the offset in the data will be apparent. To verify this as the cause of disagreement, the transformer is again demagnetized and the test repeated. If the low-current data from both runs of the second set do not agree, it is probable that the circuit is magnetizing the transformer. In this case, the connections or leads must be cleaned, tightened, or replaced before repeating the test. If the lack of repeatability is caused by transformer heating, the data should once again repeat after a brief period of no-current flow to allow the transformer to cool.

For transformers having a window-type primary winding, tests are performed to determine the sensitivity to the position of the conductor (or conductors) passing through the window. The uncertainty assigned to the calibration results is adjusted to account for this positional sensitivity. To minimize any loss of accuracy in the calibration of the transformer and subsequent use, the primary link in the window is provided with suitable spacers which position and hold the conductor in a fixed window location. The transformer thus arranged can subsequently be used in the same configuration as calibrated, minimizing the effect of the position of the primary turn. The position of the primary return conductor may also affect the ratio error and phase angle, but it is usually less critical.

Once the data have been collected from one range and burden, the test is continued to the remaining burdens, ranges, and frequencies. The trends and transformer response are examined to determine if the results are representative for that type of transformer.

### 3.6 Summarization of the Measurement Results

After the data have been collected and reviewed for consistency, the results are entered into a spreadsheet program for analysis. Figure 14 shows a typical spreadsheet used for the summarization. The averages of the current ratio errors and the averages of the phase angles are determined, and the ratio correction factor (RCF) is calculated from the relationship

$$ RCF = 1 + \text{ratio correction}. $$

The scaling from units of ppm to ratio correction factor, and conversion of the phase angles from microradians to milliradians is done in the spreadsheet. Values of estimated measurement uncertainty at 50 and 60 Hz are also calculated using the following equations:

$$ U_r = \pm [0.0075 + 0.0025(5/I_2)]\% $$

$$ U_p = \pm [0.09 + 0.01(5/I_2)](1 + |\beta|/3) \text{ mrad} $$
<table>
<thead>
<tr>
<th>FREQUENCY (Hz)</th>
<th>CURRENT (Amps)</th>
<th>RATIO</th>
<th>ERROR (PPM)</th>
<th>PHASE (URAD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.5</td>
<td>-93</td>
<td>-91</td>
<td>-548</td>
</tr>
<tr>
<td>120</td>
<td>0.5</td>
<td>-100</td>
<td>-92</td>
<td>418</td>
</tr>
<tr>
<td>180</td>
<td>0.5</td>
<td>-83</td>
<td>-82</td>
<td>-436</td>
</tr>
<tr>
<td>240</td>
<td>0.5</td>
<td>-103</td>
<td>-104</td>
<td>-195</td>
</tr>
</tbody>
</table>
3.6 Summarization of the Measurement Results

<table>
<thead>
<tr>
<th>CURRENT TRANSFORMER CALIBRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>60 A 0.5 200 40</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>400 A 0.5 10 12</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Figure 13. Current Transformer Calibration Typical Data Sheet (Continued)
CURRENT TRANSFORMER CALIBRATION PROCEDURES

Figure 14. Current Transformer Calibration Spreadsheet for Calculation of Final Results

where

$U_r$ is the estimated uncertainty in the value for the ratio correction factor
$U_p$ is the estimated uncertainty in the value for the phase angle,
$I_2$ is the nominal value of secondary current, and

$|\beta|$ is the absolute value of the phase angle in mrad.

