NBS TECHNICAL NOTE 1179

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

A Calibration Service for Wattmeters and Watthour Meters

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A Calibration Service for Wattmeters and Watthour Meters

NBS technical note

J. D. Ramboz and R. C. McAuliff

Electrosystems Division
Center for Electronics and Electrical
Engineering
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

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

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A CALIBRATION SERVICE FOR WATTMETERS AND WATTHOUR METERS

J. D. Ramboz and R. C. McAuliff

An NBS calibration service for wattmeters and watthour meters is described. The service offers measurements of percentage registration for watthour meters and percentage correction for wattmeters over a range of voltages and currents at a frequency of 60 Hz. Measurements are limited to power factors of 1.0 and 0.5, leading and lagging. The Measurement Assurance Program (MAP) for electric energy is discussed. National standards for electric energy, NBS services, special equipment and instruments, and measurement methods and procedures are described, as are error estimates and quality control. A representative Report of Calibration is included.

Key words: calibration; electric power and energy; electric standards; NBS services; watthour meters; wattmeters.

1. INTRODUCTION

The unit of ac electrical energy is established, maintained, and disseminated by the National Bureau of Standards (NBS) and is used by watthour meter manufacturers, electric utilities, and state utility commissions to ensure the accuracy of the 93 million watthour meters which register the electrical energy sold in the United States. At the present time, the annual revenue from the sale of this energy exceeds $80 billion.

The energy unit has previously been established and disseminated by NBS with an uncertainty of 0.05%. This uncertainty was appropriate when considered with respect to the performance expected from both standard- and service-type watthour meters. Recently, however, there have been improvements in both meter types, and a more accurate unit of energy is justified. Furthermore, statistical meter testing techniques, adopted by many electric utilities as a substitute for periodic testing of all meters, have demonstrated the need for an improved energy standard. With recent improvements in the power and energy measuring apparatus at NBS as well as refinements in the test procedures and statistical treatment of the data, the units of power and energy can now be disseminated by NBS with an uncertainty of 0.01% or better.

Traditionally, a constant power-time interval method has been used at NBS to establish the unit of ac energy. This method made use of an electrodynamic wattmeter to transfer a power measurement from dc to ac [1].[1] The wattmeter was then used to measure a constant ac power during an accurately measured time interval to calibrate a group of standard watthour meters with an amount of energy which was known in terms of the units of voltage, resistance, and time interval as maintained at NBS.

[1] Numbers in brackets refer to the literature references listed in section 13.

Two recent developments have made advances to the state-of-the-art in power and energy measurements. The first, a current comparator power bridge was developed in 1974 which made possible calibrations of high quality watt and watthour meters to uncertainties in the order of 0.003%. The second was the development of a precise power and energy meter by Physikalisch-Technische Bundesanstalt, Institut Berlin (PTB(IB)), which uses a multiple junction thermocouple and automatic balancing electronics to linearize certain thermal nonlinearities. These features accompanied with a precise analog-to-digital conversion and a microprocessor-based arithmetic unit give digital readings of voltage, current, power, and energy. The device can be calibrated with dc techniques and can achieve overall uncertainties also in the order of 0.003%.

Both of these devices now reside at NBS and are used periodically to calibrate the NBS reference bank of four watthour meters, the latter of which serve as comparison standards for the routine calibration of watthour meters submitted to NBS. This report discusses these instruments, the procedure and rationale of their use, and discusses the calibrations of watthour meters in general. An error analysis is included which traces the accumulation of systematic and random uncertainties from the basic standards to the final calibrations. The system hardware and test procedures are described in detail, along with discussions of the Measurement Assurance Program (MAP) for electric energy and the recently completed international comparison results between the three national laboratories of the United States, Germany, and Canada.

2. NATIONAL STANDARDS FOR ENERGY[2]

The electric power and energy metering in the U.S. at 60 Hz is the final result of a long series or chain of measurements made at NBS. The measurements and the standards and instruments calibrated by NBS achieve much of their economic importance from the necessity for accurate energy metering. Standard watthour meters are normally calibrated to an uncertainty of 0.05%. For special high accuracy tests, 0.01% can be achieved. At these accuracy levels, it is especially important to understand the basis for accurate power and energy measurements, and to make best use of the NBS services and standards [3].

Figure 2-1 shows the major electrical standards which are used by NBS in its program to establish and disseminate electric power and energy standards. The connecting lines and arrows indicate the important relationships between them. For clarity, some of the minor relationships and the kinds of calibrations performed are not shown.

The internationally accepted prototype standards of mass, length, and time are shown on the top row of the figure. The meter is defined as a certain number of wavelengths of the orange-red line of krypton 86. The atomic second is defined in terms of a specific transition period of cesium 133, and stable oscillators serve as working standards of time and frequency. The kilogram is still defined as the mass of the prototype Pt-Ir standard.

[2]Portions of this section were excerpted from an article, "Precision Power and Energy Measurements," by F. L. Hermach. See reference 2.

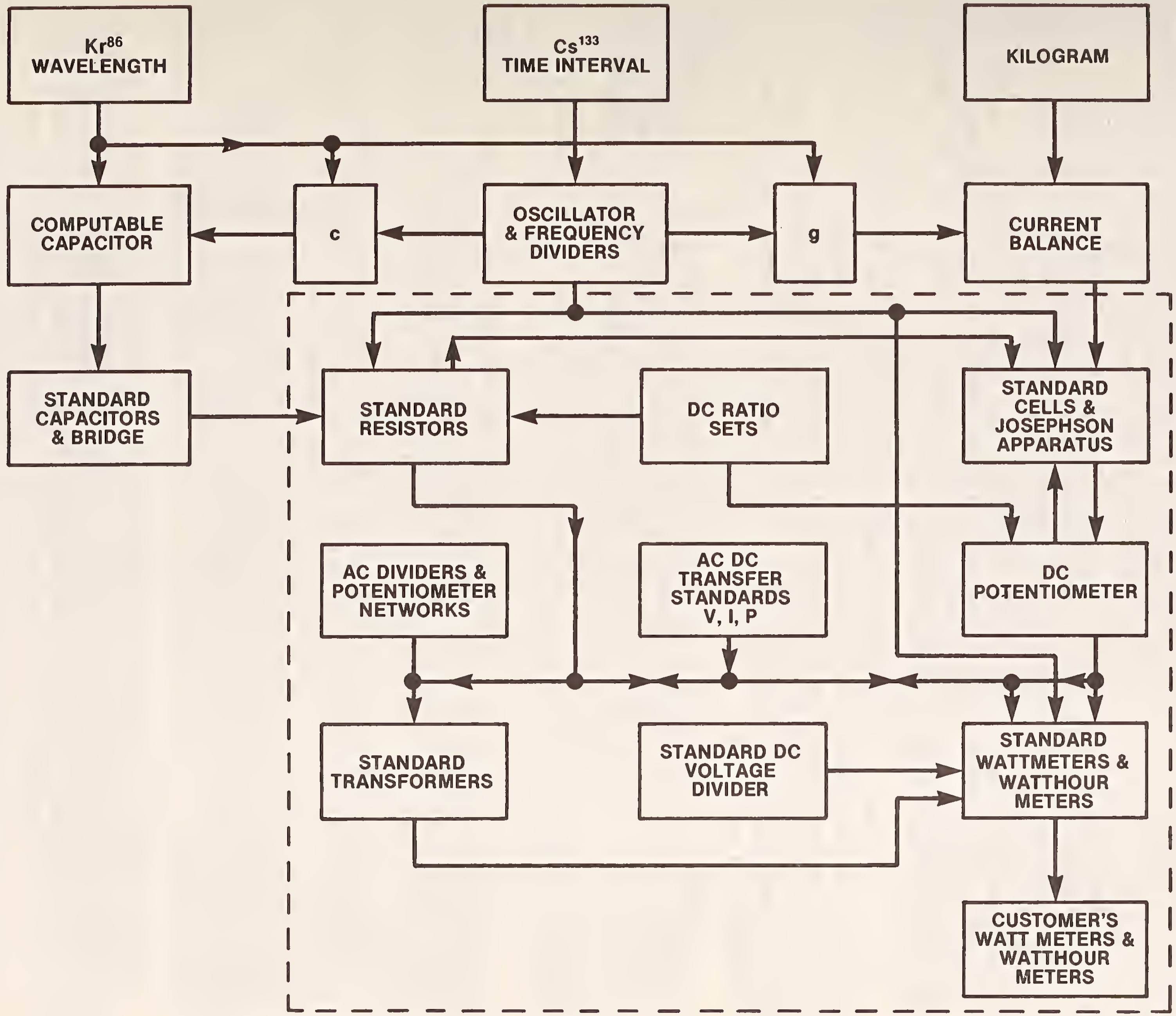

Figure 2-1. Major standards used by NBS in the calibration support of electrical energy and power.

Two experiments are performed at NBS to determine the basic electrical units in terms of these three standards and two measured constants, the speed of light in vacuum (c) and the acceleration of gravity (g). They are reasonably simple in principle, but extremely difficult and involved in practice because of the accuracy required. One experiment consists of constructing a precision calculable capacitor and computing its capacitance in electromagnetic units. It has a value of about 0.5 pF from the calculation using length and the speed of light. With remarkable bridges, step up is made to two 1000-pF capacitors across two 100,000-Ω resistors down to 1000-Ω resistors of known ac-dc difference, and then down to 1-Ω resistors [4]. The final step is made because the 1-Ω Thomas-type resistors are the most stable resistance standards known. The average resistance of a group of such resistors serves to maintain the ohm at NBS between each absolute determination.

The second experiment consists of "weighing the ampere" with a current balance, and is thus based directly on the definition of the ampere in terms of the force between current-carrying conductors. One conductor (a coil in reality) is suspended from one arm of a balance, and the change of force when its current is reversed is measured in terms of the acceleration of gravity on a known mass [5].

The parameter of dc voltage is maintained with a high precision and stability in terms of a measured frequency by means of the ac Josephson effect. A bank of saturated standard cells is monitored frequently and corrections are made for any changes in their emf's. An intercomparison is made between the absolute ampere determination of the current balance and a 1-Ω resistor by passing the current through the resistor. The resulting voltage drop is compared to the standard cell bank.

At NBS the ohm is accurately known (in terms of the defined "absolute" value) to better than 0.1 parts per million (ppm). The ampere and volt are accurate to better than 5 ppm, but the volt is maintained (thanks to the Josephson apparatus) with a precision and stability of better than 0.05 ppm.

Direct reading ratio-sets were developed at NBS to calibrate resistors by the substitution method, and to step up and down on the resistance scale. No line leads to them in figure 2-1 because their accuracy depends on ratios of resistors or turns ratio on a current comparator, not on the unit of resistance. Standard cells are calibrated by connecting the known and unknown cells in opposition and measuring the small voltage difference with a potentiometer. Potentiometers and volt boxes are calibrated with universal and direct reading ratio-sets. With these the user can then extend the dc voltage scale very accurately.

AC-DC transfer instruments are comparators for determining the equality of ac and dc currents, voltages, and powers. At NBS they serve chiefly to determine how well other ac-dc comparators do this. Since such comparators are very stable, the user can then make accurate ac measurements based on these known dc standards. They are also an important step in establishing ac power and energy standards.

For many years an electrodynamic wattmeter was the basic ac-dc transfer standard for ac power and energy measurements at NBS, and it was used to calibrate the NBS reference group of standard watthour meters periodically [6]. Now, however, a thermocouple transfer voltmeter coupled with a current comparator serves the same functions, and a thermocouple wattmeter is used for the ac calibration of the NBS reference bank of four watthour meters. Special high accuracy calibrations are also performed using the thermal wattmeter to uncertainties of 100 ppm (0.01%) or better. The calibration and use of the thermal wattmeter, the NBS reference bank of watthour meters, and associated apparatus is discussed in sections 4 and 5 of this report.

Other meter laboratories maintain groups of standard watthour meters, because these determine the commercially important unit of energy directly and simply. These laboratories send one or more meters to NBS or an independent laboratory for periodic calibration. These are the standards shown in the lower right block of figure 2-1. NBS now also provides a Measurement Assurance Program (MAP) for electric energy in which an NBS watthour meter is calibrated as an "unknown" by the meter laboratory with the user's equipment and procedures. The test results are evaluated with NBS help. The calibration and MAP services are discussed in detail in sections 3 and 9 of this report.

3. WATTHOUR METER CALIBRATION SERVICES AT NBS[3]

The National Bureau of Standards has the responsibility to establish and maintain the legal electrical units and, in addition, to make them available for use by industry, science, and government at all levels. Dissemination takes place in three ways: by routine calibration of high accuracy electrical and electronic standards and measurement apparatus, by in-situ calibrations performed on equipment which for technical reasons cannot be moved to or calibrated at NBS, and through Measurement Assurance Programs.

Routine calibrations of electrical energy standards (i.e., watthour meters) submitted to NBS are performed on a cost reimbursable basis using permanent facilities at the Bureau. These services are intended to support primary standards laboratories rather than to assign values to apparatus used by secondary laboratories. Accordingly, NBS will calibrate only standards and apparatus of the highest quality except under unusual circumstances such as to fulfill legal requirements or to resolve certain technical disputes. Those requiring support for secondary activities are encouraged to seek help from the numerous commercial calibration sources available. NBS may be of some assistance in locating a convenient source.

Normally, values of registration are reported with an uncertainty of ±0.05%. This includes a portion due to the systematic uncertainties of the calibration process and a portion due to the random components of the process. In instances where the randomness is too great, the total uncertainty may be increased to encompass the measured data.

Special high accuracy tests can be performed on quality wattmeters and watthour meters where systematic uncertainties of the test are less than ±0.01%. The overall uncertainty is a function of the random components. The random

[3]Portions of this section were excerpted from NBS Special Publication 250, "Calibration and Related Measurement Services of the National Bureau of Standards, 1980 Edition." See reference 7.

components are determined at the time of the test. Because high accuracy is required of these watthour meters, only those meters having electrical pulse outputs or high resolution registers (digital display) generally qualify for the special service. NBS should be consulted prior to submitting the meter to ensure that the particular type has the precision and stability to justify this high accuracy test. The voltage and current ranges are limited and power factors are normally confined to unity, 0.5 current lagging, and 0.5 current leading.

The NBS Measurement Assurance Program (MAP) for electric energy (NBS Technical Note 930) is designed to evaluate energy measuring equipment. An NBS-owned transport standard watthour meter is shipped to a customer, and a tie to the U.S. national energy unit is made without the down-time encountered when meters are calibrated at NBS. In addition, and more important, for those who calibrate reference standard watthour meters, a MAP standard can be used to evaluate an entire measuring system. The MAP program is discussed in detail in section 8 of this report.

Additional information regarding test point and shipping instructions are given in appendix A of this report.

4. CALIBRATION OF THE NBS WATTHOUR METER REFERENCE BANK

The major portion of the calibration workload of watthour meters submitted to NBS is done by comparing four NBS reference watthour meters and the customer's meter. A general description of the reference watthour meters is given. This section of the report also describes the equipment and process by which the four reference meters are periodically calibrated.

The block diagram of figure 4-1 shows the three principal steps, the current comparator power bridge, the thermal wattmeter, and the NBS reference bank. Electrical power is established using the NBS power bridge [8]. The thermal wattmeter is used as an intermediate step between the power bridge and the reference bank as a matter of timeliness and convenience. Although its use adds small uncertainties (discussed later) to the process, its use speeds the calibration process considerably.

The reference bank consists of four rotating-type watthour meters. These are each calibrated a minimum of four times a year (quarterly) using the thermal wattmeter. Each meter calibration consists of at least four independent measurements at the three power factor conditions of unity, half lagging and half leading. The thermal wattmeter provides a convenient and relatively fast means to perform these measurements. To simplify the number of required measurements, the NBS reference bank is always calibrated under the standard conditions of 120 V, 5 A, 60 Hz and 25°C. Ranging for other voltage and current test requirements is accomplished using precision voltage and current transformers which are discussed later.

Although the reference bank could be calibrated directly with the current comparator power bridge without the use of the thermal wattmeter (and indeed this was done before the thermal wattmeter became available), the time required to do so exceeded many times that required by using the thermal wattmeter as an intermediate step. As discussed in section 8, this intermediate step adds an uncertainty of about 10 ppm. The decreased calibration time is judged as an advantageous compromise.

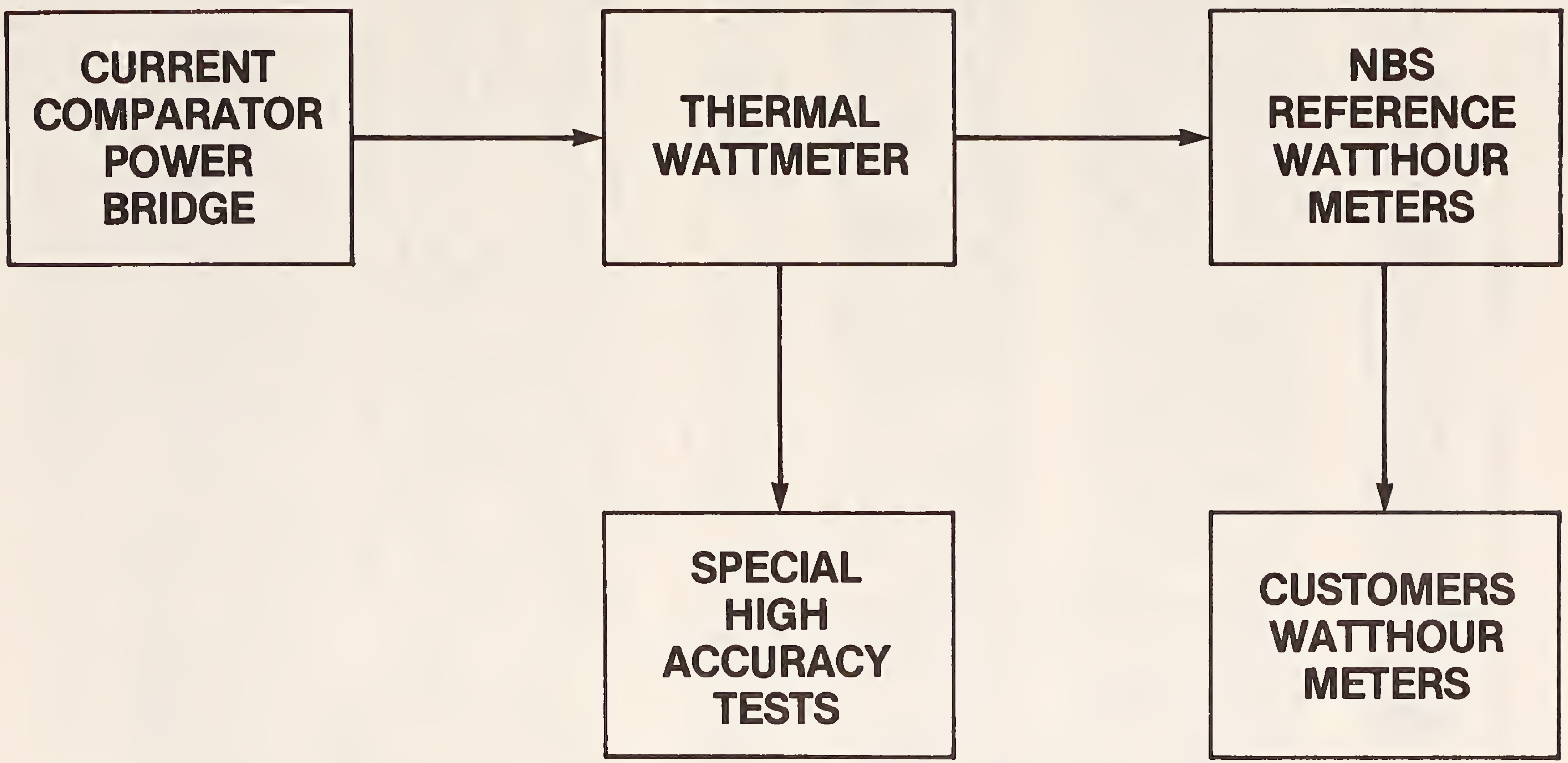

Figure 4-1. Diagram of the major measurement steps used to calibrate the NBS reference bank watthour meters. Also shown are subsequent calibrations of customers' meters.

4.1 Reference Watthour Meters -- General Description

The four reference standards are commercial induction type watthour meters. They were selected because of their simplicity and stability. They are two-stator, rotating disk-type meters having no mechanical registers, but rather an electrical pulse output.

The watthour meters contain two horizontal disks mechanically connected by a common vertical central spindle. The driving disk generates a torque proportional to the instantaneous product of the voltage and current and thus causes the spindle to rotate. Two magnet-dumping assemblies are mounted near the driving disk opposite each other and are located 90 mechanical degrees from the stators. Such an arrangement balances the driving and damping forces about the spindle so there is no net lateral thrust. The spindle and disk assembly are magnetically floated to minimize frictional forces which would result from mechanical bearings.

A signal-generating disk is mounted on the spindle about 7 cm above the driving disk. The signal-generating disk contains 500 slots near its outer edge equally spaced around its perimeter. Located above the disk is a miniature lamp which illuminates a small portion of the disk slot. Beneath the disk and directly in line with the lamp is a photoelectric sensor. When rotating, the signal-generating disk acts as an optical shutter between the lamp and photo-sensor, producing a pulse output whose frequency is proportional to the speed of rotation.

The reference watthour meters have nominal ratings of 5 A and either 120 or 240 V. At unity power factor and at rated current and voltage, the disk rotation rate is $(5/9)\pi$ rad/s (16-2/3 revolutions per minute). The watthour constants (K_h) are nominally 0.6 Wh/rev for an input of 120 V and 1.2 Wh/rev for 240-V input.

For operation in the reference bank at NBS, the watthour meters are always operated at a nominal 5 A and 120 V. Their temperatures are held constant by placing them in a thermally insulated and heated enclosure which is maintained at 25°C ±0.2°C. Furthermore, power is applied to the units continuously so that internal heating is constant. The internal lamp is also continuously lit so that its thermal contributions are insignificant. Each of the watthour meters is encased in a heavy cast aluminum housing which provides additional thermal lag time to any small temperature fluctuations which might occur within the insulated enclosure. (Figure 5-1 shows the four reference watthour meters inside the enclosure.)

Each watthour meter has a small bubble level built onto it. It is essential that the units be calibrated and used in the same vertical alignment so that the driving disk position in respect to the stator coils, damping magnets, and pivot bearings be constant. It is not critically important that the spindle, for example, be perfectly vertical, but rather that it is in the same location in use as it was when calibrated.

4.2 Current Comparator Power Bridge

The unit of electrical power (and when integrated over time, energy) is established using the NBS current comparator power bridge shown in figure 4-2. It requires only knowledge of dc voltage, ac impedance, dc resistance, current ratio, and ac-dc voltage difference.

The dc voltage supply is set to precisely 120 V with the use of a precision voltage divider, potentiometer, and standard cell. This known dc voltage is also applied to the input of the differential thermoelement voltage comparator (DTVC) whose output is adjusted for a null. The DTVC is then switched to the ac voltage and the ac supply is adjusted until the null is again achieved. At this point, the ac voltage equals 120 V rms to within experimental error of the apparatus. This ac voltage is applied to the voltage input of the thermal wattmeter being calibrated.

The same 120-V ac voltage is applied across a precision ac resistor, as shown in figure 4-2, for unity power factor. The current through the precision resistor is nominally 50 mA. The current comparator has a turns ratio of 100:1. The comparator is balanced by adjusting the 5-A current which also flows through the thermal wattmeter current circuit. By this means, a precise current of 5 A is established. The power applied to the thermal wattmeter is then calculated (at unity power factor) by

$$P_a = \frac{NV_{dc}^{\,2}}{R}\,(1 + C_{wa})\ , \tag{4-1}$$

where P_a is the apparent power applied to the thermal wattmeter,

N is the current comparator turns ratio, 100:1 in this instance,

V_{dc} is the value of dc voltage, 120 V nominally,

R is the dc value of the resistor (for unity power factor), 2.4 kΩ nominally, and

C_{wa} is a correction term accounting for the parameters of voltage, resistance, and current comparator turns ratio. (C_{wa} typically amounts to about 13 ppm for the NBS comparator at unity power factor.)

For half power factors, the same circuit is used with the addition of a voltage transformer and phase shifting capacitor as shown in figure 4-3. The value of resistance is changed to 4.8 kΩ and the current is 25 mA at 120 V. The capacitor is chosen so that total current through the comparator's coil is 50 mA and the phase angle between the impressed voltage and current is $\pi/3$ rad (or 60°). The procedure is the same as for the unity power factor test. The input power applied to the thermal wattmeter is calculated exactly as in eq (4-1) except that additional corrections must be added for the transformer and capacitor phase shifting network.

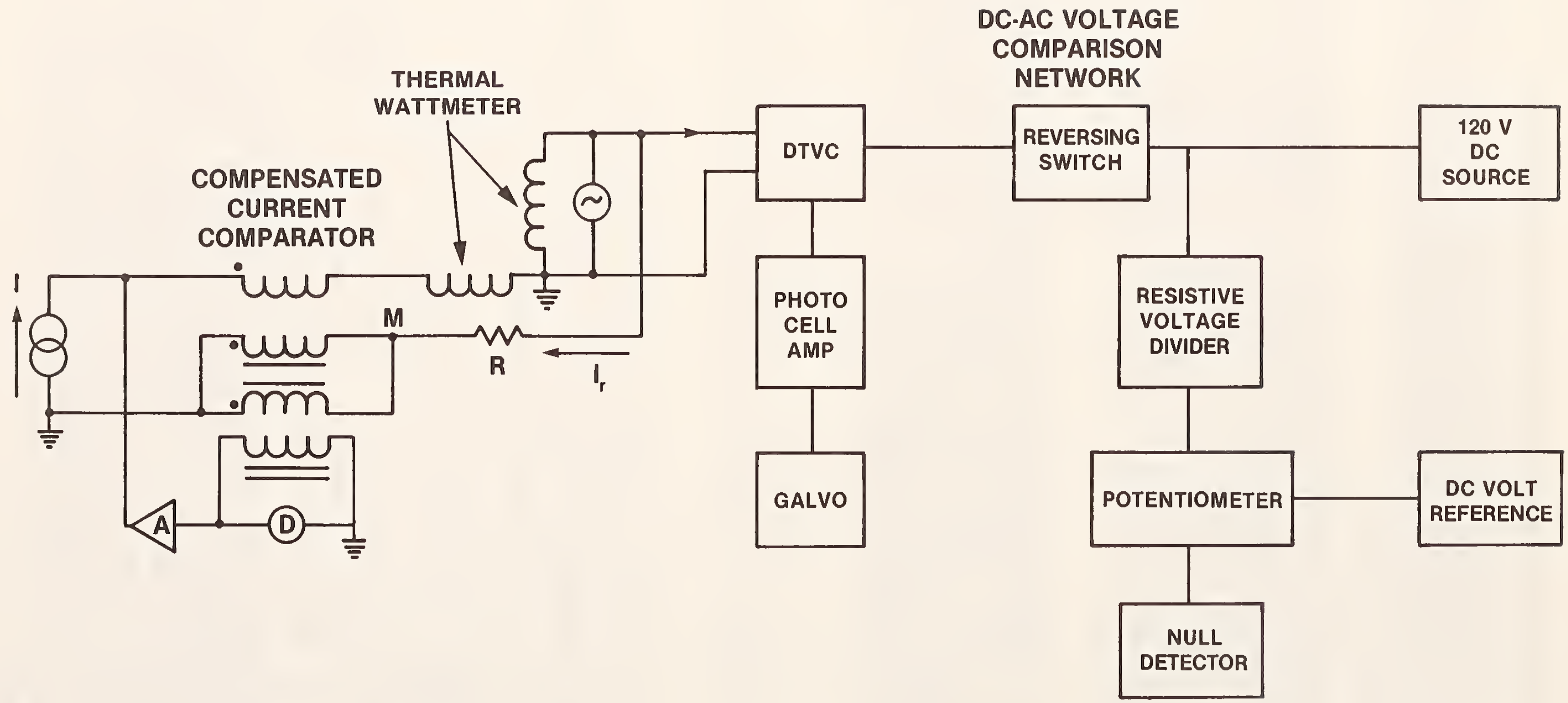

Figure 4-2. Current comparator power bridge configuration with the dc-to-ac thermoelement comparator and dc voltage measurement instrumentation (for unity power factor).

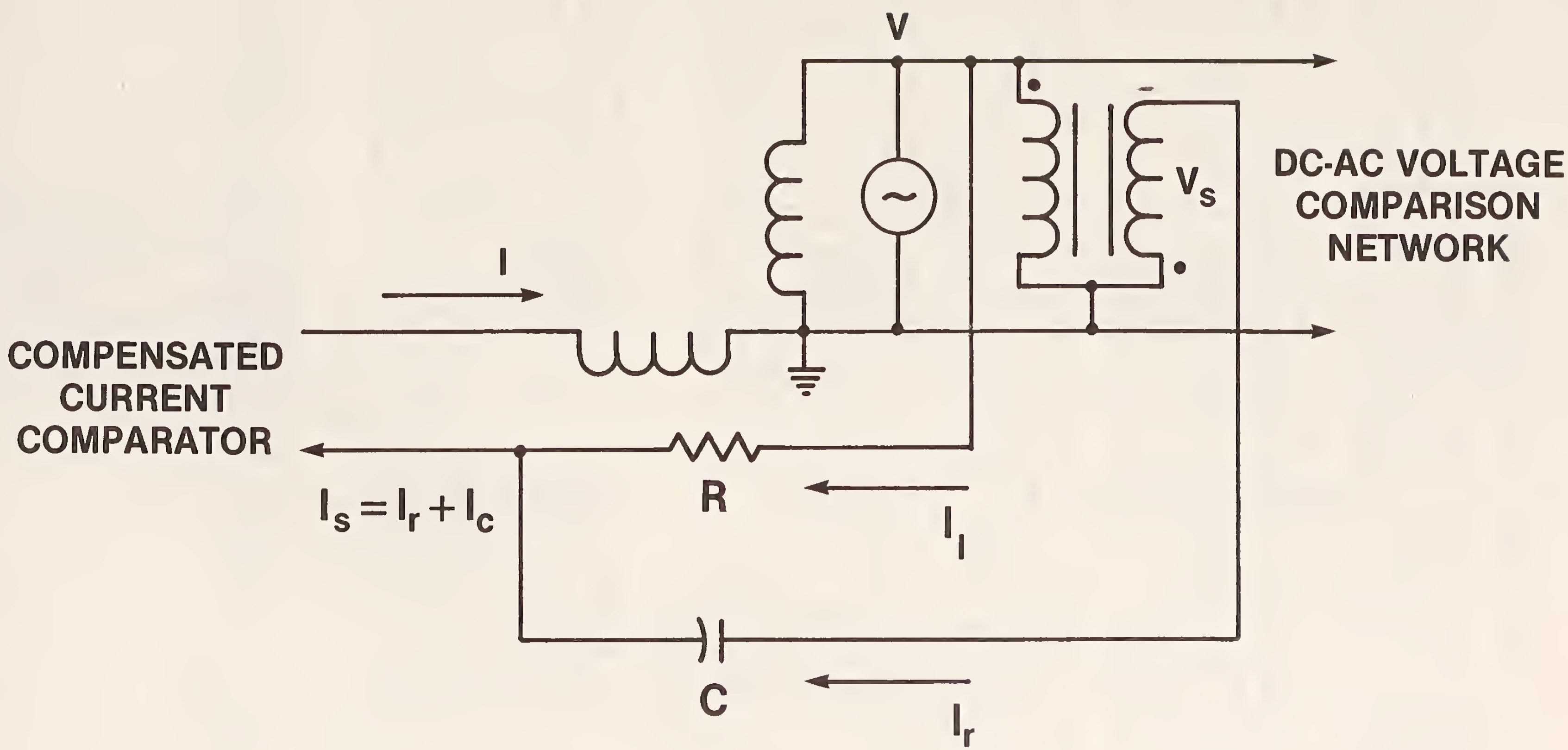

Figure 4-3. Simplified schematic of the current comparator power bridge used at half power factor. Polarity of the transformer providing voltage V_s as shown is for a lagging power factor; for a leading power factor, the transformer is changed to make it non-inverting.

4.3 Thermal Power/Energy Meter

The thermal power/energy meter[4] shown in figure 4-1 is used in the overall calibration process as a transfer standard between the current comparator power bridge and the NBS reference bank. It is also the reference standard for special high-accuracy tests with systematic uncertainties of less than 100 ppm.

The principle of operation makes use of the fact that the ac current can be compared to a dc current which is flowing through the heater of a thermoelement by comparing temperatures. Using this principle and appropriate summing and differencing circuits, a dc feedback current is added to the heater of the thermal element to continuously balance the temperature. In this way, the product of the input currents and an input voltage is converted to a dc current and the value of a resistor. A full discussion of this process is given in [9].

A simplified block diagram is shown in figure 4-4 for the thermal wattmeter. Voltage and current ranging is accomplished using precision voltage and current transformers. The signals then are applied to the thermal ac-dc transfer unit where an electronic control circuit continuously balances the ac by an equivalent dc voltage at the thermoelement's heater. The dc is measured using a precision analog-to-digital converter. The thermal wattmeter's ac-dc transfer unit feeds its output to the analog-to-digital converter. From this digital information, proper calculations can be performed by a microprocessor-based arithmetic unit to determine power precisely, accounting for scaling factors of the input transformers, amplifier gains, and other factors. By incorporating a precision time base circuit, time integration is possible so that electrical energy can be determined. Averaging times of 1, 10, and 100 s can be selected. When the 100-s averaging time has been selected, the instrument has a resolution of about 1 ppm of apparent power.

Because the circuits beyond the input transformers can be used for either an ac or dc input voltage or current, it is possible to calibrate the thermal watthour by dc measurement techniques. When performed with care, the unit can be calibrated with uncertainties of no greater than 10 to 15 ppm, about the same uncertainty as that for the current comparator power bridge. The process of calibration is, however, judged more fundamental when the current comparator power bridge is employed as the basic standard as shown by figure 4-1. Slightly more uncertainty is finally accumulated using the thermal wattmeter, but the confidence in the overall chain of calibration steps is adequate to meet present demands and an overall time savings is realized.

The thermal wattmeter is calibrated using the current comparator power bridge at least annually. The power bridge could be used to perform calibrations of high accuracy for special tests, but it is more convenient to use the thermal wattmeter for these tests.

[4] The thermal power/energy meter can function as a wattmeter or a watthour meter. When used as a wattmeter, it will be referred to as a thermal wattmeter; when used as a watthour meter, it will be referred to as a thermal watthour meter.

