were modified by linking them to solenoids with 24-V operating coils energized by means of programmable relays.

TE voltages of about 10 mV must be measured to within about 10 nV to achieve 1-ppm comparison precision, and the DVM used to measure these voltages has the resolution necessary to make such a voltage measurement when extensive averaging of data is used. The DVM has an input resistance of about 10 GΩ, a 60-Hz common mode voltage rejection >40 dB, and a dc common mode voltage rejection >150 dB. On its most sensitive range (10-mV), the peak-to-peak low-frequency noise (dc to about 10 Hz) of the DVM, with its input shorted, was measured to be about 50 nV.

The dc voltage source has 10-V, 100-V, and 1-kV ranges with six-digit voltage setting capability on each range. Its specified accuracy is 50 ppm of setting to 10-V, and 100 ppm above 10-V. The ac voltage source also has six-digit voltage setting capability for voltage ranges of 1-V, 10-V, 100-V, and 1-kV, with specified accuracies in the range of about 0.02 percent to 0.1 percent, depending on the voltage and frequency ranges. Some typical results of stability tests made on these sources will be discussed later.

A block diagram of the system is given in Fig. 1, and an overall view of the system hardware shown in Fig. 2. The desk-top computer serves as the system controller and has about 60 kbytes of user-available memory. Magnetic tape cartridges are used for program and data storage. A video display terminal (CRT) is used for data display during testing and also serves as an aid during software development. Since the computer only has three input/output slots, an I/O expander is needed to accomodate the required instrumentation. The real-time clock is used for precise control of the time interval between applications of ac or dc voltages during a test, and the printer and plotter provide test records.

As indicated in Fig. 1, communication between the computer and the stimulus and measurement instrumentation is via the IEEE 488 bus. The digital panel meters (DPMs) monitor the voltage outputs from the dc and ac sources. During testing, readings of both the dc and ac source's output voltages are obtained by the DPMs. These voltage readings are made before the voltages are applied to the test circuit. If the measured voltages differ by more than 0.5 percent from the programmed values, the test is automatically aborted. High accuracy in these voltage readings is not necessary, since TVCs can readily withstand an applied voltage which is 120 percent of rated value. For the ac source, the output voltage is attenuated by a factor of 100 before being connected to the DPM. The attenuation is necessary in order to overcome the voltage-frequency product limitation of the DPM. The counter shown in Fig. 1 monitors the frequency of the ac source. If the counter reading differs by more than about 10 percent from the programmed frequency, the test is automatically aborted. The relay actuator is used to apply 24-V dc to the operating coils of the high-voltage relays as well as to the coils of the solenoids which operate the low-thermal-emf switches.[2] These switches select the output voltage of the standard TE (E_s) or the unit-under-test TE (E_t). The voltages, E_s and E_t, are applied directly to the input of the DVM, and the DVM voltage readings are then stored in the computer's memory for later processing.

2.2 AC/DC Difference Test Procedure

One of the advantages of using a TE voltage comparator is that, since small differences in the ratio of two TE emfs are measured directly, the output emf of the test TE can be allowed to drift slightly from its reference emf value when ac, +dc, or -dc voltages are applied [2,6]. In this new system, since no TE voltage comparator is used, the requirement for holding the test TE's emf constant is quite stringent. However, with automation and the rapid response time of the voltage sources (typically 50 μs

---

[2] Construction details of the high-voltage relay and low-thermal-emf modules can be found in [7].

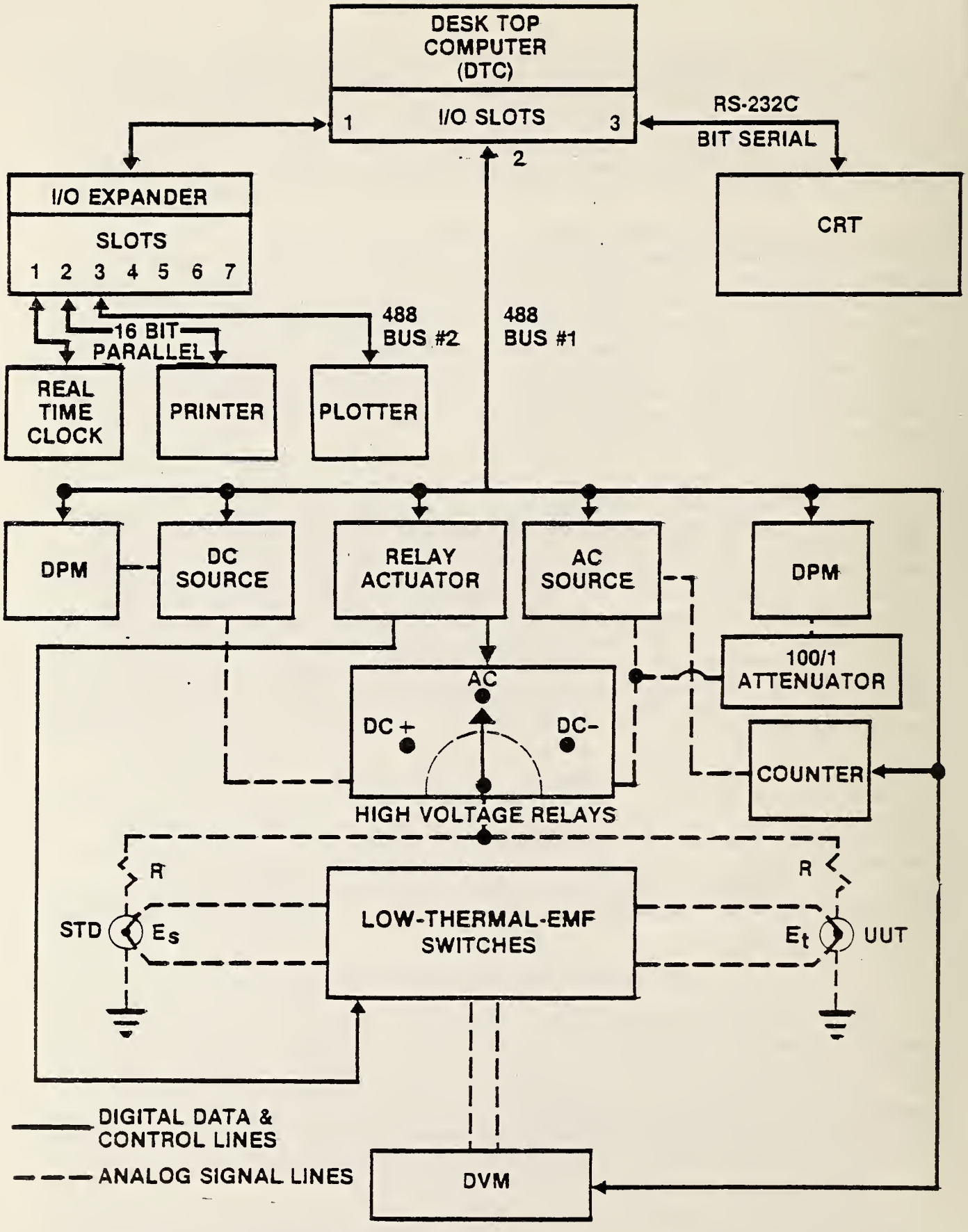


Figure 1. System block diagram

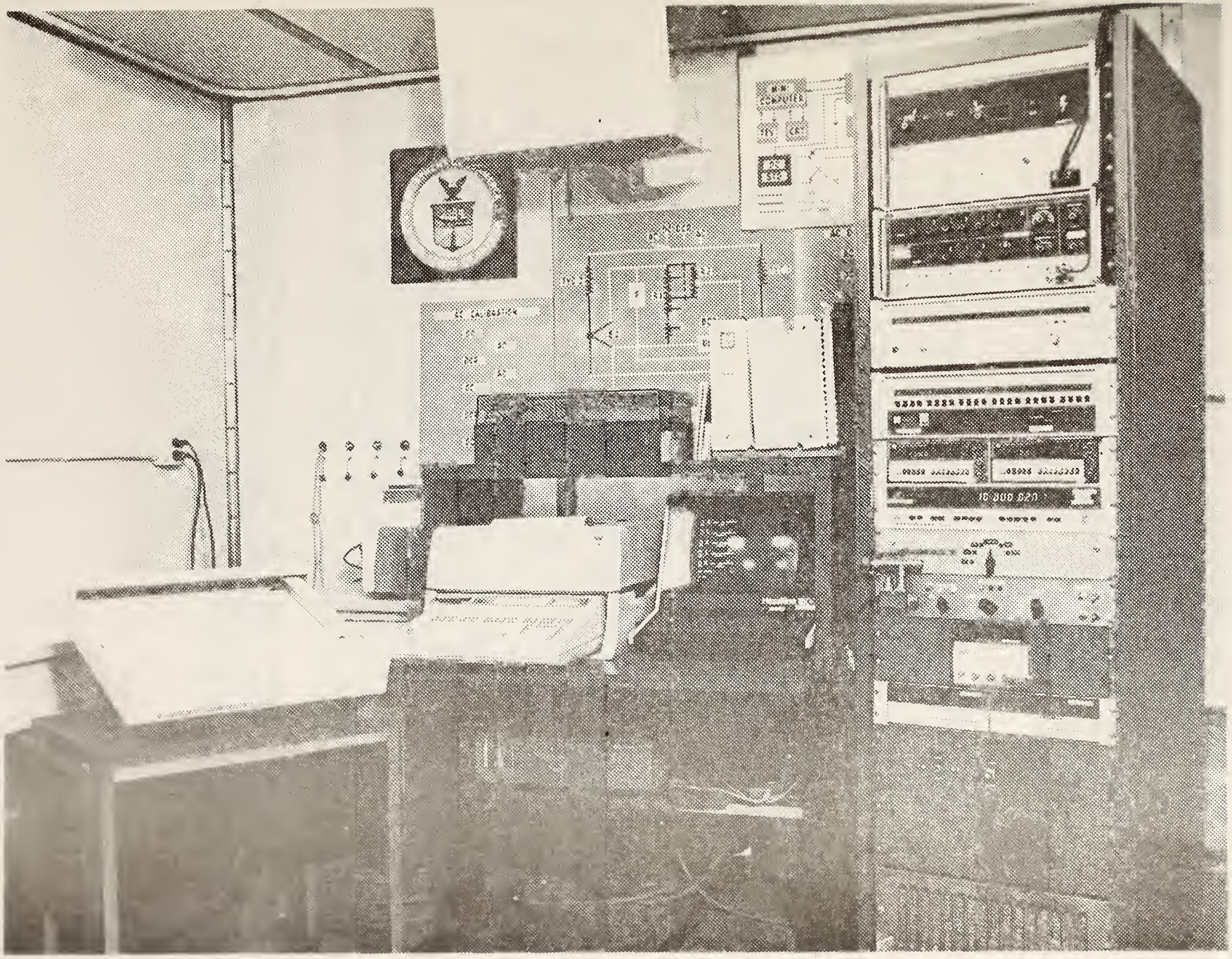


Figure 2. Automatic TVC and AC voltage calibration system.

for the dc source and a few milliseconds for small voltage changes for the ac source), the constant output requirement can be readily satisfied. The techniques used will be discussed in this section.

For a TVC with response defined by $E = KV^n$, where E is the output emf of the TE in the TVC, V is the voltage applied, and K and n are parameters characteristic of the particular TVC, the ac/dc difference is defined as

$$\delta = \frac{V_a - V_d}{V_d} , \tag{1}$$

where V_a is the applied ac voltage, and V_d is the average of the two polarities of dc voltage; i.e.,

$$V_d = \frac{V_+ + V_-}{2} . \tag{2}$$

V_a, V_+, and V_- are voltage values which give the same output emf of the TE. In a manual test system using a TE voltage comparator, the voltage difference, $V_a - V_d$, is determined by a second TVC, the standard. If the standard's response is defined as

$$E_s = K_s V_s^{n_s} , \tag{3}$$

it can be shown [2] that the ac/dc difference of the test TVC is

$$\delta_t = \frac{E_{sa} - E_{sd}}{n_s E_{sd}} + \delta_s = \frac{\Delta E_s}{n_s E_{sd}} + \delta_s , \tag{4}$$

where E_{sa} is the standard TE's emf when the voltage V_a is applied, E_{sd} is the standard TE's average emf when voltages V_+ and V_- are applied (cf. eq. 2), n_s is the standard's dimensionless characteristic n, and δ_s is the ac/dc difference (in ppm) of the standard determined as described in [1,2]. Equation 4 is numerically correct if dE_s is in nanovolts, E_{sd} in millivolts, and the "δ's" are im ppm. During a test, V_a, V_+, V_-, and V_a are adjusted until the same emf of the test TVC is obtained in each case when these voltages are applied in sequence.