Care must be exercised in interpreting the uncertainty values by noting that $U_r$ is a fraction of the ratio correction factor in percent while $U_p$ is a direct phase-angle value. For example, the measured RCF of a transformer at 5 A is 1.000123 and the phase angle is 0.315 mrad. From eqs (16) and (17), it is determined that $U_r = \pm 0.01\%$ and $U_p = \pm 0.101$ mrad. Using these uncertainty values the probable upper and lower bounds for RCF are

$$1.000123(1 \pm 0.0001) = 1.000223 \quad \text{and} \quad 1.000023,$$

and for phase angle

$$0.315 \pm 0.101 = 0.416 \quad \text{and} \quad 0.214 \text{ mrad}.$$

The eqs (19) and (20) have been selected so that the limits of the uncertainty represent a realistic characterization of the transformer being calibrated over a range of secondary currents from 10% to 100% of the rated secondary current. The uncertainties will not usually be valid for currents above the rated current or for
3.6 Summarization of the Measurement Results

Figure 15. Ratio and Phase-Angle Uncertainty as a Function of Secondary Current

Currents of less than 10% of rated current. For the ratio correction factor, the uncertainty at a secondary current of 5 A is ±0.01%, while at a secondary current of 1 A, the uncertainty doubles to ±0.02%. The uncertainty for the phase angle is not only a function of the secondary current, \( I_2 \), but also of the absolute value of the phase angle itself. For very small phase angles, the uncertainty is slightly greater than 0.1 mrad at 5 A and almost doubles to a value of 0.19 mrad at 0.5 A. Figure 15 shows plots of these functions. For the phase angle plot, the phase angle of zero is shown to represent the smallest possible uncertainty. The other values shown, 100 and 1000 \( \mu \)rad, are typical phase angles for which plots are also shown. It has been determined that these uncertainty formulas are adequate for nearly all of the calibrations performed. In the instances where it is apparent that the calculated uncertainties do not properly describe the characteristics of the current transformer, the formulas are suitably altered to describe the transformer's performance. This is discussed further in chapter 4. The formulas and values of uncertainty are stated on the Report of Calibration (or Report of Test).
CURRENT TRANSFORMER CALIBRATION PROCEDURES

3.8 The Report of Calibration

For each current transformer that is tested, a Report of Calibration (or Report of Test) is issued. The Report gives the results of the measurements made by NIST on that particular current transformer under the test conditions specified at the time of test. An example of a Report of Calibration for a current transformer is shown in Figure 16. Historical Data of Transformer Calibration

3.7 Historical Data and Expected Performance

For high-quality current transformers, the values of the ratio correction factor and the phase angle change very little, if at all, over many years. This then makes the calibration history for a particular transformer very valuable. When a transformer has been previously calibrated at NIST, the previous data are compared to the present calibration results. Figure 16 shows a typical “history” sheet. Very close agreement, within two standard deviations, is expected if the transformer is tested under the same conditions (i.e., same burdens, frequency, ratios, currents, etc.). If the results do not agree with historical data, there is usually a problem in the transformer or the test arrangement. When no previous calibration history is available, the calibration results are compared to the expected performance for the type of transformer being calibrated. Occasionally, a transformer of unusual design and performance is encountered. This occurs when a transformer is heavily compensated, for example, and the results may appear different from the typical response. In such instances, the transformer manufacturer is usually consulted to verify that the observed response is representative for that particular design.
3.8 The Report of Calibration

Figure 17. The Report of Calibration specifies the instrument that was calibrated, and includes the manufacturer, model or type, and serial number. If the transformer lacks a suitable unique serial number, NIST will mark and uniquely identify the transformer. The current ratios and frequency range are stated. The company which submitted the transformer for testing is clearly given by name and address.

Specific details of the test conditions are given, such as the current ratios, burden(s), frequency, and current, and other information such as laboratory temperature, special connections, or other pertinent conditions. Calibration results are given as ratio correction factors (RCF) and phase angle (in milliradians).

The estimated values of uncertainty are also given for both the ratio correction factors and for the phase angle. As discussed before and in chapter 4, allowances are made for both the systematic and random components of the measurement uncertainty. Values used for an individual calibration are available upon request.

The NIST test number and customer’s order number are given. Questions regarding the test or inquiries regarding the Report of Calibration (or Report of Test) should be accompanied with the NIST test number, the instrument manufacturer, model, and serial number.