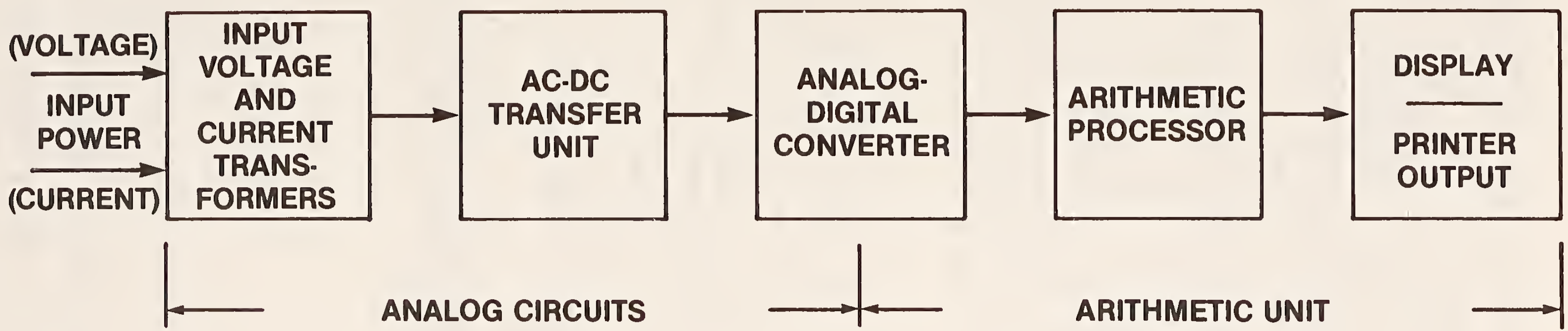

Figure 4-4. Principal components of the thermal wattmeter.

4.4 Calibration of the NBS Reference Bank

The NBS reference bank is calibrated at least four times a year using the thermal watthour meter. Standard conditions of 120 V, 5 A, 60 Hz input power of 600 and 300 W (for power factors of unity and half, leading and lagging) and a temperature of 25°C are used. After a suitable warm-up period, each of the four reference standards is individually calibrated. A time interval equivalent to at least 120 revolutions is used to ensure suitable resolution from the rotating standards of the reference bank.

The individually adjustable voltage and current power supplies in the NBS test setup are used to apply power to the thermal watthour meter and the NBS reference bank. (The supplies and controls, along with the auxiliary electronics, are described and discussed in section 5.) The potential circuits of the thermal wattmeter and the NBS reference standards are connected in parallel and excited with 120 V ac. The current circuits of the thermal wattmeter and the primary of a precision current transformer are connected in series. The secondary of the current transformer is connected to the NBS reference standard current circuits. The current is set to a value of 5 A. Power factors are set individually for unity, 0.5 lagging and 0.5 leading.

A preset counter in the NBS test console is set to a value of 60,000 which represents exactly 120 revolutions of one NBS reference standard. The output of one of the four NBS reference standards is connected to the input of the preset counter. The output from the preset counter generates a gate whose period is determined by the time required to count the 60,000. The outputs of each of the four NBS reference standards are recorded on individual counters. The preset counter output gate serves as a start and stop gate for these four counters as well as for the thermal watthour meter.

The thermal watt/watthour meter is operated as an energy reference (watthour meter) by integrating the power during the test interval. Its digital display reads in units of energy. Nominally, the amount of energy required for 120 revolutions of a NBS reference standard is 259.2 kJ (72 Wh).

The percentage registration for each of the four NBS reference standards is calculated from the ratio of the total number of pulses counted for each meter to the energy as read on the thermal wattmeter times an appropriate constant. This can be expressed as

$$R_{sx} = (C_x/J)\ H\ , \tag{4-2}$$

where R_{sx} is the percentage registration, (x = 1, 2, 3, or 4 signifies each meter),

C_x is the counter reading from one of the four NBS reference standards (x = 1, 2, 3, or 4),

J is the energy display of the thermal wattmeter in kilojoules, and

H is a factor which accounts for the rotating meter constants, conversion from units of kilojoules to watthours and a factor of 100 to convert to percent.

The factor H is calculated from

$$H = \frac{K_s}{n_s}\left(\frac{3600 \times 100}{1000}\right) = \frac{K_s}{n_s}(360) \ , \qquad (4\text{-}3A)$$

where K_s is the disk constant for the rotating reference standard (0.6 Wh/revolution for the NBS reference meters),

n_s is the number of electrical pulses per revolution of the disk in the NBS reference standard (n_s = 500 pulses/revolution for the NBS reference meters),

3600 is a factor to convert the energy units of joules to watthours,

1000 is a factor to convert kilojoules to joules, and

100 is a factor to express the results in percent.

When the term H is evaluated with the constants of K_s = 0.6 Wh/rev and n_s = 500 pulses/rev, then

$$H = 0.432 \ , \qquad (4\text{-}3B)$$

and further, from eq (4-2), the percentage registration can be expressed as

$$R_{sx} = 0.432\ (C_x/J) \ . \qquad (4\text{-}4)$$

For a nominal count of C_x = 60,000 pulses and J = 259.2 kJ, R_{sx} = 100%. The values of R_{sx} are used when the NBS reference bank is used to calibrate the customer's watthour meters to determine the value for the preset comparator setting.

5. ENERGY COMPARISON SYSTEM

Watthour meters submitted to NBS for calibration are generally tested by a direct comparison with a bank of four reference watthour meters. A description of the reference bank is given in the preceding section and figure 5-1 shows the bank in its temperature-controlled enclosure. A description of the comparison philosophy, power supplies and controls, signal conditioning and comparison electronics are given.

5.1 Watthour Meter Comparison Philosophy

There are three basic types of watthour meters which are submitted for calibration:

1. Rotating induction types with mechanical registers,

2. Rotating induction types without mechanical registers, but with electrical pulse outputs, and

3. Electronic types with pulse outputs, or digital readouts.

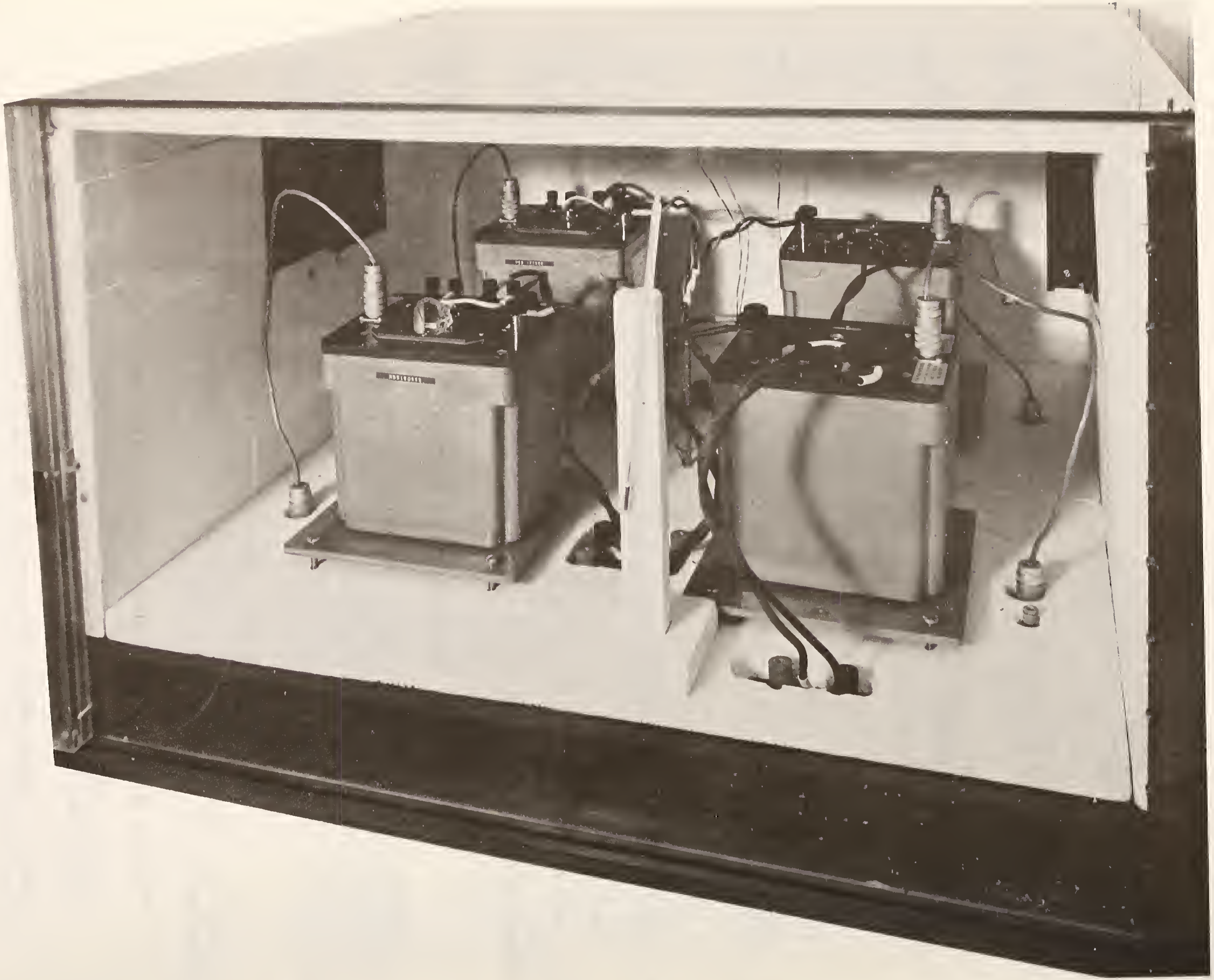

Figure 5-1. View of the four rotating watthour meters inside the thermally controlled enclosure. These meters comprise the NBS reference bank.

The following discussion of the comparison measurement philosophy is divided into two parts: one discusses meters with mechanical registers and the other discusses meters without mechanical registers. Much of the hardware, supplies, and instrumentation used are the same for both types of meters; however, the different outputs do lead to some differences in the calibration circuit.

5.1.1 Primary Circuit Configuration

Figure 5-2 shows the primary connections that are used for all watthour meter tests and calibrations. Basically, the voltage circuits of the reference watthour meters and the unit being tested are connected in parallel so that each meter has the same voltage applied. By the same reasoning, the current circuits of the reference and the units being tested are connected in series so that the same current flows through each of the instruments. In this manner, equal "apparent" input power is "dissipated" in the reference and test watthour meters. Note, however, that the input circuits of the reference watthour meters have both a precision voltage and a precision current transformer. This arrangement permits a range of voltage and current values to be selected for the watthour meter being tested, while at the same time maintaining a constant input voltage of 120 V and current of 5 A for the reference meters. This is desirable because the reference watthour meters are calibrated only at a minimal number of test conditions, namely, inputs of 120 V and 5 A at the required power factors. The transformer characteristics are known and the errors have been minimized so that their effect is negligible.

The circuit also contains three meters which measure the input values of voltage, current, and power to the reference watthour meters. The voltage and current supplies are separately adjusted (magnitude and phase) to achieve the desired test conditions for the reference watthour meters. Reference conditions are normally 120 V, 5 A, and 600 W for unity power factor, or 300 W for half-power factor.

Power factor is not displayed. The product of the voltage and current indications is the apparent power. The wattmeter indicates the real power. By definition, the ratio of the real power to the apparent power is the power factor.

In all instances, "phantom loading" of the watthour meters is utilized, that is, the voltage and current sources are separate. By this means, the apparent power for 120 V and 5 A is 600 W; however, the only power dissipated is in the leads and the watthour meter coils and is small compared to 600 W. This minimizes the size and power ratings of the supplies and controls and eliminates the need for large stable loads.

5.1.2 Comparison System for Watthour Meters With Registers

The configuration for the comparison calibration of watthour meters having registers which are visually read is shown in figure 5-3. The primary wiring for the watthour meter being tested is fundamentally as that shown in figure 5-2, with the addition of a relay-controlled switch in the voltage circuit. The purpose of this relay is to apply voltage to the meter at the beginning of the test and interrupt the voltage at the end of the test. The time interval during which the voltage is applied (and hence the time that the meter under test is running) is controlled by the output of a digital preset comparator. For sufficient resolution and accuracy, it is desirable to obtain a minimum of 30 revolutions for each of the watthour meters being tested.

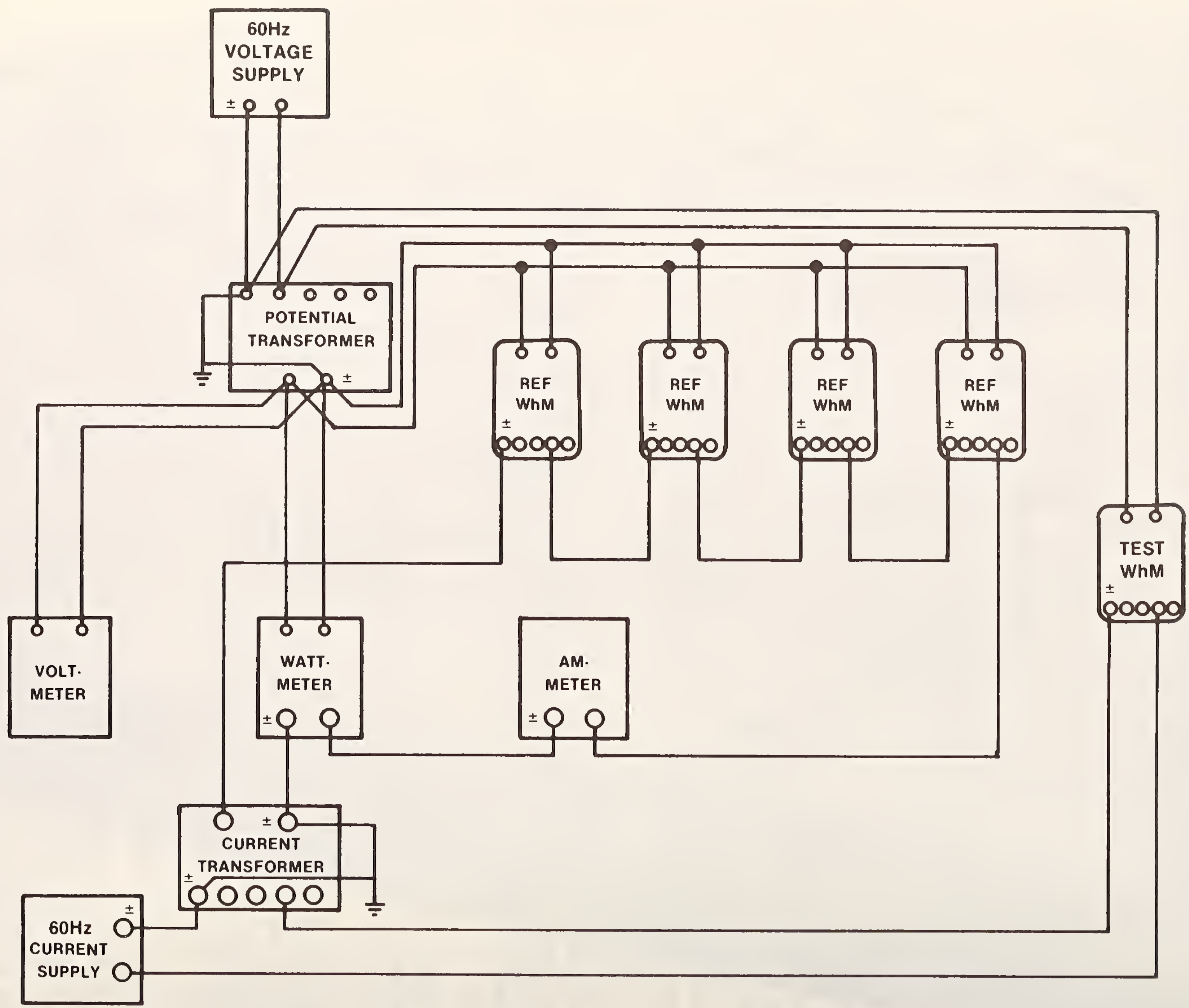

Figure 5-2. Basic wiring connections for the voltage and current circuits for the four reference watthour meters and the watthour meter being tested.

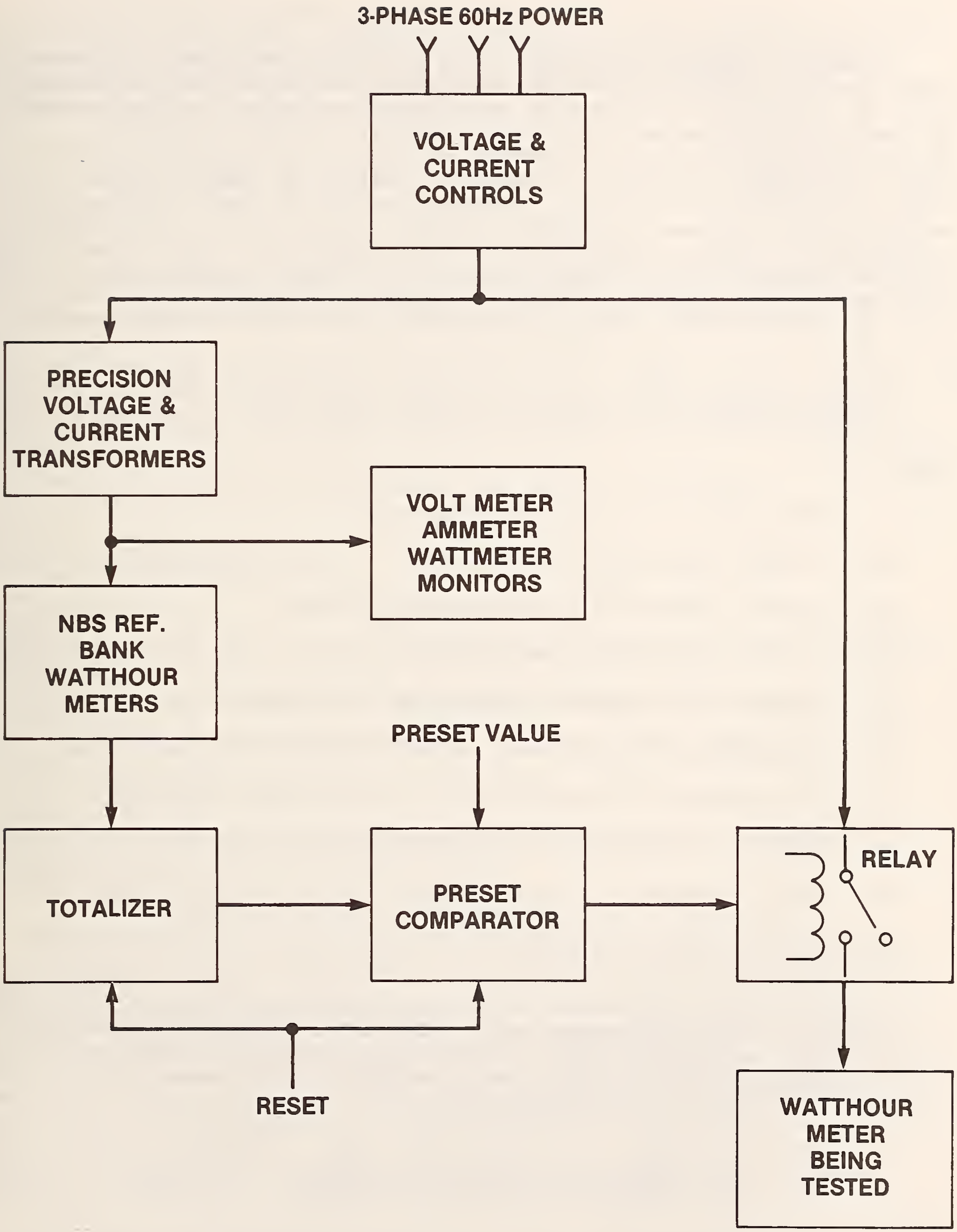

Figure 5-3. Basic configuration for the comparison calibration of a watthour meter having registers.

As seen in figure 5-3, the outputs from the NBS reference bank of watthour meters go into a totalizer where they are summed. With meters having 500 output pulses per revolution, the output per meter for 30 revolutions is 15,000 counts. For four nominally equal meters, the totalized count for 30 revolutions is 60,000 counts. When a value, for example, of 60,000 is dialed into the preset digital comparator, and the test is begun by resetting the comparator, the relay in the potential circuit for the meter under test is closed, thus applying voltage to that instrument. Meanwhile, the NBS reference bank is continuously running and its output is counted and fed to the comparator. When a count of 60,000 is achieved in the comparator, the relay is opened, the meter under test stops, and its registers are read and recorded. The exact value which is to be set into the preset comparator is calculated from the following expression:

$$C = \frac{V_R}{V_A} \times \frac{I_R}{I_A} \times \frac{K_t}{K_s} \times \left[r_s \, n_s (R_{s1} + R_{s2} + R_{s3} + R_{s4})/100 \right], \qquad (5\text{-}1)$$

where

C = the value to be set into the comparator,

V_R = voltage range of meter being tested,

V_A = nominal voltage applied to meter being tested,

I_R = current range of meter being tested,

I_A = nominal current applied through meter being tested,

K_t = disk constant of meter being tested in watthours per revolution,

K_s = disk constant of reference meters in watthours per revolution,

r_s = number of revolutions of the reference watthour meters,

n_s = number of output pulses per revolution for the reference meter, and

R_{s1}, R_{s2}, R_{s3}, R_{s4} = the percentage of registration for each of the four reference watthour meters.

Equation (5-1) can be somewhat simplified by substituting specific values for the NBS reference bank watthour meters operation, namely, K_s = 0.6 watthour per revolution, and n_s = 500 pulses per revolution. When this is done, the preset comparator setting for the reference watthour meter in terms of the number of revolutions, r_s, can be expressed as

$$C = \frac{V_R}{V_A} \times \frac{I_R}{I_A} \times K_t \left[\frac{25}{3} r_s (R_{s1} + R_{s2} + R_{s3} + R_{s4}) \right]. \qquad (5\text{-}2)$$

The values that are used for R_{s1}, R_{s2}, R_{s3}, and R_{s4} are derived from the calibration of the four NBS reference watthour meters at specific power factors. This is discussed in section 4.

Once the test is complete using the preset comparator's values as calculated using eq (5-1), the average number of revolutions that the reference watthour meters have rotated is exactly 30 (to within experimental error). Therefore, the percentage registration for the watthour meter being calibrated can be calculated from the following expression:

$$R_t = \frac{V_R}{V_A} \times \frac{I_R}{I_A} \times \frac{K_t}{K_s} \times \frac{r_t}{r_s} \times 100 \ , \qquad (5\text{-}3)$$

where R_t = percentage registration for the watthour meter being tested, and

r_t = number of revolutions of the watthour meter being tested.

The remaining terms have been described earlier. For example, if r_s = 30, K_s = 0.6, $V_R = V_A$, $I_R = I_A$, and K_t = 0.6 watthour per revolution, and if the meter under test achieved 30.027 revolutions during the time that the reference meters revolved 30 revolutions, then the percentage registration would be R_t = 100.09.

The time required for a test can be derived from the equation

$$t_s = \frac{60 \times K_s \times r_s}{V_s \times I_s \times (PF)} \ \text{min} \ , \qquad (5\text{-}4)$$

where t_s = the time that the watthour meters being tested are running in minutes,

V_s = the voltage applied to the reference watthour meters,

I_s = the current flowing through the reference watthour meters, and

(PF) = the power factor.

The factor of 60 in eq (5-4) changes the time units from hours to minutes. The remaining terms are as previously described.

5.1.3 Comparison System for Watthour Meters With Pulse Outputs

The configuration for the calibration of watthour meters having electrical pulse outputs is shown in figure 5-4. The primary wiring for the potential and current circuits for the four reference watthour meters and the meter being tested is as shown in figure 5-2. The sources and controls are identical to those described previously as is the use of the NBS reference bank, totalizer, and preset comparator. The difference is seen in the connection of the watthour meter being tested. With this configuration, the excitation voltage and current to the meter being tested are continuously applied. This approach minimizes two sources of uncertainty. First, measurements are taken only after self-heating effects have stabilized. Second, inertial effects which occur when rotating meters are started and stopped do not influence the measurement.

The counter monitoring the output of the meter being tested is gated by the preset comparator. The gate time is given by eq (5-4) and is usually no less than the time required for the meter being tested to achieve approximately 30 revolutions. Hence the output pulses from the watthour meter being calibrated are accumulated for one gate period of t_s minutes.

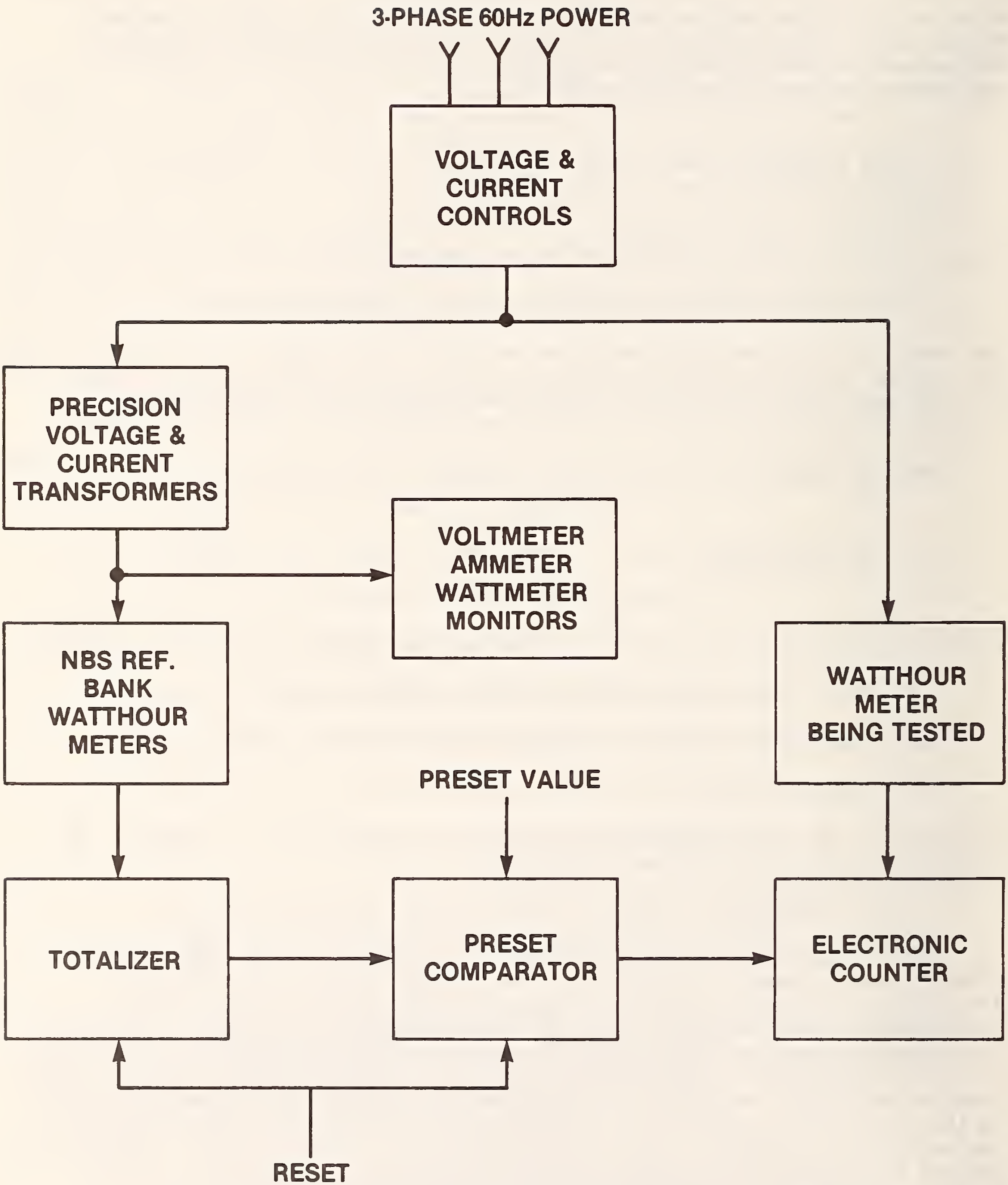

Figure 5-4. Basic configuration for the comparison calibration of a watthour meter having electrical pulse outputs.

The preset comparator input value is calculated as before in eq (5-1). The percentage registration for the meter being calibrated is

$$R_t = \frac{V_R}{V_A} \times \frac{I_R}{I_A} \times \frac{K_t}{K_s} \times \frac{N_t}{n_t r_s} \times 100 , \qquad (5\text{-}5)$$

where R_t = percentage registration for the watthour meter being calibrated,

V_R = voltage range of the meter being tested,

V_A = nominal voltage applied to meter being tested,

I_R = current range of the meter being tested,

I_A = nominal current flowing through meter being tested,

K_t = disk constant of meter being tested,

K_s = disk constant of reference watthour meter,

N_t = number of output pulses from meter being tested,

n_t = number of pulses per revolution for meter being tested, and

r_s = number of revolutions of the reference watthour meters.

For example, if an electronic watthour meter that had a full-scale voltage range of 120 V, a current range of 5 A, an equivalent disk constant of 0.6 and gave 1000 output pulses per equivalent revolution were operated at a test current of 3 A, then from eq (5-2), the preset comparator value for 50 revolutions of reference watthour meter bank would be nominally 100,000. From eq (5-5), the percentage registration for an output pulse count of N_t = 29,970 would be R_t = 99.90%.

5.2 Comparison System Hardware

The watthour meter calibration hardware consists of: 1) two adjustable power sources, one for the voltage inputs to the watthour meters and the second for the current inputs; 2) a test table which provides for convenient connections to meters being tested; 3) precision voltage and current transformers for testing at levels different from those used with the NBS reference watthour meters; and 4) the comparison electronics for reading the output pulses of both the reference meters and meters being tested. This group of equipment is discussed in this section. Circuit details are shown and discussed in appendix B.

5.2.1 Power Supply and Control Hardware and Circuits

The four NBS reference watthour meters and the meters being tested derive their electrical stimulus from two separate sources, one for the voltage circuit and the other for the current circuit. By this means, "phantom" loading is achieved eliminating the need to either supply or dissipate large amounts of electrical power. This also eliminates the need for a variety of high power loads. Both the voltage and current sources are driven from the line power. During the warm-up period, power is derived directly from the commercial power lines through suitable controls and transformers. During calibration, system power is obtained from a three-phase electronic power supply whose input is single phase 120-V 60-Hz power. This electronic supply generates a nearly sinusoidal, three-phase voltage in a wye-connected output whose frequency is tightly synchronized with the input power line. The major advantage of using this electronic power source rather than the three-phase power lines is its low distortion (less than 0.75% total harmonic distortion) and its amplitude stability (within 0.5% for 10 hours, 1% for 10 days). Either the three-phase power line or the electronic power source can be selected using a four-pole double-throw switch which then routes the power to the voltage, current, and power factor controls.

The output from the voltage control circuit feeds directly into a step-up transformer having turns ratios of 1:1, 1:2, and 1:4, thus providing output voltages of at least 120, 240, and 480 V, respectively. The primary is fused and isolated from the secondary. The three output voltages are switch selectable and are applied to the watthour meter under test and to the precision potential transformer which feeds the NBS reference bank watthour meters.

The output of the current control circuit is connected to two step-down transformers through a link arrangement. The transformers are rated at 240 B input on each primary and 2-V output on each secondary. These transformers are used for output currents of 3 A and greater. For currents less than 3 A, these transformers are bypassed and the output from the current control circuit is fed directly to the watthour meters. When used, the transformers provide for the following output current ranges: 3 to 25 A, 20 to 40 A, and 30 A to the maximum attainable. The maximum short circuit current is near 100 A; however, the usable maximum current depends on the total impedance of the current circuit.

The step-down transformers used to supply the test current are never used at more than about half their rated input voltage. The phase integrity for both the step-up voltage transformer and the step-down current transformers is such that the vector relationship (shown in appendix B) is nominally maintained, that is, no phase inversions are made by these transformers.

5.2.2 Precision Voltage and Current Transformers

Because the four reference watthour meters in the NBS bank are operated under standard conditions of 120 V at 5 A, precision voltage and current transformers are employed between the circuits supplying the watthour meters being tested and the four reference watthour meters to allow tests at other voltages and currents.

Two precision voltage transformers are used, one at a time, depending on voltage range, and each has a multi-tapped primary and fixed secondary. The secondary voltage is always set to 120 V by the system voltage and phase control and read by a system voltmeter also shown in figure 5-2. The voltage transformers have the primary taps listed in table 5-1. The input voltage is nominally as stated when there is 120 V on the secondary. The installed transformer is generally used. The second transformer is portable and connected into the system when needed, particularly for voltages of 208 and 277 V.

Table 5-1. Available test voltages in volts

Installed transformer primary voltage taps		Portable transformer primary voltage taps	
110	250	120	277
115	260	208	480
120	440	240	600
125	460		
130	480		
220	500		
230	520		
240			

For tests which require 120 V to be applied to the watthour meters being calibrated, neither potential transformer is used, but rather the meters and the reference bank are energized directly from the voltage supply.

The secondary of the installed voltage transformer is burden compensated to reduce its errors. No subsequent corrections need be applied. No compensation is used for the portable transformer, and corrections must be applied when it is used. The secondary burden for the voltage transformer consists of the reference bank of four watthour meters, a voltmeter, and a wattmeter, as shown in figure 5-2.

To enable the NBS reference bank to operate at a level of 5 A, a precision current transformer is employed which has a multi-tapped primary. It is a two-stage, amplifier-aided transformer as shown in figure 5-5. The advantage of a transformer of this design lies in the tertiary winding which senses the errors in the secondary current, and supplies a correcting current via the feedback amplifier [10,11]. The result is a transformer having errors on the order of the square of errors in a conventional transformer of comparable size. With this design, errors of less than a part per million can be achieved over a wide range of burdens.

The precision current transformer has primary taps selected to provide a wide range of currents from 0.5 to 100 A. Table 5-2 gives the values of primary current for a secondary current of 5 A.