In the automated system the test TVC's output emf is held constant in the following manner. With the nominal dc voltage applied to the test TVC, an output emf, E_{set}, is measured which is called the "set-point" voltage. In all subsequent applications of ac and dc voltages to the test circuit of

Fig. 1 the computer is used to adjust the voltage applied so that the test TVC has an output very nearly equal to E_{set}. A four-step procedure is used for making ac/dc difference measurements. The procedure consists of applying a sequence of ac, +dc, -dc, and ac voltages to both TVC's at approximately equal time intervals. The following operations are performed for each step in the procedure presently used with the system.

First, the nominal ac or dc voltage is applied, the test emf, E_t, is measured, and a difference voltage, dE_t, is calculated as

$$dE_t = E_{set} - E_t \ . \tag{5}$$

If the difference voltage is not sufficiently small, as discussed below, a voltage correction, dV_t, is calculated from

$$dE_t/n_t E_t = dV_t/V_t \ . \tag{6}$$

Hence,

$$dV_t = (dE_t/n_t E_t)V_t \ . \tag{7}$$

The correction, dV_t, is added to the nominal voltage, V_n, and a "reset" voltage, $V_r = V_n + dV_t$, is applied. The test emf, E_t, is measured again, and a second voltage correction, dV_2, is calculated using equations 5 and 7. The output emf of the standard TE, E_s, is now measured. A correction for the emf of the standard TE, dE_s, is calculated, using dV_2 to compensate for any deviation of the actual emf of the test TE from the set point E_{set}; i.e.,

$$dE_s = (n_s E_s dV_2)/V_r \ . \tag{8}$$

The corrected emf for the standard TE is then

$$E_{s1} = E_s + dE_s \ . \tag{9}$$

A discussion of the exact measurement procedure used is given below.

After completing the sequence of four steps by applying successively ac, +dc, -dc, and ac voltages, the ac/dc difference of the test TVC, δ_t, is calculated as

$$\delta_t = \frac{E_a - E_d}{n_s E_{sd}} + \delta_s, \tag{10}$$

where E_a is the average of the standard's corrected emfs determined for the two applications of ac voltage; E_{sd}, n_s, and δ_s are as defined in equation 4; and E_d is

$$E_d = \frac{E_{s1+} + E_{s1-}}{2}, \tag{11}$$

where E_{s1+} is the corrected emf calculated as in equation 9 when +dc is applied, and E_{s1-} is the corrected emf when -dc is applied.

In the computations previously discussed, account is taken of the finite resolution of the ac and dc voltage sources. The voltage setting remains unchanged if the output emf of the test TVC is close enough to the set-point voltage (E_{set}) that a least-significant-digit change in the voltage in the voltage source's output will provide no decrease in the magnitude of the calculated difference, dE_t.

A test run consists of four determinations of ac/dc difference and the average of the four determinations is calculated and printed on the system's printer. In general, three runs are normally made at each test voltage and frequency.

In order to increase the reliability of the emf measurements made by the DVM, and, therefore the reliability of the results, a unique measurment procedure is used. The procedure is necessary to compensate for instabilities in the ac or dc voltage sources or linear drifts in the standard or test TVCs. After the dc reset voltage V_r has been applied to the test TVC, five readings of its emf are obtained as illustrated in Fig. 3. The standard's average emf is obtained next by taking ten readings of its TE emf. If the standard deviation of an observation of the ten readings is > 300 nV, (300 nV = 17 ppm for a 10 mV TE emf with n = 1.8) the first reading is discarded and an eleventh reading is taken. The average of readings two through eleven is calculated and the standard deviation test limit again applied. The process continues until the average of any ten consecutive readings passes the standard deviation limit test. Up to ten attempts are made to obtain an average emf value with a standard deviation of an observation $\leq$ 300 nV. The test is aborted if the tenth attempt is unsuccessful.

When the ten reading average of the standard's emf is within the standard deviation test limit, five readings of the test TVC's emf are again obtained. As illustrated in Fig. 3, the average test TVC's emf is calculated as

$$E_t = \frac{E_{t1} + E_{t2}}{2} \quad . \tag{12}$$

where E_{t1} is the average of the first of the five test emfs, and E_{t2} is the average of the second of the five test emfs. The value of E_t obtained from equation 12 is used to calculate dE_s using equations 5, 7, and 8.

As the preceding equations show, the values of the exponent n for both the test and standard TVCs must be known. The exponent varies with applied voltage, and its variation can be determined by doing "n-tests." These tests will be discussed in the next section. For the standard TEs, the coefficents in the equation expressing the value of n as a function of output emf are stored in a data file in the system software. Once the operator has specified which standard TE is being used, the standard TE's output emf is measured with a +dc voltage applied, and the value of n_s is automatically computed. The values of the test TE's coefficients for n must be manually typed into the computer at the beginning of a test. To guard against mistakes in entering data, the computed values of n for the test TE must be within the limits 1.4 to 2.1.

An additional safeguard is contained in the ac/dc difference program to avoid application of voltages great enough to damage the TEs. When the reset voltage, V_r, is calculated, its value must be less than 120 percent of the rated voltage of the TVC. If the calculated reset voltage is outside this limit, the program aborts.

2.3 Other System Capabilities

2.3.1 AC Voltage Calibrations

As mentioned above, the system can readily be used to calibrate ac voltage calibrators using TVCs with known ac/dc differences. The output voltage of the test calibrator replaces the output voltage of the system's ac source, and the test calibrator's correction can be determined in terms of a calibrated dc source and the known ac/dc differences of the standard voltage converters used.

The correction to the test calibrator (in ppm) is

$$C_t = \frac{E_a - E_d}{nE_d} + \delta_s + C_{dc} \ , \tag{13}$$

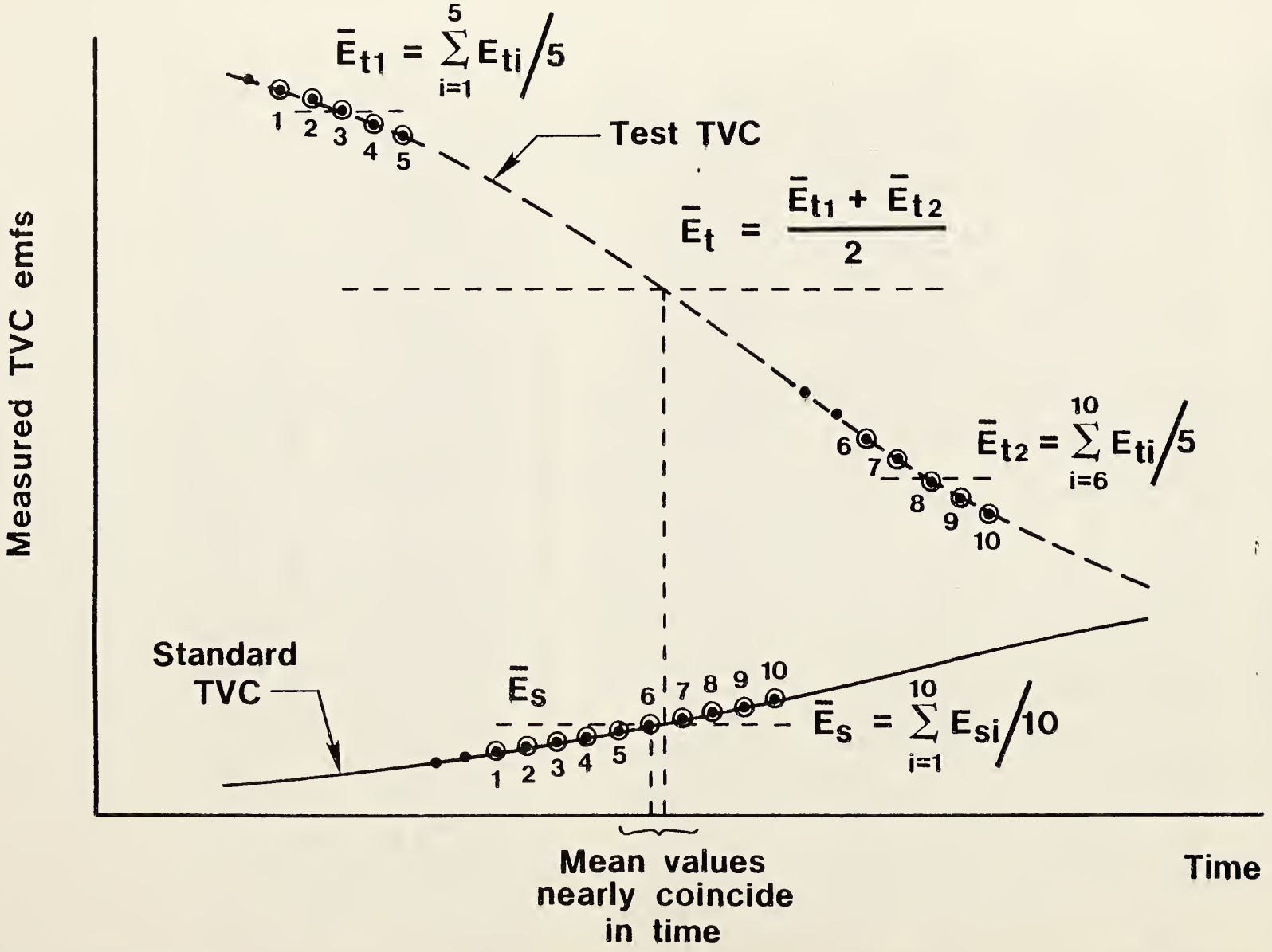


Figure 3. Present measurement procedure for obtaining average values of TVC emfs that compensates for drifts and obtains nearly simultaneous values for the mean values.

where E_a is the average of the measured emfs of the TVC with ac voltage applied, E_d is the average emf with direct voltage of both polarities applied, n_s is as previously defined, δ_s is the correction (in ppm) to the standard, and C_{dc} is the correction (in ppm) to the dc voltage source's nominal output obtained from calibration data. As in the case of ac/dc difference tests, the correction is in ppm if E_a-E_d is in nanovolts and E_d in millivolts. A simplified block diagram of the system connected for such an application is shown in Fig. 4.