Reports of Calibration are issued for calibrations that are considered routine in that the specific device or others of its type have been calibrated previously at NIST. They are characterized by their secondary currents being in the range from 0.5 to 5 A, and the items under calibration are sufficiently stable to warrant uncertainty statements of about ±100 ppm and ±100 μrad.

The Reports of Test, on the other hand, are issued for special tests where the deviations from routine are significant. Special Tests may be performed to accommodate unusual operating characteristics and unusual accuracy requirements, e.g., to perform measurements beyond the determination of ratio correction and phase angle. Special Tests usually require additional experimental setups and additional investigation and are performed on an “at cost” basis.
CURRENT TRANSFORMER CALIBRATION PROCEDURES

REPORT OF CALIBRATION

CURRENT TRANSFORMER
10-1200 to 5 Amperes, 25-500 Hertz, 25 Volt-Amperes
Knun-Betare Model 3121/C, Serial Number 1234

Submitted by
Peyew Public Gas & Electric Co.
100 Main Street
Sommeware, Ohio 45891

<table>
<thead>
<tr>
<th>Frequency (hertz)</th>
<th>Secondary Current (amperes)</th>
<th>Current Ratio</th>
<th>Phase Angle (milliradian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>A</td>
<td>0.5</td>
<td>2 x 0.99991</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>0.99991</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0</td>
<td>0.99991</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0</td>
<td>0.99990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.0</td>
<td>0.99990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>0.99989</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.0</td>
<td>4 x 0.99989</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.0</td>
<td>10 x 0.99990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.0</td>
<td>20 x 0.99989</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.0</td>
<td>240 x 0.99991</td>
</tr>
<tr>
<td>400</td>
<td>A</td>
<td>5.0</td>
<td>20 x 0.9998</td>
</tr>
</tbody>
</table>

Date of test: January 30, 1990
Temperature: 23°C

Figure 17. Typical Report of Calibration
Secondary burden A consisted of a resistance of 0.20 ohm in series with an inductance of 140 microhenries.

At a frequency of 60 hertz, the uncertainty for the values of ratio does not exceed \( \pm[0.0075 + 0.0025(5/I_s)]\) percent, and for the values of phase angle does not exceed \( \pm[0.09 + 0.01(5/I_s)] \cdot (1 + |\beta|/3) \) milliradians, where \( I_s \) is the secondary current in amperes and \( \beta \) is the reported value of phase angle in milliradians. At a frequency of 400 hertz, the uncertainty for the value of ratio does not exceed \( \pm2 \cdot [0.0075 + 0.0025(5/I_s)] \) percent, and for the value of phase angle does not exceed \( \pm3 \cdot [0.09 + 0.01(5/I_s)] \cdot (1 + |\beta|/3) \) milliradians. These figures include allowances (available on request) for both the random and the systematic errors of the calibration process.

For the Director,
National Institute of Standards and Technology

Kalie Braetour, Group Leader
Applied Electrical Measurements
Electricity Division

Test No. 728/123456-90
Purchase Order No. 8-00331/A
Date: January 30, 1990

Figure 17. Typical Report of Calibration (Continued)
4 MEASUREMENT UNCERTAINTY ANALYSIS

4.1 General Considerations

Several considerations are important in preparing the uncertainty estimates for the calibration of current transformers. The total measurement uncertainty arises from both (1) the NIST standards and test equipment and (2) the device under test. The former source of error is well characterized; the latter, usually being the dominant one, may not be. In addition, many transformers submitted to NIST for calibration are built for special purposes and have unique characteristics. Even for the widely used transformers, the accuracy of each unit is strongly affected by the conditions under which it is used and calibrated, that is: the nominal ratio, the value of the burden, the magnitude of the current, and the electromagnetic environment. To achieve the maximum accuracy, many transformers and even test points would have to be evaluated separately rendering the process prohibitively expensive and uneconomical for the customers. An approach has been taken to develop an error budget that includes most of the transformers. For exceptionally stable transformers, higher accuracies are possible under Special Test provisions and additional cost. Accuracies might be lowered for transformers whose stabilities are inferior.