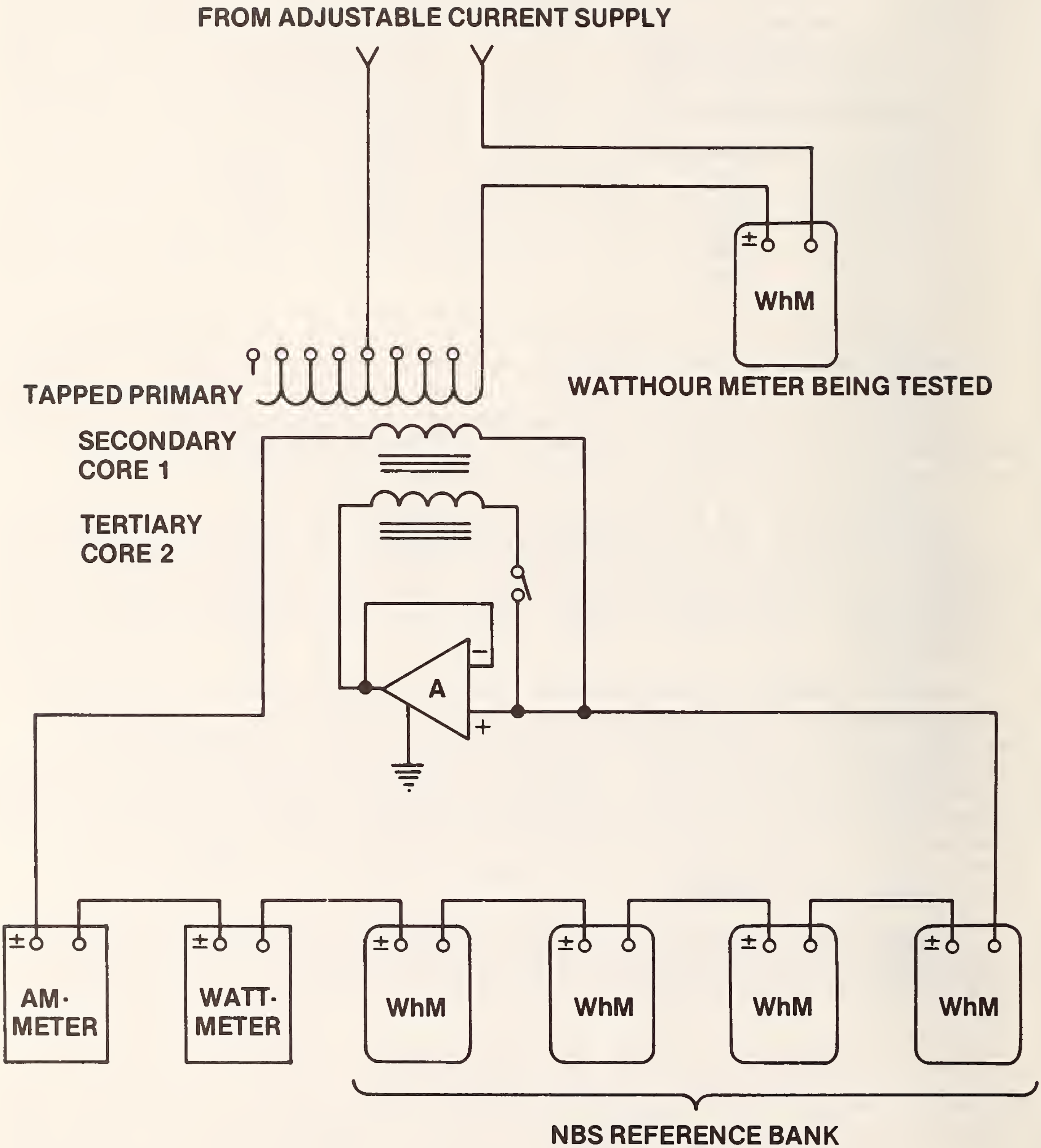

Figure 5-5. Details of the current circuit showing the two-stage amplifier-aided precision current transformer.

Table 5-2. Available test currents in amperes

Primary current taps	
0.5	10
0.75	12.5
1	15
1.25	20
2	25
2.5	30
3	37.5
3.75	40
4	50
5	75
7.5	100

The operational amplifier used with the current transformer has a balance trim adjustment which is set such that the amplifier's dc output is nulled. A pair of binding posts on the panel provide for connection to the amplifier output. A switch is also provided which disconnects the tertiary winding; this function is used principally for troubleshooting purposes. In normal operation, the switch is at the closed position.

Because of the large number of primary turns (1200), a relatively large voltage (for a current transformer) exists across the primary, and capacitive errors can result. This transformer has been compensated to reduce such errors; however, for the compensation to be effective, the marked terminals of the primary and secondary windings must both be grounded.

The secondary burden for the current transformer consists of the reference bank of four watthour meters, an ammeter, and a wattmeter. These are shown in the block diagram of figures 5-2 and 5-5.

5.2.3 Signal Conditioning and Pulse-Counting Electronics

The signal conditioning and pulse-counting electronics process the pulse outputs from the NBS reference bank to gate the 120-V potential circuit for watthour meters with registers or to condition and count the pulses from watthour meters having pulsed outputs. Figure 5-6 shows a photograph of the equipment rack housing these electronics and shows the counters and the panels where connections are made to the circuits. Figure 5-7 shows a simplified block diagram of the signal conditioning and pulse-counting electronics.

Connections are made to watthour meters being calibrated by suitable connectors on the front panels. The fundamental flow of signals is from left to right as drawn in figure 5-7. Watthour meters' output pulses are fed to signal conditioners, adders, gates, display selectors, and finally to electronic counters. The output of the adder in the reference channels feeds the sum of the four reference watthour meters to a preset comparator, whose output generates a suitable gate for stopping the counters when the preset value is reached.

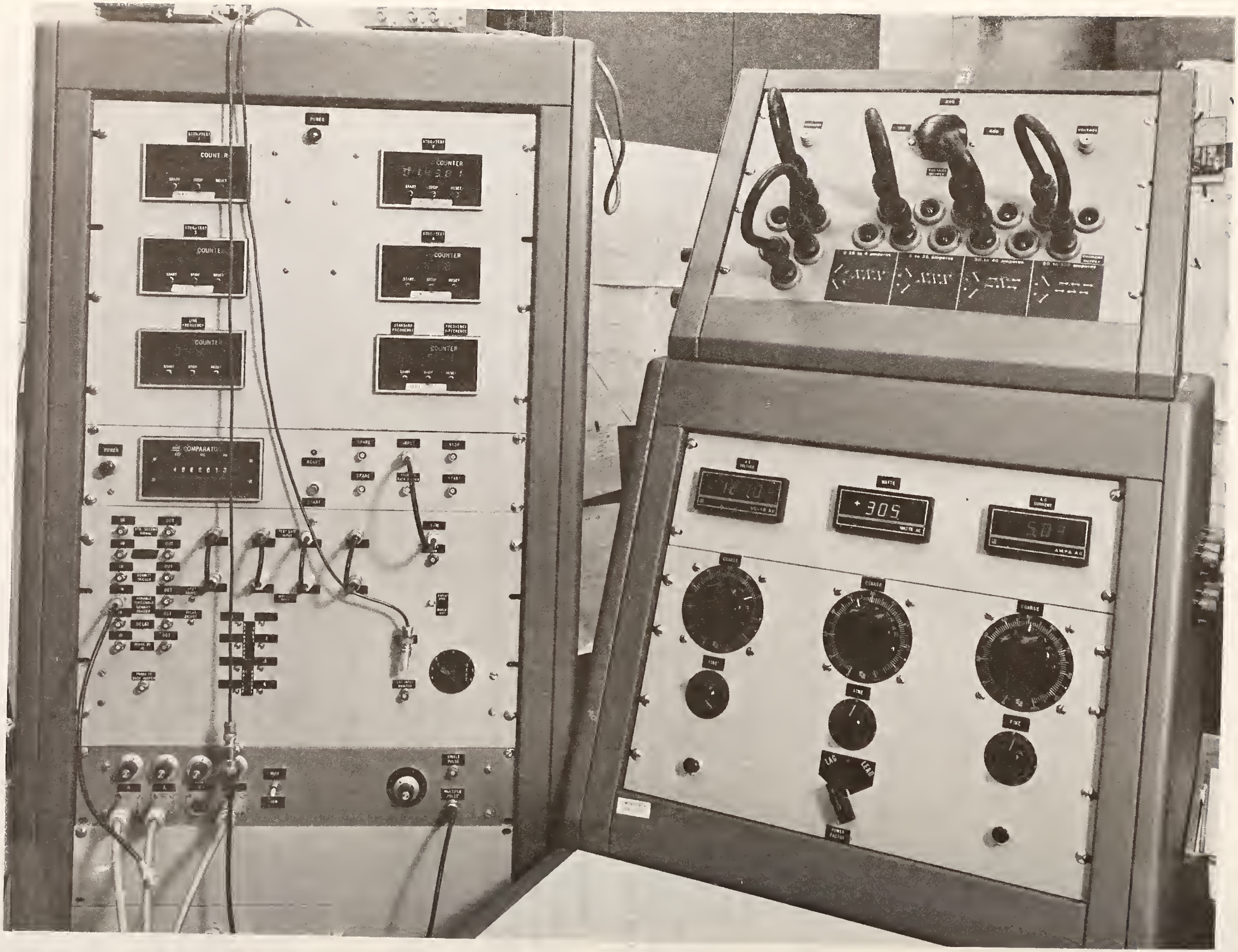

Figure 5-6. View of the equipment panels for the signal conditioning and pulse-counting circuitry.

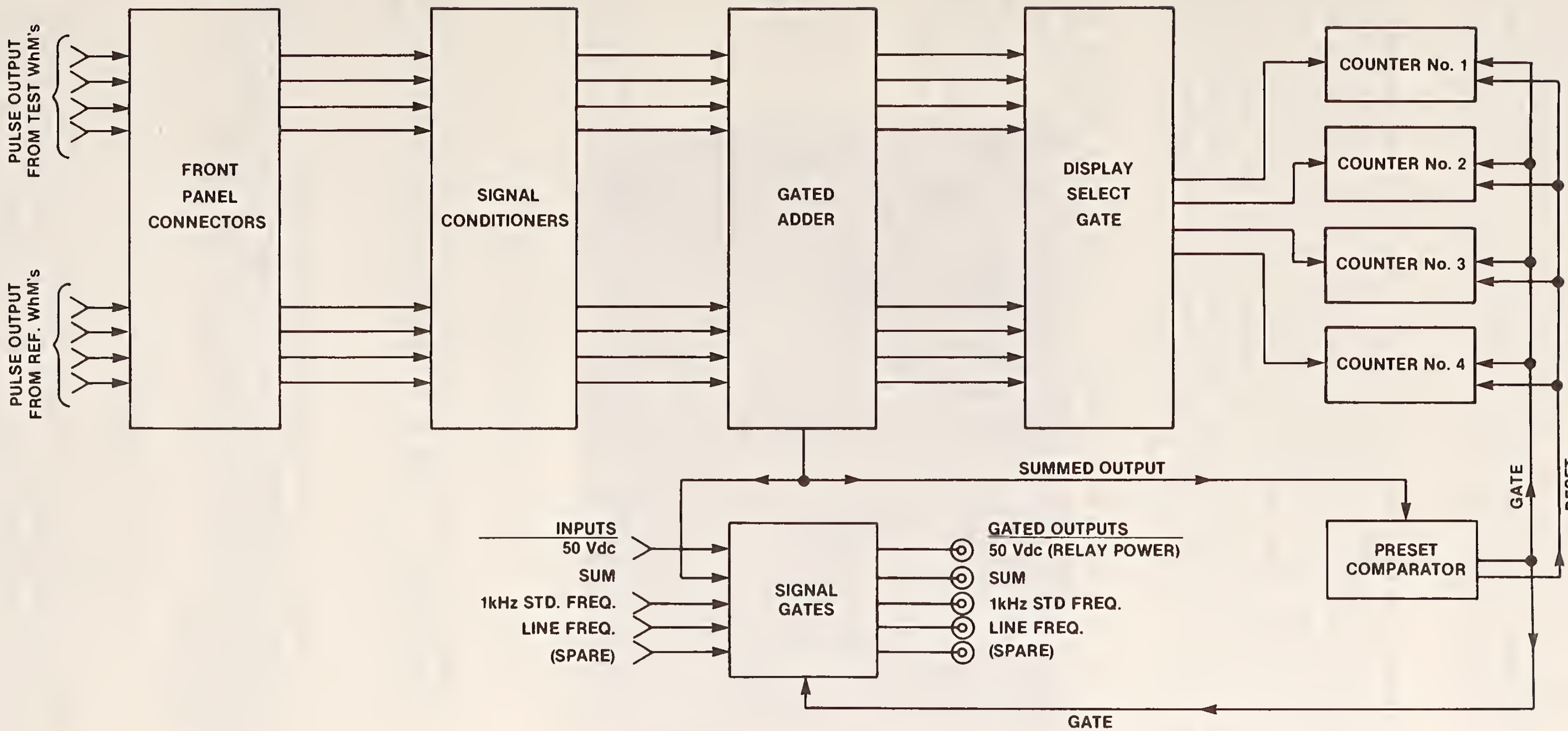

Figure 5-7. Simplified block diagram for the signal conditioning and pulse-counting electronics.

The wave shape of the "pulse outputs" from watthour meters having slotted discs are near sinusoidal and as such do not serve well as triggering sources for the subsequent pulse adders and electronic counters. To improve the pulse wave shapes and to make them compatible with TTL circuitry, signal conditioning circuits are used.

The signal conditioners consist of a comparator made of an operational amplifier and variable resistor, and a Schmitt trigger. The amplifier and resistor create a variable threshold feature which is required because the input sine wave is offset and never passes through zero volts. Figure 5-8 shows typical wave shapes of the output of a slotted-disc type watthour meter at the input to the signal conditioner (top trace) and the output of the Schmitt trigger (bottom trace). This square wave is adjusted for symmetry by the variable threshold resistor and is fully TTL compatible for the subsequent circuits. Symmetry is not essential but is a convenient basis for adjustment.

The pulse adder circuit serves two purposes. First, it provides an output which is the "sum" of the four reference channels (derived from the four reference watthour meters), and second, it individually gates the four test channels. The reference channel and the test channel outputs are conditioned so that relatively narrow pulses, about 20 μs wide, appear at the outputs independent of the input pulse widths, which typically are no shorter than about 10 to 30 ms. The input pulse widths are determined by the rotational speed of watthour meters with disks and by internal circuits for electronic-type meters.

As shown in figure 5-7, the outputs of the four reference channels and the four test channels are directed to the eight inputs on the display-select circuit. The purpose of this circuit is to select electronically the reference channels or the test channels for display on the electronic counters.

5.2.4 Auxiliary Electronic Circuits

Auxiliary electronic circuits are used to shape, generate, and gate signals such as the standard frequency and the line frequency. These circuits and their functions are discussed below.

5.2.4.1 Line Frequency Circuits

It is desirable to measure the test frequency at which the reference and test watthour meters are being used. The NBS laboratory has available a standard frequency of 1 kHz. Comparison against this standard frequency is accomplished as follows.

A phase-locked-loop circuit is used to generate an output signal near 1 kHz which is phase-locked to the line frequency. This signal and the standard 1 kHz are connected to separate electronic counters which are gated during the test. By comparing the two counters' readings, an accurate measurement of the mean line frequency can be obtained.

5.2.4.2 Gated Relay

The TTL driven relay is used to control a +50-V dc line which controls mercury-wetted relays on the test bench. These relays are used to open and close the voltage circuits to watthour meters having readable registers. This then starts the watthour meters being calibrated and stops them at the end of the test, and is described in section 5.1.2.

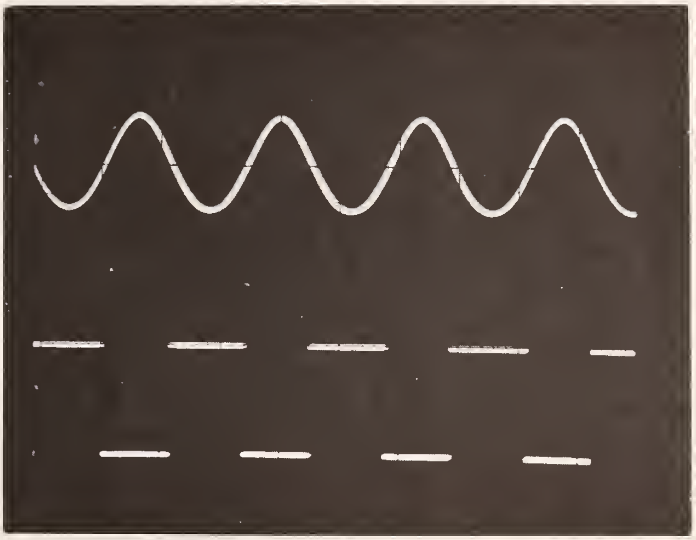

Figure 5-8. Typical wave shape of the output of a slotted-disc type watthour meter (top) and signal conditioned output after the Schmitt trigger circuit (bottom).

5.3 Test Bench Wiring and Features

The test bench provides access to the voltage and current circuits. It has four stations allowing four meters to be calibrated simultaneously.

The current circuit is a continuous series loop including the four stations and the precision current transformer primary. The voltage circuits are wired in parallel so that the same voltage appears across each station and across the primary of the precision potential transformer. Each station's voltage lead goes through a relay and switch. The relays are controlled by the preset comparator and closed at the beginning of the test and opened at the conclusion. Thus for watthour meters having registers, these relays start and stop the meters by applying and removing the voltage to the meter. A switch in parallel with the relay contacts allows the relays to be bypassed. This is desirable while the meters are "warming up" prior to calibration and also for electronic-type watthour meters that do not require starting and stopping. The latter are tested with voltage applied continuously.

If all the stations are not in use, the current connections at the unused stations must be shorted with a heavy link to provide circuit continuity. The voltage terminals are left open at the unused stations.

Leveling pads are available at each station with built-in bubble levels. These pads are used for rotating standards which require leveling before use.

6. PROCEDURE FOR CALIBRATING WATTHOUR METERS

The procedure for the calibration of watthour meters involves several steps including preparation, laboratory measurements, data recording, and issuance of the Report of Calibration.

6.1 Initial Inspection and Preparation

When a watthour meter is received, it is physically examined for damage or other factors that may be apparent which could affect its performance and calibration. The customer's order is examined to ascertain what is desired in the way of requested calibration ranges, etc. Presuming that no apparent damage is evident and that the request is understood and falls within the NBS calibration capability, the necessary documents are prepared. If damage is evident or suspected, or if there are questions regarding test conditions, etc., the customer is contacted and the problems are discussed and resolved prior to beginning the calibration.

A file is maintained for each meter submitted to NBS for calibration. It records the NBS test folder number and the date of tests, as well as the meter's nomenclature and identification (i.e., serial number or other unique identification).

A data worksheet is prepared which indicates all pertinent data regarding the instrument, including meter manufacturer, model, type, serial number, and any known modifications. The test number, date of test, and laboratory personnel performing the calibration are each noted. The customer submitting the meter for calibration is also listed. The data columns are headed with the parameters of the test, namely,

Preset comparator value
Voltage range
Applied voltage
Current range
Applied current
Power factor
Counter reading or register reading
Line frequency, and
Standard frequency.

For each day of calibration, the ambient room temperature, relative humidity, and the air temperature of the reference bank enclosure are each recorded. Figure 6-1 shows a typical data worksheet.

The preset comparator value is calculated by using eq (5-1). The preset value is recorded on the data sheet for each set of test conditions. After the above preparations have been made, the watthour meter can be installed.

6.2 Installation of the Watthour Meter

The installation involves selecting the test bench station at which the watthour meter is to be calibrated, leveling the meter (if required), and connecting the proper leads from the test bench to the meter. Station four is usually reserved for an NBS monitor standard which is used and calibrated with each daily run. On unused bench positions, the current terminals are shorted and the voltage terminals are left open. Voltage and current are then increased to the appropriate operating levels (normally 120 V, 5 A at 0.5 power factor) and the test meters are allowed to warm up from one to four hours depending upon the type of meter and test.

6.3 Testing Procedures

The power supply controls are set to zero and the necessary taps changed according to the test point conditions listed on the prepared data sheet. The comparator is set to the preset value of the test point as recorded on the data sheet. For meters having registers, the voltage switch is turned to "off" and the registers are zeroed. The test is initiated with the "start" button which clears and enables the comparator and the counters.

When the test ends, the meter value (as indicated on the counter or the meter register) and line and standard frequencies are each recorded. The test is then repeated. The meter and frequency readings are again recorded when the second run ends. After the second run, the voltage and current are reduced to zero and the appropriate connections are changed for the next set of test conditions. This is repeated until a pair of readings have been obtained for each test condition. A second set of data is obtained for each test point at least one day later so that a minimum of four readings have been made, two pairs, on two different days. At the end of the test or day, the power supplies are reduced to provide "idle" power for the meters overnight and for weekends and holidays. This is important, especially for rotating standards.

7/30/81 Room Temp. 23.5 Bank Temp. 25.0 Rel. Hum 43%

7/31/81 Room Temp. 23.3 Bank Temp. 25.0 Rel. Hum. 44% TEST # 123456

NBS-506B —Analysis paper
(3-75)

DATE 7/30-31/81

Company XYZ UTILITY COMPANY Serial Number 0000

Preset Value	Voltage Range	Applied Voltage	Current Range	Applied Current	Power Factor	0000	Control Std.	Line Freq	Std. Freq	
120024+1	120	120	1.0	0.5	1.0	30009	30000	215811	215815	
						30007	29999	215815	215814	
						30009	29999	215919	215909	
						30008	30000	215937	215911	
59948+1	120	120	5	5	0.5	30002	29995	108159	108154	
						30002	29995	108161	108149	
						30001	29994	108027	108016	
						30002	29994	108029	108004	
60012+1	120	120	5	5	1.0	30006	29995	216222	216282	
						30005	29994	216142	216117	
						30006	29993	216302	216289	
						30006	29995	216298	216268	
60200+1	120	120	5	5	0.5 ld	29988	30000	216402	216388	
						29988	29997	216437	216393	
						29992	30002	216134	216111	
						29992	30001	216064	216065	
60012+1	120	120	15	15	1.0	30000	30002	108494	108493	
						30000	30001	108152	108147	
						30000	29998	108004	107999	
						29999	29997	108037	108034	
100020+1	120	120	50	30	1.0	30009	30000	180310	180279	
						30009	29999	180258	180217	
						30009	29998	180324	180297	
						30007	29998	180403	180354	
59948+1	240	240	5	5	0.5	30005	29995	216123	216117	
						30007	29995	216113	216081	
						30010	29998	215965	215936	
						30008	29997	215947	215900	
60012+1	240	240	5	5	1.0	30009	29996	108097	108080	
						30009	29995	108032	107999	
						30009	29996	108081	108065	
						30009	29996	108009	107986	

WATTHOUR METER CALIBRATION

USCOMM-NBS-DC

Figure 6-1. Typical data worksheet for a watthour meter having electrical pulse outputs.

6.4 Data Analysis

After the second set of data has been recorded, the average of the four readings is obtained and the percentage registration is computed. The percentage registration calculation is made using the following relationship:

$$R = \frac{(\text{Rdg } 1 + \text{Rdg } 2 + \text{Rdg } 3 + \text{Rdg } 4)/4}{\text{Nominal Count}} \times 100 , \qquad (6\text{-}1)$$

where Rdg 1, Rdg 2, Rdg 3, and Rdg 4 are the four readings taken during calibration, and the denominator is the expected nominal count. As an example, for the data given in figure 6-1, the first four data readings are 30007, 30007, 30009, and 30003, which are all counter readings for the four tests at 120 V, 5 A, and unity power factor. The nominal count (denominator) is 30000. Therefore, the percentage registration is 100.0217.

The mean test (line) frequency can be calculated from the ratios of the line and standard frequency counters. If the 60-Hz line frequency were exact, then the two counter readings would be the same (within extremely small errors due to the NBS standard frequency and the ±1 count of each counter). The line frequency can be calculated from the following relationship:

$$f_{\text{line}} = \frac{(C_1 + C_2 + C_3 + C_4)}{(S_1 + S_2 + S_3 + S_4)} \times 60 , \qquad (6\text{-}2)$$

where C_1, C_2, C_3, and C_4 are the counter readings for the line frequency, and S_1, S_2, S_3, and S_4 are the counter readings for the standard frequency during the calibration period. For the example given above from data of figure 6-1, the four counter readings for the "line frequency" and the four standard frequencies lead to

$$f_{\text{line}} = \frac{(215811 + 215815 + 215917 + 215937)}{(215815 + 215814 + 215909 + 215911)} \times 60 \qquad (6\text{-}3)$$

$$= 60.002 \text{ Hz} ,$$

which is only about 36 ppm greater than the nominal value of 60 Hz. The test frequency is generally very close to nominal 60 Hz and is generally of no great concern in the routine calibration of watthour meters inasmuch as the frequency corrections are usually small.

After the completion of the test, the test parameters and the four counter readings (or four register readings) are entered into a computer. The computer calculates the percentage registration and prepares the Report of Calibration. As part of the computer computations, the data for the monitor standard are also entered and its registration calculated. The standard deviations are computed for both the data of the meter being tested and the monitor.

The computer results are checked to ensure that errors were not made when entering the data into the computer. The results are also compared to previous calibrations of the same instrument to detect abnormal drifts or changes. The results from the monitor standard are examined to ensure that the calibration process was in control. If all factors seem acceptable, the Report of Calibration is prepared giving the test conditions and results. The Report is then reviewed by no fewer than two persons for accuracy in all aspects.

7. REPORT OF CALIBRATION

For each watthour meter that is suitable for test and submitted to NBS, a Report of Calibration is prepared. This Report is a legal document attesting to the results of the measurements made at NBS on that particular instrument under the test condition specified at the time of test. A typical example of a Report of Calibration is shown in figure 7-1(a). The report consists of a cover page which specifies the instrument being calibrated by manufacturer, model or type, and serial number. The voltage and current ranges as well as the frequency are stated. The company or utility which submitted the instrument is clearly given by name and address.

Specific details of the test conditions are given such as laboratory temperature, warm-up time, the number of disk revolutions for rotating type meters, and any special electrical connections or conditions. The estimated uncertainty in assigning the values of registration (derived from the systematic and random components of error estimates) is given. The cover sheet also gives the NBS test number, the customer's order number, and the date on which the Report was prepared.

The second page of the Report (fig. 7-1(b)) gives values of percentage registration at specific voltages, currents, and power factors. The voltage and current columns are divided into the full-scale range and the nominal voltage and current applied during the test.

The reported values of percentage registration are computed as discussed in sections 5 and 6 of this report. The values are usually reported to the nearest hundredth of one percent (two significant decimal places).

8. ERROR ANALYSIS

An error analysis is presented herein which begins at the fundamental electrical standards at NBS and progresses through the calibration of customers' meters. Figure 8-1 shows the basic chain of steps which includes the NBS reference bank of four meters, the Measurement Assurance Program (MAP) transport meters, routine calibrations of customers' meters, and special high accuracy tests.

In figure 8-1, a set of uncertainty values is given between each step. The value outside the parenthesis is the power factor and is either 1 or 0.5. The first value inside the parenthesis is the estimated systematic component of uncertainty assigned at that step of the measurement process. The second value is the estimated random uncertainty of the process and is expressed as three standard deviations, $3s_m$, of the mean. Both the systematic and random

FORM NBS-443
(REV. 11-68)

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

REPORT OF CALIBRATION

PORTABLE STANDARD AC WATTHOUR METER
120, 240, 480 Volts, 1.0, 5.0, 15.0, 50.0 Amperes, 60 Hz
Rheed-Wright Meter Company Type UR-100
Serial No. 0000

Submitted by

XYZ Utility Company
1234 Main Street
Somewhere, New York 12345

This watthour meter was tested at rated frequency with alternating current of practically sinusoidal waveform. Testing was performed in July 1983 at a room temperature of approximately 23°C. The instrument was placed on a level table.

The meter was energized for four hours before the test. Tests were run so that the meter disk completed close to 30 revolutions during the test period. The leads in series with the voltage coil of the meter had negligible resistance. At 0.5 power factor the current lagged the voltage, except as noted.

The results shown in the attached table are the averages of four or more runs at each test point. The values of registration have an uncertainty of 0.05%. This figure includes allowances (available on request) for both the random and systematic errors of the calibration process.

For the Director
National Engineering Laboratory

Cal E. Braytor, Group Leader
Applied Electrical Measurements
Electrosystems Division

Test No.: 722/225888
Order No.: ABC123
Date: July 31, 1983

Figure 7-1(a). Report of Calibration for a typical watthour meter.

XYZ Utility Company
Intrument Type UR-100
NBS Test No. 722/225888
Test Dates 15 July to 22 July 1983

Voltage Range	Voltage Applied (Volts)	Current Range	Current Applied (Amperes)	Power Factor	Percentage Registration — Instrument Serial Number 0000
120	120	1.0	0.5	1.0	100.12
120	120	5.0	2.5	0.5	100.13
120	120	5.0	2.5	1.0	100.10
120	120	5.0	5.0	0.5	100.08
120	120	5.0	5.0	1.0	100.10
120	120	5.0	5.00	0.5LEAD	100.11
240	240	15.0	3.00	1.0	100.08
240	240	15.0	30.00	0.5	100.09
240	240	15.0	30.00	1.0	100.13
240	240	50.0	50.00	0.5	100.12
240	240	50.0	50.00	1.0	100.11
240	277	5.0	2.50	1.0	100.13
480	480	5.0	2.50	1.0	100.10

Figure 7-1(b). Report of Calibration for a typical watthour meter.

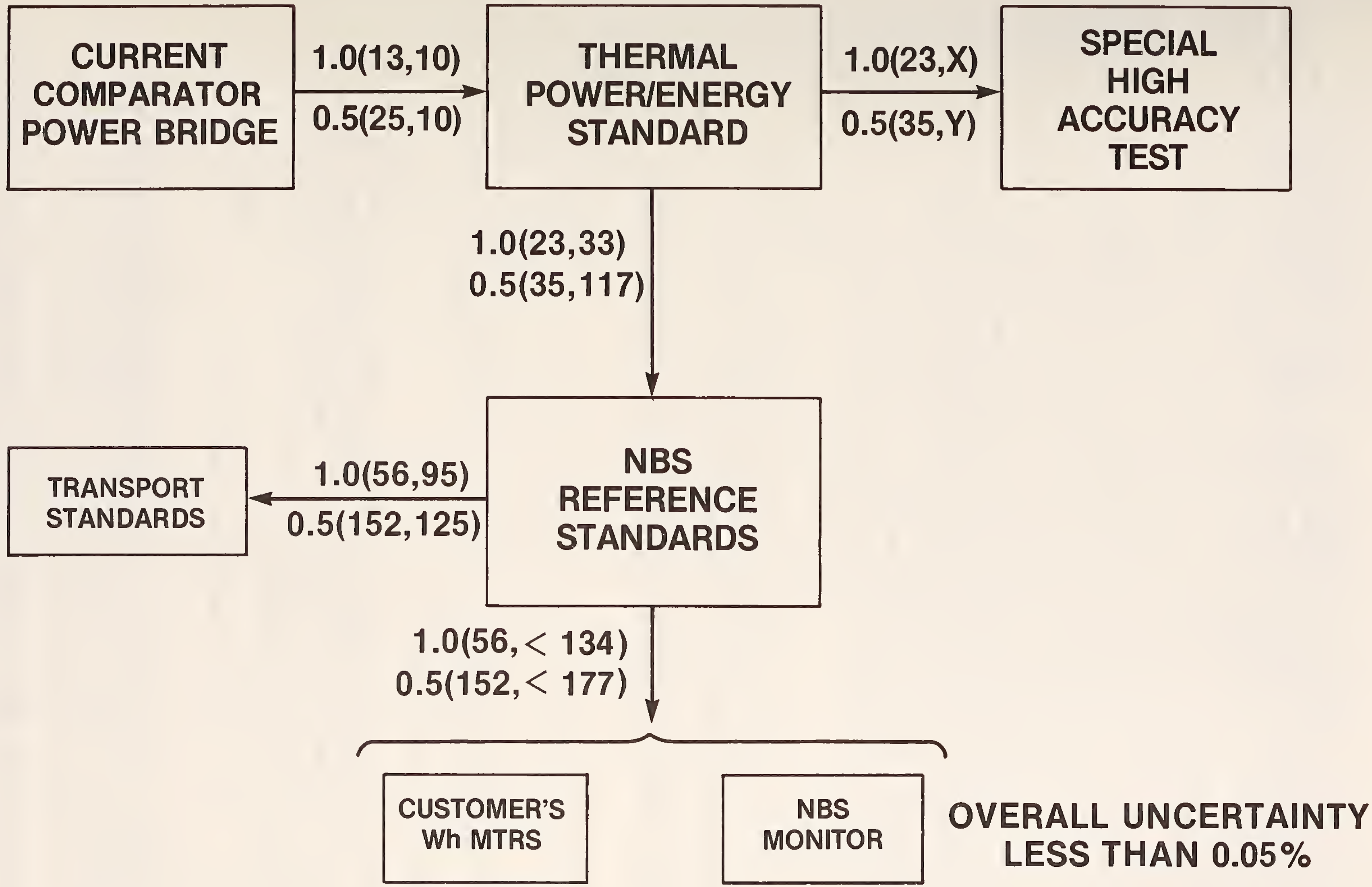

Figure 8-1. Major steps and uncertainties for the entire calibrations process for watthour meters at NBS. This figure traces the measurement chain from the NBS power bridge to the routine calibration of customer's watthour meters. The uncertainties (in ppm) of each measurement step for unity and half power factors are shown in parentheses, where the first value is the estimated systematic uncertainty and the second value is the estimated $3\sigma/\sqrt{N}$ random component of uncertainty. The values used for the transport standard are typical random uncertainties at NBS; for the actual values for each MAP transport standard, see table 8-3.

components are given in parts per million (ppm). All uncertainties are measured in terms of real power or energy. For example, the first process step is the calibration of the thermal watt/watthour standard by the current comparator power bridge, which at unity power factor has an estimated systematic uncertainty of 13 ppm and an estimated random uncertainty, $3s_m$, of 10 ppm.

The systematic and random components of uncertainties are combined using the relationship shown below:

$$U_T = SU + 3s_m , \qquad (8\text{-}1)$$

where

U_T = the total uncertainty of a particular measurement step,

SU = the systematic uncertainty associated with that step, and

s_m = the standard deviation of the mean.

$$s_m = s/\sqrt{N} , \qquad (8\text{-}2)$$

where

s = the standard deviation of an observation, and

N = the total number of independent observations used to calculate $\overline{x}$.

$$s = [\Sigma(x_i-\overline{x})^2/(N-1)]^{1/2}, \qquad (8\text{-}3)$$

where

x_i = the i^{th} observation, and

$\overline{x}$ = the mean of the values of x_i .

As can be seen, the random uncertainty varies inversely with the square-root of the number of measurements performed in a set. Also, a limit of three standard deviations is used to encompass the randomness of the process. For the process shown in figure 8-1, the total uncertainty for any one step is used as the systematic uncertainty for the following step.

8.1 Current Comparator Power Bridge

The watthour meter calibration chain begins with an NBS current comparator power bridge [8] which establishes an ac voltage (at power frequency which is compared to dc standards through a thermal transfer process. An ac resistor provides a proportional in-phase ac current that is scaled to 5 A by the current comparator. This process was discussed in detail in section 4.1 of this report.

The uncertainties that are attributed to the current comparator power bridge involve systematic effects that include inaccuracies in the reference standards used in addition to bias from individual instruments. These combine with random uncertainties when using the power bridge to calibrate the thermal power/energy standard.

The estimated uncertainties from systematic effects in the current comparator system at unity power factor are listed in table 8-1. Contributions from voltage, current ratio, and the ac resistor are evaluated from information derived from calibrated system components or from direct measurement. Drifts or aging effects between calibrations of the system components are not included.