For ac calibrations a program called ACCAL is used (see Table 4, Appendix B). As illustrated in Fig. 4, only one TVC is required and, as for ac/dc difference tests, the ten reading sequence of the TE's output emf is used (cf. $\overline{E}_s$ of Fig. 3). However, a different sequence of applying voltages to the TVC is used. The voltages are applied successively as ac_1, +dc, ac_2, -dc, and ac_3. The standard TVC's n coefficient is calculated using the TE average output emfs measured with +dc and -dc applied. A first correction, δ_1, is then calculated using

$$C_1 = \frac{\frac{(E_{a1} + E_{a2})}{2} - E_{d+}}{nE_d} , \qquad (14)$$

where $E_d = \frac{E_{d+} + E_{d-}}{2}$, and the other terms are as defined above. A second correction is computed as

$$C_2 = \frac{\frac{(E_{a2} + E_{a3})}{2} - E_{d-}}{nE_d} , \qquad (15)$$

and finally, the first average correction, C_{t1}, is computed as

$$C_{t1} = \frac{C_1 + C_2}{2} . \qquad (16)$$

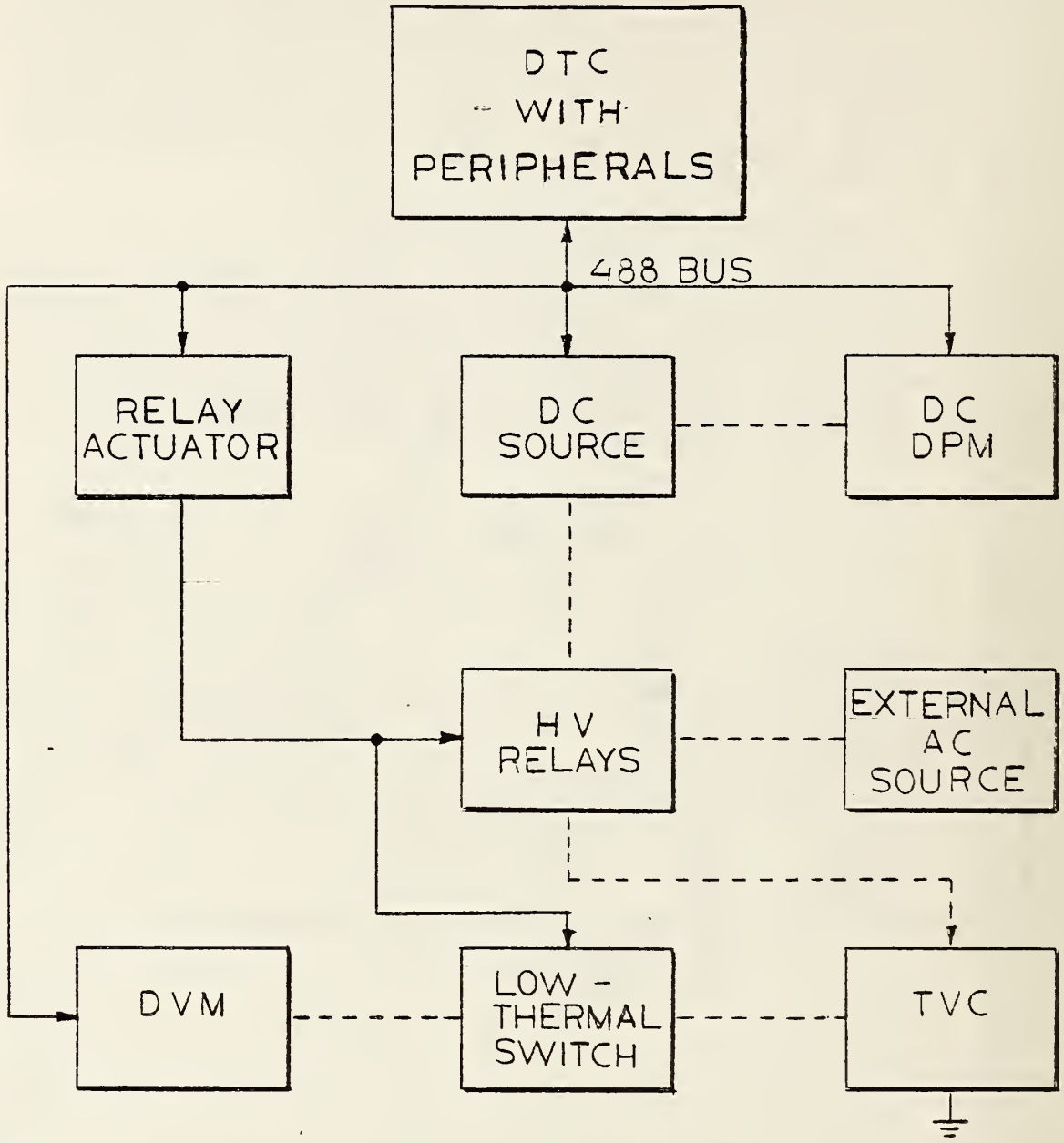


Figure 4. Block diagram of system when used to calibrate an external ac source.

As for ac/dc difference tests, four determinations constitute a test run. The average correction C_t of equation 13 is computed as

$$C_t = (C_{t1} + C_{t2} + C_{t3} + C_{t4})/4 + \delta_s + C_{dc} \quad . \qquad (17)$$

This measurement technique is very useful also for calibrating precision ac DVM's. Since a correction, say C_{t1}, has just been determined for the ac source, the correct ac voltage applied to the standard TVC has just been determined. With a DVM connected at the input of the TVC, the DVM's reading can be recorded, and using the correction C_{t1}, a correction for the test DVM can then be determined.

2.3.2 Stability Tests

To control the variability in the test data, it is important to make sure that the voltage sources are quite stable. Thus, a progam called STABLE was written which uses the system's DVM to measure the stability of the voltage sources with time. Figure 5 illustrates typical stability test data for the dc source. At a nominal setting of 10 V, 20 voltage readings were taken over a time interval of about 20 minutes. The deviation of the measured voltage (in ppm) from the nominal voltage is defined as

$$\frac{\Delta V}{V} = \frac{V_1 - V_2}{V_2} \times 10^6 \quad , \qquad (18)$$

where V_1 is the measured value, and V_2 is the nominal value. The maximum deviation measured was 1.3 ppm and the mean deviation was 0.6 ppm. The standard deviation of an observation was 0.5 ppm, and the 3σ limits for the mean were ± 0.3 ppm. The results indicate that the dc source has acceptable stability and is well within its specified accuracy of 50 ppm.

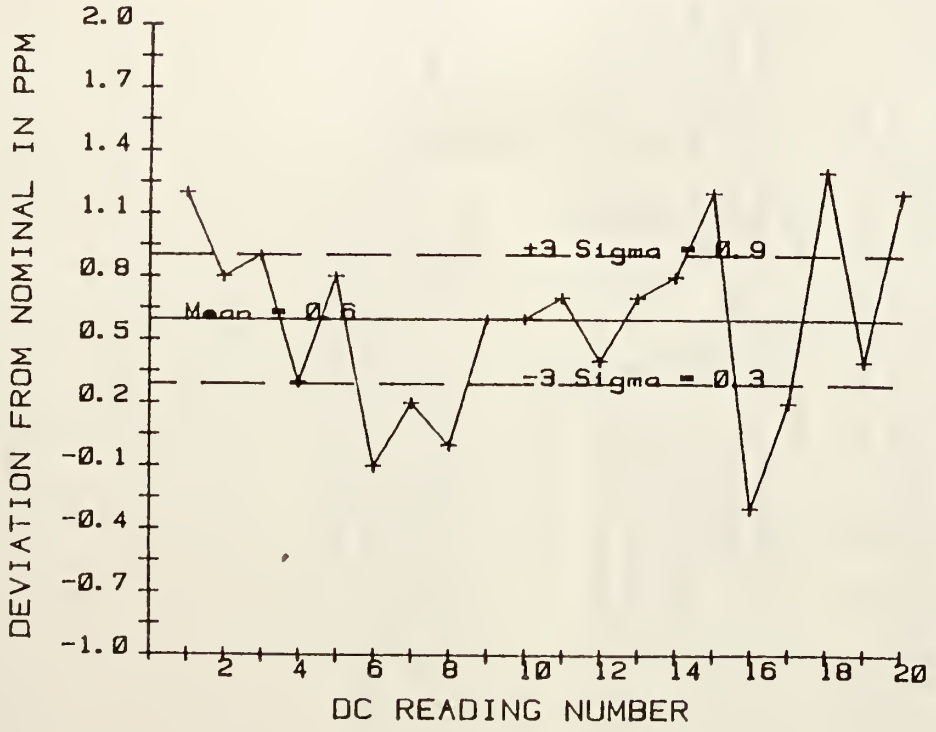
Typical results for a test of the ac source's stability are also shown in Fig. 5. Again, 20 readings were obtained during a 20-minute time interval. The test voltage was 10 V at a frequency of 20 kHz. Here the range of deviations was 40 ppm with the mean being 19 ppm. The standard deviation of an observation was 9 ppm, and the 3σ limits for the mean were ± 6 ppm. The discrete 10-ppm steps in the plotted data are due to the fact that the system DVM's resolution on its 10-V range is limited to 10 ppm.

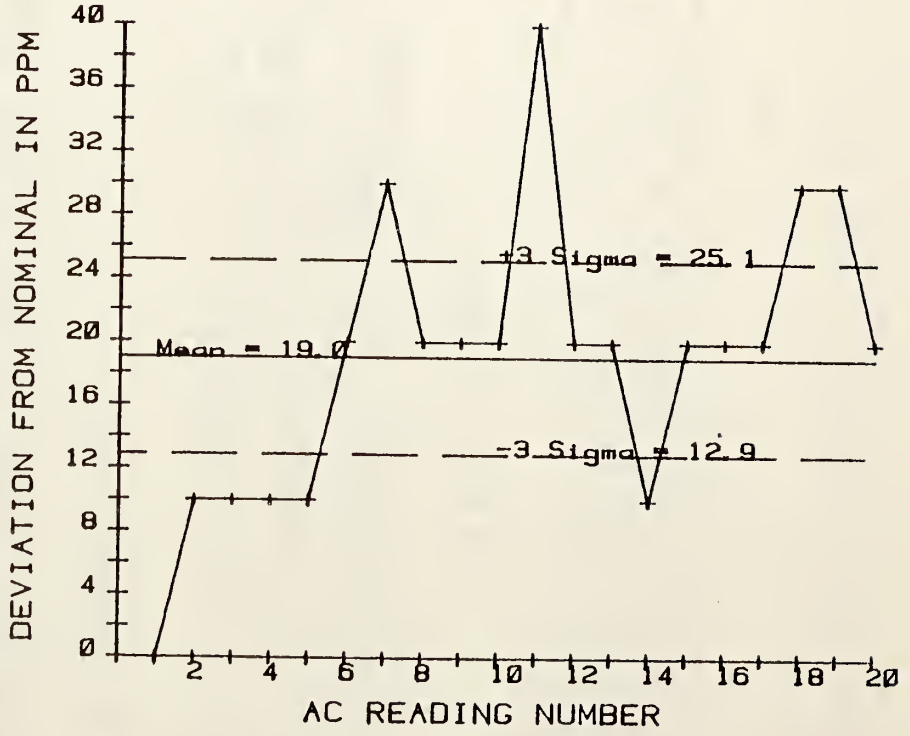
2.3.3 TE Tests

As mentioned in the previous section, one important test that is readily performed automatically is that of determining a TE's "n" characteristic. Typical results for a 2.5-mA, VHF-type TE which was tested with a nominal 3-V range resistor are illustrated in Fig. 6.

STABILITY TEST

OBSERVER: 001 DATE: 01 APRIL 1981 NUMBER OF READINGS: 20





DC: MIN =-0.3 MAX = 1.3 RANGE = 1.6

AC: MIN = 0 MAX = 40 RANGE = 40

NOMINAL VOLTAGE = 10 V FREQUENCY = 20 kHz TIME DELAY = 0 s

TOTAL TIME ELAPSED FOR STABILITY TEST = 0 h 20 min 51 s

Figure 5. Plots from stability testing program.