4.2 Accuracy Evaluation of NIST Standards and Equipment

4.2.1 Current Comparators

The customers' transformers are calibrated at NIST on a relative basis against current comparators that are designed and built to have negligible corrections when used for routine calibrations. To achieve this, the current comparators themselves must be calibrated on a more fundamental or "absolute" basis. Complete "absolute" calibration is an involved and lengthy undertaking for a multi-range current comparator. Often the limits of errors of a current comparator can be determined by indirect means. Both approaches have been used at NIST. For example, as the current comparators were constructed, indirect evaluations and tests were used. Later, all finished devices were calibrated on a fundamental basis at several nominal ratios to ensure that the indirect approaches are valid and that the corrections are negligible, as planned. Table 5 shows estimates of systematic uncertainties for three of the NIST compensated current comparators and the test set.
4.2 Accuracy Evaluation of NIST Standards and Equipment

Table 5. Systematic Uncertainties in NIST Equipment

<table>
<thead>
<tr>
<th>SOURCE OF UNCERTAINTIES</th>
<th>Ratio (ppm)</th>
<th>Phase Angle (μrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Range CCC*</td>
<td>±8</td>
<td>±8</td>
</tr>
<tr>
<td>Mid-Range CCC</td>
<td>±3</td>
<td>±3</td>
</tr>
<tr>
<td>Primary feed</td>
<td>±8</td>
<td>±8</td>
</tr>
<tr>
<td>Secondary feed</td>
<td>±8</td>
<td>±8</td>
</tr>
<tr>
<td>High-Range CCC</td>
<td>±5</td>
<td>±5</td>
</tr>
<tr>
<td>Test Set</td>
<td>±(1+0.005</td>
<td>α</td>
</tr>
</tbody>
</table>

*CCC—Compensated Current Comparator

The fundamental measurement of transformer ratios at NIST relies on a build-up ("bootstrap") technique whereby two transformers or current comparators with known ratios are used to calibrate a third one [5] [7]. The starting point is a 1:1 current comparator that can be self-calibrated by connecting the primary and secondary windings in series. Two calibrated 1:1 current comparators are then used to calibrate a 2:1 current comparator.

The secondary windings of all three are connected in series. The primary currents of the two 1:1 current comparators are added and applied to the primary winding of the 2:1 current comparator. The new ratio is the sum of the two previously known ratios. The process can be continued for higher ratios. Three identical multi-range current comparators are required. In the literature the approach has been called the \( m + n \) technique since the new ratio is the sum of the two previous ones, \( m + n \) [5].

Another bootstrap technique, in which the new ratio is the product of two previously known ratios \( (m \times n \) technique), is also utilized at NIST [8]. Two multi-range current comparators or current transformers are used, plus a small current comparator for comparing two unequal secondary currents in the ratio of 2:1 and 2.5:1. The primary windings of the full-range current comparators are connected in series while the secondary windings are connected to the small current comparator. For example, a 240:1 ratio can be calibrated with known 120:1 and 2:1 ratios.

Two amplifier-aided current transformers were calibrated by the \( m \times n \) method. These, in turn, were used to check at least a few ratios on each of the three current comparators used for routine calibrations.

The build-up calibration process requires a large amount of time and equipment. Also the uncertainties tend to accumulate with every step and may lead to unrealistically high values at large ratios. Nevertheless, it is a rigorous approach and therefore
a highly desirable means for checking other approaches, including the indirect techniques discussed in the following paragraphs. Fortunately, the problem is mitigated by the fact that current comparators and similar devices have permanently stable ratios. Usually a minimum number of transformers are then calibrated on a fundamental basis and others calibrated on a relative basis.