As table 8-1 shows, uncertainties in the dc voltage determinations are attributed to a standard cell, potentiometer, voltage divider, a reversing switch, and power supply regulation. A reversing switch is used for dc voltage reversal into the thermal transfer device. The error caused by the voltage drop across the switch due to an estimated switch contact resistance of 3 mΩ is about 0.5 ppm. Another 0.5 ppm is added for the dc power supply regulation characteristics during thermal element switching. The amount of uncertainty in the dc voltage determination is estimated as 5.1 ppm. The ac-dc difference of the differential thermocouple comparison process has been determined to be about 2 ppm when establishing the value of ac voltage. Each of the individual contributions are combined in a root-sum-square manner. The total uncertainty in the voltage determination is estimated to be 5.5 ppm. Because the applied energy is proportional to the square of the voltage, the uncertainty in energy is taken as twice that of the voltage uncertainty resulting in an uncertainty estimate of 11 ppm.

Table 8-1. Systematic uncertainties for current comparator power bridge in ppm at unity power factor

Item	Magnitude	Subtotal	Total
DC voltage			
standard cell	4		
potentiometer	3		
voltage divider	1		
reversing switch	0.5		
dc power supply regulation	0.5		
root-sum-of-squares		5.1	
AC voltage			
dc/ac difference of DTVC		2	
root-sum-of-squares (dc + ac)		5.5	
Total voltage 2 x (dc + ac)			11
Current ratio			1.1
Resistor			6.4
Total systematic uncertainty bound			
root-of-sum-of-squares			13

Uncertainties in determining current ratio are attributed to the fact that an exact balance cannot be attained to better than about 20 μV. This results in an unbalance uncertainty of 0.1 ppm. Current comparator transformer corrections amount to about 1 ppm and other effects amount to less than 0.5 ppm in the worst case. The total uncertainty assigned for the current ratio is 1.1 ppm (table 8-1). The ac resistor, when calibrated, had an ac-dc difference uncertainty of 5 ppm and a dc resistance uncertainty of 4 ppm. These combine to an uncertainty of 6.4 ppm. The total systematic uncertainty bound, calculated by a root-sum-square method from the above contribution, is 13 ppm for unity power factor.

Table 8-2 lists the estimated uncertainties for the current comparator system at half power factor. Additional terms are those for the "voltage transformer quadrature correction" and the "capacitor conductance" calibrations. The uncertainty in the transformer's quadrature correction is 5.3 ppm.

The uncertainty in the capacitor conductance is 19.6 ppm. Also note that the uncertainty values associated with the current ratio are somewhat larger under the conditions of half power factor than at unity power factor due to unbalance conditions. The overall estimated systematic uncertainty assigned to the current comparator power bridge is 25 ppm at half power factor. When using the current comparator at 0.5 power factor leading, the voltage transformer is simply reversed in polarity, and hence the same uncertainty applies to a leading or lagging power factor.

Table 8-2. Systematic uncertainties for current comparator power bridge in ppm at 0.5 power factor

Item	Magnitude	Subtotal	Total
DC voltage			
same as table 8-1		5.1	
AC voltage			
dc/ac difference of DTVC		2	
root-sum-of-squares (dc + ac)		5.5	
Total voltage 2 x (dc + ac)			11
Current ratio			4.1
Resistor			
same as table 8-1			6.4
Voltage transformer quadrature	5.3		5.3
Capacitor conductance	19.6		19.6
Total systematic uncertainty bound			
root-of-sum-of-squares			25

8.2 Thermal Power/Energy Standard

The thermal power/energy standard is the reference standard for the rest of the measurement chain and is discussed in section 4.2 of this report and also in [9]. Its calibration and associated uncertainty are verified annually by the power bridge.

The systematic uncertainties, as stated above, are 13 ppm and 25 ppm at unity and half power factors, respectively. The random components are based on the results of the international comparison [12]. Based on nine independent measurements, the $3s_m$ figures for both unity and half power factors are estimated to be no greater than 10 ppm. Therefore, the total uncertainties of the calibration are 23 ppm at unity and 35 ppm at half power factor. These values are assigned as the systematic uncertainties for the thermal power/energy standard when calibrating the four NBS rotating standard watthour meters.

8.3 NBS Reference Bank

The unit of energy is maintained by the mean registration of a bank of four reference standard watthour meters. They are each periodically calibrated (every three months) by the thermal watt/watthour standard. A least-squares linear fit as a function of time is made to the mean registration for the bank order to compensate for drift in the individual meters. The value assigned to the bank is the predicted value from the fit at the time of calibration. The estimated random error associated with the assigned value depends on the number of data points and the scatter of points about the fitted line as estimated by the residual standard deviation of the fit. Figures 8-2 and 8-3 show the results of these calibrations.

Based on twelve intercomparisons over three years, the standard deviation of the assigned value, s_m, is 11 ppm for unity power factor and 39 ppm for half power factor. The limits to random error for the calibration of the bank, expressed as $3s_m$, become 33 and 117 ppm at unity and half power factor, respectively. The total uncertainty of the values assigned to the reference bank can be computed from eq (8-1). These values, 56 ppm at unity power factor and 152 ppm at half power factor, then become the systematic uncertainties for measurements made by the NBS reference bank.

8.4 Energy MAP Transport Standards

The NBS reference bank is used in the Energy Measurement Assurance Program (MAP) to assign values of registration to the transport standards. The MAP process is discussed thoroughly in [14] and an overview is presented in section 9 of this report.

As discussed in section 8.3, the assigned systematic uncertainties associated with the reference bank are 56 ppm and 152 ppm, respectively, for unity and half power factor. The random components, however, require special consideration since the MAP transport standards are used only to transfer the unit from NBS to a participating laboratory. Long-term drifts in these standards are much more difficult to assess because they undergo unknown environmental changes during shipping. Short-term performance is more important because the transport standards are calibrated before and after shipment. Therefore, the random

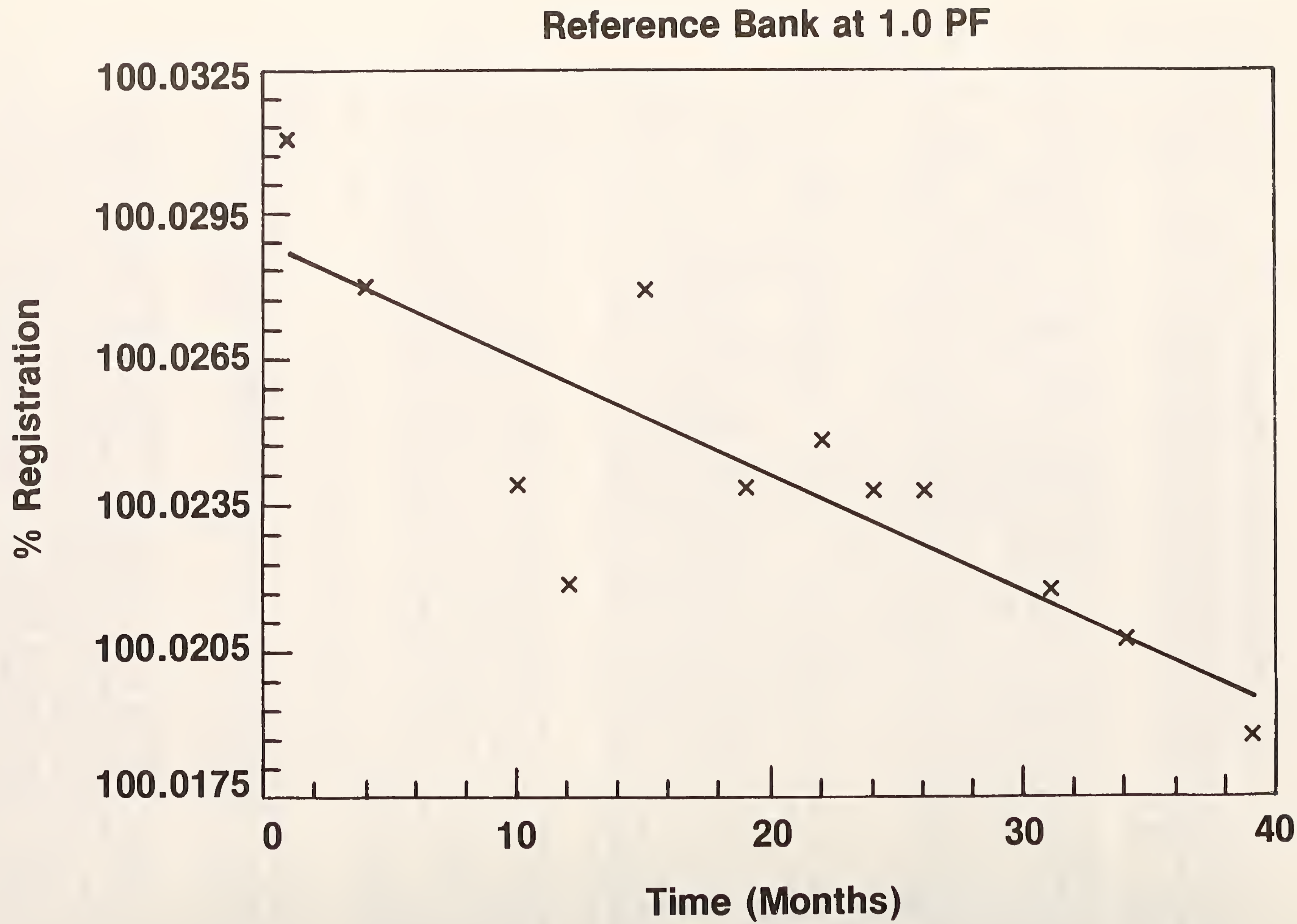

Figure 8-2. Measurement results for the NBS reference bank at unity power factor. Residual standard deviation is 0.0020%.

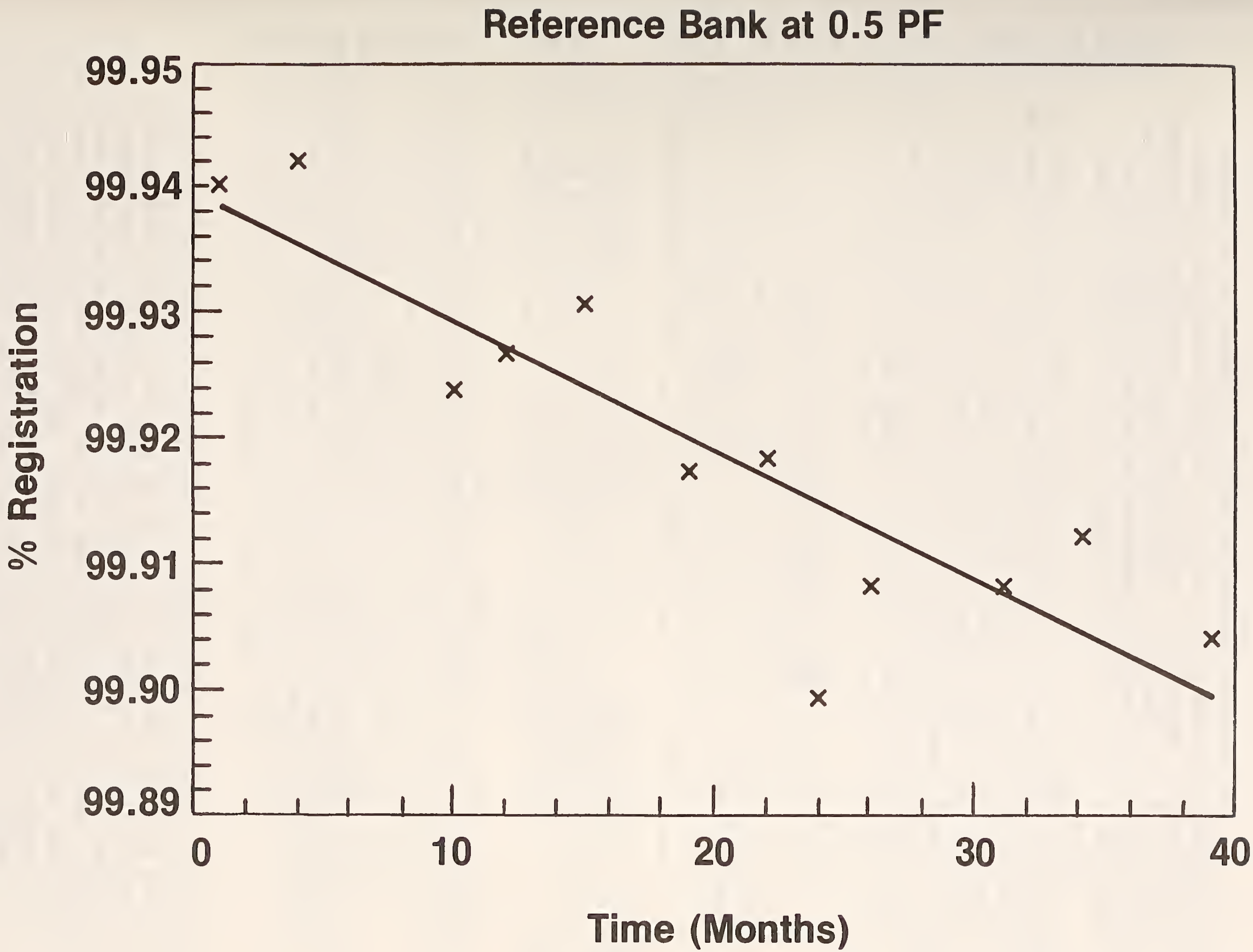

Figure 8-3. Measurement results for the NBS reference bank at half power factor. Residual standard deviation is 0.0068%.

error associated with measurements made at NBS is estimated by pooling the short-term standard deviations calculated for each MAP comparison. These short-term values are computed from four independent observations taken over a two-week interval, and the pooled or assigned standard deviation for each transport standard is the weighted root-mean-square result of all of the short-term standard deviations which have been calculated for that standard.

The random component of uncertainty of a MAP transfer depends not only on the random error associated with the NBS process but also on the random error associated with measurements made at the participating laboratory. Transport standard performance is shown in table 8-3, where the first figure in each column represents the random component of uncertainty associated with the NBS calibration of each transport standard. The values in parentheses are typical components of random uncertainties encountered at the participating laboratories. Values are calculated from pooled short-term standard deviations where N = 4.

Table 8-3. Random uncertainties of five typical MAP transport standards

Transport standard		Pooled $3s_m$ in ppm	
No.	Type	Unity power factor	Half power factor
089	Electronic	106 (237)	155 (283)
092	Electronic	65 (120)	151 (114)
420	Electronic	73 (137)	91 (152)
628	Electromechanical	106 (210)	129 (139)
681	Electromechanical	109 (112)	117 (162)
	Weighted rms	95	125

8.5 Calibration of Customers' Meters

An alternate method of transferring the unit of energy involves the calibration of a customer's watthour meter at NBS. There are two services available -- high accuracy calibrations and routine calibrations.

8.5.1 High Accuracy Calibrations

The high accuracy calibration service compares customers' wattmeters or watthour meters directly to the thermal watt/watthour standard. The systematic uncertainties of this process are 23 ppm and 35 ppm for unity and half power factor, respectively. The random uncertainties will depend upon the individual meters submitted for test and are shown in figure 8-1 as the variables X and Y. The total uncertainty at each power factor will be computed by eq (8-1), where s is the standard deviation estimated during the two- to three-week testing period. This service is limited to two test points (1.0 and 0.5 power factor) allowing up to nine independent measurements at each point. Estimated total uncertainties similar to those assigned to the reference bank are expected.

8.5.2 Routine Calibrations

The routine calibration service allows up to three customers' watthour meters to be tested simultaneously at a wide variety of test points. Because only two independent measurements are made at each point, it becomes very difficult to predict the random component of error with a high degree of confidence. Therefore, certain assumptions are made regarding "typical" random errors. As mentioned earlier, short-term estimates of random error of several types of NBS MAP transport standards are summarized in table 8-3. It is felt that these transport standards are typical of the meters submitted for test at NBS. Moreover, most watthour meters sent to NBS for calibration are used very much like the MAP transport standards in that they are calibrated by the customer's reference standards, shipped to NBS for test and then recalibrated upon return to the customer's laboratory (the short-term performance is of primary interest). The data analysis for these meters can thus make use of the extensive statistical studies available for the MAP transport standards. The weighted "rms" values at the bottom of table 8-3 are used for meters tested at NBS. The major difference between the error analyses of the MAP and the routine calibration service is that the routine calibrations are based on two independent observations instead of the four used in MAP. The NBS values shown in table 8-3 must therefore be multiplied by the square root of two. This yields typical random limits for the routine calibration service of 134 ppm at unity and 170 ppm at half power factor which are shown in figure 8-1. These, combined with the reference bank systematic uncertainties, give total uncertainties of 190 ppm at unity and 322 ppm at half power factor.

The 0.05% accuracy statement presently reported for this calibration service is based on a statistical study of watthour meters in use 15 years ago. It is expected that this statement will be modified in the near future to reflect the improvements in both systematic and random uncertainties that have occurred over the past several years.

The quality of this calibration service is monitored by a check standard which is a commercial watthour meter tested simultaneously with each customer's meter. The performance of this meter over an eight-month period is shown in figures 8-4 and 8-5. The $3s_m$ limits for the average of two independent observations based on 114 averages are 84 ppm at unity and 141 ppm at half power factor. This is somewhat better than the random limits assigned to the calibration process and indicates that these limits are reasonable assessments of the process precision. A rigorous test of process control is made by comparing a short-term standard deviation (determined from the most recent tests) to the long-term value by an "F" test similar to the one described in [13].

9. ELECTRICAL ENERGY MEASUREMENT ASSURANCE PROGRAM

The fundamental concepts of a Measurement Assurance Program began at NBS in conjunction with the National Conference of Standards Laboratories (NCSL) in the early 1970's [14]. A laboratory participating in this program periodically determines its measurement process offset from NBS by testing one or more NBS transport standards as part of that laboratory's normal workload. Using the NBS standard greatly relieves the laboratory of the cost and responsibility of maintaining their own transfer standard and of determining the standard's characteristics, especially those which might be affected by the shipping

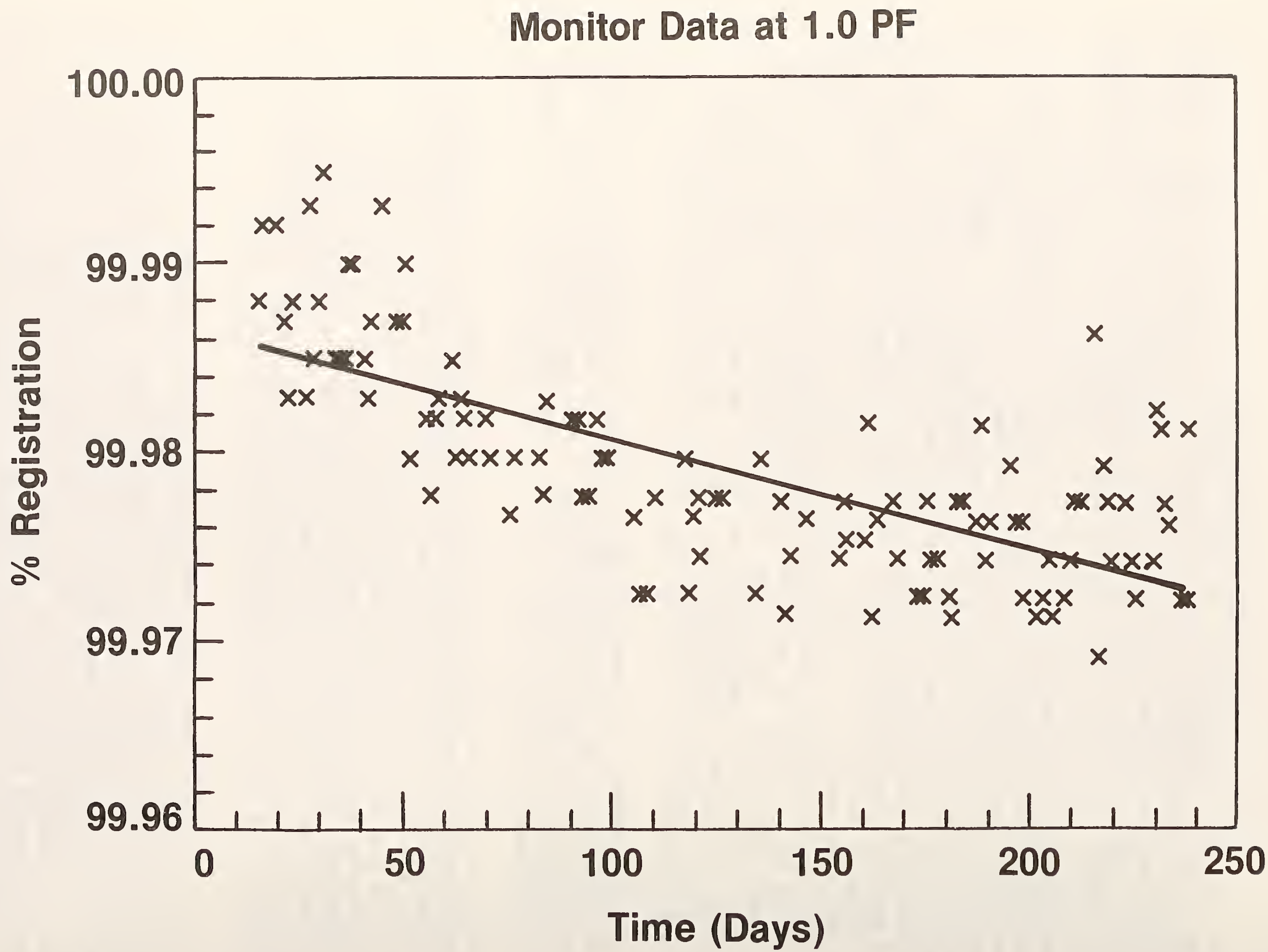

Figure 8-4. Measurement results for the NBS monitor watthour meter (check standard) at unity power factor. Residual standard deviation is 0.0039%.

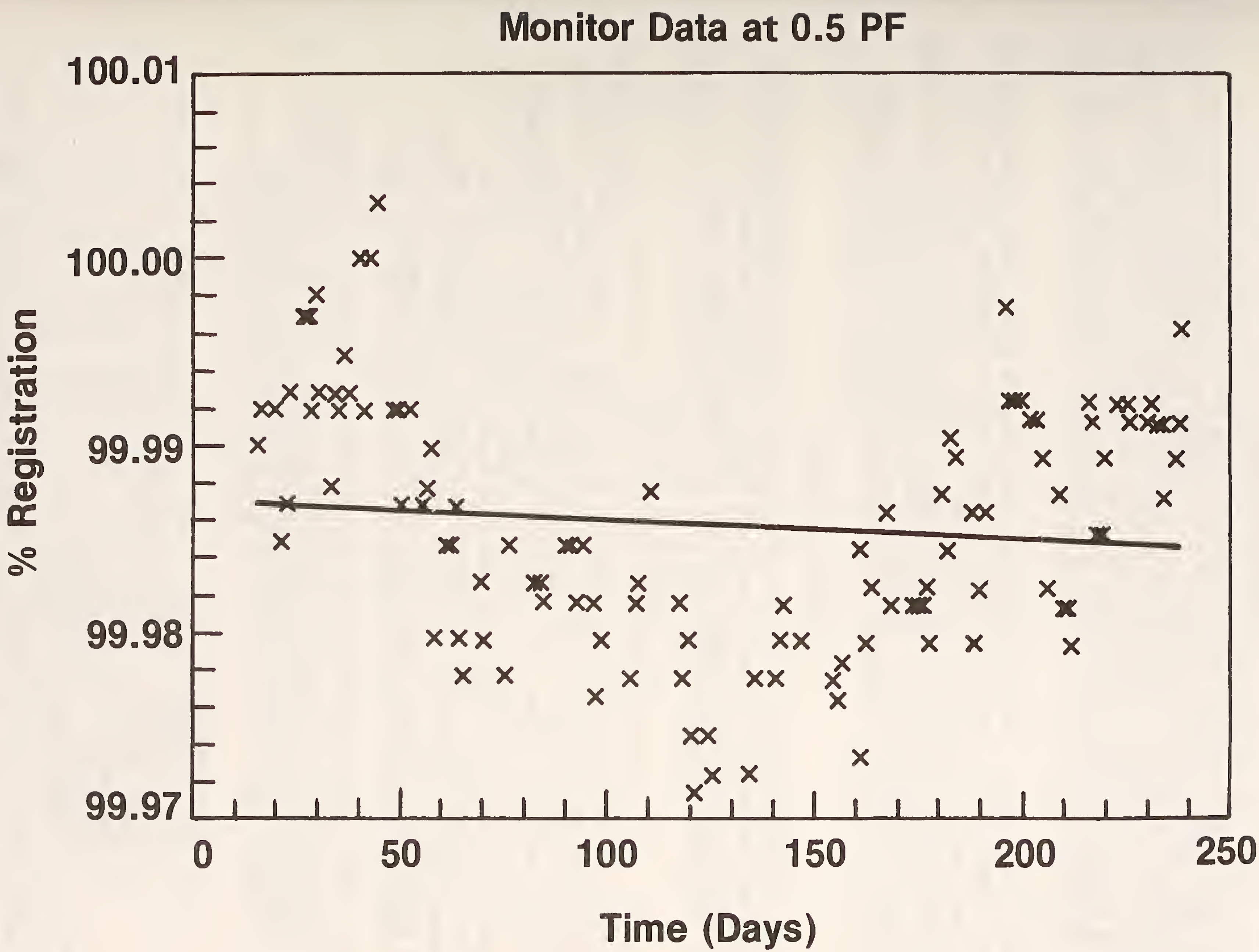

Figure 8-5. Measurement results for the NBS monitor watthour meter (check standard) at half power factor lagging. Residual standard deviation is 0.0066%.

environments. By carrying out the transfer of the measurement unit (in this instance, electrical energy) onsite, with the procedures normally used for its regular workload, statements can be made regarding the uncertainty of its regular measurement process. When this is accompanied by a program of continuing surveillance of the workload by remeasuring a set of their working standards, the laboratory can gain assurance of the validity of their calibration uncertainty statements, and a degree of quality control is being exercised. A feasibility study of alternate methods of dissemination of the unit of energy was made by an EEI-NBS Research Associate in the early 1970's [15]. The MAP for electrical energy began in 1975 [13].

Before shipment to the participating laboratory is made, a set of measurements is made at NBS. The instrument is then shipped and the laboratory performs its set of measurements and returns the instrument to NBS. NBS then makes a second set of measurements and the results are analyzed. Upon completion of the analysis, a report is issued giving the difference between the measurement parameter maintained by the participating laboratory and the legal unit maintained by NBS. The report also includes a complete error analysis of the measurement process.

9.1 Transport Standards

The transport standards used for the electrical energy Measurement Assurance Program are high quality commercial watthour meters, similar to those used by the utilities. The transport standards have been well characterized by a careful measurement program at NBS.

9.2 Measurement Process

Three sets of measurements are made on each transport standard used for the electrical energy MAP. The first set is made at NBS by the process discussed in section 6 of this report. It is compared directly to the NBS reference bank of four watthour meters. Four readings are made, two each on two different days. The unit is then shipped to the participating laboratory. That laboratory measures the transport standard with the techniques and apparatus normally used for their workload. Eight measurements are made in four sets of two measurements each. Each of the four sets are done on different days. Upon return to NBS, an additional two sets of two measurements are made. In all, each laboratory has made eight measurements each to complete the data set.

The registration of the transport standard may be affected by variations in the test conditions and the test environment at the participating laboratory. The laboratory is therefore asked to record the average value of each parameter that might affect the watthour meter's registration during the test. The accepted standard test conditions for the transport standards are listed below:

Input voltage:	120 V
Input current:	5 A
Input power:	600 W, and 300 W
Power factor:	1, 0.5
Frequency:	60 Hz
Waveform:	Sinusoidal
Temperature:	25°C.

Other information such as lead resistances, circuit used for testing, long-term standard deviations of the participating laboratory, etc., are sought and space is provided on the reporting form.

9.3 MAP Data Analysis

During the data analysis, a normalizing procedure is used which compensates for the effects of the above parameters if different than their nominal values. This procedure uses coefficients for each of the parameters which were determined earlier for each standard. By employing such a normalizing procedure, the overall accuracy is improved. The laboratory computes and reports their values for the registration noted as r_{LAB}. When the results are processed at NBS, the corrections are performed to compute the normalized registration, R_{LAB}, by the relationship

$$R_{LAB} = r_{LAB} + P_{LAB} , \tag{9-1}$$

where P_{LAB} is the normalizing term. (See [13] for a more complete explanation.)

The difference in percentage registrations assigned at the participating laboratory and at NBS is given by

$$\Delta R = R_{LAB} - R_{NBS} , \tag{9-2}$$

where R_{NBS} is the normalized mean of the registrations, r_{NBS} computed before shipment, and r'_{NBS} computed after return to NBS.

The total uncertainty of ΔR using a three standard deviation limit is calculated from

$$U_{\Delta R} = SU_{NBS} + \left(\frac{3}{\sqrt{N}} \quad s^2_{LAB} + s^2_{NBS} \right)^{1/2} , \tag{9-3}$$

where SU_{NBS} is the systematic uncertainty of the NBS calibration process,

s_{LAB} is the standard deviation of the participants measurement process,

s_{NBS} is the standard deviation of the NBS measurement process, and

N is the number of independent observations made at each laboratory. (An independent observation for these measurements is defined as a set of two or more readings separated by at least several hours from any other set of readings.)

Systematic errors in a laboratory process can be determined by calibrating the NBS transport standard watthour meter as a working standard. If the laboratory corrections are adjusted so that $\Delta R = 0$, the uncertainty due to systematic errors of their process can be reduced to the uncertainty, $U_{\Delta R}$, of the NBS transport standard. Random errors can be determined through local statistical analysis by the participant using a group working standard calibrated many times over a long period. Using this type of information, obtained from the MAP report and local statistical analysis, the laboratory can determine the uncertainty, U_{LAB}, in their calibration process, where

$$U_{LAB} = U_{\Delta R} + 3 \frac{s_{LAB}}{\sqrt{N}} . \qquad (9\text{-}4)$$

The reader is encouraged to study NBS Technical Note 930 "A Measurement Assurance Program for Electric Energy" (see [13]).

9.4 MAP Results

Results for electric energy MAP show an overall improvement in transferring the standard energy unit from NBS. The program can thus decrease measurement uncertainties and tie the utility industry closer to the legal unit of energy. For purposes of illustrating this improvement, typical data are shown in figures 9-1 and 9-2 for measurements made at unity power factor and half power factor lagging, respectively. For each figure, three different symbols designate different laboratories. The symbol location indicates the mean value of the measured difference, ΔR, between NBS and the utility. The length of the vertical bar of each point represents the total uncertainty assigned to that set of measurements, previously defined as $U_{\Delta R}$, eq (9-3).

For measurements made at unity power factor (fig. 9-1), all three laboratories show a convergence towards zero difference. Initial measurements indicated a difference in excess of 1000 ppm (0.1%). After four MAP interchanges, the mean differences were improved to be between about 200 to 400 ppm (0.02 to 0.04%). The more recent data show the mean to lie within the total uncertainty (i.e., the length of the uncertainty "bars" pass through zero difference).

For half power factor lagging (fig. 9-2), the same converging trend is evident. In the case of the data represented by the symbols o and Δ, the trend is a settling of the means toward zero difference. For the data shown by the symbol □, the uncertainty is larger, but of more concern; there is an apparent "drift" in the process causing the mean difference to increase rather than decrease. Even though the total uncertainty still encompasses zero difference, the results suggest that this measurement process may not be in control and further investigation should be made.

Because the electric energy MAP has been in operation for only about five years, an abundance of data is not available. However, as time progresses charts similar to figures 9-1 and 9-2 will show the degree of overall improvement that the MAP process has made in electric energy measurement.

10. INTERNATIONAL COMPARISONS OF ELECTRICAL ENERGY STANDARDS

Two international comparisons of electrical power measurements were made in 1976. The most notable involved the national laboratories of Germany, Canada, and the United States. Namely the Physikalisch-Technische Bundesanstalt-Institut Berlin (PTB(IB)), the National Research Council of Canada (NRC(EE)), and the National Bureau of Standards (NBS). The second comparison was carried out between NBS and NRC(EE). Both are documented in [12].

The ensuing discussion of this section is a direct synopsis of that paper with emphasis being placed on the NBS results in comparison to the other two laboratories. This comparison improves the confidence of electrical power and energy measurements made at NBS.

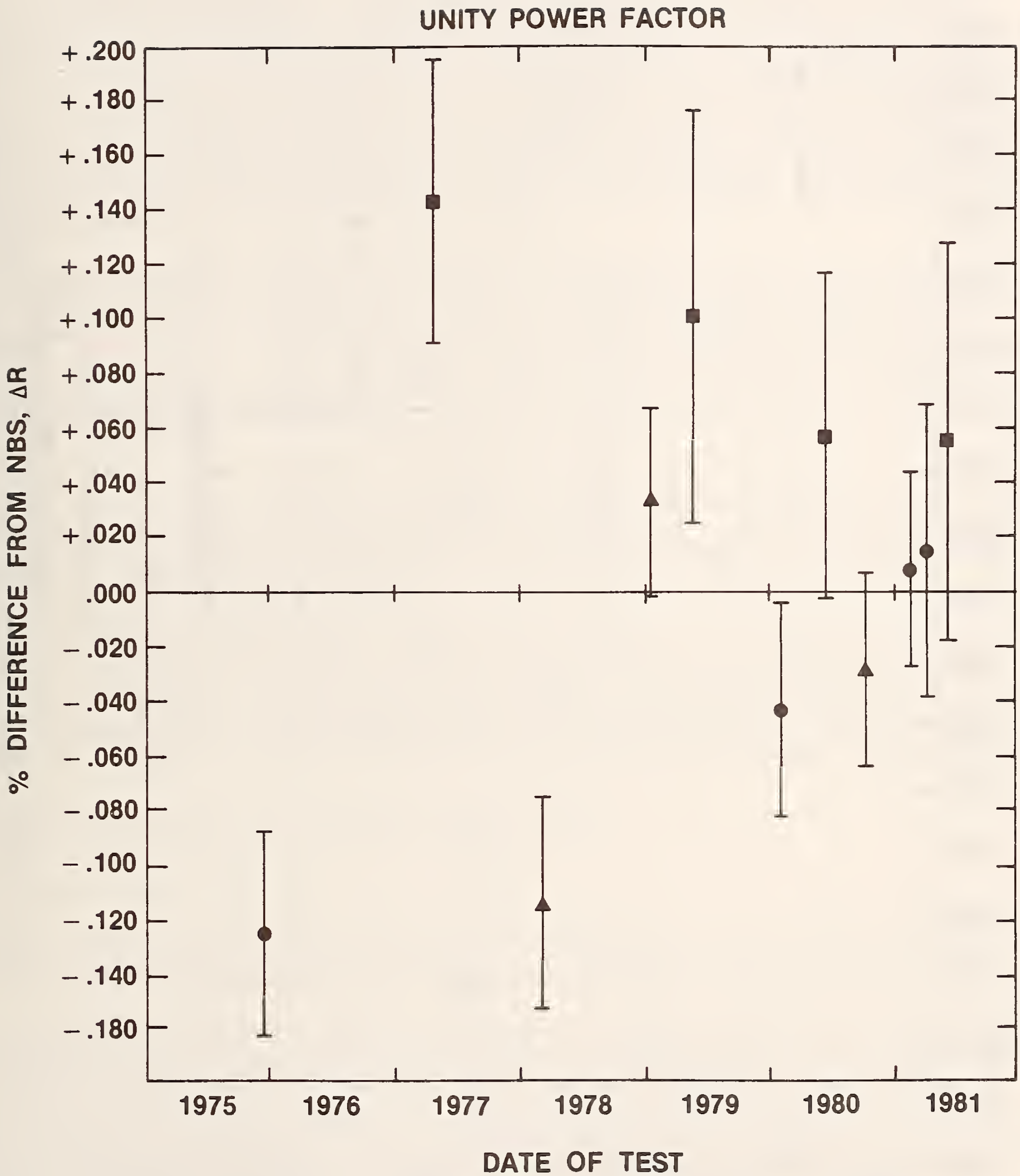

Figure 9-1. Measurement results from the MAP for electric energy for three large utility companies. Tests made at unity power factor. (See eq (9-2).)