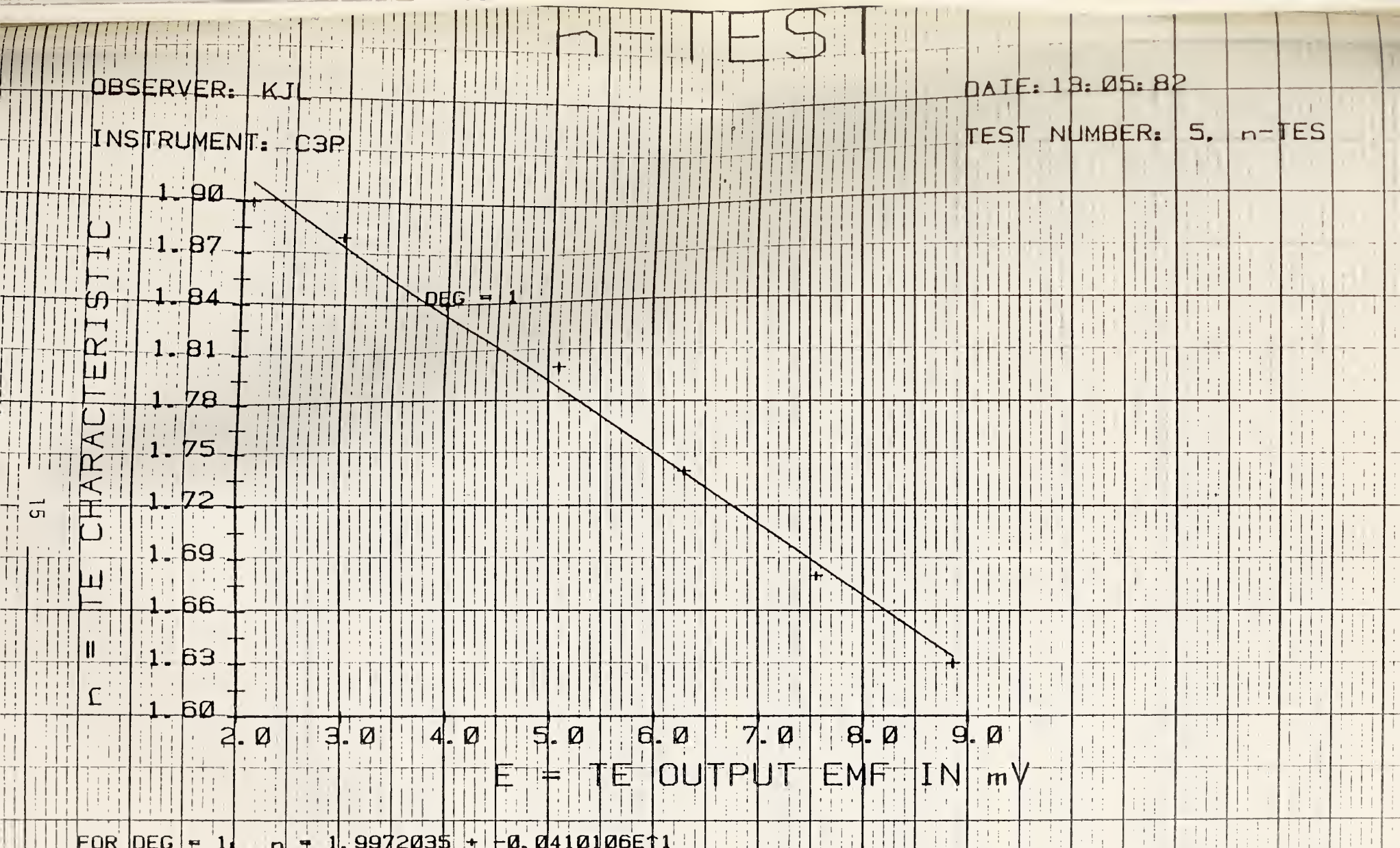


Figure 6. Plot from n test curve fitting program.

The characteristic n is defined by

$$n = \frac{\Delta E/E}{\Delta V/V} , \qquad (19)$$

where ΔE is the measured change in output emf for small changes in applied voltage ΔV, V is the nominal test voltage for the TVC, and E is the measured emf at the nominal test voltage. ΔV is programmed to be ± 0.5 percent of nominal test voltage V. Sufficient time is allowed after each voltage change for the TE to reach its final emf value.

For the results shown in Fig. 6, the TVC was tested from 50 to 110 percent of rated voltage. The total elapsed time to obtain the seven data points was about 1.25 hours.

Each value of n is computed as the average of four determinations at any given voltage. A least-squares analysis of the data provides the option of obtaining a fitted curve using up to a fourth-degree polynomial. An analysis of variance table and residual standard deviation are computed and printed so that the "goodness-of-fit" of the computed equation for n as a function of TE output emf can be determined. The printed data sheet also shows the values of n(measured) - n(computed). The figure shows an example of a linear fit which, in most cases, provides sufficient accuracy. The coefficients 2.00 and -0.04 are either stored in the computer's data file (for a standard TE) or are typed by the operator into the computer program for the TE under test at the beginning of an ac/dc difference test.

The dc reversal difference (DCRD) of a TE can also be readily determined. DCRD is defined as the difference in applied values of both polarities of dc voltage required to produce an equal output emf (or "constant output") of the test TE [7]. In order to facilitate DCRD measurements, "constant input" emf, α, is actually measured. This α is related to the DCRD by a factor of 1/n as

$$DCRD = (1/n)(\alpha) = (1/n)\ \frac{E_+ - E_-}{(E_+ + E_-)/2} , \qquad (20)$$

where E_+ and E_- are the TE output emfs with equal +dc and -dc (or "constant input") voltages applied, and n is as previously defined.

During acceptance tests of some TEs, the data showed much greater variation of DCRD from unit to unit than had been expected. The only information available indicated that the DCRD should reach a maximum value between 70 and 80 percent of rated heater current and should approach a zero value close to 100 percent of rated current. The results obtained did not

substantiate this information. Hence, a program was written to determine the DCRD as a function of applied voltage. Typical results for a 5-mA, UHF-type TE tested with a 60-V range resistor are shown in Fig. 7. In this test the voltage was varied from 50 to 120 percent of its rated value in 2-percent increments. It should be noted that the plotted data show α; hence, the DCRD values referred to a constant output emf would be smaller by the factor of n (see equation 15). In this test, the maximum α was about 700 ppm at 58 percent of rated voltage, and the minimum was about -330 ppm at 120 percent of rated voltage.

At the time the DCRD testing program was developed, the information on DCRD variation was limited. However, in the intervening time Inglis [9] has published a substantial amount of information in this area. Investigations at NBS have not been as extensive as those of Inglis, but, in general, the results obtained are in agreement with his published data.

The response time of a TE is also a characteristic which can readily be measured using the automatic system. Response time is obtained by making measurements of a TE's emf when full rated voltage is suddenly applied to the TE. The calculated response time, t, is the time taken for the output emf to reach 1 - (1/e) of its final value. Typical results for a 2.5-mA, VHF-type TE are shown in Fig. 8.

For the interested reader, detailed documentation (see Appendix C for an example) is available upon request for most of the automatic test programs which are described in this report.

3. MEASUREMENT RESULTS AND UNCERTAINTIES

Manual calibration systems have been in operation for many years at NBS, and their uncertainties have been documented [1-3]. DC reversal difference, self-heating and ambient temperature effects, drift effects due to nonequal time intervals between emf measurements, unbalanced lead impedances, induced voltages from electromagnetic fields, and operator fatigue and lack of skill are some of the more common sources of error. The process of determining an estimated total uncertainty for a system is based upon 1) a history of measurement results, 2) careful measurements of standards with accurately known corrections, 3) theoretical analysis of sources of errors, along with, preferably, 4) intercomparison tests using two independent test methods [3]. A combination of processes 2 and 4 was used for the initial evaluation of the present automated system. The primary emphasis was placed on comparison of results obtained with a well-characterized manual system and those obtained with the new system.

A single-range (3-V), coaxial-type TVC was tested using established manual techniques, followed by tests on the automated system. The results obtained from the two test systems are shown in Table 1.

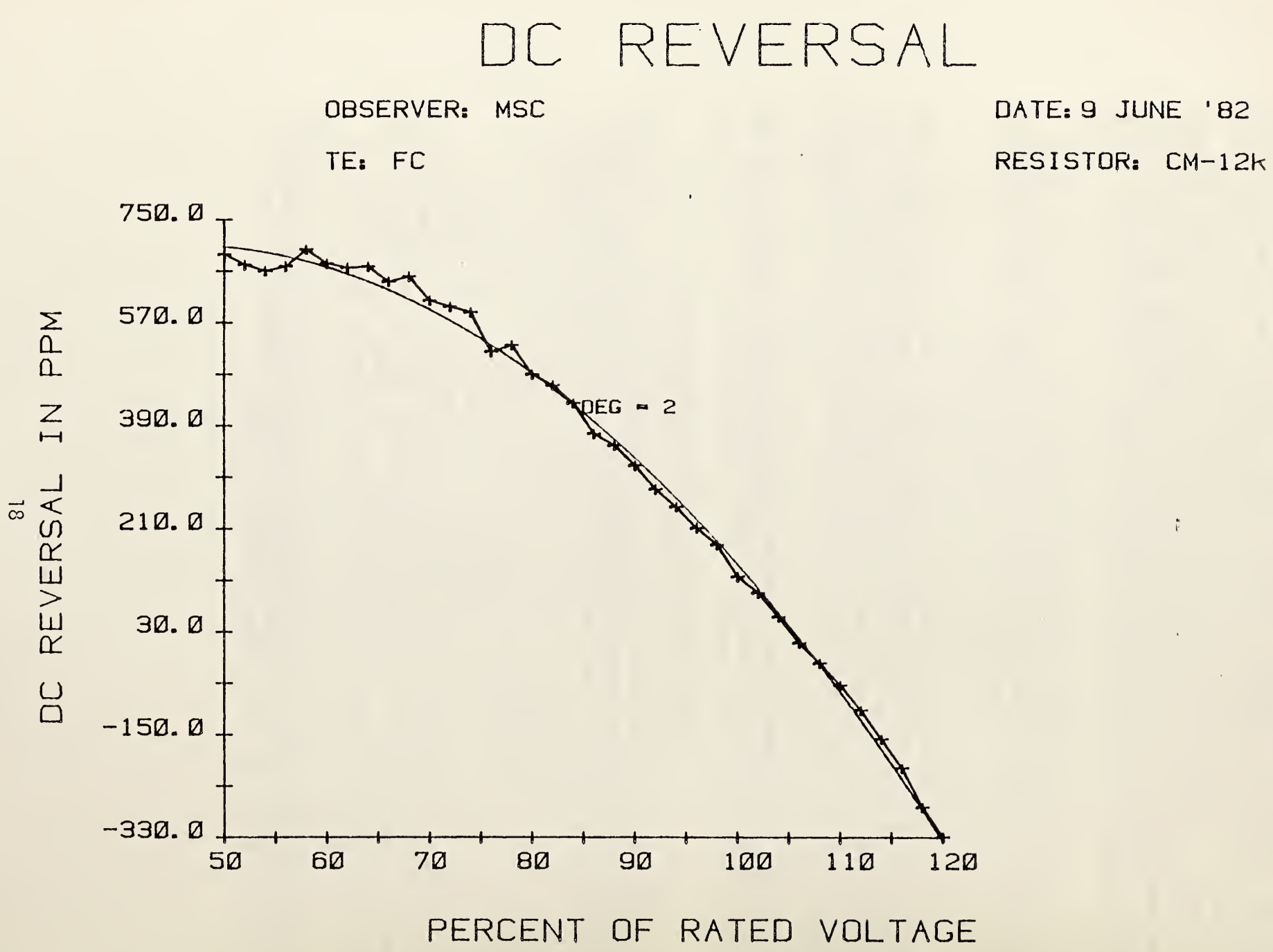


Figure 7. Plot from dc reversal difference program.