There are two types of intrinsic errors in current comparators: leakage flux causing magnetic errors, and internal capacitances causing capacitive errors. Both types of errors are well understood and can be controlled by the design of the current comparator. The limits of both can be estimated from indirect measurements.

With respect to the magnetic error, the worst-case leakage flux can be simulated and its effects measured. For example, two concentrated ratio windings with the same number of turns can be placed at the diametrically opposite parts of the core. Alternatively, one of the windings can be distributed along the core, the other concentrated. Both configurations will result in large leakage flux. The two windings are connected in series opposition and the device is calibrated on a fundamental basis as a 1:1 current comparator. The number of turns in the windings can be small to minimize the capacitive error. The test is performed with the worst-case and realistic geometries of the ratio windings. Under all conditions, the magnetic error should be insignificant for a well-designed current comparator.

Current comparators wound on toroidal cores are particularly sensitive to the leakage fields with certain geometries, for example, when the magnetic field is radial with respect to the toroid. External current loops can be used to simulate such fields.

High-permeability toroidal cores inherently minimize the relative magnitude of the leakage flux. Further reduction is achieved by placing a magnetic shield between the ratio and detection windings. The magnetic shield tends to short circuit the leakage flux, thus preventing its entry into the toroidal core and the detection winding. The aim is to provide sufficient magnetic shielding so that the error is negligible even in adverse winding configurations.

Different types of magnetic shields, their effectiveness and the errors resulting from the leakage flux have been thoroughly investigated in a current comparator designed for an impedance bridge [9]. The worst-case error for an unshielded current comparator can be several tens of ppm. Yet a simple judiciously designed shield made of high-permeability material will reduce the error to a sub-ppm level. A multi-layer, high-performance shield reduces the error below a part in $10^8$.

The capacitive errors are caused by the turn-to-turn capacitances in the same ratio winding, by the winding-to-ground capacitances, and by the winding-to-winding capacitances. The latter are eliminated by electro-static shields, but the former two may be dealt with as follows.

The turn-to-turn and winding-to-ground capacitances tend to divert some of the
current from passing through all of the turns in a winding. They effectively produce a capacitive shunt across the ratio windings. In the primary winding, the number of turns in many cases is below 100 with negligibly small internal capacitances. The secondary windings in mid- and high-range current comparators have significant internal capacitances that could cause possible errors if there were voltage across these windings. However, when operated with the primary feed, there is a very small voltage across the secondary windings and, hence, negligible capacitive error. This is not so when the secondary feed is used and up to 200 volts can be introduced in the secondary winding producing capacitive error of the order of 10 ppm. The capacitive error is partly compensated by the external capacitor, \( C_e \), in figure 8.

The low-range current comparators with a nominal ratio of less than unity present a special problem. The voltage in the primary winding is high regardless of whether primary or secondary feed is used when the device is operated as a compensated current comparator. The auxiliary current transformer in figure 10 removes the need of the compensated current comparator to serve as a power transformer and thus reduces the voltage across the windings. As a result, the capacitive error can be greatly reduced.

### 4.2.2 Test Set

The test set is a minor contributor to uncertainties. Because of the added circuitry it could act as a receiver of electromagnetic interference. The circuit that generates the correction current has accuracy limitations. The test set has a fixed uncertainty component of \( \pm 1 \) ppm and \( \pm 1 \) \( \mu \)rad, and another uncertainty component that depends on the magnitude of the injected current. The latter is \( \pm 0.5\% \) of the ratio correction and \( \pm 0.5\% \) of the measured phase angle. Expressed algebraically the uncertainties become \( \pm (1 + 0.005|\alpha|) \) ppm for the ratio correction, and \( \pm (1 + 0.005|\beta|) \) \( \mu \)rad for the phase angle, where \( \alpha \) and \( \beta \) are the test set readings.