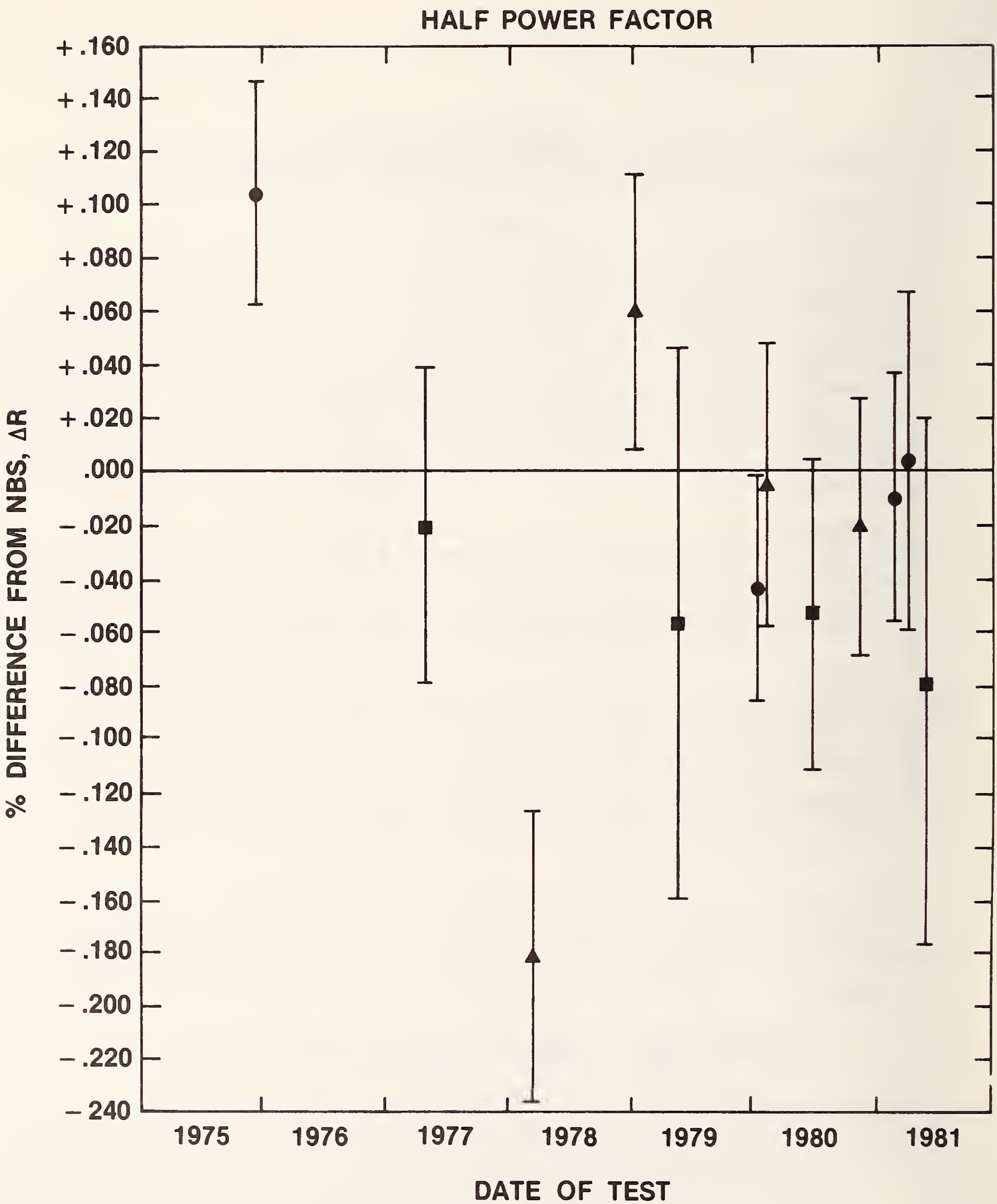

Figure 9-2. Measurement results from the MAP for electric energy for the same three utility companies as shown in figure 9-1. Tests made at half power factor lagging. (See eq (9-2).)

Prior to 1976, a precision comparison of electrical power between laboratories was not practical inasmuch as a considerable number of sensitive instruments would have had to be shipped. This is because ac power is a derived quantity involving basic standards of dc voltage, resistance, and ac-dc transfer. This situation was altered significantly by the development of a sufficiently accurate, stable, transportable thermal wattmeter at PTB(IB). The wattmeter is based on a thermal ac-dc transfer principle [9] which is discussed in section 4 of this report. The wattmeter was calibrated at PTB(IB), then shipped to NBS and NRC(EE), where repeated sets of measurements were made. The instrument was then returned to PTB(IB), where it was recalibrated.

The measurement method that NBS used is described in detail in section 4 of this report, and the appropriate errors are given and discussed in section 8. As discussed therein, the NBS current comparator power bridge is employed as the NBS basis of establishing the legal unit of electrical power. It was this same power bridge and related apparatus that was used to perform the measurements for the international comparisons.

The PTB(IB) thermal wattmeter provides means for the precise measurement of voltage and current as well as for power. Though these parameters were indeed measured and analyzed during the comparison process, only the power measurement results will be given here inasmuch as it is power and energy measurements that are of prime concern in this report.

The conditions of test were essentially the same at all laboratories, that is, 120 V, 5 A, 60 Hz, and either 600 W or 300 W, depending on the power factor. During the calibrations of the thermal wattmeter, readings were recorded over a period of several days. The average errors of the instrument as well as three standard deviation limits of the random uncertainty were calculated from these data.

The listed quantities are defined as follows.

Errors: $(P_W - P_A)/S$,

where P_W is the active power indicated by the wattmeter, P_A is the active power applied to the wattmeter, and S is the apparent power.

The results are shown in table 10-1 and are illustrated in figure 10-1. The calibrations PTB(IB)-1 are those made by PTB at the beginning of the comparison and PTB(IB)-2 at the end. In deriving the averages quoted, each of the PTB calibrations is given half weight. It is apparent from the two PTB values that the wattmeter calibration was relatively unaffected by either the transport conditions experienced between laboratories or the time period of four months taken to accomplish the intercomparison.

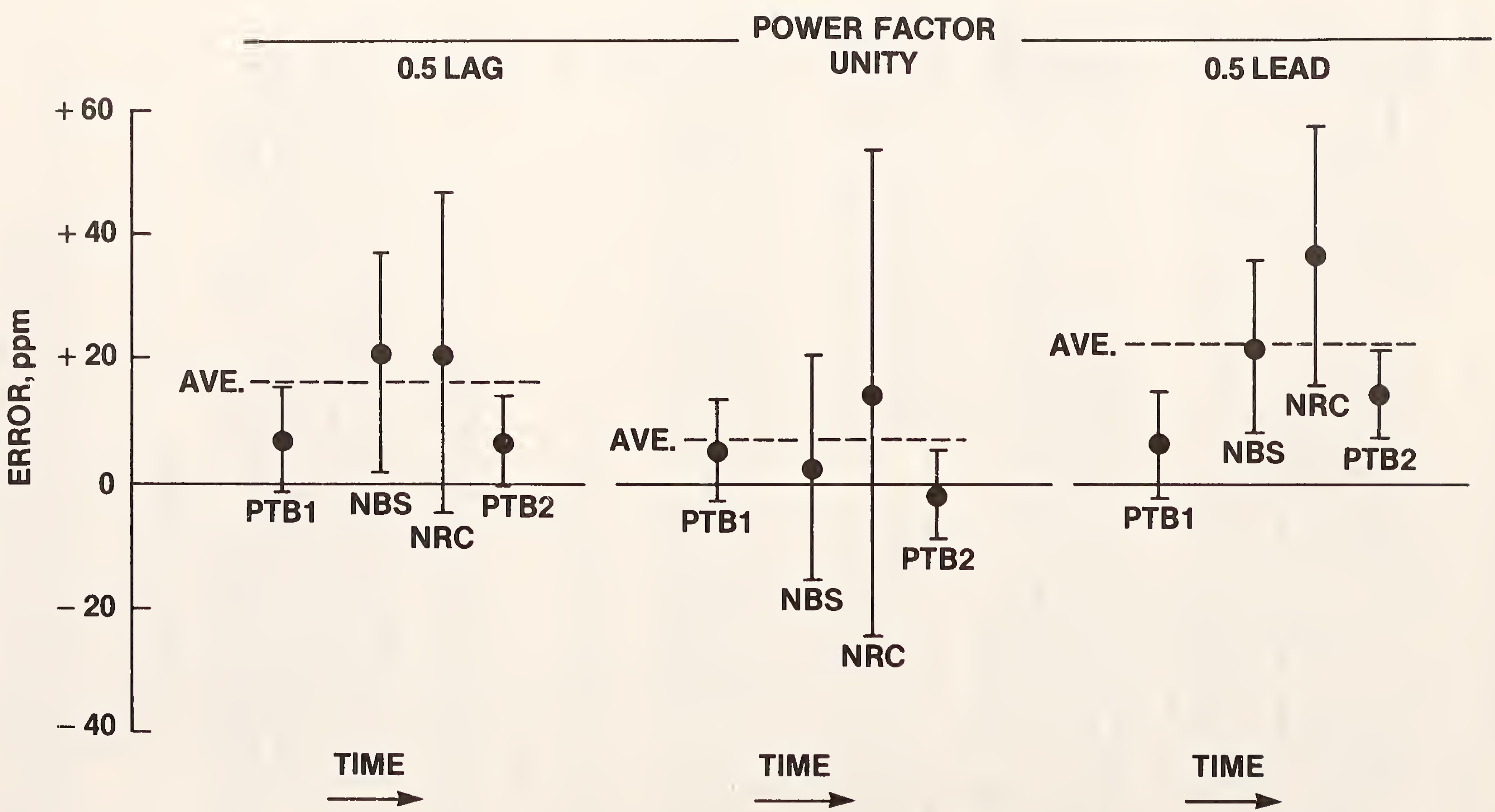

Figure 10-1. Results from the international comparison of electrical power and energy at unity and half power factors.

Table 10-1. Calibrations of the PTB Wattmeter
(In ppm of apparent power at 120 V, 5 A, and 60 Hz)

Laboratory	Errors[a]			Random uncertainty limits ($3s_m$)			Number of measurements		
Power Factor	-0.5(lag)	1.0	+0.5(lead)	-0.5	1.0	0.5	-0.5	1.0	0.5
PTB(IB)-1	+ 7(8)	+ 5(8)	+ 7(8)	3	3	3	7	7	7
NBS	+20(16)	+ 2(17)	+21(14)	4	7	1	12	12	9
NRC(EE)	+20(25)	+14(39)	+36(21)	9	9	6	5	10	5
PTB(IB)-2	+ 7(7)	- 1(7)	+14(7)	2	2	2	9	9	9
Average	+16	+ 6	+22						

[a]Total uncertainty is shown in parenthesis after each error value.

Examining the results, no laboratory differed by more than ±15 ppm from the average, with reference to apparent power at unity and half power factors (both leading and lagging). This is consistent with estimates of error limits of each of the three participants. At unity power factor, NBS agreed exactly with the average of the PTB(IB) results.

At half power factor (both leading and lagging) the errors as measured by all three laboratories indicated a positive shift with respect to the values at unity power factor. About 10 ppm of this shift was later determined to be the result of a nonlinearity of the thermal wattmeter. However, a residual discrepancy appears as an offset of the PTB(IB) results as compared to those results reported from both NBS and NRC(EE). The cause of this offset is unknown at the time of the writing of the paper [12].

The results of a separate comparison between NBS and NRC(EE) using two commercial wattmeters of the time division multiplier (TDM) type are shown in table 10-2. The reported difference is computed from the average value obtained by the base laboratory, at the beginning and end of the comparison period, and is compared with the value obtained at the other laboratory. The average value was used because instabilities of the order of 50 ppm were observed for both instruments during the exchange period. While the commercial meters were not as stable as the PTB(IB) instrument, the results are still very impressive. It is apparent that commercial power instruments warrant measurements of higher accuracy than is now generally quoted.

Table 10-2. NBS/NRC(IEE) Comparison using commercial wattmeters
(In ppm of apparent power at 120 V, 5 A, and 60 Hz)

Wattmeter	(NBS-NRC) at power factor		
	-0.5(lag)	1.0	+0.5(lead)
1	+30	- 5	+16
2	-30	-40	-58
Average	0	-22	-21

11. SUMMARY

The basic concepts and philosophy of extending the measurement chain from the fundamental units of mass, length, and time to the calibration of NBS reference watthour meters and then to the ultimate calibration of watthour meters sent to NBS is presented. The hardware used in such a chain of measurements and the test procedures employed are discussed in detail. The associated uncertainty of each step in the chain is examined and these results are documented herein. A sample Report of Calibration is included with an accompanying explanation.

The NBS Measurement Assurance Program (MAP) for electric energy is discussed with results shown over the period since MAP's establishment in 1975 to the present time. The results given show that the utilities participating in the program have adjusted their values so that their measurement uncertainties have decreased from typically ±0.10% to values typically ±0.02%. This five-fold improvement demonstrates the value of the MAP to the electric utility industry.

Results of international comparisons for energy measurements are given. The national laboratories of the United States (NBS), Canada (NRC), and West Germany (PTB) each participated. All laboratories' results agreed to within ±15 ppm (±0.0015%) on the average with reference to apparent power at power factors of 1, 0.5 lagging, and 0.5 leading. These results were consistent with the uncertainty limits estimated by each of the participants.

With recent improvements of hardware, standards, measurement procedure, and data analysis, electric energy calibrations with systematic uncertainties of less than ±100 ppm (±0.01%) can be performed. Where the random component of uncertainty is small, the overall uncertainty may be less than ±100 ppm. Based on this performance, NBS is now offering special high accuracy calibration of quality watthour meters to uncertainties of ±100 ppm.

12. ACKNOWLEDGMENTS

The authors would like to express gratitude to the following staff members at the National Bureau of Standards for their help in preparing this report: Mr. N. M. Oldham, who helped design the present system and, in particular, much of the electronic hardware, provided much useful information as well as reviewing the manuscript thoroughly; Mr. T. M. Souders who designed the current transformer and provided information regarding transformers and their errors; Dr. K. J. Lentner who designed the current comparator power bridge and assessed its errors; Mr. J. D. Neal who constructed most of the hardware; Mr. J. Jones who operated the system and gave practical information regarding its use; and Mrs. C. Croarkin who performed statistical analyses of much of the data and summarized the results to a useful form. Dr. R. E. Hebner, Group Leader of the Applied Electrical Measurements Group, provided overall guidance and made many helpful suggestions. Appreciation is given to Mrs. S. Kelley, Mrs. L. Bequette, Mrs. B. Meiselman, Mrs. B. Frey, Mrs. J. Palla, and Mrs. B. Oravec, who prepared the manuscript with the finest of attitudes and quality.

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APPENDIX A*

NBS CALIBRATION SERVICES OF WATTHOUR METERS

A.1 Technical Information

Only portable standard watthour meters (rotating standards and electronic types) will be accepted for test. These tests consist of determinations of the percentage registration of the meter "as received." If meters are to be cleaned and adjusted this must be done before the Requests from Federal agencies, or from State agencies, for calibrations are submitted for test. The Bureau does not undertake the cleaning and adjustment of meters and does not knowingly begin tests on faulty meters.

Before tests can be started, the test conditions must be completely specified by the user as to current and voltage ranges to be tested, frequency, applied voltage and current, and power factor. Test voltages should be chosen from the following values: 1, 2, or 4 times 110, 115, 120, 125 and 130 V (but not to exceed 480 V). Test currents should be chosen from the following values: 1, 10, or 100 times 0.5, 0.75, 1, 1.25, 1.5, 2, 2.5, 3, 3.75, 4, 5, 7.5 A (but not to exceed 50 A). Tests at other voltages or at power factors other than 1.0, 0.5 current lagging and 0.5 current leading will be considered as special tests. Unless otherwise specified, test runs on portable standard watthour meters are of approximately 100 seconds duration. The meters are energized for at least four hours at rated voltage and current on one range before starting the test. Normally values are reported with an uncertainty of ±0.05%.

A.2 Calibration Requests, Watthour Meter Shipping, Insurance and Risk of Loss

A formal purchase order for the calibration or test should be sent before or at the time the standard is shipped. This should provide clear identification of the apparatus being submitted and give separate instructions for return shipment, mailing of report, and billing. To minimize the time during which equipment is out of service, usually one can arrange to delay shipment until the test is scheduled to start.

Requests from Federal agencies, or from State agencies, for calibrations or tests on material to be used on private or Federal contract work should be accompanied either by purchase order or by letter or document authorizing the cost of the work to be billed to the agency. The Bureau's acceptance of purchase orders does not imply acceptance of any provisions set forth in the order contrary to the policy, practice, or regulations of the National Bureau of Standards or the U.S. Government. The purchase order should clearly state

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*Portions of this section were excerpted from NBS Special Publication 250, "Calibration and Related Measurement Services of the National Bureau of Standards, 1980 Edition." See reference 7.

special or necessary conditions of test where appropriate (i.e., operating frequency, power factor, etc.). Requests for measurement services from foreign sources should be sent to:

Office of Measurement Services
National Bureau of Standards
Washington, DC 20234 .

NBS staff will provide assistance for individual measurement problems. The headquarters of the National Bureau of Standards is located in Gaithersburg, Maryland, approximately 25 miles northwest of Washington, D.C. The calibration of watthour meters is performed at the Gaithersburg site by the Electrosystems Division (722) of the Center for Electronics and Electrical Engineering of NBS. Inquiries may be made by directing correspondence to:

National Bureau of Standards
Electrosystems Division (722)
Metrology Building, Room B344
Washington, DC 20234 .

The reader is encouraged to obtain a copy of the NBS Special Publication 250, Calibration and Related Measurement Services of the National Bureau of Standards, and is available at the following places:

Superintendent of Documents
Government Printing Office
Washington, DC 20402

Office of Measurement Services
National Bureau of Standards
Washington, DC 20234

Field Offices of the Office of Field Services
Department of Commerce

Program Information Office
National Bureau of Standards
Boulder, CO 80303

Federal Depository Libraries.

The appendix of SP 250 listing current services and fees is issued twice yearly (June and December) and is available free from:

Office of Measurement Services
National Bureau of Standards
Washington, DC 20234

Program Information Office
National Bureau of Standards
Boulder, CO 80303 .

Scheduled work assignments for calibrations and other tests generally will be made in the order in which confirmed requests are received. However, Government work may be given priority. For the regular services, the workload is usually such that the turnaround interval, between the date a customer's apparatus is received and the date it is prepared for return shipment, will be not more than 45 days. Some types of instruments may require a longer time, particularly if their abnormal behavior requires reruns to check reliability. The customer who can spare his instrument for only a short time usually can arrange by letter or phone for shipping it to NBS just as his assigned starting date approaches. Generally, the acknowledgment of the purchase order gives the expected completion date. When prearrangements are made, most meters can be calibrated and returned within ten working days.

Limited staff precludes NBS from undertaking repair activities. Therefore, all apparatus submitted for calibration should be free of defects and in proper working order. Electrical contacts should be in proper condition both mechanically and electrically. Due to the delicate nature of most watthour meters, it is advisable to pack them extremely carefully. Special reusable shipping containers customized for this purpose are a worthwhile consideration.

A report is issued upon the calibration of each meter. This report contains the measured values of each of the appropriate attributes of the device and their uncertainties relative to the legal units. Additional uncertainties associated with certain other effects may be quantified from additional measurements. NBS personnel can assist in setting up the appropriate experiments. Reports of Calibration for watthour meters are discussed in section 7 of this report and an example of a typical report is given.

NBS neither requires nor recommends intervals between NBS calibrations for watthour meters. These calibration intervals depend upon the performance of the individual standard and the accuracy requirements of its application. These must both be determined by the user. Some state utility commissions have established calibration intervals they have determined to be necessary for watthour meters.

Shipment of apparatus to NBS for calibration or other tests should be made only after the customer has accepted the estimate of cost and the tentative scheduling. Repairs and adjustments on apparatus submitted should be attended to by the owner since NBS will not undertake them except by special arrangement. Apparatus not in good condition will not be calibrated. If defects are found after calibration has begun, the effort may be terminated, a report will be issued summarizing such information as has been found, and a fee may be charged in accordance with the amount of work done.

The customer should pack apparatus sent to NBS so as to minimize the likelihood of damage in shipment and handling. In every case, the sender should consider the nature of the apparatus, pack it accordingly, and clearly label shipments containing fragile instruments or materials. Care should be taken in selecting the best mode of transportation.

To minimize damage during shipment resulting from inadequate packing, the use of strong reusable containers is recommended. As an aid in preventing loss of such containers, the customer's name should be legibly and permanently marked on the outside. In order to prolong the container's use, the notation REUSABLE CONTAINER, DO NOT DESTROY should be marked on the outside.

Shipping and insurance coverage instructions should be clearly and legibly shown on the purchase order for the calibration or test. The customer must pay shipping charges to and from NBS; shipments from NBS will be made collect. The method of return transportation should be stated and it is recommended that return shipments be insured, since NBS will not assume liability for their loss or damage. For long-distance shipping it is found that air freight provides an advantage in reduction of time in transit. If return shipment by parcel post is requested or is a suitable mode of transportation, shipments will be prepaid by NBS but without covering insurance. When no shipping or insurance instructions are furnished, return shipment will be made by common carrier collect and uninsured.

The risk of loss or damage in handling or testing of any item by NBS must be assumed by the customer, except when it is determined by the Bureau that such loss or damage was occasioned solely by the negligence of Bureau personnel. In such cases, the owner may apply for reimbursement.

Shipments of watthour meters to NBS for calibration should be directed to:

National Bureau of Standards
Electrosystems Division, MET B165
Rt. I-270 and Quince Orchard Road
Gaithersburg, Maryland 20878 .

APPENDIX B

WATTHOUR METER COMPARISON SYSTEM HARDWARE AND CIRCUITS

The watthour-meter calibration hardware consists of: 1) two adjustable power sources, one for the voltage inputs to the watthour meters and the second for the current inputs; 2) a test table which provides for convenient connections to meters being tested; 3) precision voltage and current transformers for testing at levels different from those used with NBS reference watthour meters; and 4) the comparison electronics for reading the output pulses of both the reference meters and meters being tested. This group of equipment will be discussed in detail in this appendix.

B.1 Power Supply and Control Hardware Circuits

The four NBS reference watthour meters and the meters being tested derive their electrical stimulus from two separate sources, one for the voltage circuits and the other for the current circuits. Figure B-1 shows the basic circuit. Power can be derived from either a commercial power line (208 V, three-phase), or from a three-phase electronic power supply. The electronic power supply provides a three-phase voltage of better stability and less distortion than the voltage derived from the commercial power lines. Either the three-phase power line or the electronic power source can be selected using a four-pole double-throw switch as shown in figure B-1, which then routes the power to the voltage, current, and power factor controls shown in figure B-2.

Voltage, current, and power factor can each be adjusted by the controls shown in figure B-2. These controls are fed from a 208-V three-phase wye connected line (with neutral). Each parameter has a coarse and a fine adjustment configured from variable transformers. By the proper selection of the three-phase lines and adjustments of the controls, the voltage to the watthour voltage circuits can be set, the output voltage for the current transformer for the current circuit can be set, and the power factor can be suitably adjusted.

Switch S3 selects the power factor condition of unity, lead, or lag and feeds the properly phased voltage to transformers T4 and T5 for the current adjust. Transformer T4 is tapped about 40% up and feeds T5 and a step-down transformer T6. The secondary of transformer T6 is in series with the output of T4 such that these voltages add. The combination of the 40% tap on T4, transformer T5, and the step-down ratio of transformer T6 creates the fine adjustment, having a voltage range of about 3% of a setting. Transformer T10 is for isolation and phase inversion and has a nominal 1:1 ratio.

For the three conditions of power factor, the following pairs of phases are selected by switch S3 and these voltage phases are applied to the transformer T4.

Power factor	Voltage phase
Unity	B to C
Lead	B to A
Lag	A to C

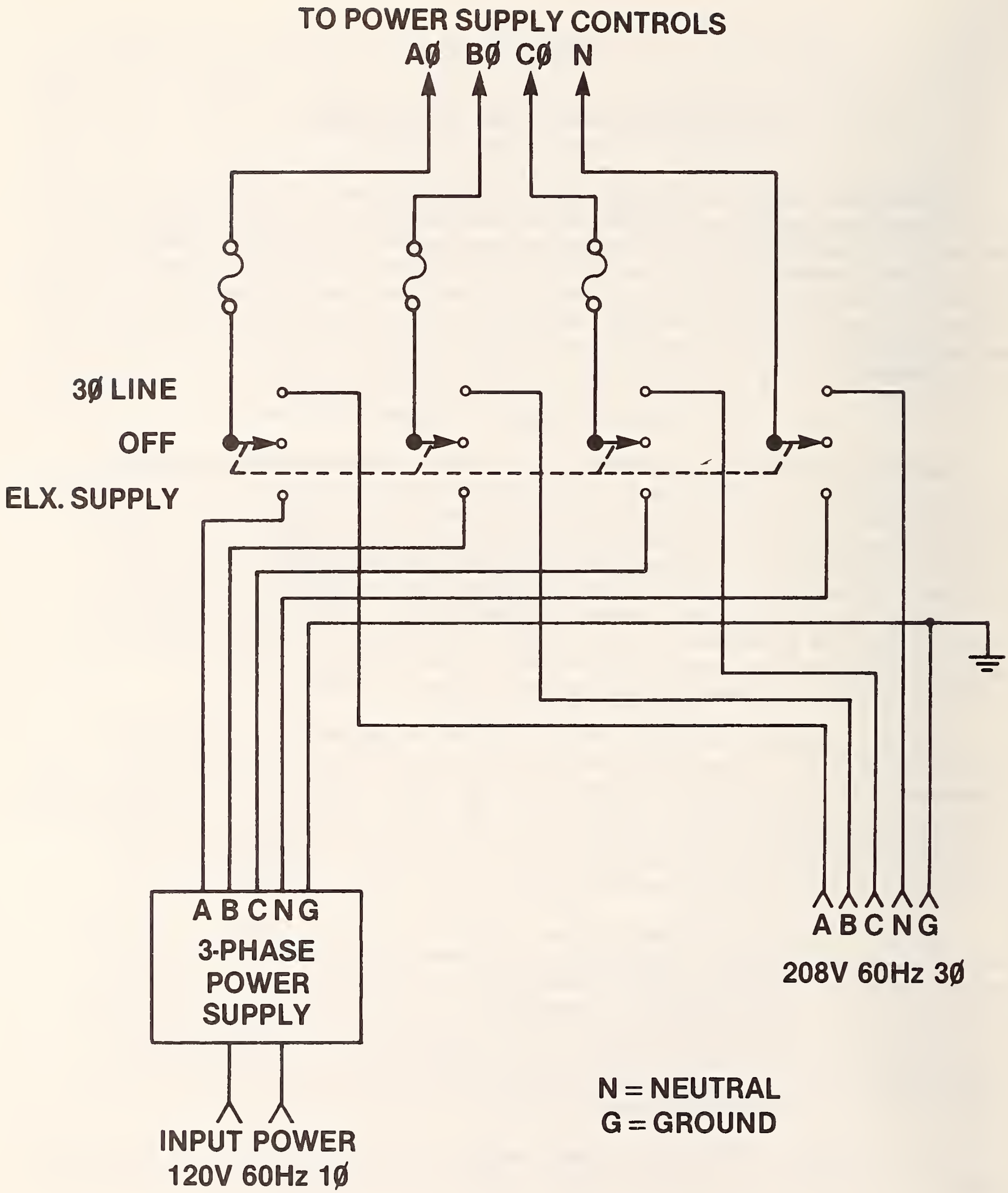


Figure B-1. Watthour meter calibration system power sources, switch selectable between the 208-V three-phase power lines or the three-phase electronic power supply.

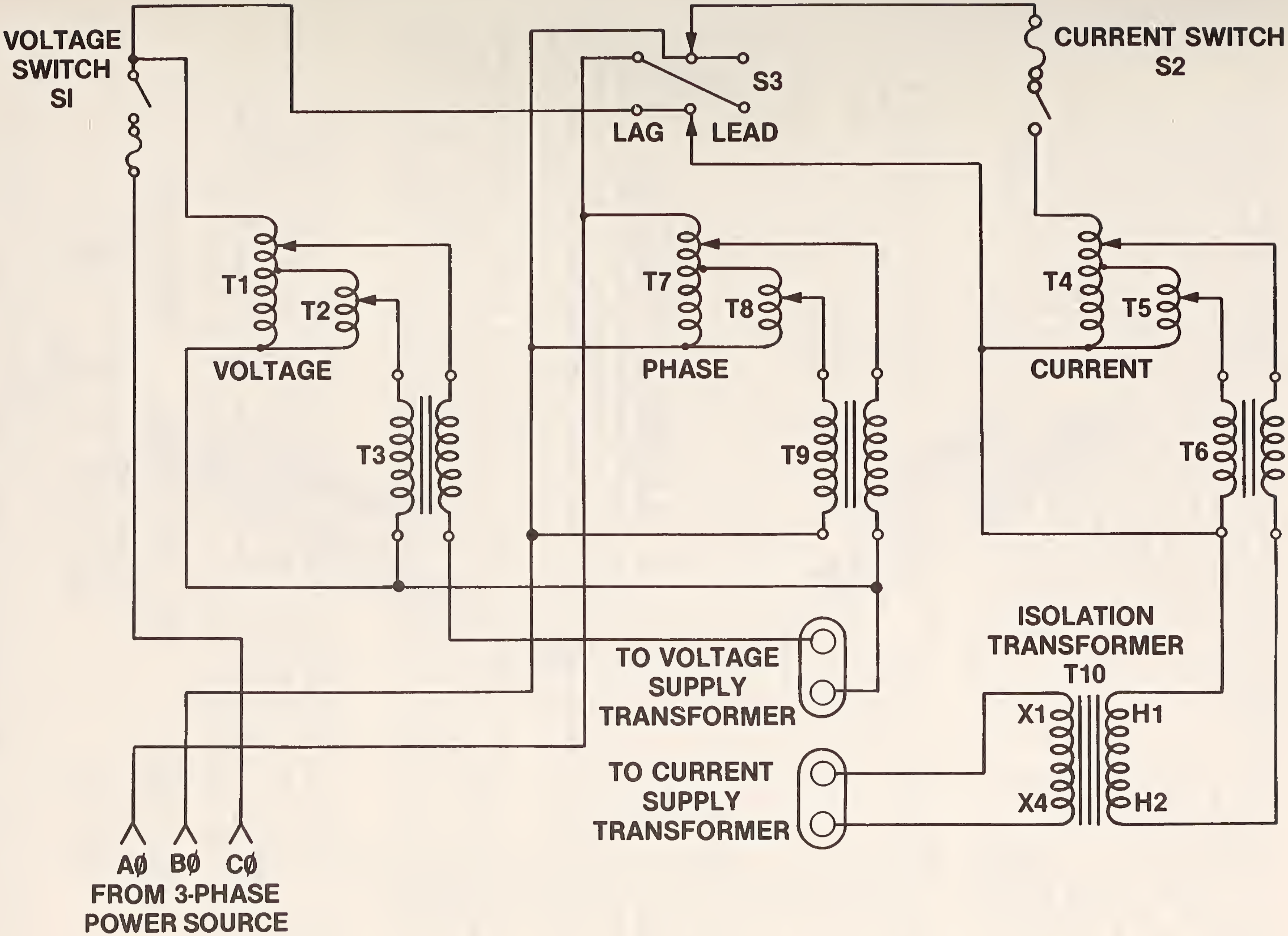


Figure B-2. Voltage, current, and power factor controls.

Figure B-3 is the phasor diagram which shows the voltage output phasors for the three conditions of power factor from the current adjustment transformers. The output voltage is connected to step-down current transformers discussed later; the test current for the watthour meters will be in-phase with this voltage thus generated by the current controlled adjustments. The current phasor for unity power factor is in-phase with the line-to-line voltage V_{CB}. (The subscripted notation designates the voltage from phase C to phase B, namely, $V_{CB} = (V_C - V_B)$. Similar notation is used later in this discussion for the other phased voltages.) The current phasor for a leading power factor is in-phase with V_{AB} and for a lagging power factor, with V_{CA}. Note that the phase difference between V_{AB} and V_{CB} and the difference between V_{CA} and V_{CB} is nominally 60°. This, as will be seen later, generates the required phase shift for the power factors of 0.5 leading and lagging.

The voltage used for the watthour meter potential circuits is adjustable in both its amplitude and phase. Transformers T7 and T8 are fed from phases A and B of the input three-phase line. Transformers T8 and T9 are used for fine adjustment. The output of these transformers serves as one side of the output voltage for the watthour meter testing as well as a reference voltage for transformers T1, T2, and T3. The output from the secondary of transformer T3 is the other side for the watthour voltage circuits. Figure B-4 shows a phasor diagram for the voltage adjustment output voltage V_p. The variable K_1 is a ratio of the output voltage from transformer T9 to the input voltage to transformer T7, and, likewise, variable K_2 is the ratio of the output voltage of transformer T3 to the input of transformer T1. When nominally set for an output voltage, V_p, of 120 V, K_1V_{AB} is about 60 V and K_2V_C is about 104 V with the phase angles as shown in figure B-4. As can be seen from the vector diagram and figure B-2, adjustments of either the "voltage" or "power factor" controls (transformers T1 and T7, respectively) will cause the output voltage vector V_p to change in magnitude and phase. Because transformer T1 has more effect over the voltage and less on the power factor than does transformer T7, the former is labeled as the voltage control.

When the two phasor diagrams as shown in figures B-3 and B-4 are superimposed as shown in figure B-5, the relationships between the current and voltage vectors are apparent for the three conditions of power factor generally used in calibration and testing (i.e., unity and ±0.5). Vectors with open arrows represent the circuit currents and arrows which are solid represent circuit voltages. Voltage V_p is the test voltage.

When the test voltage V_p is in-phase with i_{unity}, a power factor of 1 is realized. When the power factor selector switch S3 is turned to the "lead" position, the current vector leads the voltage vector V_p by nominally 60°. When lag condition is selected, the current vector lags the voltage V_p by 60°. Also illustrated by figure B-5 and shown below, the range of phase adjustment for each of the power factor settings of the selector switch S3 is 90°.