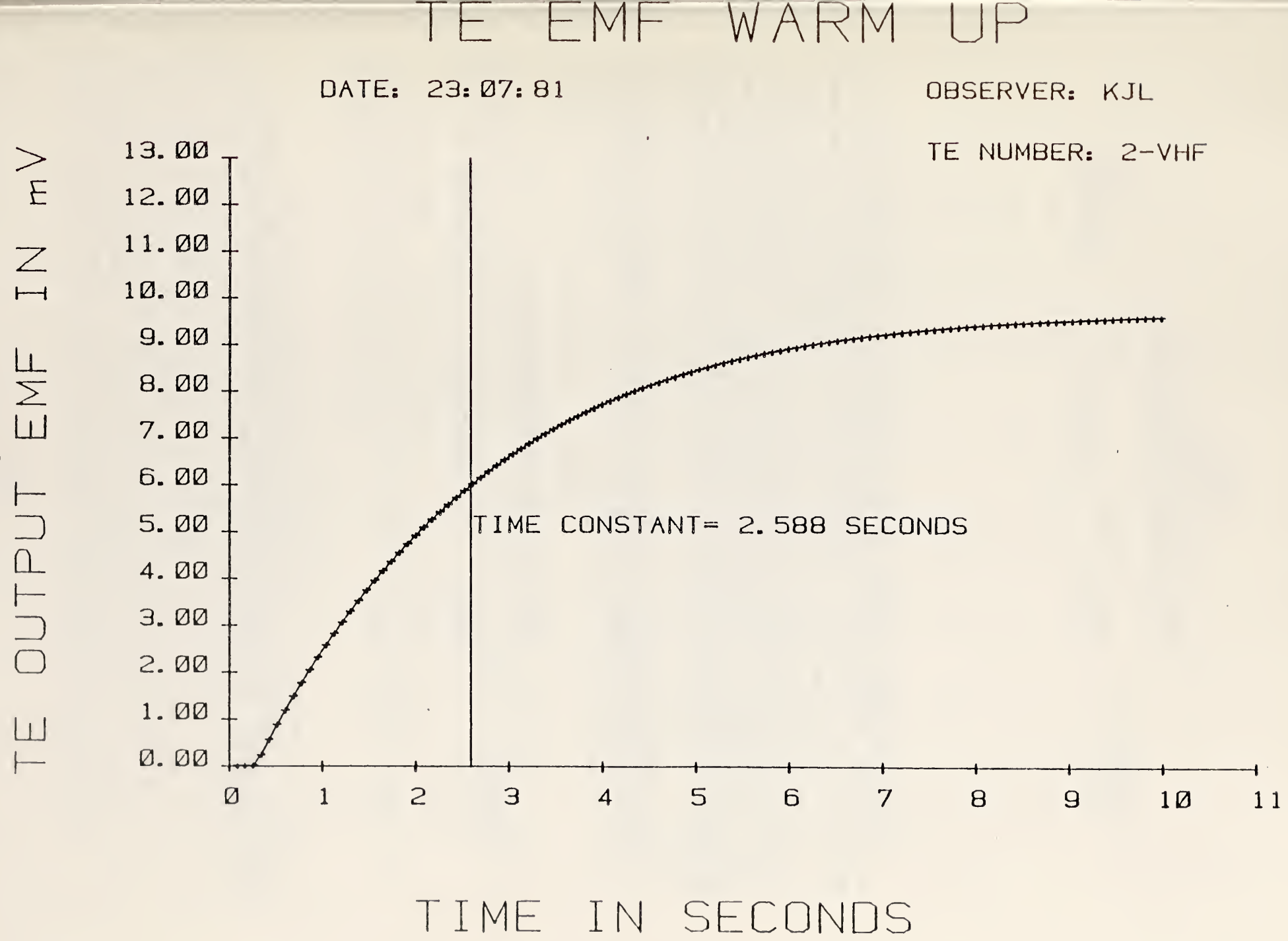


Figure 8. Plot from TE thermal response time program.

TABLE 1

3-V TVC AC/DC DIFFERENCE (ppm)

Frequency kHz	Manual	Automatic	Difference
0.02	0	2	-2
20	1	-9	10
50	-1	-9	8
100	-1	-4	3

For the automatic system, the values reported are the average of 12 determinations of the transfer standard's ac/dc difference. The random uncertainty was calculated as three times the standard deviation of the mean of the 12 observations, with the result that 3σ = 21 ppm for the worst case. For the manual system, three times the standard deviation of a comparison of two TVCs, plus an allowance for systematic errors in the comparison process, ranges from 6 ppm at 1 kHz to 12 ppm at 100 kHz [10]. In each case the differences between the results obtained with the two test methods is less than the combined uncertainties for a comparison of the same TVCs by the two methods.

A second test was made using a 10-V range TVC as a transfer standard. The test results are listed in Table 2.

TABLE 2

10-V TVC AC/DC DIFFERENCE (ppm)

Frequency kHz	Manual	Automatic	Difference
20	-4	-17	13
50	-3	-7	4
100	-1	6	-7

Both the 3-V and 10-V TVC transfer standards had small ac/dc differences. Therefore, a third intercomparison test was conducted using a transfer standard with large, but accurately known differences. The results of this test are listed in Table 3.

TABLE 3

50-V TVC AC/DC DIFFERENCE (ppm)

Frequency kHz	Manual	Automatic	Difference
5	29	26	3
10	56	52	4
20	121	121	0
50	320	310	10

The test results summarized in the three tables suggest a possible systematic uncertainty since the automatic system gave lower values for all but three test frequencies. Further investigation is required to evaluate whether or not this uncertainty is significant.

As was mentioned previously, the results reported are initial intercomparison tests. Neither sufficient tests were run nor data obtained to come to any definite conclusions regarding the systematic or random uncertainties of the automatic test system. However, since the difference of the ac/dc difference measurements for the three voltage converters tested did not exceed ±15 ppm, it appears that the new system should be able to achieve total uncertainties much less than had originally been anticipated. Further testing will be done to verify this hypothesis. Such testing will include a "build-up" process from a reference voltage of 10 volts to about 200 V at various frequencies. Also, a "step-down" testing process from the 10 V level to about 2 V will be performed.

In order to investigate the effects due to random uncertainties, repeat tests need to be done each day, for several tests. Analysis of the data from the replicated tests should provide statistical information on the "within day" and "between day" test data variability.

In any event, the small magnitude of the differences obtained in the intercomparison tests are significant in that each TVC transfer standard was tested on two completely different calibration systems using different converters as the reference standard.

4. CONCLUSIONS

The results indicate that it is feasible to make fully automatic precision ac/dc difference measurements at any one voltage. The principal advantage of the system is the elimination of the need for any type of manually- or automatically-balanced TE comparator, permitting the system to be assembled using commercially available instrumentation, except for the switching modules. This approach, therefore, should make automation attractive to many calibration laboratories faced with the need to make ac/dc difference measurements. Moreover, the system can be used as a nearly self-calibrating meter calibration system. Measurements can be done with minimal operator intervention, eliminating tedious and fatiguing manual

operations. Hence, personnel presently engaged almost exclusively in manual ac/dc difference tests can be freed to do other work. Experience gained during many years of testing with manually operated systems at NBS has shown that the precision of the test results is dependent upon operator skill. The automatic system's precision is independent of operator skill, elminating this variable in the experimental uncertainty.

5. ACKNOWLEDGEMENTS

The authors are indebted to M. S. Carter who wrote much of the software and solved many difficult programming problems encountered in developing the system. S. G. Tremaine, L. Freeman and E. V. Byland also made valuable contributions to some of the programs which have become part of the total system software. C. B. Childers helped greatly by doing the measurements on the manual system.

6. REFERENCES

[1] F. L. Hermach, E. S. Williams, "Thermal Converters for Audio-Frequency Voltage Measurements of High Accuracy," IEEE Trans. Instrum. Meas., Vol. IM-15, pp. 260-268, Dec. 1966.

[2] E. S. Williams, "Thermal Voltage Converters and Comparator for Very Accurate AC Voltage Measurements," J. Res. Nat. Bur. Stand. (U.S.), Vol. 75C, pp. 145-154, Dec. 1971.

[3] F. L. Hermach, "AC-DC Comparators for Audio-Frequency Current and Voltage Measurements of High Accuracy," IEEE Trans. Instrum. Meas., Vol. IM-25, pp. 489-494, Dec. 1976

[4] R. S. Turgel, "A Comparator for Thermal AC-DC Transfer Standards," ISA Trans., Vol. 6, No. 4, pp. 286-292, 1967.

[5] K. J. Lentner, et al, "A Semiautomatic System for AC/DC Difference Calibration," IEEE Trans. Instrum. Meas., Vol. IM-29, pp. 400-405, Dec. 1980.

[6] E. W. Williams, "A Thermoelement Comparator for Automatic AC-DC Difference Measurements," IEEE Trans. Instrum. Meas., Vol. IM-29, pp. 405-409, Dec. 1980.

[7] K. J. Lentner, S. G. Tremaine, "A Semiautomatic AC/DC Thermal Voltage Converter Calibration System," NBSIR 82-2576, Sept. 1982.

[8] "American National Standard for AC-DC Transfer Instruments and Converters," NASI C100.4 - 1973, Amer. Nat. Stand. Inst., Inc., 1430 Broadway, New York, NY 10018.

[9] B. D. Inglis, "Errors in AC-DC Transfer Arising From a DC Reversal Difference," Metrologia, Vol. 17, pp. 111-117, 1981.

[10] F. L. Hermach, "Analysis of Uncertainties of NBS Thermal Voltage and Current Converters", NBSIR 84-2903 (In Press).

APPENDIX A

System Equipment List

The use of trade names or company products does not constitute endorsement or recommendation by the National Bureau of Standards, and does not imply that the products named are necessarily the best available for the purpose.

1. Computer and peripherals

   a. Hewlett-Packard 9825T Desk Top computer (with 64 kbytes of memory)
   b. Hewlett-Packard 98034A 488 interface (2 each)
   c. Hewlett-Packard 98035A real time clock with options 002 and 025
   d. Hewlett-Packard 9866B option 025 thermal printer
   e. Hewlett-Packard 9872B option 025 plotter
   f. Hewlett-Packard 98036A serial interface with 98241 test adapter
   g. Hewlett-Packard 9878A I/O expander
   h. Hazeltime 1500 video display terminal
   i. Hewlett-Packard 98226A printer cradle
   j. Hewlett-Packard documentation software PN 09825-10020
   k. Hewlett-Packard statistical software PN 09825-15030
   l. Hewlett-Packard 59300-10001 HPIB verifications cassette with service notes 5312A-2 and 59306A-4
   m. Hewlett-Packard 59405-66503 HPIB test card
   n. Hewlett-Packard I/O extender board assembly PN 98124-67901

2. Tektronix P6007100 probe PN 010-0165-00 (shown as 100/1 attenuator in Fig. 1.

3. Hewlett-Packard model 3438 Digital Multimeter, option 15 with rack flange kit, PN 5061-0074, (2 each, shown as DPM in Fig. 1)

4. a. Hewlett-Packard 5300B counter mainframe with service note 5300B-1
   b. Hewlett-Packard 5301 10 MHz counter module with service note 5301A-1
   c. Hewlett-Packard 5312A HPIB interface module
   d. Hewlett-Packard 10853A rack mount kit for 5300B counter
   e. Hewlett-Packard 10548A service support package with service note 5300B-1

5. a. Hewlett-Packard model 59306A relay actuator (2 each)
   b. Rack mount kit, PN 5061-0094
   c. Rack flange kit, PN 5061-0074

6. a. Guildline Model 9577 precision digital voltmeter (shown as DVM in Fig. 1)
   b. Option 03 three terminal input lead (2 each)
   c. Option 07 low thermal lead kit
   d. Input connectors (2 each no part number)

e. Option 08 service manual
f. Option 09 service kit
g. Option 10 calibration cover
h. Option 11 488 interface

7. a. Electronic Development Corporation (EDC) model 501J rack mount dc voltage calibrator with minimum 25 mA current output
b. Option B, sixth decade
c. Option C, standby/ready signal
d. Option D, 100 mV range
e. Option J, bipolar operation
f. 488 interface kit, PN KT-48
g. Option AM-1, manual control panel and display (BCD)

8. EDC, model RA4 high voltage amplifier with 1kV output at 25 mA minimum current

9. a. John Fluke Manufacturing Co. 5200A Programmable AC Calibrator and 5205A Precision Power Amplifier
b. Option 05, 488 interface for 5200A
c. Rack kit for 5200, PN M07-205-600
d. Rack kit for 5205, PN M10-205-600

10. Low-Thermal-Emf switching module (NBS design)

11. High-Voltage-Relay switching module (NBS design)

APPENDIX B

Major Programs

In this appendix, a list of the major programs used in the ATS is given. A brief explanation of the purpose of each program is also given. Detailed documentation, such as the example given in Appendix C, is available for most of the programs. A summary of the programs is given in Table 4.

1. Program name: STABLE

STABLE is a program which is used to check the stability of the system's dc and ac sources. These stability tests are useful to determine whether or not the sources are functioning properly. Occasionally, ac/dc difference test results appear to be erratic, and the stability tests are a convenient method to ascertain whether the erratic results may be due either to the ac or dc source, or both. Stability of the sources is measured by using the system's real time clock and DVM whose function, reading rates, and ranges are remotely controlled. The program computes the deviation from nominal voltage in ppm, and prints the values of measured voltage and the deviation.

When a stability test is complete, the operator has the option of plotting the measured deviations as a function of time using a program named PLOTTER.

2. Program name: n-TEST

As discussed in the text, this program is used to determine a TE's dimensionless characteristic "n." To determine the equation for "n" as a function of TE output emf, (in mV), a program called "STATIS" is loaded and executed at the end of an n-test. The operator has the option of obtaining up to a fourth-order polynominal equation using a least-squares curve fitting algorithm. A plot of the actual measured n versus TE emf and the fitted curve can also be obtained as an option.

3. Program name: DCRD

This program is used to determine a TE's dc reversal difference as defined by eq (16) of the text. The operator has the option of testing at any one fixed value of a TE's heater current. Both the constant input and constant output values of dc reversal difference are computed. Finally, the response time of the test TE is determined. Response time is defined as the time it takes for the TE to reach 63.2 percent of its final (99 percent level) emf when full rated heater current is applied as a step funtion. If the operator desires, a program called EMF PLOTTER is loaded and executed. This program plots the data obtained during a response time test.

4. Program name: ACCAL

This program is used to calibrate an ac voltage calibrator, whether that of the ATS or an external unit, or a precision DVM. The program is discussed in Section 2.3.1 of the text.

5. Program name: ACDC

This program is used for ac/dc difference testing, and is discussed in Section 2.2 of the text. At the beginning of the test, the operator types into the computer the parameters of test voltage, frequencies, and number of runs per frequency. One run consists of four determinations of ac/dc difference, with each determination and the average of the four values printed. The test is made completely automatically at any one fixed voltage.

Table 4. ATS Software Summary

Program Name	Purpose	Options	Approximate Lines of Code	Approximate No. of Bytes
STABLE	Check stability of ac and dc sources	Repeat; Plotter	400	12,500
PLOTTER	Plot results of STABLE	Replot	150	4,000
n-TEST	Determine n of a TE	Rerun: STATIS; 50-120% rated TVC range:	200	6,800
STATIS	Up to fourth order curve fit of n-TEST data	Repeat: Repeat n-TEST: DCRD: Plot: Replot	200	5,800
DCRD	Measures constant input and constant output dc reversal diff of a TE. Also correct DCRD when n≠2.	Rerun: TIME CNST: DCRD	250	9,000
TIME CNST	Measures response time of a TE	EMF PLOT	30	900
		This program is a subroutine option of DCRD which can be run without doing a DCRD test.		
EMF PLOT	Plots response time data	None	30	900
ACCAL	Calibrate an ac calibrator	Repeat: Delete Data: Change voltage: Change frequency	300	10,000
AC/DC DIFF	Calibrate a UUT for ac/dc difference automatically at one fixed voltage	10 runs/frequency: 20 frequencies/test	550	16,500

APPENDIX C

Typical Software Documentation

Generally, the documentation available for the major programs used in the ATS consists of 1) a narrative description of the program operation, 2) a list and explanation of variables used in the program, 3) a program listing, 4) a listing of variables by program line numbers, and a listing of labelled subroutines, 5) a program flow chart, 6) a list of special function keys (if any are used) and the commands which each key executes, and 7) sample data output.

In this appendix an example of the documentation for the program called EMF PLOT is presented. The programming language used is the Hewlett-Packard language commonly known as HPL.

EMF PLOT PROGRAM DOCUMENTATION

NARRATIVE PROGRAM DESCRIPTION

EMF PLOT is a program which is called by the program DC REVERSAL WITH TIME CONSTANT to plot the emf values obtained in the time constant turn-on test and to plot the time constant. EMF PLOT can only be used when the maximum emf value obtained in the time constant test is less than or equal to 13 mV, and the time constant is less than or equal to 10 seconds.

The program begins by opening all relays and clearing the IEEE 488 bus, which were used in DC REVERSAL WITH TIME CONSTANT. A message is then displayed instructing the operator to load the plotter paper before continuing. The plotter select code is set to 805 and a plotter clear is executed to reset the plotter to its default values. The scale is then set.

Pen number four (blue) is selected before the labeling begins. The plotter then labels the graph using the observer's name, the date, and the TE number input in DC REVERSAL WITH TIME CONSTANT. Pen number one (black) is then selected to draw and label the X- and Y-axes. A character size of one is executed, and pen number three (red) is selected to plot the points.

The loop which plots the emf value vs the time of the reading in seconds is initialized after the first point is plotted. The points are plotted until one of two conditions is met, either 17 points have been plotted, or the time and emf value are equal to zero. When either of these conditons is met, control jumps out of the loop. Pen number three (green) is selected, and the time constant value is plotted in the form of a straight line and labeled.

The pen is returned to its holder, an ending message is displayed, and the tape is then rewound.

VARIABLE LIST FOR EMF PLOT

Note: All variables except the simple variables X and R are dimensioned if necessary and assigned values in the program "DC REVERSAL WITH TIME CONSTANT"

SIMPLE VARIABLE	DESCRIPTION
K	Time constant in ms.
R	Loop control variable used to label the X-axis.
X	Loop control variable used to plot the emf values vs. time.

ARRAY	DESCRIPTION
T[*]	Time of emf reading in ms.
U[*]	emf value.

STRING ARRAY	DESCRIPTION
F$	TE number.
H$	Date of test.
N$	Observer's name.

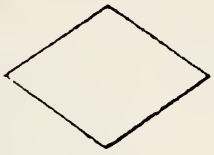
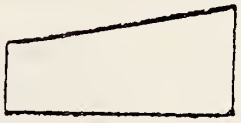
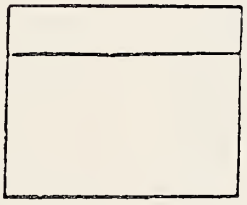
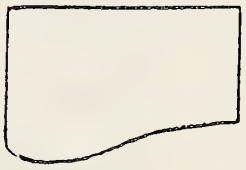
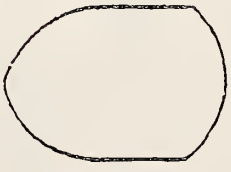
PROGRAM LISTING FOR EMF PLOT.

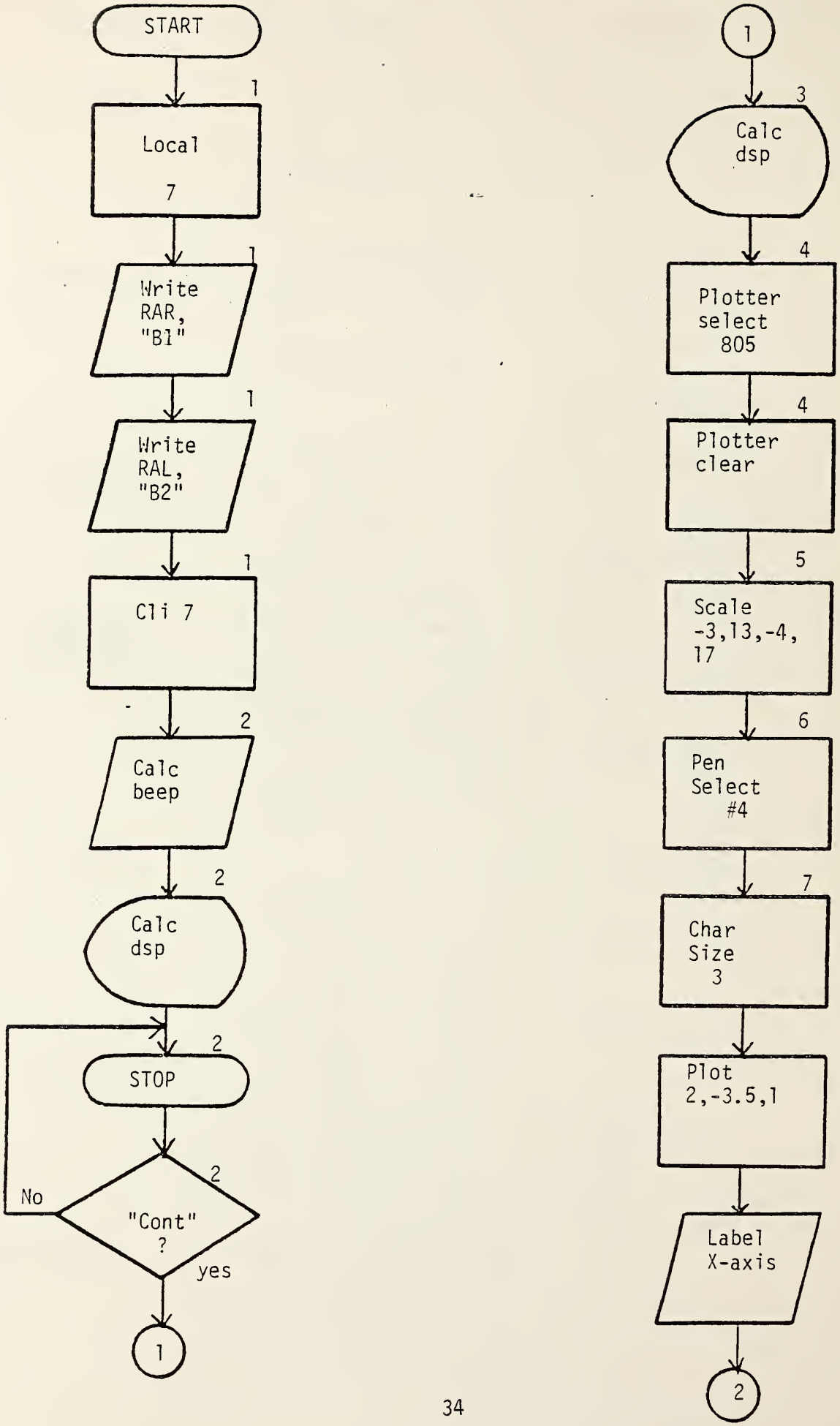
```
 0: 'EMF WARM UP PLOTTER  VERSION 1 MARCH '81. V=4A,T=1,F=17":
 1:    lcl 7;wrt "RAR","B1";wrt "RAL","82";cli 7
 2:    beep;dsp "LOAD PAPER, PRESS CONTINUE";stp
 3:    dsp "WATCH PLOTTER!!"
 4:    psc 805;pclr
 5:    scl -3,13,-4,17
 6:    pen;pen# 4
 7:    csiz 3;plt 2,-3.5,1;lbl "TIME IN SECONDS"
 8:    csiz 3,2,1,90;plt -2,-.2,1;lbl "TE OUTPUT EMF IN mV"
 9:    csiz 4;plt 2,15.5,1
10:    lbl "TE EMF WARM UP"
11:    plt 1,14.3,1;fxd 0
12:    csiz 1.6;lbl "DATE: ",H$
13:    plt 7.5,14.3,1
14:    lbl "OBSERVER: ",N$
15:    plt 7.5,13,1;lbl "TE NUMBER: ",F$
16:    pen# 1;fxd 0
17:    xax 0,1,0,11
18:       for R=0 to 11;plt R-.23,-.8,1;lbl R;next R
19:    fxd 2;yax 0,1,0,13,1
20:    csiz 1;pen;pen# 3;plt T[1]/1000,U[1]*1000,1;pen
21:       for X=2 to 117
22:       if T[X]=0 and U[X]*1000=0;sto 26
23:       plt T[X]/1000,U[X]*1000,2;pen
24:       cplt -.33,-.25;lbl "+"
25:       cplt -.67,.25;next X
26:    pen;pen# 2;plt K/1000,0,-2
27:    fxd 3;plt K/1000,13,-1;plt K/1000,5
28:    csiz 1.6;pen;cplt .2,0;lbl "TIME CONSTANT=",K/1000," SECONDS"
29:    pen# ;beep;dsp "END OF EXECUTION";rew;end

     908 bytes    30153 check sum
```