Power factor	Phase shift range[1]	Nominal phase
Unity	+30° to -60°	0°
Lead 0.5	0° to +90°	+60°
Lag 0.5	-30° to -120°	-60°

[1]A positive angle is considered as a counterclockwise rotation. Phase shifts are with respect to the voltage vector V_p.

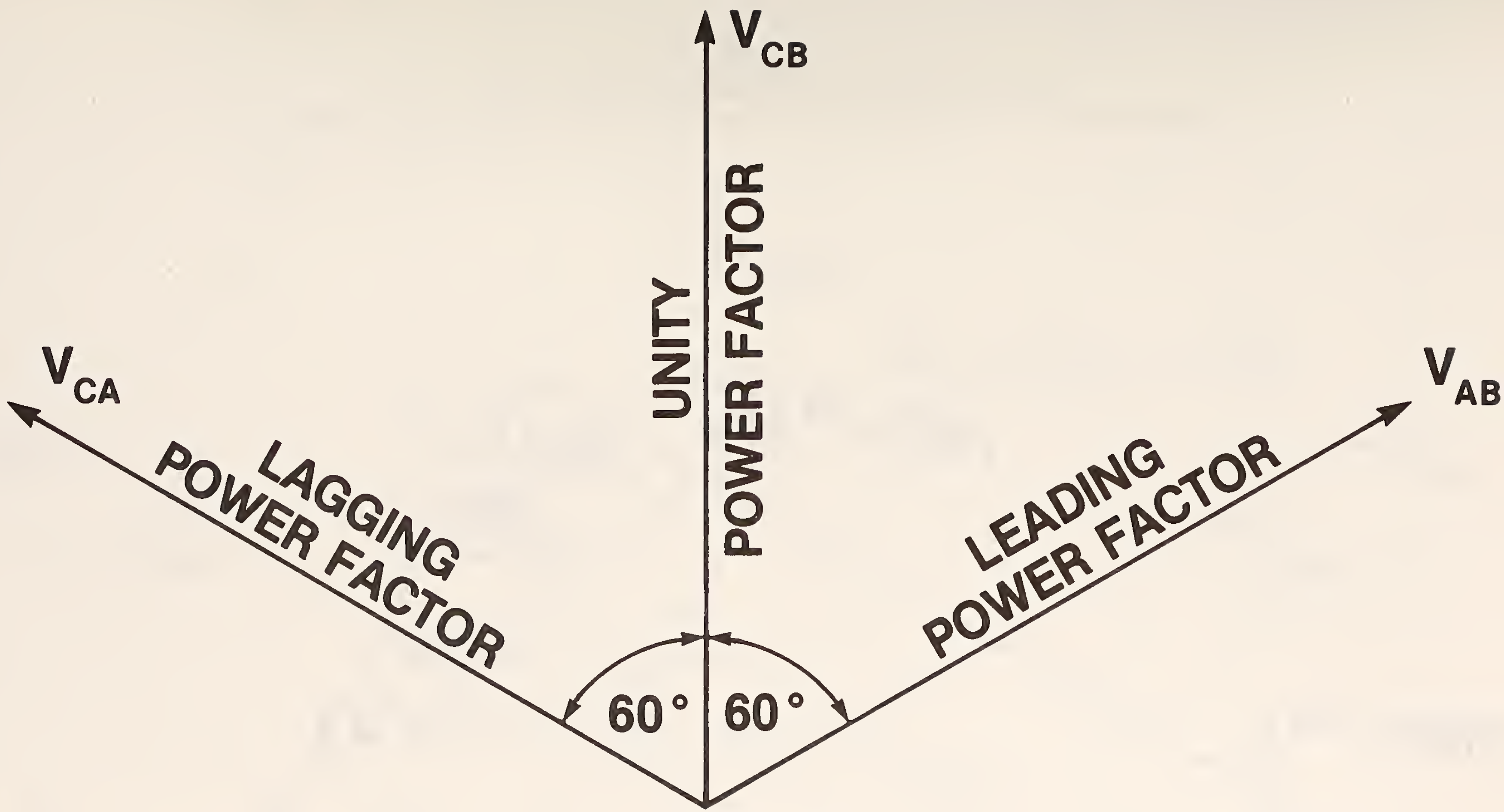


Figure B-3. Phasor diagram for the output voltage from the current adjustment controls and isolating inversion transformer (transformer T10 of fig. B-2).

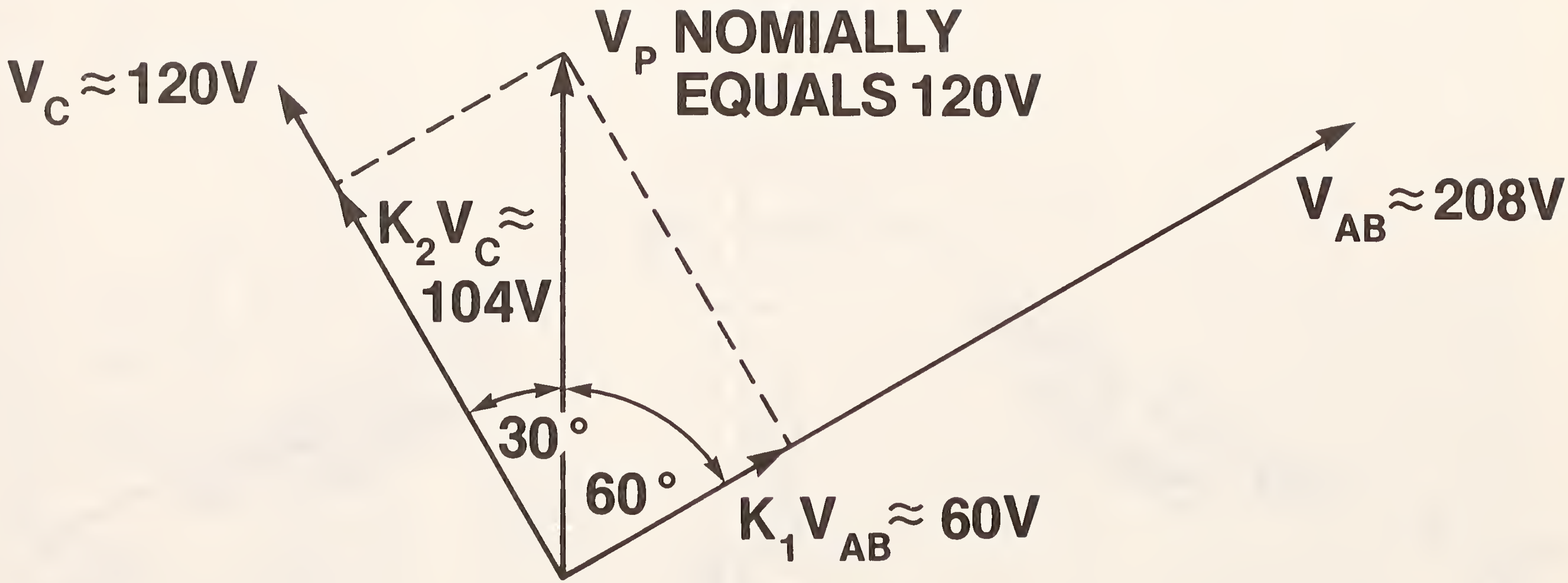


Figure B-4. Phasor diagram for the output voltage V_p for the voltage circuits for the watthour calibration system.

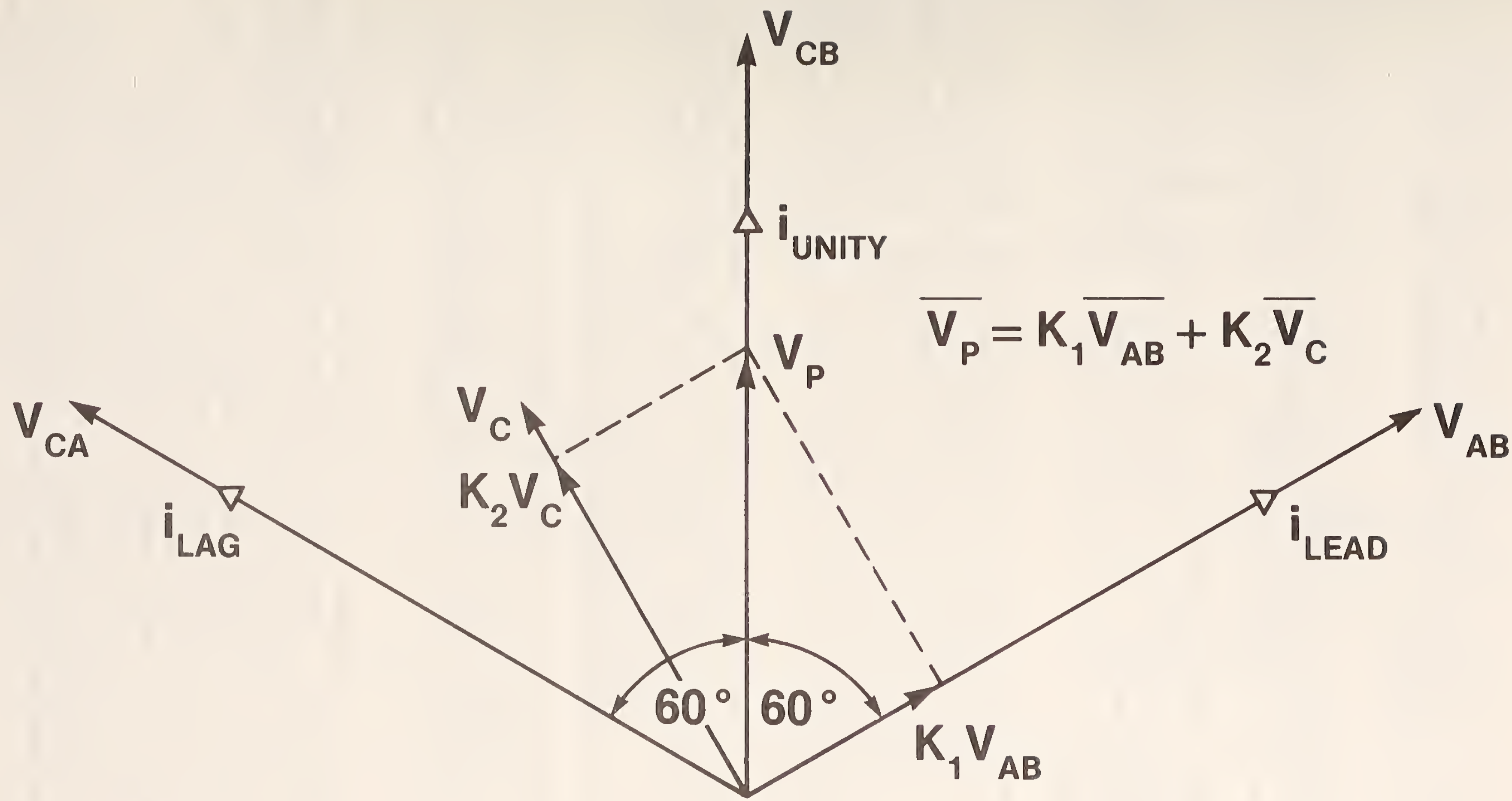


Figure B-5. Phasor diagram showing the current, voltage, and power factor relationships for power factors of unity, half lag, and half lead.

Note that the angular range is 90° of phase adjustment for the voltage vector, but for nominal conditions the angles are either 0° or ±60°. The control latitude permits adjustments about the desired power factor and also voltage over ranging, if necessary.

Note that the voltage vector V_p is nominally the same for all testing, i.e., its adjustment is always within a fixed range with respect to the three-phase line voltages. Power factor selection is accomplished by switching the test current vector into one of three possible angles as shown and discussed above.

The output from the voltage control circuit feeds a step-up transformer having turns ratios of 1:1, 1:2, and 1:4, thus providing output voltages of at least 120, 240, and 480 V, respectively. The three output voltages are switch selectable as shown by figure B-6. The selected voltage is applied to the watthour meter under test and to the precision voltage transformer which feeds the NBS reference watthour meters.

The output of the current control circuit is connected to two step-down transformers through a link arrangement. The transformers are rated at 240-V input on each primary and 2-V output on each secondary. Figure B-7 shows the basic arrangement and figure B-8 shows the link arrangements. These transformers are used for output currents of 3 A and greater. For currents less than 3 A, these transformers are bypassed and the output from the current control circuit is fed directly to the watthour meters. When used for output currents of greater than 3 A, the transformer primaries are connected in parallel and a voltage from 0 to 208 V can be impressed.

The four secondaries are then linked in three basic configurations such that current from 3 A to near 100 A can be obtained. The maximum current into a short circuit is near 100 A; however, typical maximum currents are about 30 to 50 A, depending on the total impedance of the current circuit.

B.2 Signal Conditioning and Pulse-Counting Electronics

The signal conditioning and pulse-counting electronics process the pulse outputs from the NBS reference bank, meters, and to either gate the 120-V potential circuit for watthour meters with registers or to condition and count the pulse outputs for watthour meters having pulsed outputs. Figure 5-6 shows a simplified block diagram of the signal conditioning and pulse-counting electronics.

Connections are made to watthour meters being calibrated by suitable connectors on the front panels. These provide for not only system input of the pulses from the meters having such, but also provide for lamp and bias voltages for meters requiring them. The fundamental flow of signals is from left to right as drawn in figure 5-6. Watthour meters' output pulses are fed to signal conditioners, adders, gates, display selectors, and finally to electronic counters. The output of the adder in the reference channels feeds the sum of the four reference watthour meters to a preset camparator, whose output generates a suitable gate for stopping the counters when the preset value is reached.

To facilitate this discussion, reference is made to figure B-9 which is a detailed block diagram expanded from that shown in figure 5-6. Here the blocks are arranged by circuit board and are identified as A through G. Coaxial connectors

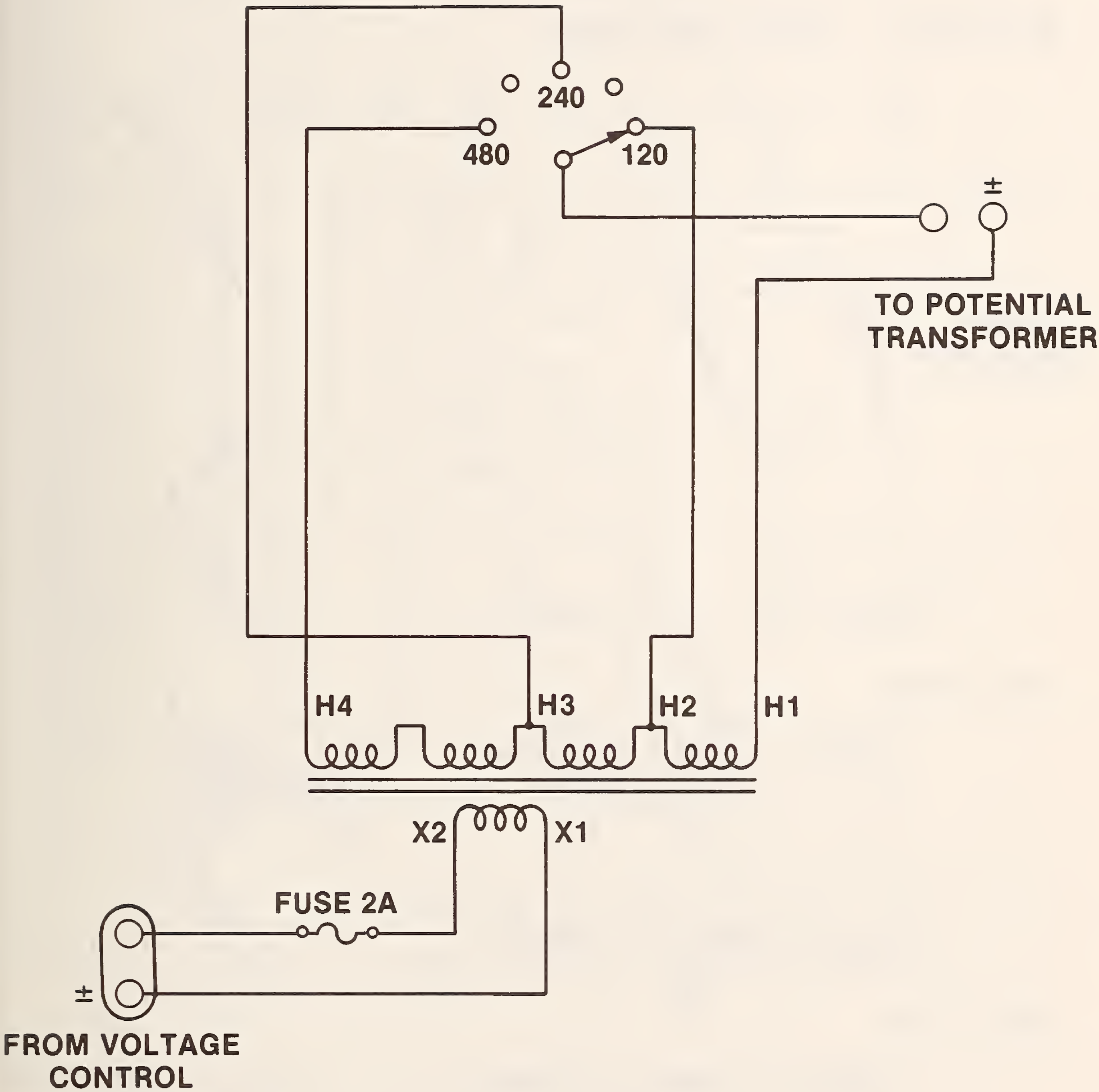


Figure B-6. Switch selectable system output voltages for 120, 240, or 480 V.

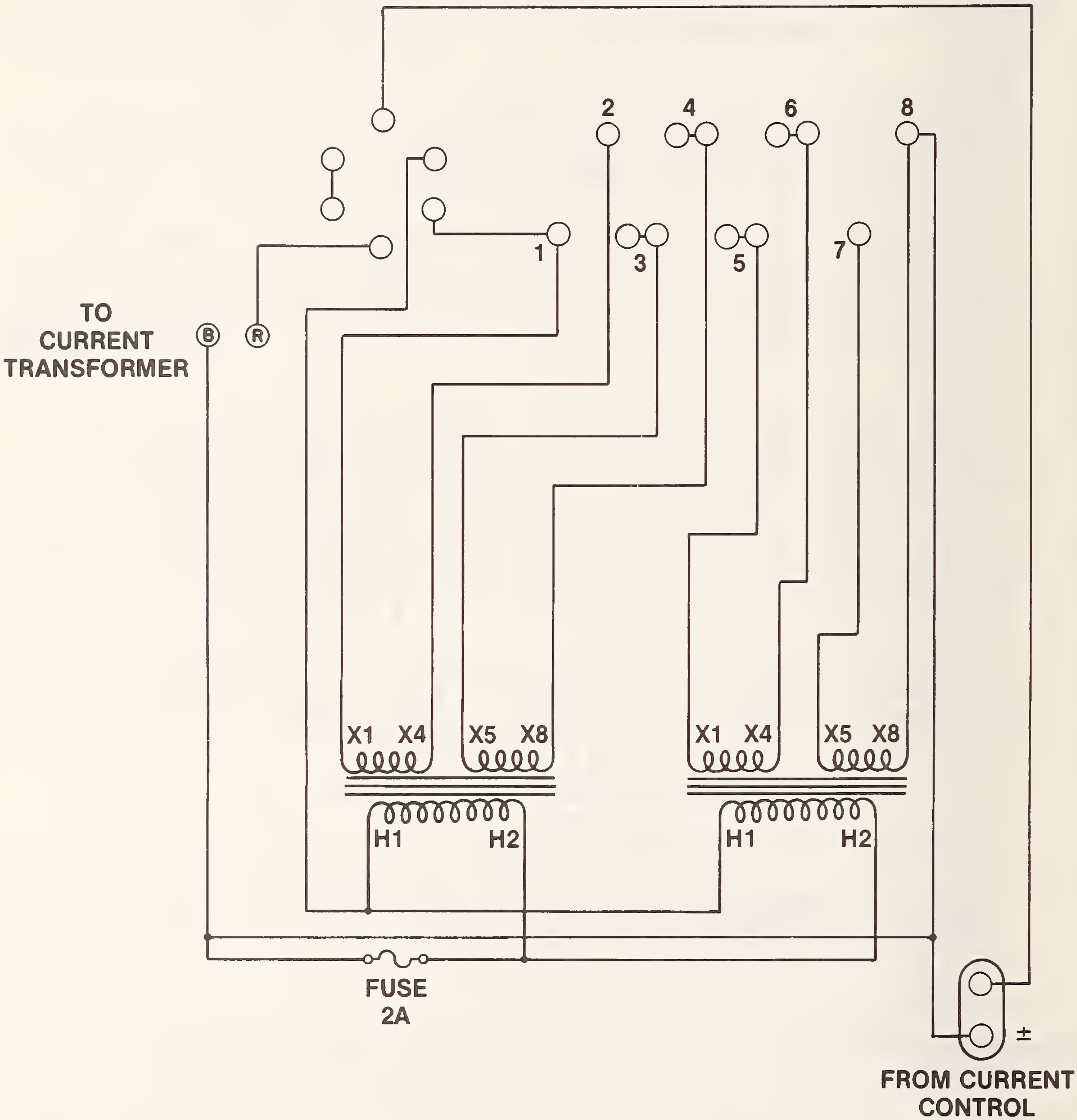


Figure B-7. System current supply transformers and link terminals for output currents from 3 to about 100 A.

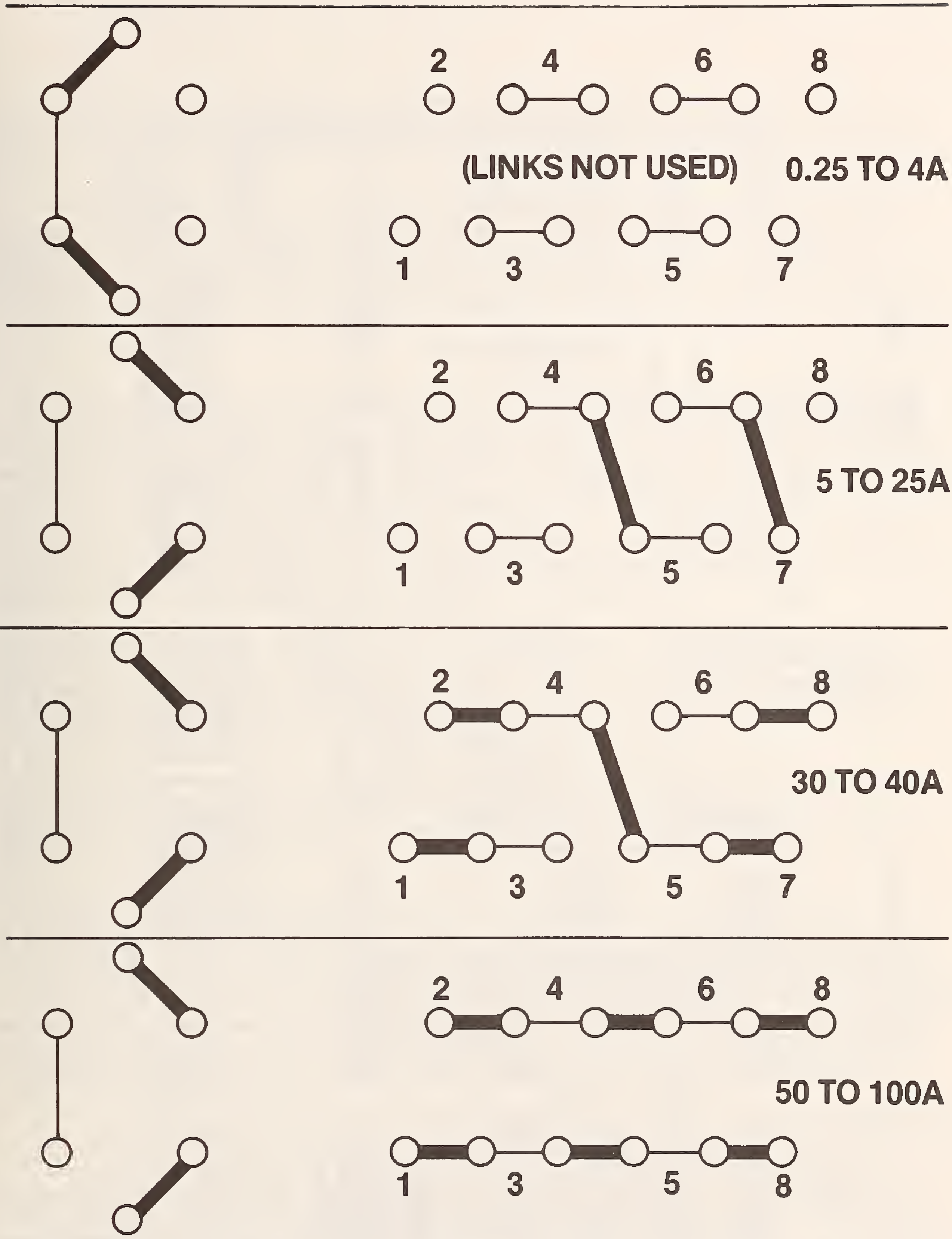


Figure B-8. Current supply transformer linking arrangements for different current ranges. Light lines are permanently wired; heavy lines are externally connected jumpers used to complete the circuits.

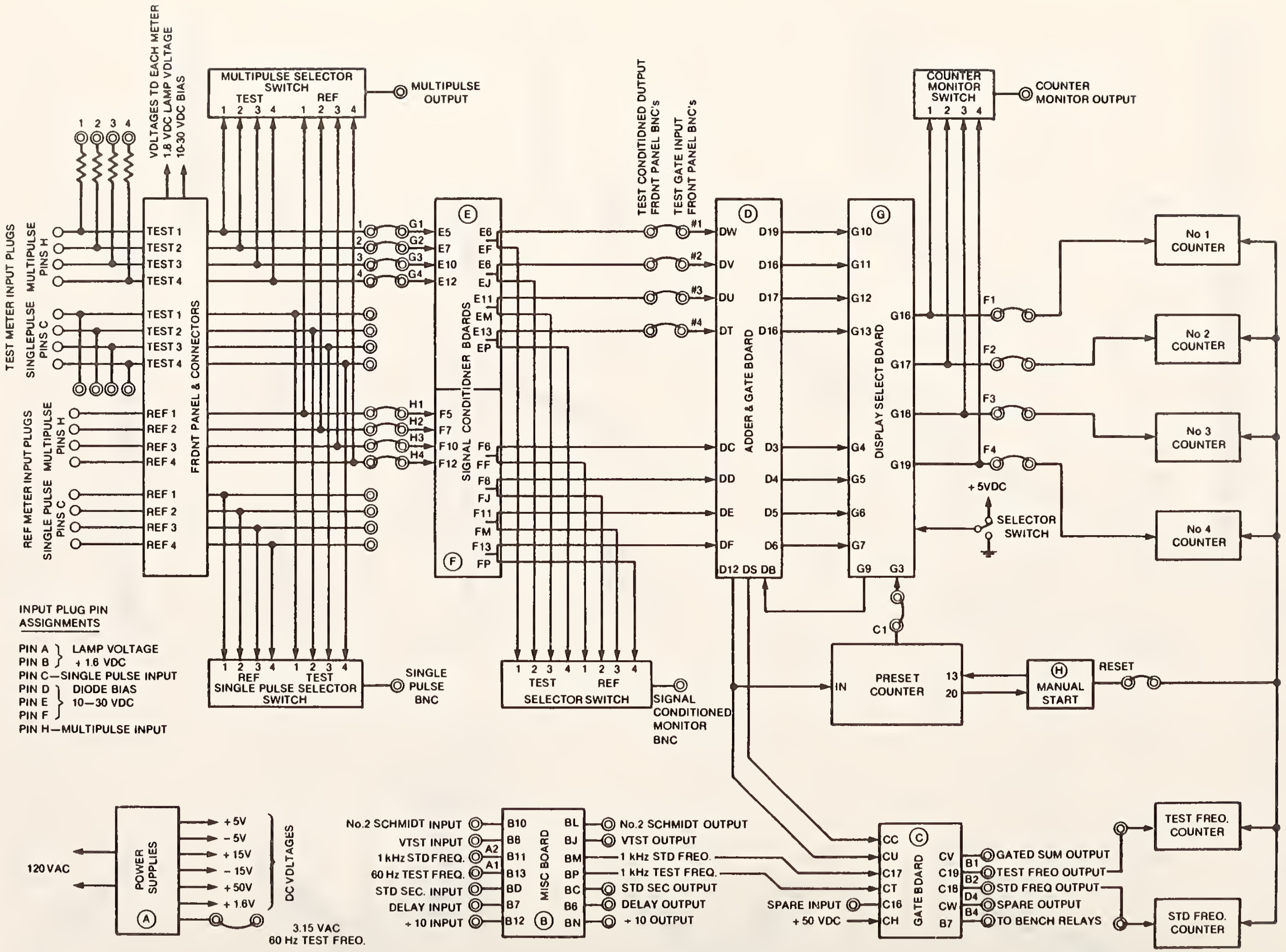


Figure B-9. Detailed interconnection diagram for the signal conditioning and pulse-counting electronics.

are used at certain strategic circuit locations for inputs, outputs, and at monitoring points. Throughout the ensuing discussion, reference will be made to figure B-9 in conjunction with individual drawings of particular circuits.

A major portion of the circuitry is located on circuit boards which are mounted in a chassis. Each board plugs into a 44-pin connector. The numbers for the pins used are shown on each board. (A hybrid numbering system is employed using numbers from 1 to 22, and 22 letters from A to Z, with the letters G, I, O, and Q being omitted from the sequence.) All pins are not used.

B.2.1 Input Connections

Figure B-10 shows the four multipin input connectors, eight coaxial connectors, and the four variable resistors. Note that two kinds of inputs can be accommodated, "single pulse" and "multiple pulse" inputs. For single pulse, one pulse per watthour meter disc revolution is received. For multiple pulse, a number of pulses are received per revolution of the disc. Single-pulse operation uses pin C of the connector while pin H is used for the multiple pulse inputs. The multipin connector also provides for bias voltage and for lamp voltage as shown for the watthour meters being tested. The variable resistors are used to optimize input pulse wave shape.

Figure B-11 shows the four multipin connectors for the input from the reference bank of four watthour meter standards. These connectors are located on a panel at the rear of the rack cabinet. Bias voltage and lamp voltage is also passed through these connectors. Pulse shaping variable resistors are also seen with their adjustments located on the rear panel.

Except for location and one ground connection, the inputs for the four input test stations and the inputs from the four reference watthour meters are the same. Pin E of the multipin connector is grounded for the test watthour meters whereas it is not for the reference meters.

Signal outputs are picked up at the coaxial rear panel connectors as indicated on the detailed block diagram, figure B-9, and on figure B-12. Two front panel, ganged, eight-position, selector switches are wired to the input connector circuits so that any one of the test inputs or any one of the reference inputs can be monitored, principally on an oscilloscope. These switch selectable outputs connect to front panel connectors labeled SINGLE PULSE OUTPUTS and MULTI PULSE OUTPUTS. Short jumper cables provide the interconnections of the signal pulses to the inputs of the eight channels of signal conditioning.

B.2.2 Signal Conditioning Circuits

The wave shape of the "pulse outputs" from watthour meters having slotted discs are near sinusoidal and as such do not serve well as triggering sources for the subsequent pulse adders and electronic counters. To improve the pulse wave shape and to make them compatible with TTL circuitry, signal conditioning circuits as shown in figure B-12 are used. There are two circuit boards, E and F, which are identical.

The signal conditioners consist of an operational amplifier and variable resistor, and a Schmitt trigger. The amplifier and resistor create a variable threshold feature. The input signal, though sinusoidal, can be offset from

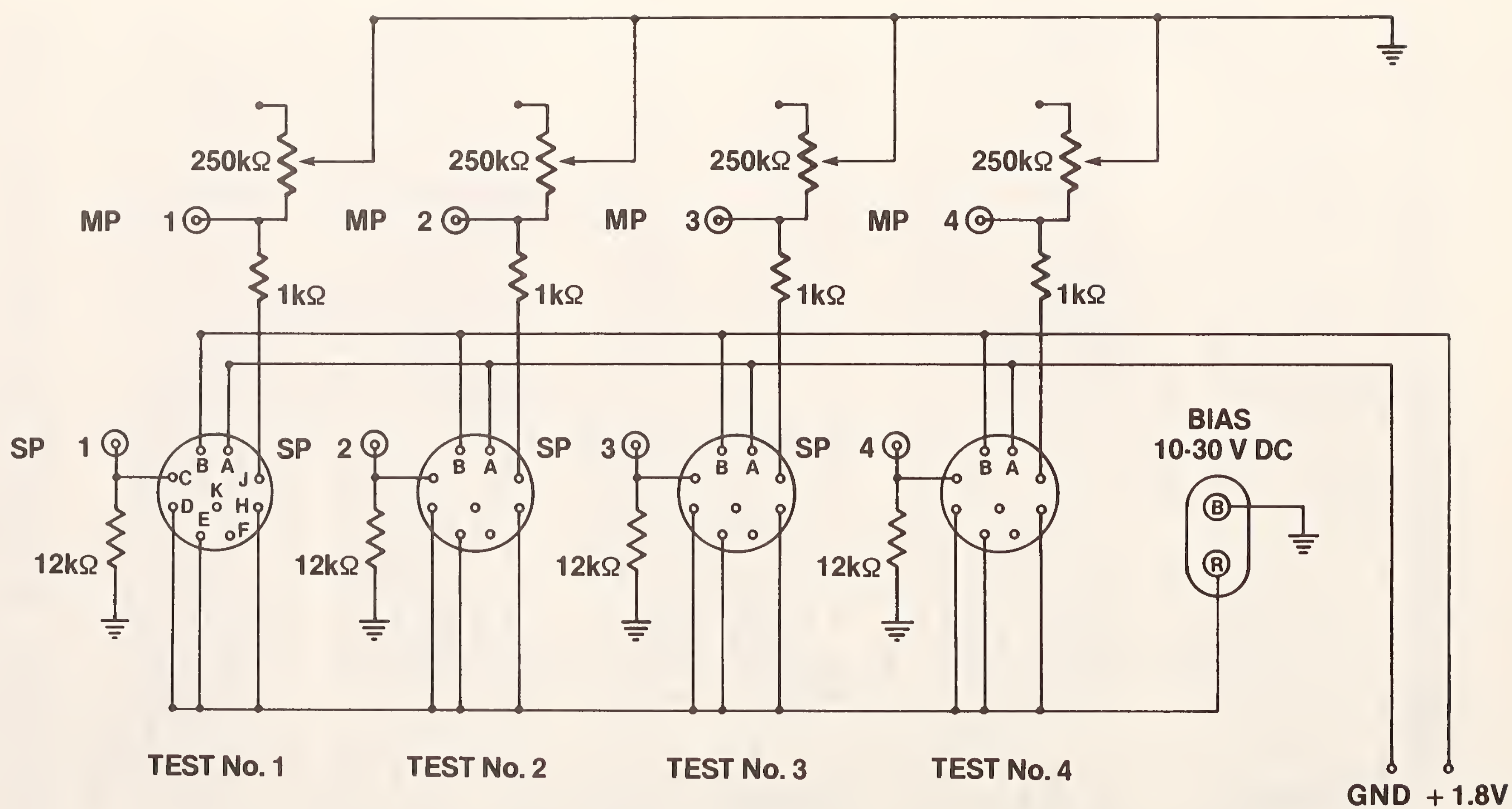


Figure B-10. Pulse input connections for the four stations of the test watthour meters.