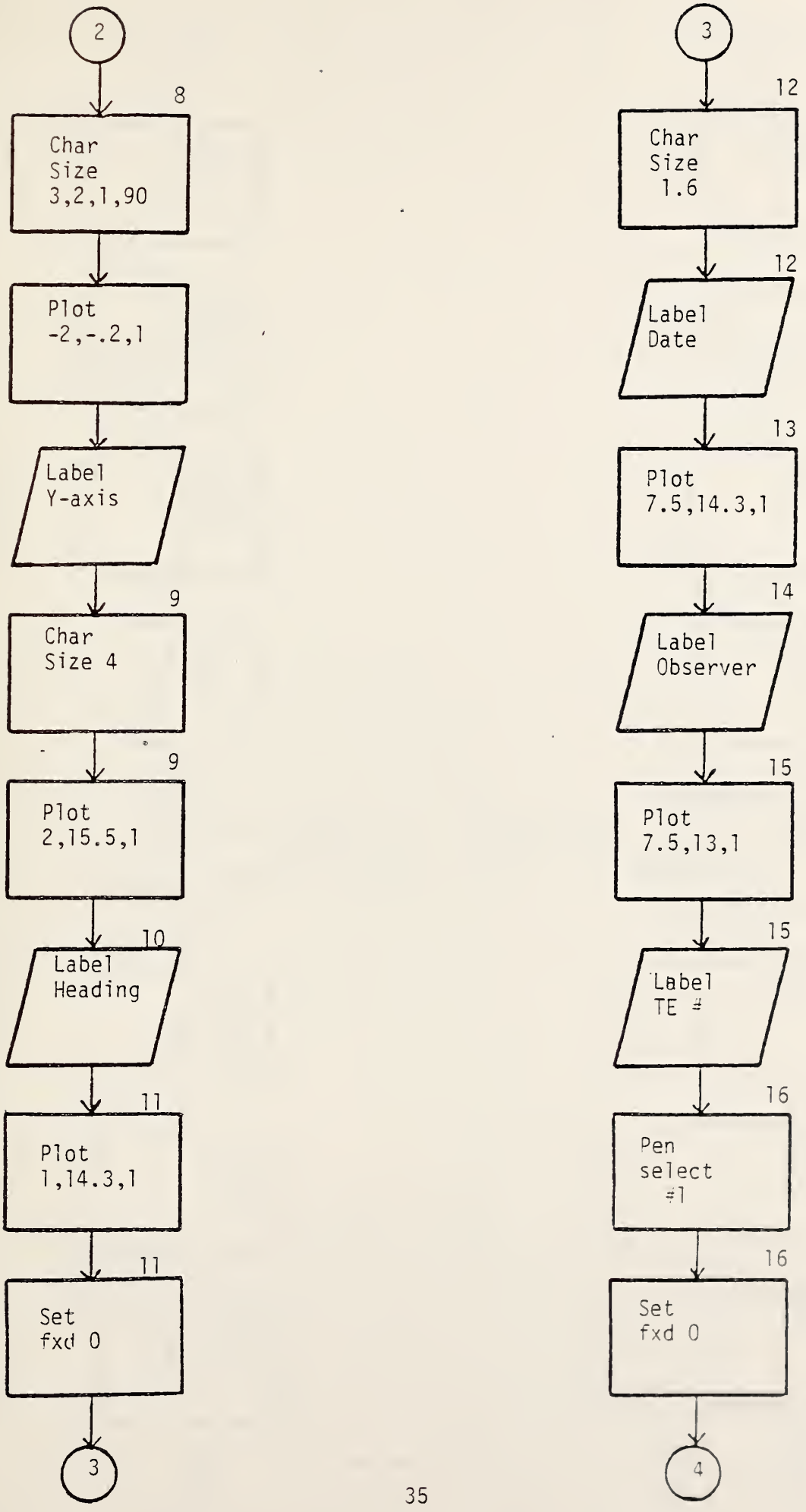
VARIABLE LISTING FOR EMF PLOT.

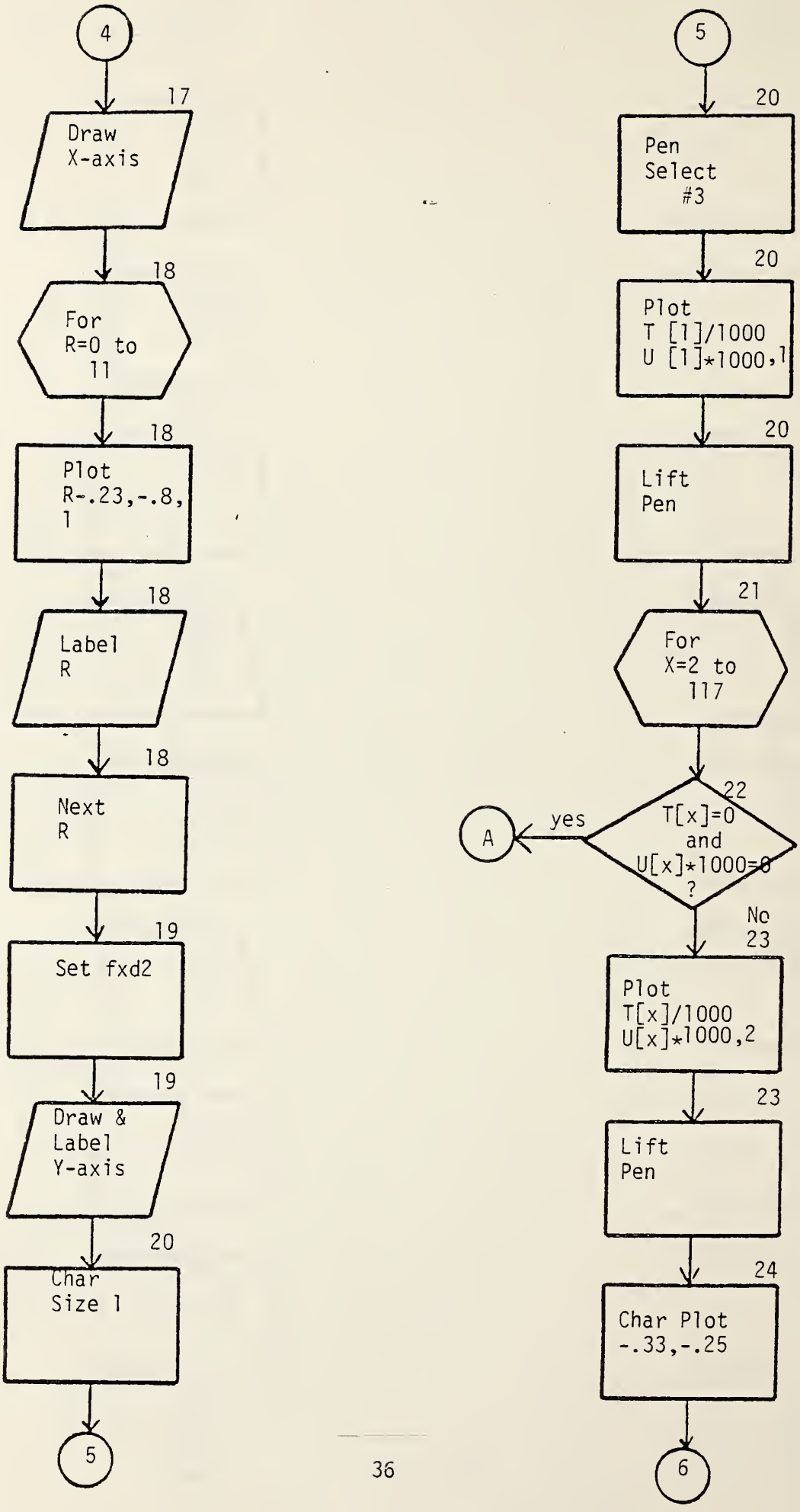
```
K
    26    27    27    28

R
    18    18    18    18

X
    21    22    22    23    23    25

TC
    20    22    23

UC
    20    22    23

F$
    15

H$
    12

N$
    14

 26:
    22
```

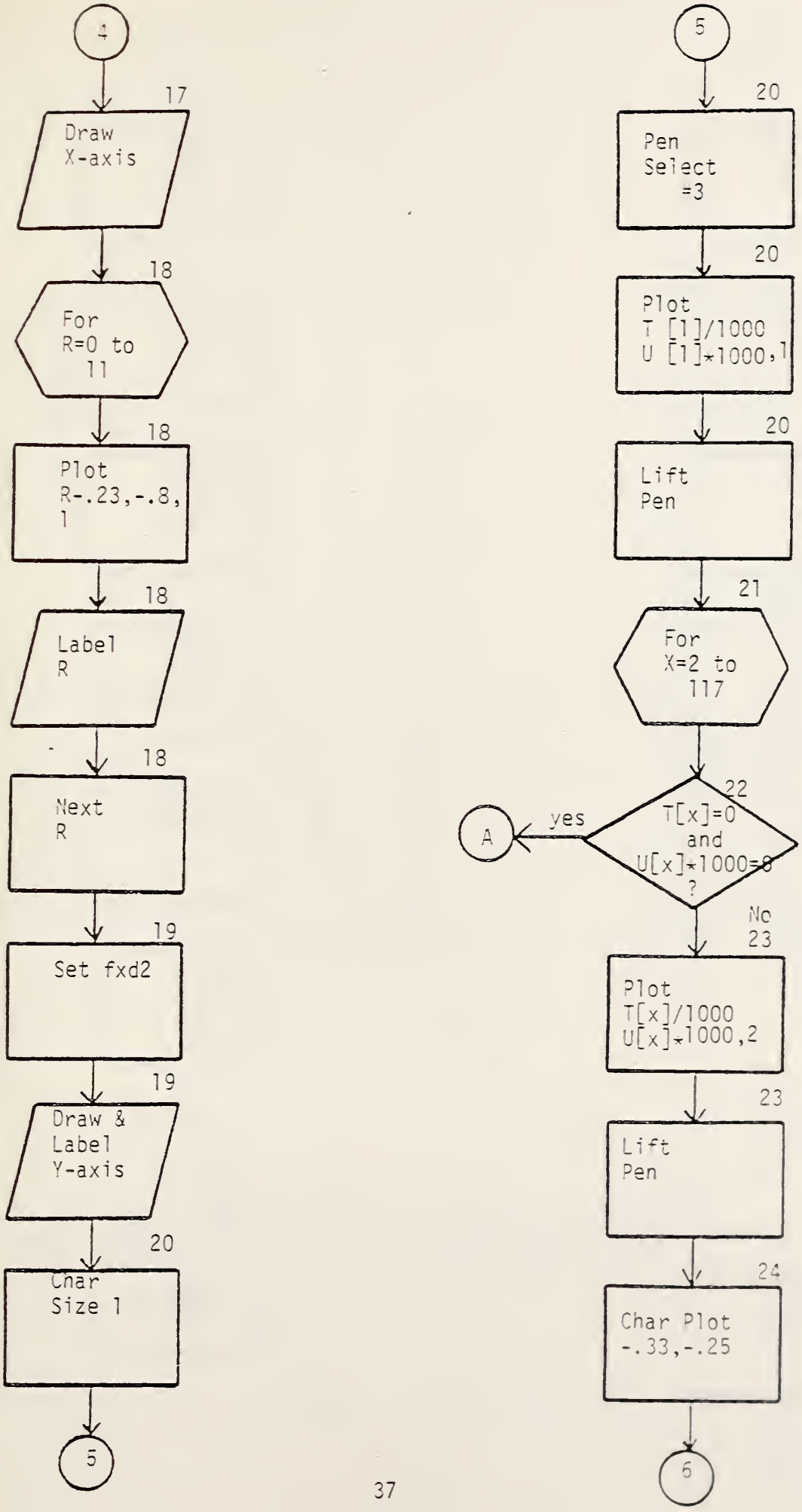
DEFINITION OF FLOWCHART SYMBOLS

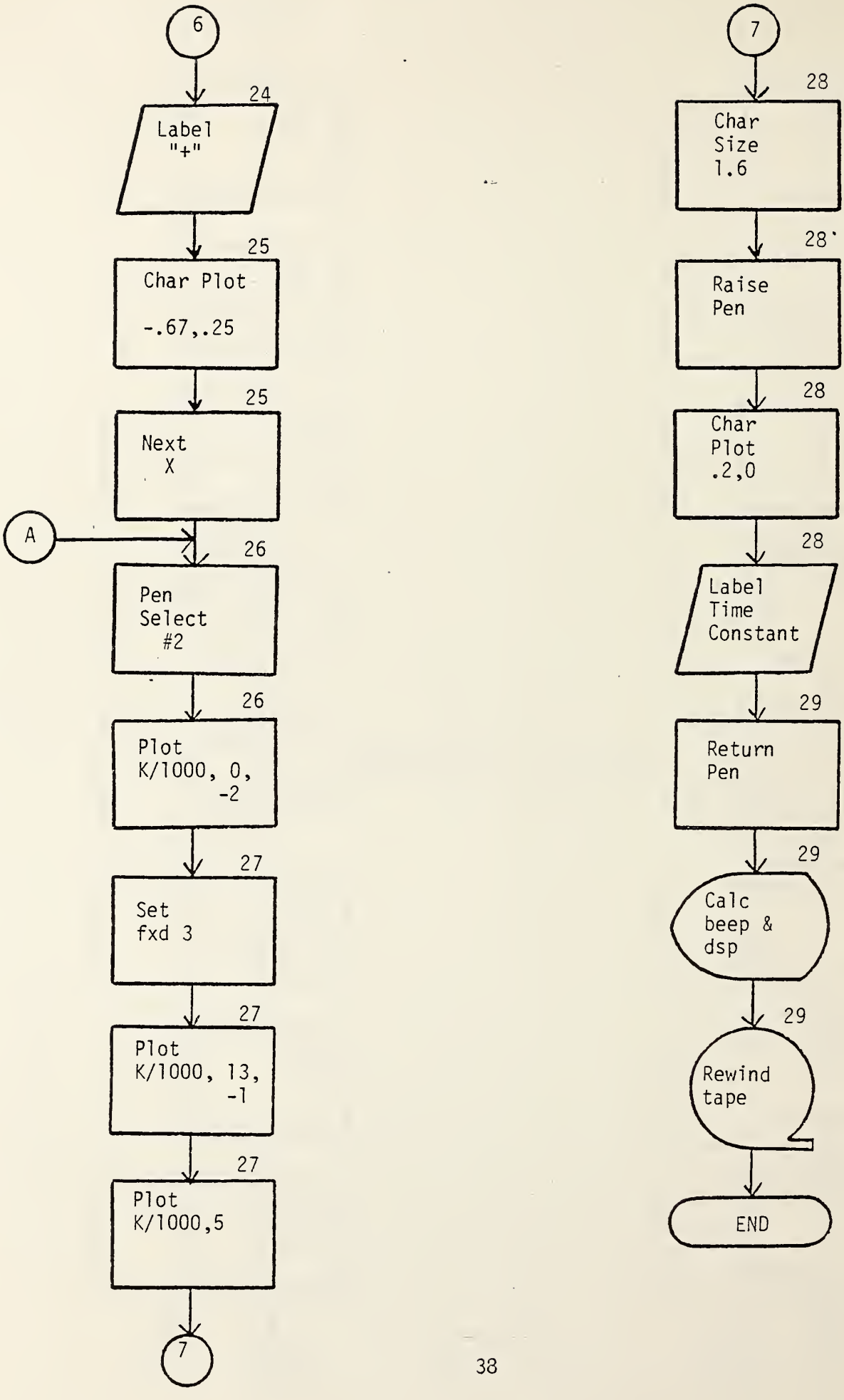
DEFINITION	SYMBOL	SYMBOL	DEFINITION
Terminal			Magnetic Tape
Decision			Preparation
Manual Input			Connector
Process			Auxiliary Operation
Input/Output			Comment
Document			Branching Table
Display			Program Flow


START
1
Local
7
1
Write
RAR,
"B1"
1
Write
RAL,
"B2"
1
Cli 7
2
Calc
beep
2
Calc
dsp
2
STOP
2
No
"Cont"
?
yes
1
1
3
Calc
dsp
4
Plotter
select
805
4
Plotter
clear
5
Scale
-3,13,-4,
17
6
Pen
Select
#4
7
Char
Size
3
Plot
2,-3.5,1
Label
X-axis
2


2
8
Char
Size
3,2,1,90
Plot
-2,-.2,1
Label
Y-axis
9
Char
Size 4
9
Plot
2,15.5,1
10
Label
Heading
11
Plot
1,14.3,1
11
Set
fxd 0
3
3
12
Char
Size
1.6
12
Label
Date
13
Plot
7.5,14.3,1
14
Label
Observer
15
Plot
7.5,13,1
15
Label
TE #
16
Pen
select
#1
16
Set
fxd 0
4


4
17
Draw
X-axis
18
For
R=0 to
11
18
Plot
R-.23,-.8,
1
18
Label
R
18
Next
R
19
Set fxd2
19
Draw &
Label
Y-axis
20
Char
Size 1
5
5
20
Pen
Select
#3
20
Plot
T [1]/1000
U [1]*1000,1
20
Lift
Pen
21
For
X=2 to
117
22
T[x]=0
and
U[x]*1000=0
?
yes
A
No
23
Plot
T[x]/1000
U[x]*1000,2
23
Lift
Pen
24
Char Plot
-.33,-.25
6


4
17
Draw
X-axis
18
For
R=0 to
11
18
Plot
R-.23,-.8,
1
18
Label
R
18
Next
R
19
Set fxd2
19
Draw &
Label
Y-axis
20
Char
Size 1
5
5
20
Pen
Select
=3
20
Plot
T [1]/1000
U [1]*1000,1
20
Lift
Pen
21
For
X=2 to
117
22
T[x]=0
and
U[x]*1000=0
?
yes
A
No
23
Plot
T[x]/1000
U[x]*1000,2
23
Lift
Pen
24
Char Plot
-.33,-.25
6

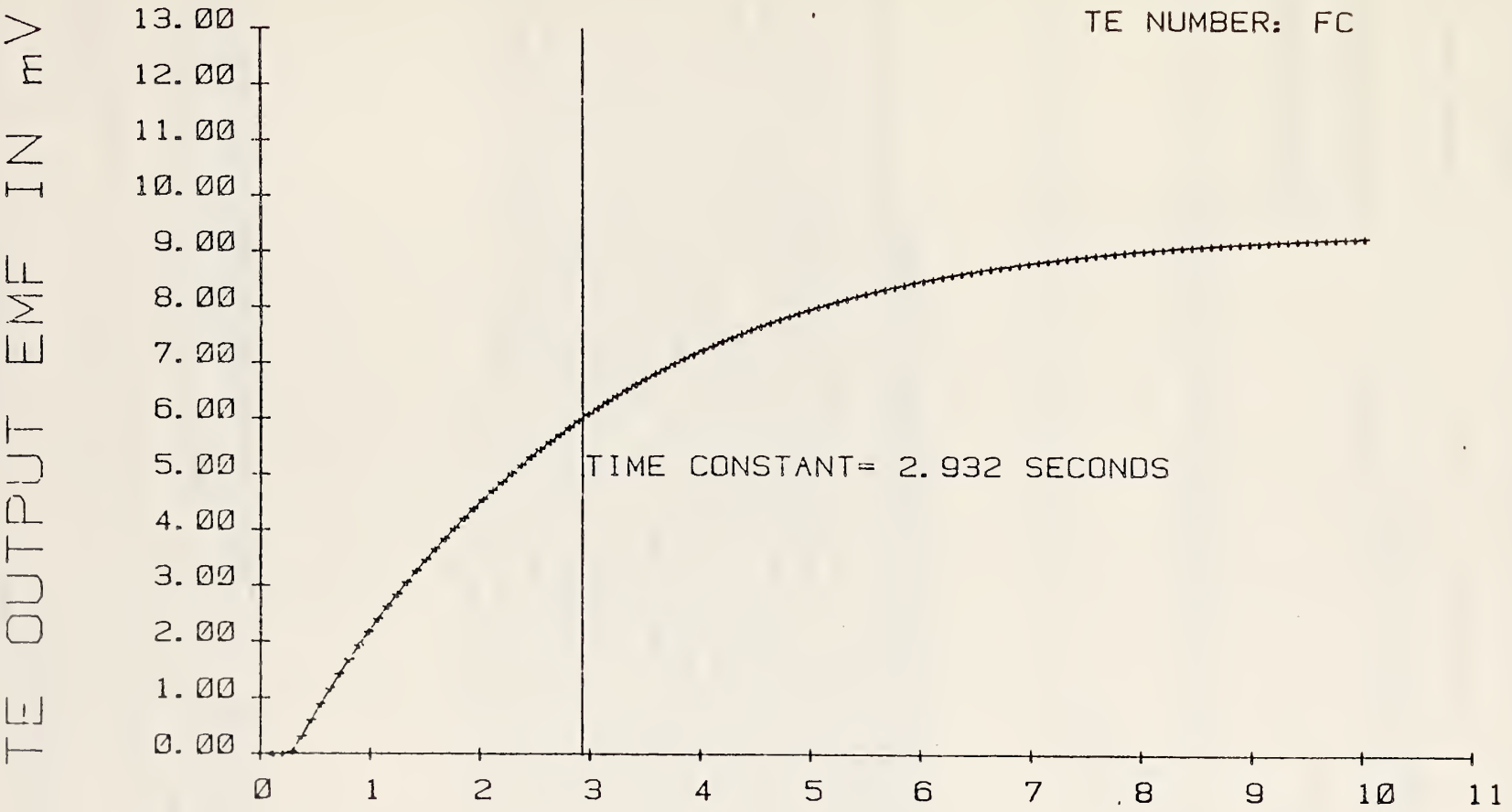

6
24
Label
"+"
25
Char Plot
-.67,.25
25
Next
X
A
26
Pen
Select
#2
26
Plot
K/1000, 0,
-2
27
Set
fxd 3
27
Plot
K/1000, 13,
-1
27
Plot
K/1000,5
7
7
28
Char
Size
1.6
28
Raise
Pen
28
Char
Plot
.2,0
28
Label
Time
Constant
29
Return
Pen
29
Calc
beep &
dsp
29
Rewind
tape
END

TE EMF WARM UP

DATE: 13:07:81

OBSERVER: MSC

TE NUMBER: FC



NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 84-2973	2. Performing Organ. Report No.	3. Publication Date November 1984

4. TITLE AND SUBTITLE

AN AUTOMATIC AC/DC THERMAL VOLTAGE CONVERTER AND AC VOLTAGE CALIBRATION SYSTEM

5. AUTHOR(S)

K. J. Lentner, D. R. FTach, and B. A. Bell

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Sponsored in part by:
U. S. Department of Defense
Calibration Coordination Group

10. SUPPLEMENTARY NOTES

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

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

An automatic ac/dc difference calibration system is described which uses direct measurement of thermoelement emfs. In addition to ac/dc difference testing, the system can be used to measure some important characteristics of thermoelements, as well as to calibrate ac voltage calibrators and precision voltmeters. The system operates over a frequency range from 20 Hz to 100 kHz, covering the voltage range from 0.5 V to 1 kV. For all voltages the total measurement uncertainties expected (including the uncertainty of the specific reference thermal converters used) were 50 parts per million (ppm) at frequencies from 20 Hz to 20 kHz, inclusive, and 100 ppm at higher frequencies up to 100 kHz. The results of initial intercomparisons between the new system and the manual NBS calibration system, using single-range, coaxial-type, thermal voltage converters as transfer standards, are reported. The results show that the agreement between the two systems is better than the uncertainties originally expected, since the intercomparison of ac/dc differences differed by no more than 15 ppm.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

ac/dc difference; ac voltage measurement; automation; calibration; metrology; thermal voltage converter

13. AVAILABILITY

☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

45

15. Price

$8.50