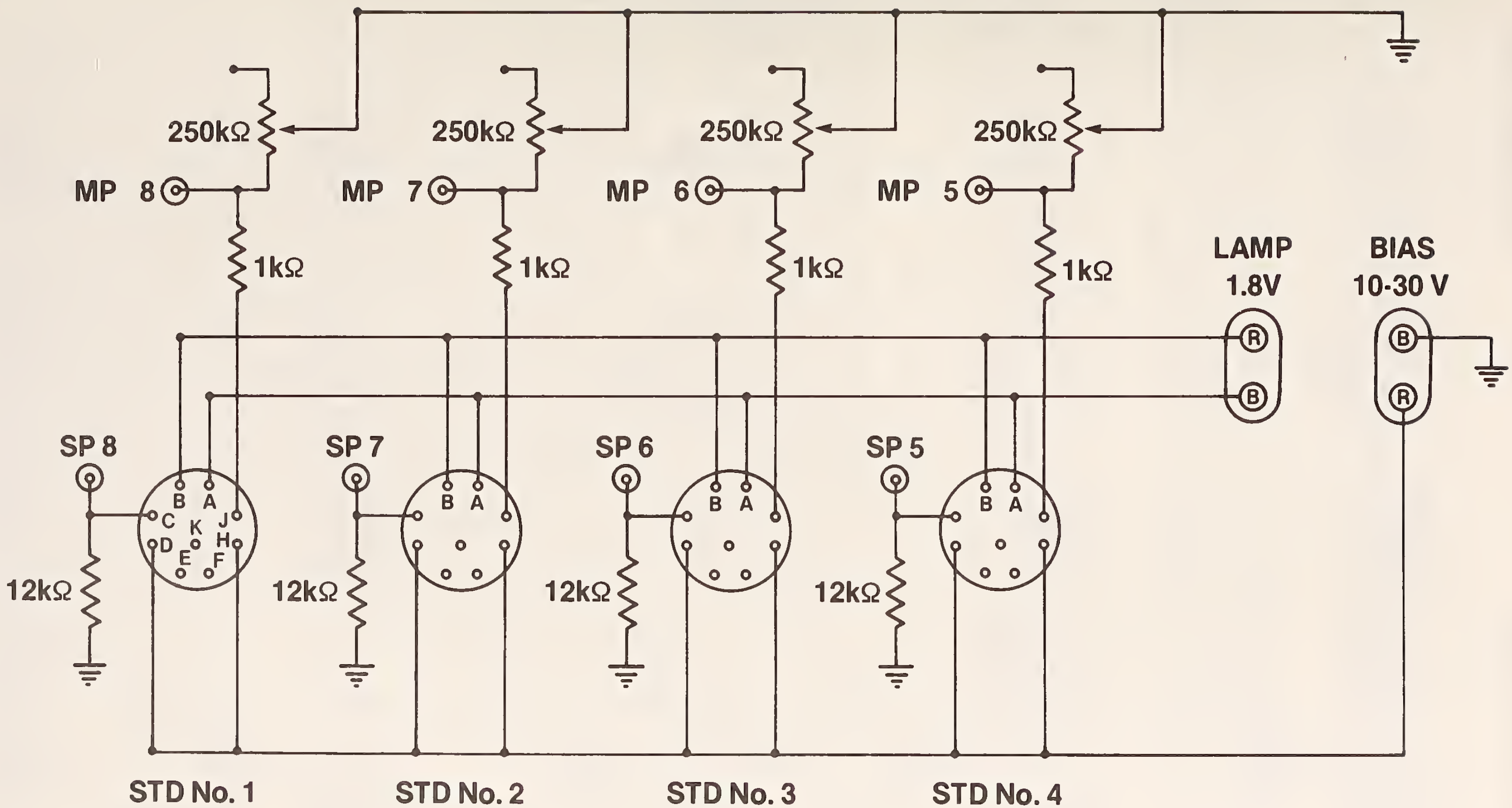


Figure B-11. Pulse input connections for the four reference watthour meters of the NBS reference bank.

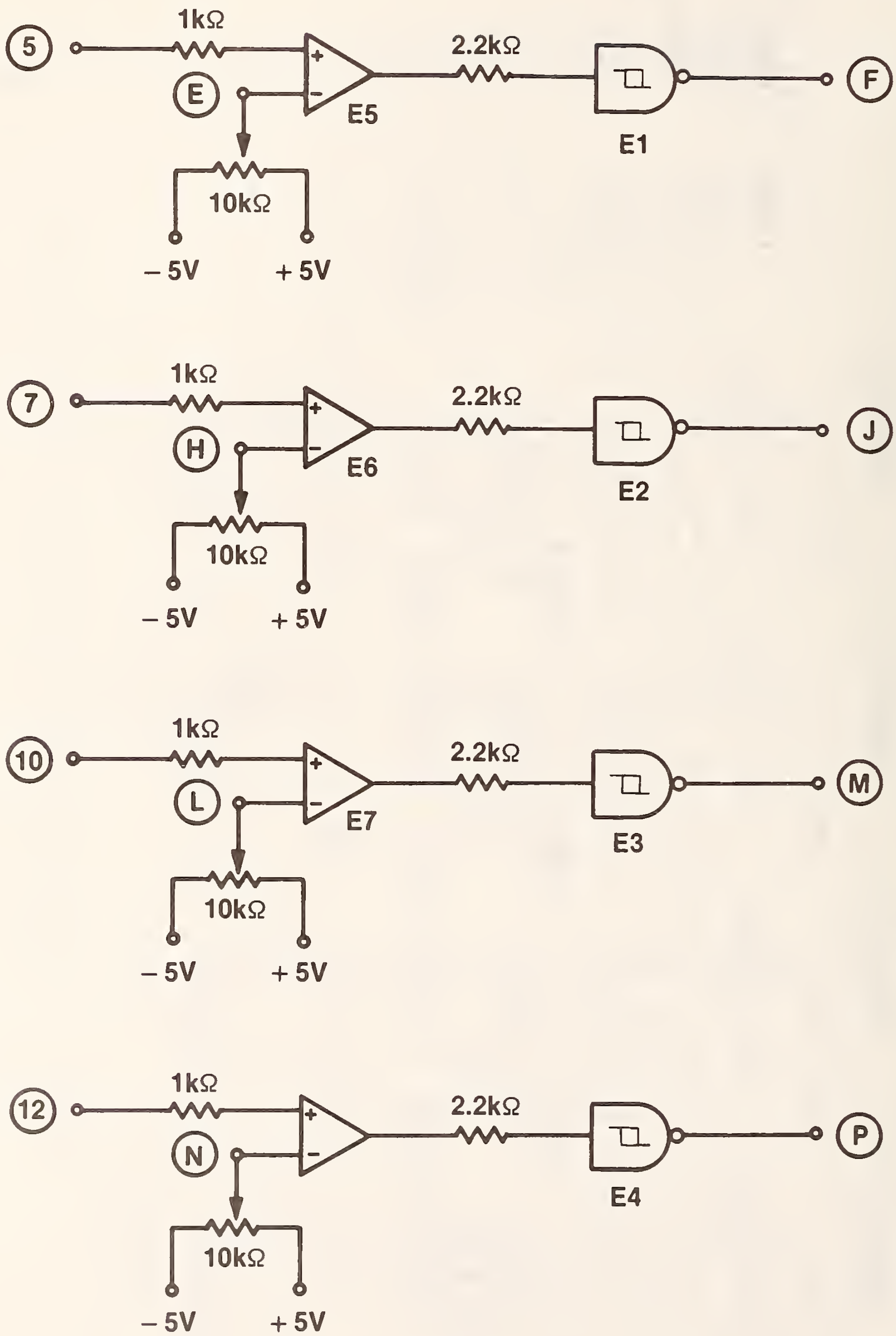


Figure B-12. Signal conditioning circuits for the wave shaping of the output pulses from the four test and four reference channels (circuit boards E and F).

zero volts. Figure 5-8 shows typical wave shapes of the output of a slotted disc-type watthour meter at the input to the signal conditioner and the output of the Schmitt trigger. Note the square wave shape of the output. This square wave is adjusted for symmetry by the variable threshold resistor and is fully TTL compatible for the subsequent circuits.

The numerals and/or letters in circles represent pin numbers on the circuit board. The letter/numeral associated with each of the integrated circuit (IC) components, for example, refers to the type of IC that is employed. A list of these appears in appendix C. For example, E1 is one in a package of four "dual 4-input positive NAND Schmitt trigger," type 7413.

The square wave outputs from the Schmitt triggers go to a switch which can select any one of the eight signal conditioned channels. The switch output feeds a connector labeled SIG COND MONITOR on the front panel. The four reference channels go directly to the pulse adder circuit board as indicated by figure B-9. The four test channels go to the pulse adder board through pairs of jumpered connections which provide for channel flexibility and monitoring.

B.2.3 Pulse Adder and Gate Circuits

The pulse adder circuit serves two purposes. First, it provides an output which is the "sum" of the four reference channels (derived from the four reference watthour meters) and gates this output and, second, it individually gates the four test channels. The reference channel and the test channel outputs are also "clocked" so that relatively narrow pules, about 20 μs wide, appear at the outputs independent of the input pulse width, which typically are no shorter than about 10 to 30 ms.

Figure B-13 shows the circuit used to sum the conditioned output pulse of the four reference watthour meters. The four inputs are connected to pins C, D, E, and F for standards 1, 2, 3, and 4, respectively. Each of these inputs feeds into the "clock" input of a type D, positive edge triggered flip-flop, with the D input held high by connecting it to the +5 V bus. The preset input is left unconnected and floats to a high state. The clear inputs are at a high state initially. Initially, the Q outputs from each of the four type D flip-flops are in a low state and remain low until an input pulse appears at the individual clock inputs. When the input leading edge goes positive, the output at Q goes from low to high and will remain high until reset by the clear input going to a low state, at which time Q also goes low again, waiting for the next positive going leading edge to occur at the input. In this manner, each input pulse is latched up until reset by the clear input.

The Q outputs from each flip-flop feed the inputs D1, D2, D3, and D4 of a 4-bit cascaded priority register as shown in figure B-13. Input P0 is held low by grounding it. The "summed" output appears at P1 which ties to pin 11 and pin M on the circuit board. A 50-kHz clock pulse, ck, is applied to the strobe input, G. The simple 50-kHz clock is shown in figure B-14 and is contained on the same circuit board. The priority register, thus configured, will scan the inputs from D1 to D4 with every strobe input pulse. If the input is high (indicating a pulse had set the flip-flop high), then an output will appear both at the P1 output and at the respective "Y" output for a duration of about one strobe period. The Y outputs in conjunction with the NAND gate and clock pulse ck are used to reset the D-type flip-flop at the CLR input. This

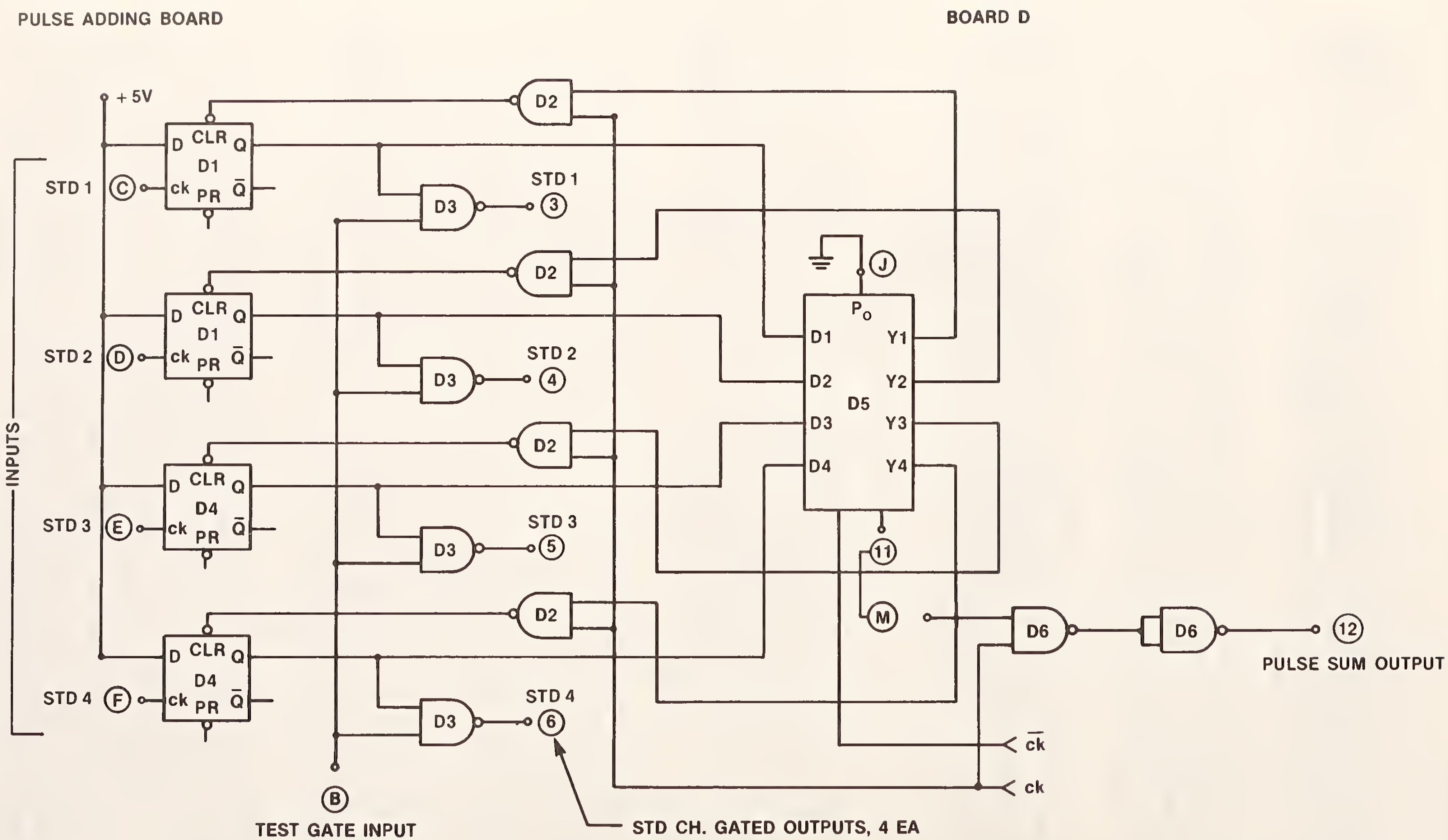


Figure B-13. Pulse-adding circuits for the conditioned outputs of the four reference watthour meters.

PULSE ADDING BOARD

BOARD D

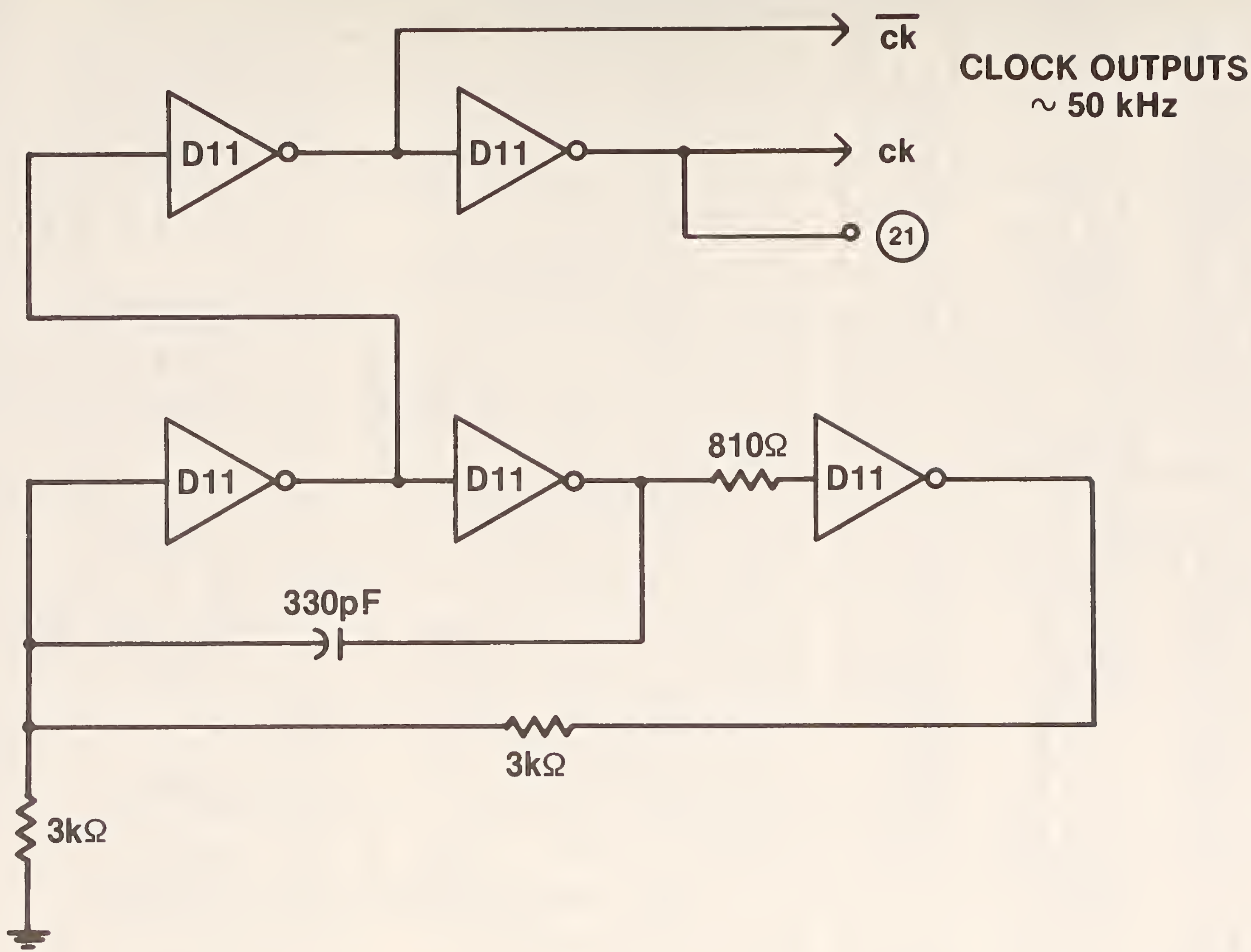


Figure B-14. Simple clock circuit used to drive the 4-bit cascaded priority registers in the pulse-adding and gating circuits.

arrangement provides a 20-μs pulse out at P1 for each input to the flip-flops, regardless of when the input occurred. If inputs to the flip-flops are simultaneous, the priority register will "scan" them and provide individual outputs, the lower priority output being one strobe period later.

The strobe rate is running more than 1000 times faster than the highest watthour meter input pulse rate, thus there is no way in which input pulses can overrun themselves or be missed in the output. The "summed" output is buffered and clocked by two cascaded NAND gates as shown by figure B-13 and appears at pin 12 circuit board.

Four individual outputs are also available on pins 3, 4, 5, and 6, which correspond to the reference watthour meters, 1, 2, 3, and 4, respectively. These outputs are inverted and gated by NAND gates D3. The test gate is derived from the preset counter of the comparator and is applied at pin B of the pulse adding board. (See fig. B-9 for the preset counter location in the overall circuit.)

A second circuit very similar to the pulse adder described above is on the same circuit board and is used to process the four test channels. This is shown in figure B-15. Positive edge triggered type-D flip-flops are used to hold the inputs from each of the four test channels. The operation of these flip-flops and the 4-bit cascaded priority register is identical to that described above for the pulse adding circuit. The D inputs to the flip-flops are each gated by the test gate so that when it is in the high state, input pulses at the clock input will latch the flip-flop with a high output on Q. Each Q output is tied directly to the output pin on the board, namely, pins 16 through 19. The priority register and NAND gates are clocked such that the D-type flip-flops are reset one clock period after being set. Thus the circuit outputs appear as TTL pulses of approximately the width of one clock period. Even though a summed output appears at the P1 output of the priority register, it is not used. Output pulses can appear only when the test gate, input pulses, and clock pulses are simultaneously present.

B.2.4 Display Select Gates

As shown by figure B-9, the outputs of the four reference channels and the four test channels are directed to the eight inputs on the display-select circuit board. The purpose of this circuit is to select electronically the reference channels or the test channels for display on the electronic counters. The circuit which does this is shown in figure B-16 and is comprised of NAND gates for the electronic selection. Signal inputs from the four reference channels are connected to pins 4 through 7. The four test channels connect to pins 10 through 13. A double-pole, single-throw switch as shown in figure B-16 applies either a high (+5 V) or a low (0 V) to pins Y and 21. If Y is high, then 21 is low, and vice versa. This logic controls all eight NAND gates to either select the four test channels or the four reference channels.

The two hex inverters, G7, in the control select circuit (at pins Y and 21) serve as buffers between the switch and the input NAND gates; also, if this were ever to be driven by TTL logic, it provides less fan-out loading to that logic. The outputs appearing at pins 16 through 19 are inverted from the corresponding inputs. Each of these four outputs tie to connectors and to a front panel rotary switch marked COUNTER MONITOR which in turn feeds a front panel connector labeled COUNTER INPUT MONITOR. The connectors F1 through F4 are normally connected to the display counters 1 through 4.

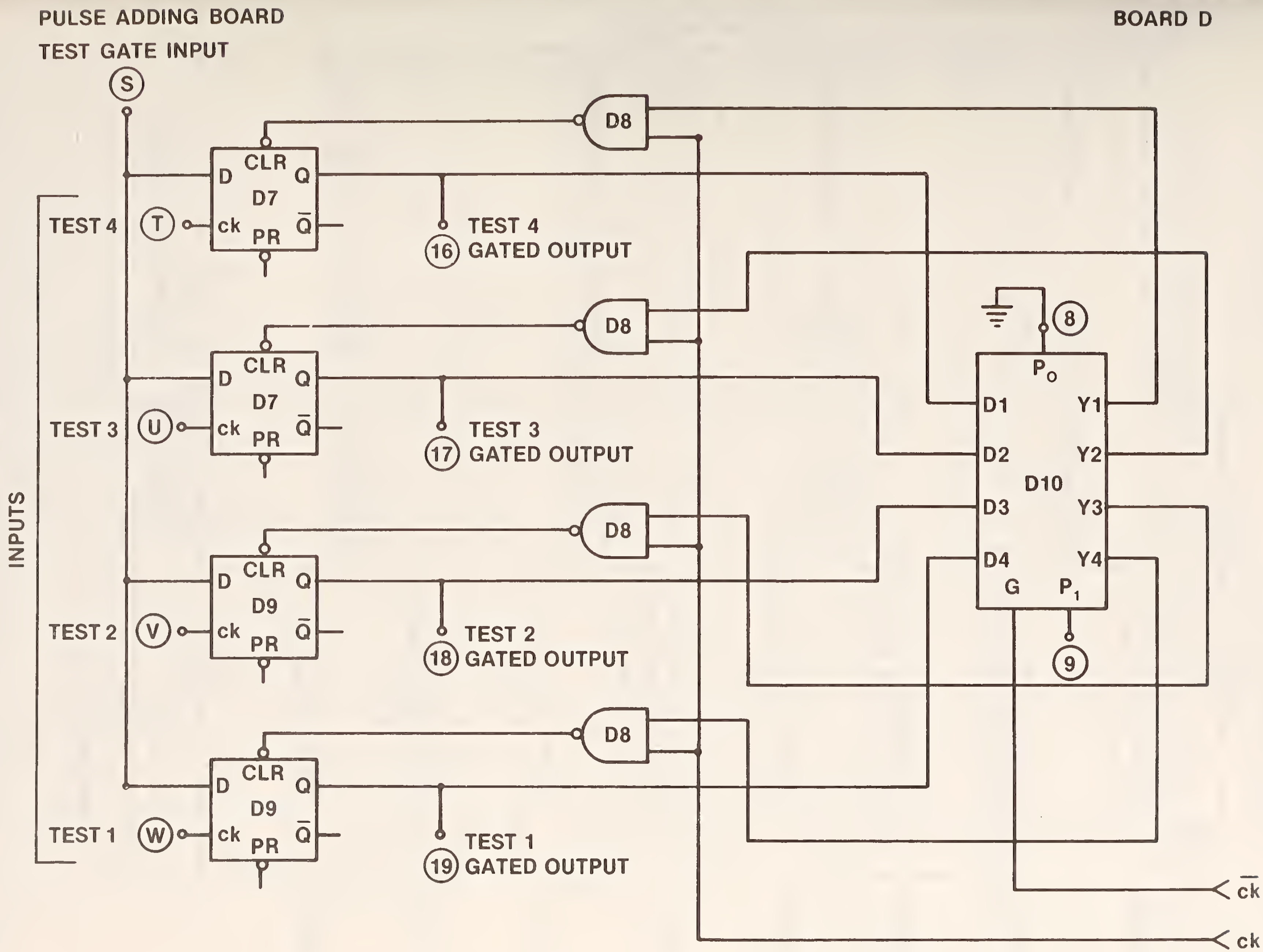


Figure B-15. Pulse-gating and clocking circuit for the four test channels.

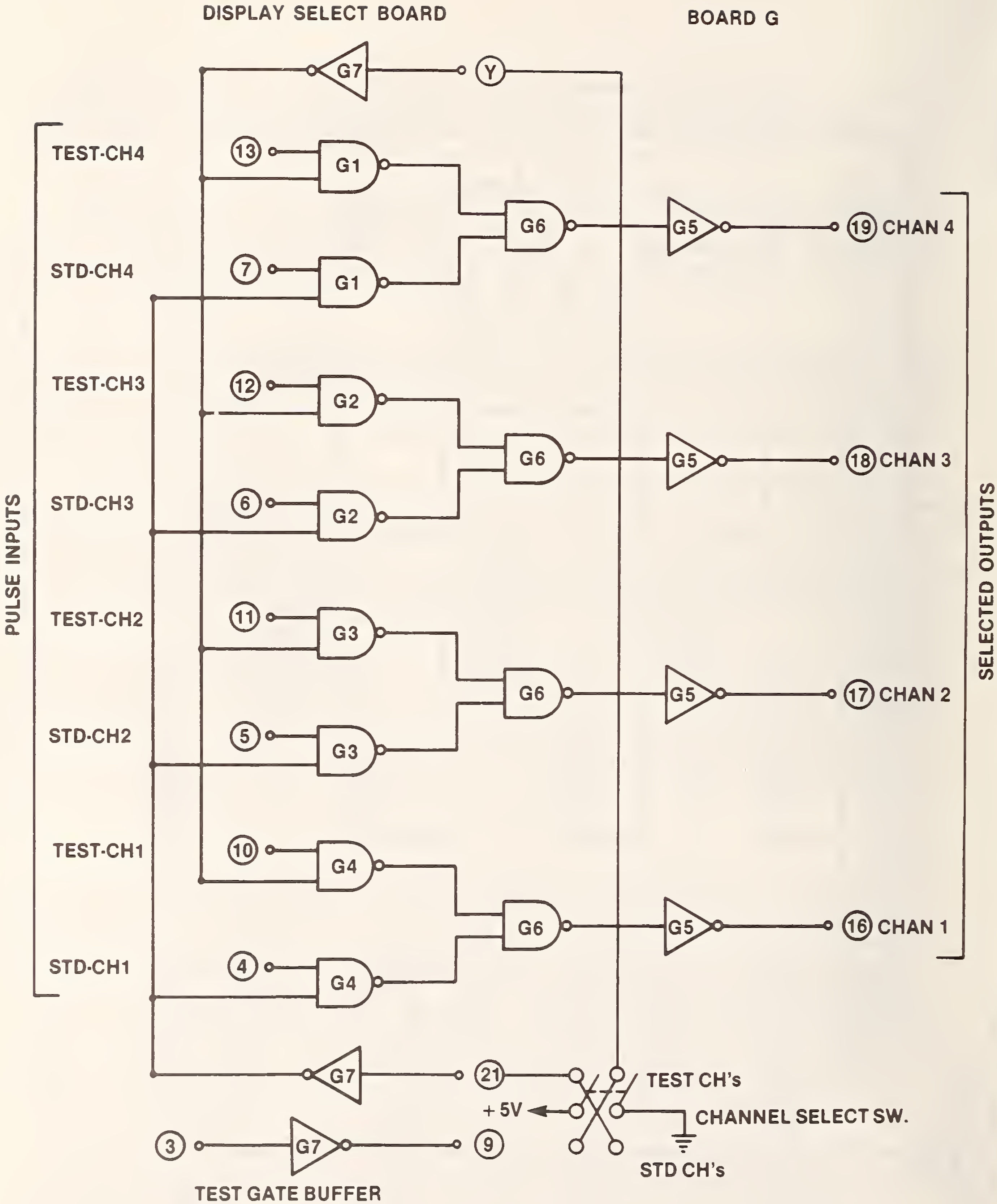


Figure B-16. Counter display selector circuits.

B.2.5 Auxiliary Electronic Circuits

A number of auxiliary electronic circuits are used to shape, generate, and gate signals such as the standard frequency, and the line frequency. Figure B-9 shows these located on circuit boards B and C. These circuits and their functions are discussed below.

B.2.5.1 Line Frequency Circuits

The NBS standard frequency of 1 kHz is a sinusoidal voltage which is fed to a Schmitt trigger as shown in figure B-17 at pin 11. The shaped standard frequency output (now at TTL levels) is connected to pin M and goes to the gate board, circuit board C, as shown in figure B-9.

A 3.15-V line-frequency signal is obtained from a center-tapped filament transformer. This provides an input of the test-line frequency. This is connected to the input of another Schmitt trigger at pin 13 as shown in figure B-18. The input Schmitt trigger shapes the sinusoidal waveform to a symmetrical square wave compatible with TTL levels. A type 565A phase-locked-loop integrated circuit is used, in conjunction with appropriate counters, to generate an output signal of 1 kHz which is phase-locked to the line frequency.

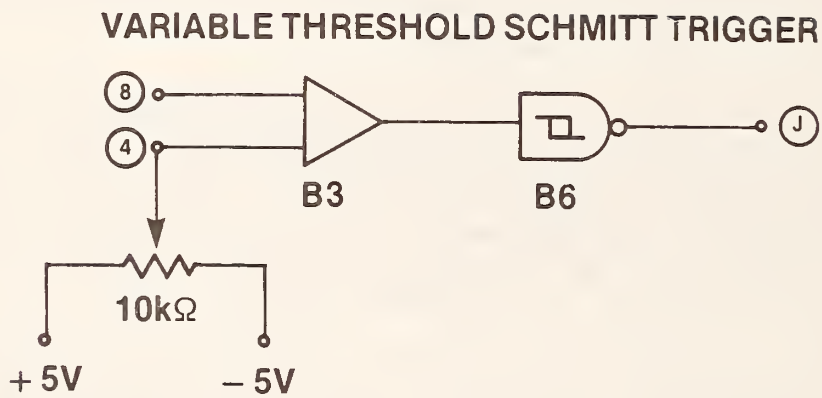
The 5.1-kΩ resistor and the 300-pF capacitor at the 565A set up a free running frequency of approximately 6 kHz. This signal is buffered by two cascaded NAND gates and feeds two cascaded divide-by-10 decade counters. This divided output of 60 Hz is fed back into the phase-locked-loop circuit to complete the loop. The free running 6 kHz is now phase locked to the line frequency. The 6-kHz signal also feeds into a divide-by-6 counter which then has a nominal output frequency of 1 kHz at pin P. This output goes to the gate board C as shown in figure B-9.

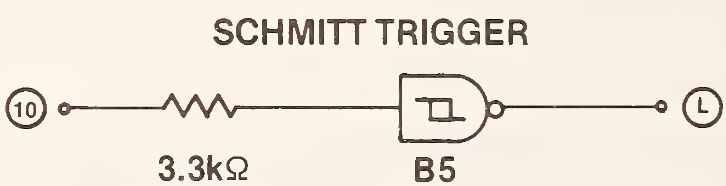
B.2.5.2 Standard Second Signal Circuit

A type 74122 retriggerable monostable multivibrator is used to shape the standard 1-s tone "tics" from the WWV standard time broadcasts. The "tics" are comprised of a five-cycle burst of a 1-kHz signal precisely gated to begin every second. The circuit is shown in figure B-19. In order to generate a single pulse from this tone burst, the retriggerable monostable multivibrator triggers on the first positive rise of the burst. If only one trigger were received, the pulse width would be as determined by the following relationship:

$$t_W = 0.32\ R_T C_T\ (1 + 700/R_T)\ ,$$

where R_T is the value in ohms of the timing resistor and C_T is the value capacitance in farads of the timing capacitor. For the circuit values shown, R_T = 56 kΩ and C_T = 0.1 μF. The normal pulse width is about 1.8 ms if the multivibrator is not immediately retriggered. However, the second cycle of the tone burst occurs 1 ms from the first, which is less than the 1.8 ms time constant and therefore retriggers the multivibrator before it has time to reset. This process continues so that the output is held high because of the repeated retriggering of the multivibrator by the five cycles in the tone burst. At approximately 1.8 ms after the fifth cycle, the output goes low. The final pulse width under these conditions is 5 ms plus t_W or about 6.8 ms. The standard time signal has a longer burst every 60 seconds to mark the minutes.





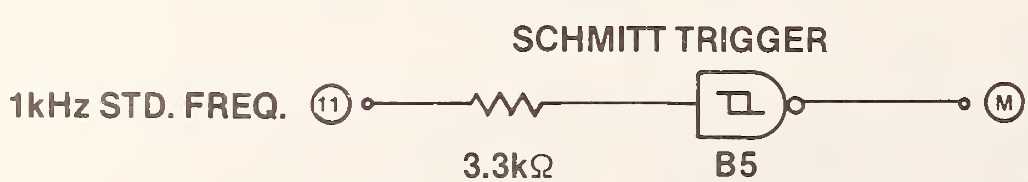


Figure B-17. Schmitt triggers on the auxiliary board.

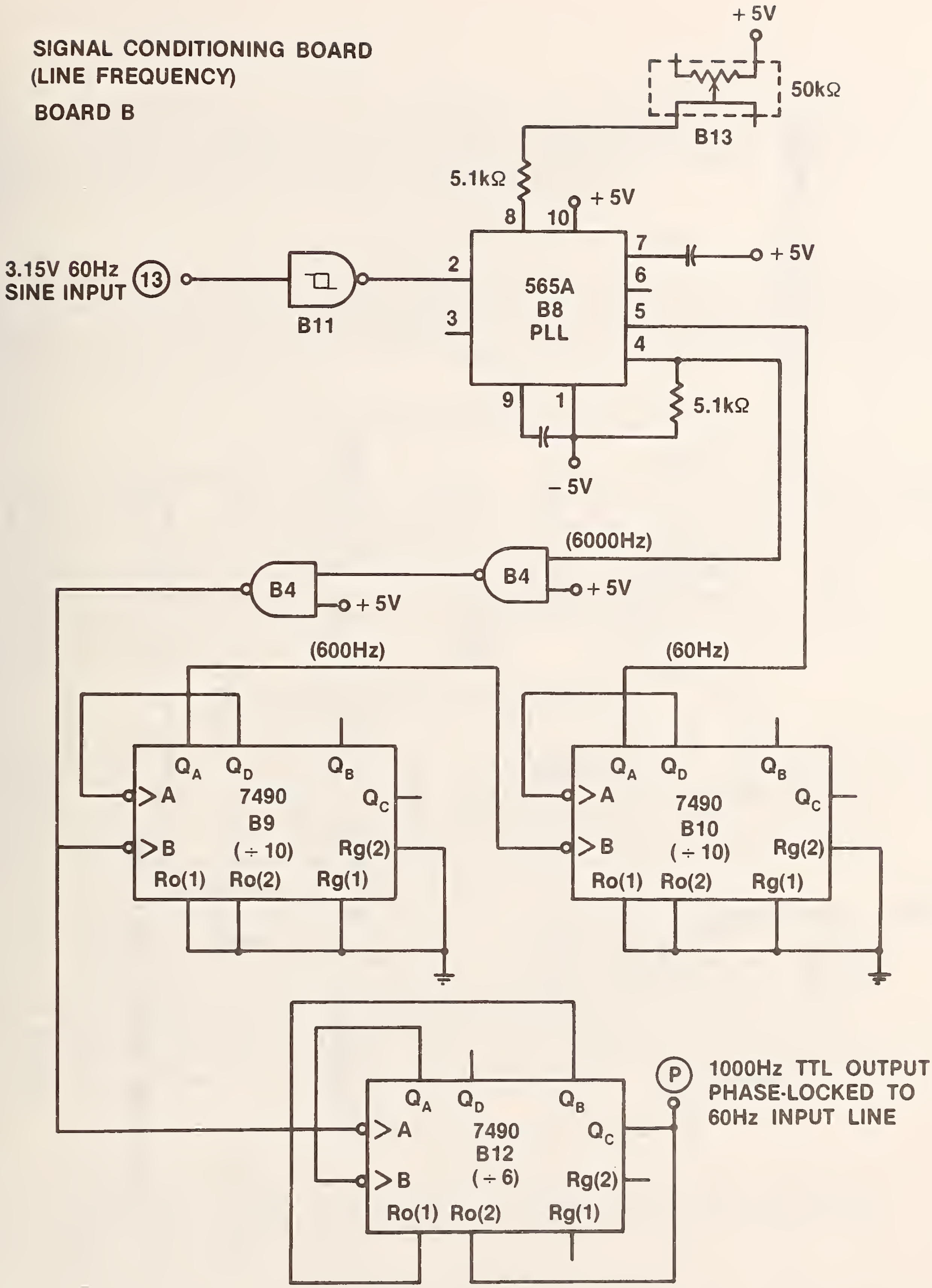


Figure B-18. Line frequency phase-locked-loop circuitry. The 60-Hz input line frequency is regenerated into a phase-locked 1000-Hz signal.

SIGNAL CONDITIONING BOARD (STD. SEC. SIGNAL) BOARD B

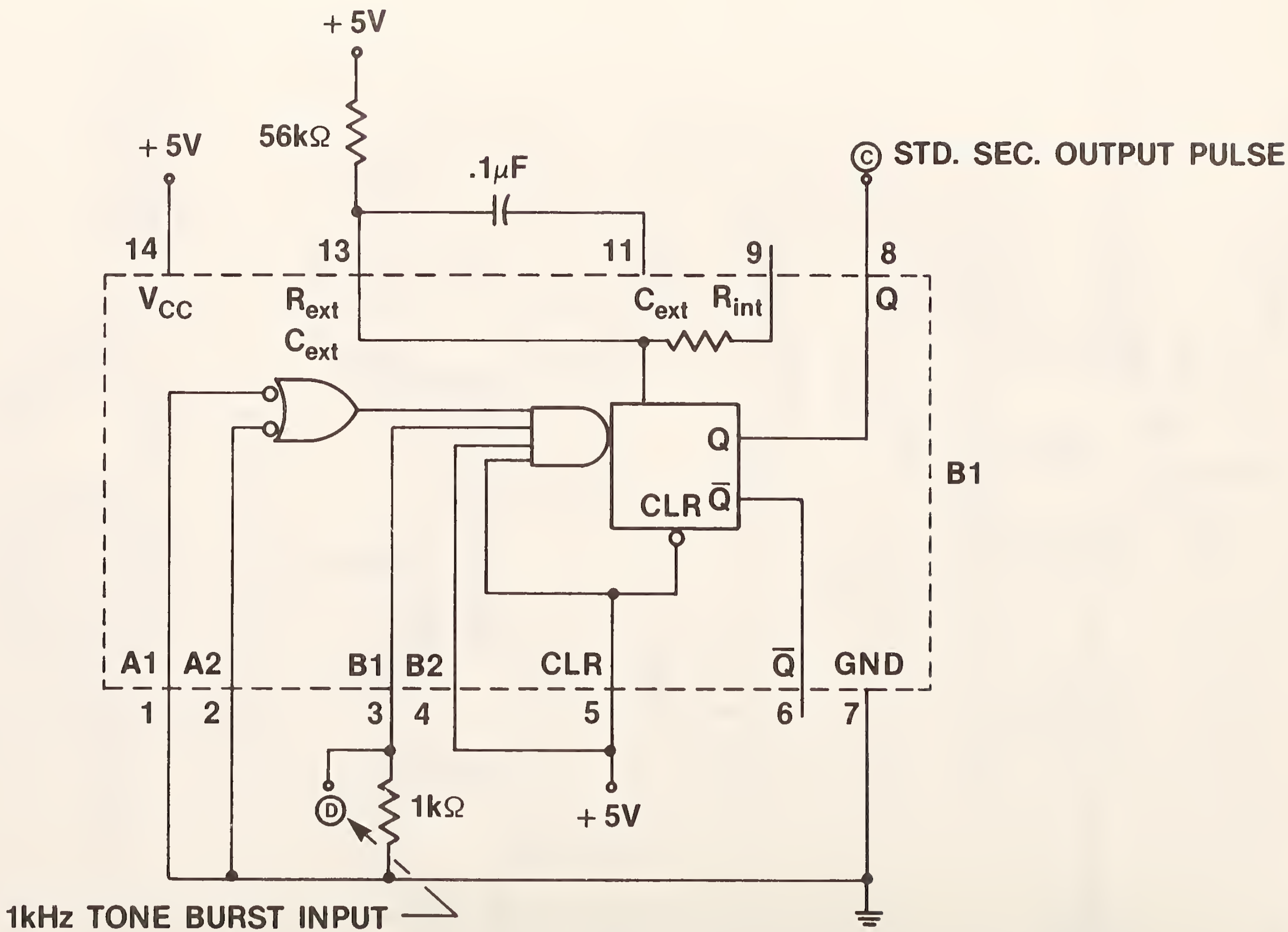


Figure B-19. A retriggerable monostable multivibrator used to generate a standard one-second pulse from WWV broadcast signal.

The multivibrator operates exactly the same for this longer burst except it is held on longer and the output is the length of the burst plus 1.8 ms. The "standard second" output can be used to gate counters and other electronic apparatus used in the calibration of watthour meters.

B.2.5.3 Auxiliary Schmitt Trigger Circuit

An auxiliary Schmitt trigger is accessible through front panel connectors. This circuit can be used to improve the shape of signals before further processing. Occasionally, a watthour meter output will be such that wave shaping will be necessary before further testing can be done. The circuit is located on board B and is shown by figure B-17.

B.2.5.4 Variable Threshold Schmitt Trigger Circuit

An auxiliary variable threshold Schmitt trigger is accessible by front panel coaxial connectors. This circuit is identical to those used for the input signal conditioners as described in section B.2.2. Sinusoidal input signals where amplitudes are not symmetrical about zero volts can be handled by this circuit to provide a symmetrical square wave output with TTL compatibility. Usual practice is to adjust the variable resistor for waveform symmetry. Symmetry is not essential, but does provide a convenient means for adjustment. The circuit is shown in figure B-17.

B.2.5.5 Pulse Delay Circuit

A pulse delay (pulse stretcher) circuit is included on circuit board B and is used to lengthen certain pulses to a width determined by the adjustment of a variable resistor. The circuit uses a type 555 timer as a one-shot multivibrator as shown in figure B-20. The input at board pin 7 feeds to NAND gate which helps to shape the input pulse and buffer the timer's input. The pulse delay circuit can generate pulses of adjustable width from about 1 ms to 10 s.

An example for its use is in the calibrations of house-type watthour meters. In some instances, there is only one slot or "optical hole" in the rotating disc. If, under selected test conditions, the disc is rotating very slowly, the transition of the optics from dark to light is poorly defined just as the hole begins to pass the light and unstable multiple triggering can occur if precautions are not taken. The delay circuit triggers once and then waits for the selected time before resetting. Thus, multiple pulse outputs are avoided and the disc revolutions can be counted electronically.

B.2.5.6 Pulse Divide-by-10 Circuit

A pulse divide-by-10 circuit is included on circuit board B. Front panel coaxial connectors provide convenient access to the circuit input and output. The purpose of this circuit is to provide a means of reducing the pulse rates, if too great, by a factor of 10.

The circuit uses a decade counter as shown in figure B-21. It is wired and operates exactly the same as the divide-by-10 decade counters used in the line frequency phase-locked-loop circuit described earlier. The circuit generates one output pulse for every ten input pulses. The circuit requires a TTL compatible input.

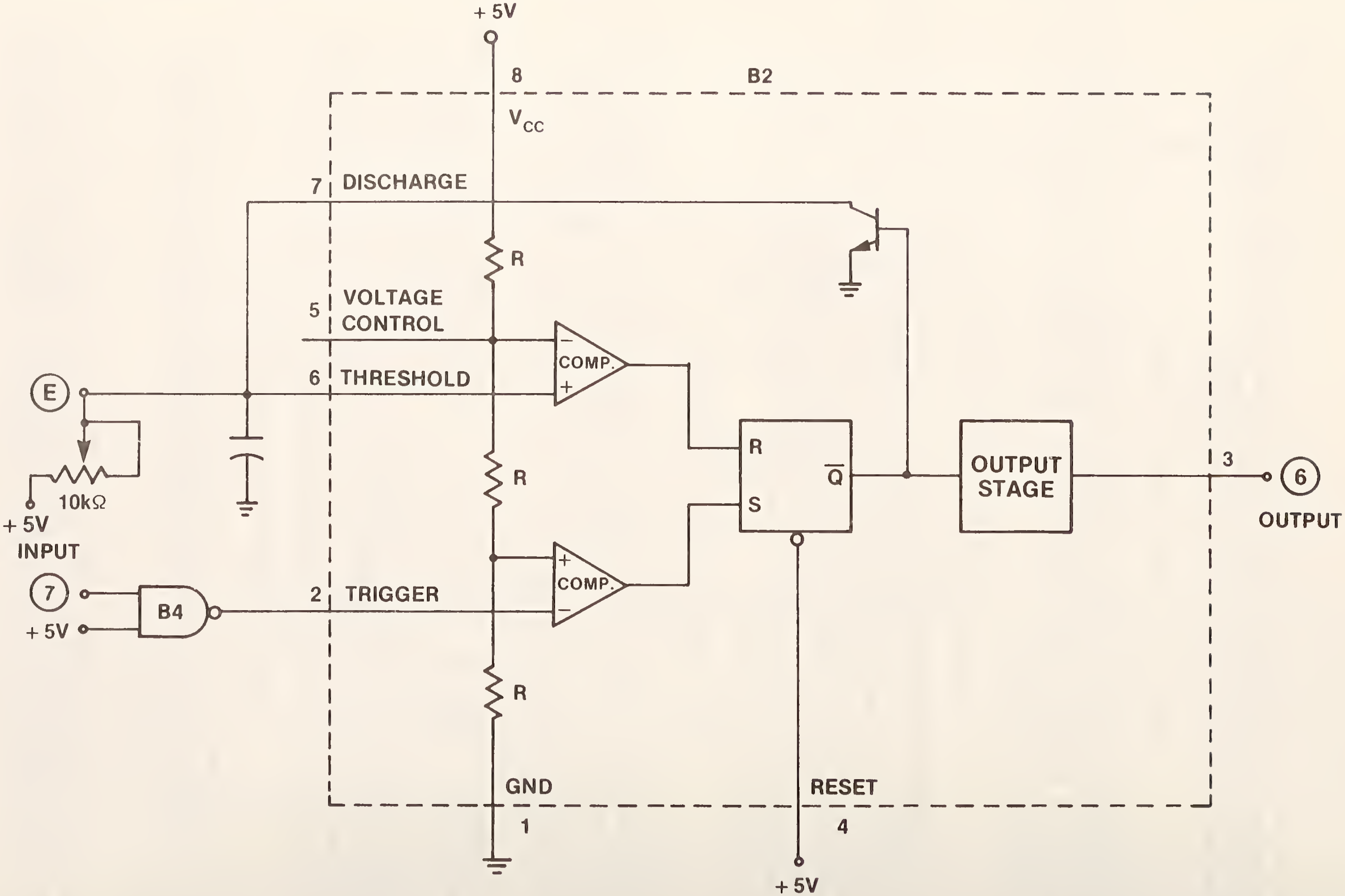


Figure B-20. Pulse delay circuit; delays input pulse by 10 ms to 10 s, adjustable by the 10-kΩ variable resistor.

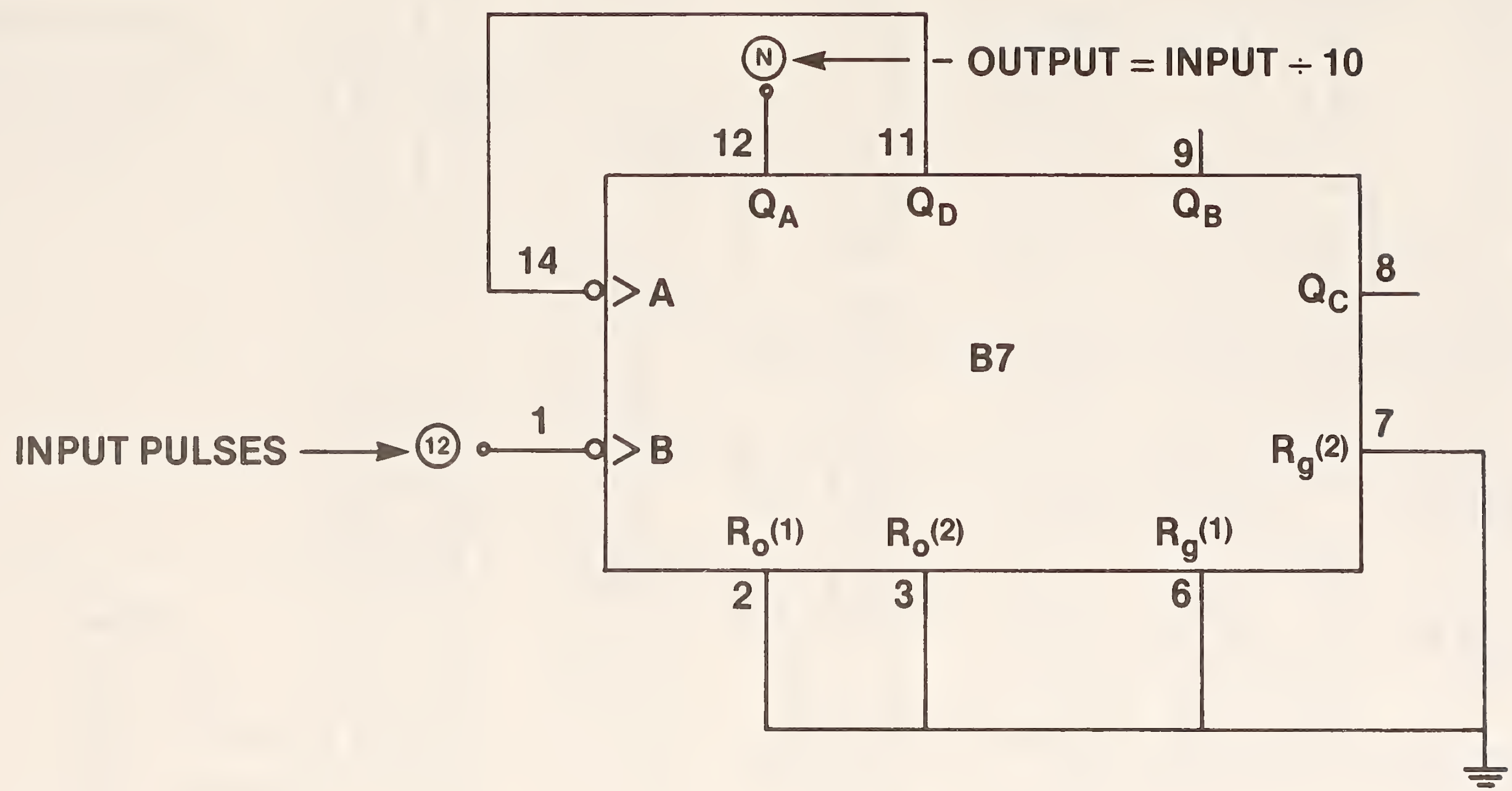


Figure B-21. Pulse divide-by-10 circuit where the output pulse rate is one-tenth that of its input.

B.2.5.7 Miscellaneous Gate Circuits

The gates on circuit board C are of two types: 1) electronic non-inverting NAND gates, and 2) a NAND gate-driven SPST relay. Figure B-22 shows the circuits for each. The input controlling test gate is applied at connector pin C and is derived from the preset counter (see fig. B-9).

The electronic gates provide the gating of three signals used in the calibration of watthour meters. At connector pin C the summed output from the pulse adder is connected. These pulses are allowed to pass through for a period of the test gate. The gated sum acts as the input to the preset counter (see fig. B-9). The standard 1-kHz NBS frequency and the phase-locked 1-kHz signal derived from the line frequency are also gated as shown by figure B-22. The fourth electronic gate is currently not used.

The NAND gate-driven SPST relay is used to control a +50-V line which feeds mercury-wetted relays on the test bench. The latter relays are used to open and close the voltage circuits to the watthour meters having readable registers. The SPST relay is closed for the length of time that the test gate is high. This then starts the watthour meters being calibrated and stops them at the end of the test.

The diode and the 0.1-μF capacitor on the output of the relay provide suppression of the transient voltage caused by opening the voltage to the bench relays. Without these suppression components, contact arcing could occur at the SPST relay contacts.

B.2.5.8 Reset and Start Circuit

The reset and start circuit shown in figure B-23 works in conjunction with the preset counter. A single-pole, double-throw push button switch on the front panel activates the reset and start operations. A pair of NAND gates tied into the switch act as switch debounce circuits. The signal coming from pin 20 of the comparator provides a "ready" indication on a panel-mounted LED.

The reset is connected to each of the four pulse counters as well as to the two frequency counters and four relays in the test bench voltage circuits. When the START button is pushed, it clears each of these six counters, starts the preset comparator counter, and closes the test bench potential relays. When the comparator reaches its preset values, the test gate goes to a low state which, through the appropriate gates, stops the inputs to each of the counters and opens the relays.

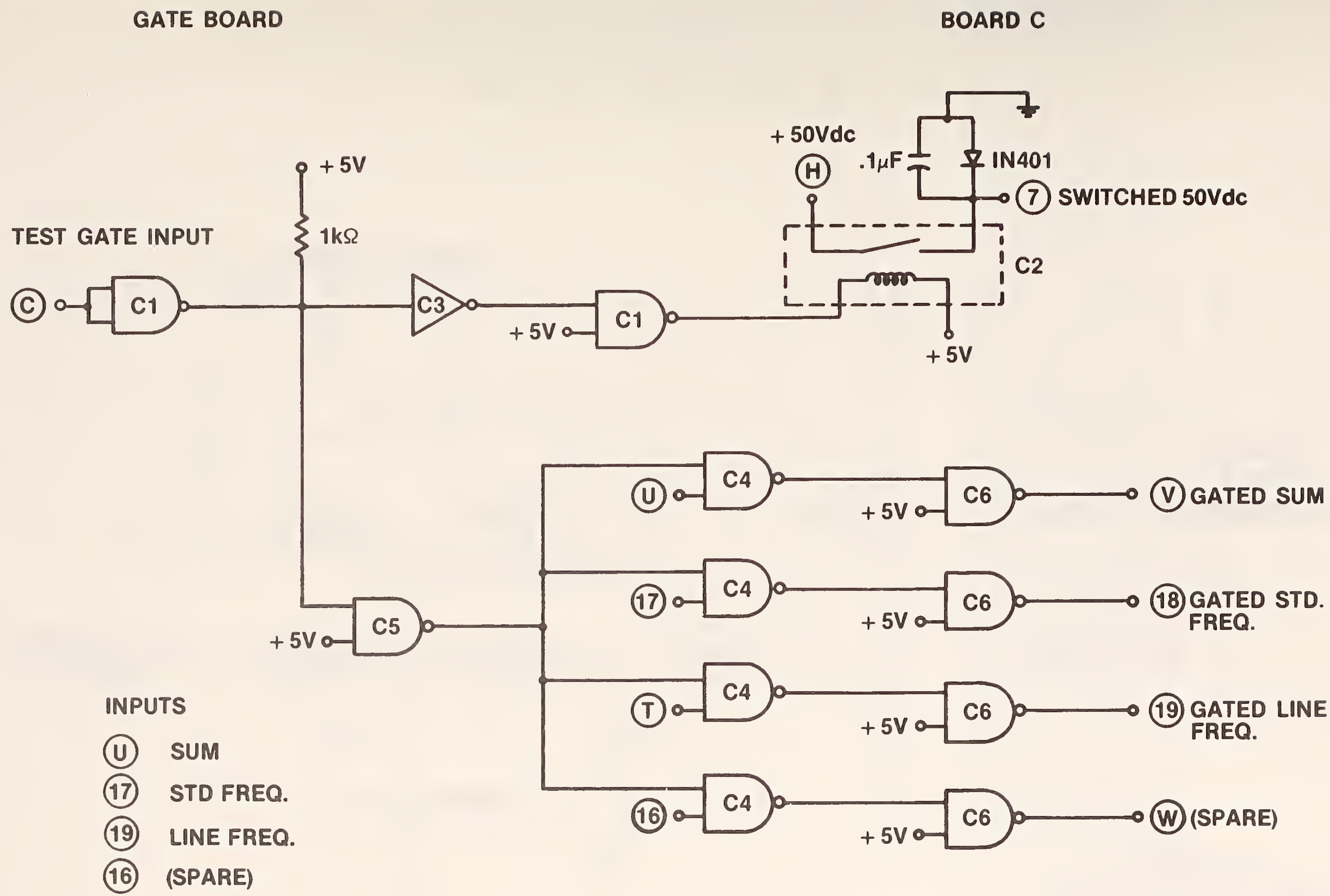


Figure B-22. Miscellaneous gate circuitry and gated relay power.

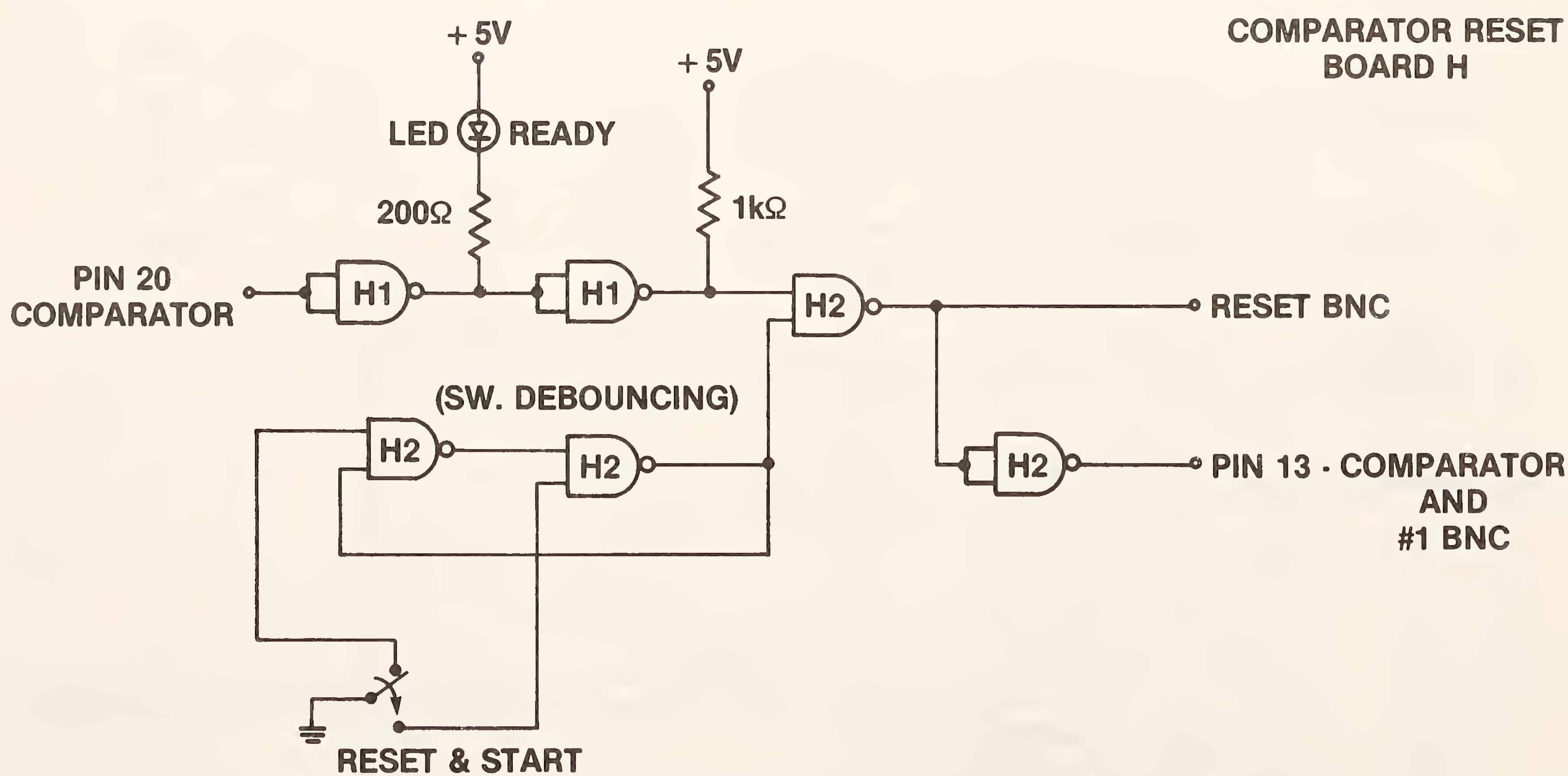


Figure B-23. Reset and start circuitry.

APPENDIX C

INTEGRATED CIRCUIT COMPONENT LISTING

Table C-1 of this appendix lists the integrated circuit (IC) components that are used in the signal conditioning and pulse-counting electronics circuitry. The IC identifiers are shown on the figures in section 5 by a letter (B through H) and a numeral (1 through 11). The letter designates the circuit board on which the IC is located. The numeral is a serial identifier. For example, IC D4 is located on board D. From table C-1 it is seen that D4 is a type 7474. Table C-2 gives nomenclature information regarding these ICs. Table C-3 lists the circuit boards and relates them to the respective figures in section 5. It also provides a brief nomenclature and functional description for each board.

Table C-1. Integrated circuit (IC) component listing for signal conditioning and pulse-counting electronics

	Circuit board identifier					
IC COMPONENT IDENTIFIER	B	C	D	E,F	G	H
1	74122	7403	7474	7413	7420	7403
2	555	(640-1)	7400	7413	7420	7400
3	741	7404	7400	7413	7420	
4	7400	7400	7474	7413	7404	
5	7413	7400	74278	741	7404	
6	7413	7400	7400	741	7400	
7	7490		7474	741	7404	
8	565		7400	741		
9	7490		7474			
10	7490		74278			
11	7413		7404			

Table C-2. IC nomenclature for components used in signal conditioning and pulse-counting electronics

IC type	Nomenclature
555	Timer
565	Phase-locked loop
(640-1)	Relay (Electromechanical component)
741	Operational amplifier
7400	Quad 2-input positive-NAND gates
7403	Quad 2-input positive-NAND gates with open collector outputs
7404	Hex inverters
7413	Dual 4-input positive-NAND Schmitt triggers
7420	Dual 4-input positive-NAND gates
7474	Dual D-type positive-edge triggered flip-flop with preset and clear
7490	Decade, divide-by-12, and binary counter
74122	Retriggerable monostable multivibrators with clear
74278	4-bit cascadable priority registers

Table C-3. Circuit board nomenclature, functions, and figure reference

Board	Figure	Nomenclature and function
A	B-9	Power supply connector board
B	B-17	Signal-conditioning Schmitt triggers
	B-18	Signal-conditioning, line-frequency, phase-locked loop
	B-19	Signal-conditioning, standard second signal
	B-20	Signal-conditioning, pulse delay
	B-21	Signal-conditioning, pulse divide-by-10
C	B-22	Gate board
D	B-13	Pulse-adding, standard channels
	B-14	Pulse-adding, clock
	B-15	Pulse-adding, test channels
E,F	B-12	Variable threshold Schmitt triggers
G	B-16	Display select gate board, test gate buffer
H	B-23	Comparator reset

APPENDIX D

DETAILED PROCEDURE FOR THE CALIBRATION OF WATTHOUR METERS

D.1 Installation of and Connections to the Watthour Meter

The installation involves the selection of the test bench station at which the watthour meter is to be calibrated, leveling the meter (if required), and connecting the proper leads from the test bench to the meter. Station four is usually reserved for an NBS monitor standard which is used and calibrated with each daily run. This provides an independent check on the system operation and performance.

For rotating types of watthour meters, leveling is necessary. If the meter has its own level indicator, the three adjustable supports of that station's pad are adjusted to bring the instrument to a level position. If the meter does not have a level indicator, then the bubble level on the pad is used.

Next, the potential and current leads are connected to the watthour meter being calibrated. As a safety precaution all controls at the control console (viz., voltage, power factor, and current) are set at their minimum settings to preclude the chance of electrical shock. This also avoids the possibility of subjecting the meters to surge currents which could cause magnetization errors to occur, or of accidentally overranging the meters. The proper polarity of the current and potential leads must be observed. A reversal of one set of leads can cause serious errors, especially for rotating-type meters. Each connection is to be tight and insulated.

For any of the four test bench positions not being used, the current terminals are shorted. The voltage terminals of the same should be switched to "off" to remove the voltage from the unused terminals on the bench. For electronic-type watthour meters, it is necessary that auxiliary power is supplied to the instrument, usually 120-V, 60-Hz single-phase power.

For those test stations being used, the voltage and current connections on the test bench terminals and meter terminals are rechecked to be correct. The meter terminals should be connected to the 120-V and 5-A taps. The voltage switch on the test bench for the meters in the circuit should be in the "on" position. The voltage should be connected and the current transformer should be connected such that the 5-A tap is used. The power supply should be switched to 120 V for the voltage supply and the connections on the current supply should indicate 5 to 25 A position. (See figs. B-6 and B-8 in appendix B.)

The voltage and current are increased slowly. While still at low voltage and current, rotary meters are inspected. If the meter disk runs in reverse, return current and voltage to zero and change the polarity of the terminals which appear to be causing the reversal. Then increase the voltage and current to their proper values.

For watthour meters having pulse outputs, connection is made so that the counter units are used. Initially the counter to be used is examined to verify that it, as well as the counters for line and standard frequencies, is running.

The presence of bias and lamp voltages is verified by observing a pulse output (usually on an oscilloscope) from the watthour meter after voltage and current have been applied to the unit. The voltage and current are then increased to 120 V, 5 A, at 0.5 power factor lag. The meters are allowed to warm up from one to four hours -- usually for four hours.

D.2 Testing Procedures

Before beginning the test, the temperature of the NBS reference bank watthour meters is checked. If it is within 25.0° ±0.2°C, calibration may proceed.

The power supply controls are set to zero and the necessary taps changed according to the test point conditions listed on the prepared data sheet. Connection is made to the current and voltage taps of the meter and current and voltage transformer taps, as necessary. Also, power supply connections for the current and voltage supplies are changed when needed to provide the required voltage and currents.

The power supply is set to 120 V, 5 A, and 0.5 power factor lag. Once done, one may change power factor as needed. If the test is to be at 0.5 power factor lag, the point is ready to be run. If the test is at unity power factor, the current is reduced first to zero, the power factor switch changed to unity, and current returned to 5.00 A. For a 0.5 power factor lead (or any other leading power factor) the procedure done for unity power factor is repeated, and adjustment of the watts indicator is made to achieve 0.5 power factor lead (or any other leading power factor). If a lag value is other than 0.5 power factor lag, adjust the watt indication for the required power factor.

The comparator is set to the preset value of the test point as recorded on the data sheet. For rotary or disk-type meters, the voltage switch is turned to "off" and the registers are zeroed. The test is now ready to run. The START button is pressed and the line and frequency counters are checked to ensure they are counting. For meters having registers, their operation is checked. For meters having pulse outputs, the appropriate counter is checked to ensure that it is counting.

When the test ends, the meter value (as indicated on the counter or the meter register) and line and standard frequencies are each recorded. The START button is again pressed and the test repeated. The meter and frequency readings are recorded when the second run ends. The temperature of the room and reference bank are also noted.

After two or more runs, the voltage and current are reduced to zero and the appropriate connections are changed for the next set of test conditions. This is repeated until a pair of readings have been obtained for each test condition.

At the end of the test or day, the power supplies are set to about 75 V and 0.75 A on the 1-A range at 0.5 power factor lag. This provides "idle" power for the meter overnight and for weekends and holidays. This is important, especially for rotating standards. A second set of data is obtained for each test point at least one day later so that a minimum of four readings have been made -- two pairs -- on two different days.

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J. D. Ramboz and R. C. McAuliff

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Same as item 6.

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 NBS calibration service for wattmeters and watthour meters is described. The service offers measurements of percentage registration for watthour meters and percentage correction for wattmeters over a range of voltages and currents at a frequency of 60 Hz. Measurements are limited to power factors of 1.0 and 0.5, leading and lagging. The Measurement Assurance Program (MAP) for electric energy is discussed. National standards for electric energy, NBS services, special equipment and instruments, and measurement methods and procedures are described, as are error estimates and quality control. A representative Report of Calibration is included.

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

Calibration; electric power and energy; electric standards; NBS services; watthour meters; wattmeters.

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