### 4.3 Errors Originating in Transformers Being Tested

The ratio in good instrument transformers does not have drift over time. However, short- and long-term fluctuations are observed in the measured ratio correction and phase angle. These can be treated as random errors if adequate time and resources are available to obtain sufficient data. This is possible with some transformer types that are submitted to NIST often, but not with others that are one-of-a-kind or are calibrated infrequently.

The observed instabilities in transformers have well-known physical bases, such as magnetization, heating effects, burden sensitivity, and winding geometry. The limits of variations due to the above causes can be estimated from the properties.
of the device or can be determined from auxiliary tests. From a knowledge of the transformers and the results of past tests, a list of errors, table 6, has been prepared.

The estimated values in table 6 represent the limits of variations originating from the indicated sources. The equivalent circuit of figure 2b and eq. (2) are useful for estimating the source of error. It should be emphasized that the values in table 6 are approximations for typical transformers submitted to NIST for calibration. More stable transformers, e.g., two-stage types, are available in which instabilities are lower by one or two orders of magnitude. Less stable transformers have also been encountered by NIST. In both cases the stability and quality of the device usually becomes apparent soon after the tests have been started.

For estimating the values in table 6, \( Z_m \) has been assumed to be 1000 \( \Omega \), the series inductive reactance being three times larger than the equivalent loss resistance. Thus, \( X_m = 949 \Omega \) and \( R_m = 316 \Omega \). The secondary leakage impedance is assumed to be resistive with a value of \( R_2 = 0.5 \Omega \). Similarly, the burden impedance is assumed to be resistive with \( R_B = 0.5 \Omega \).

### Table 6. Estimated Possible Instabilities in a Typical Transformer Under Test

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>Ratio</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correction (ppm)</td>
<td>Angle (μrad)</td>
</tr>
<tr>
<td>1. Core magnetization</td>
<td>±5 to ±15</td>
<td>±16 to ±48</td>
</tr>
<tr>
<td>2. Uncertainty in burden</td>
<td>±6</td>
<td>±19</td>
</tr>
<tr>
<td>3. Transformer temperature</td>
<td>±19</td>
<td>±19</td>
</tr>
<tr>
<td>4. Current value</td>
<td>±6</td>
<td>±9</td>
</tr>
<tr>
<td>5. Primary winding position</td>
<td>±3</td>
<td>±9</td>
</tr>
<tr>
<td>6. Electromagnetic interference</td>
<td>±10</td>
<td>±10</td>
</tr>
</tbody>
</table>

1. The most serious source of error in current transformers is residual magnetization of the core. Even if steps are taken to minimize it, some residual magnetization will be generated by switching transients and small direct currents in the circuit caused by rectification in oxidized connections or by thermal electromotive forces. Magnetization reduces the effective permeability of the core and thus the magnetizing impedance. A range of instabilities is given for this effect. The estimated minimum effect is \( ±3\% \) variation in the magnetizing impedance which is achievable under laboratory conditions following demagnetization of the core. The estimated maximum variation in \( Z_m \) is \( ±10\% \), a value that could be expected after a period of use without demagnetization.

2. The burden uncertainty arises from the accuracy to which the burden can be set and then maintained due to temperature changes. A 2% allowance is made for the initial setting of the burden and 2% for the heating effects. The changes
in the burden directly affect the indicated ratio corrections and phase angles by changing the ratio $R_B/Z_m$ (see figure 2). In the absence of the external burden, temperature changes affect the ratio $Z_2/Z_m$. A 4% uncertainty is assumed due to ambient temperature and self-heating effects in $R_2/Z_m$.

4. The nonlinearity of the core causes changes in $Z_m$ with current, especially at low permeabilities and currents. It is assumed that $Z_m$ changes by 10% between the secondary currents of 0.25 and 0.75 A. If in the calibration the 0.5-A value can be maintained within $\pm 0.1$ A, the uncertainty from this source will be $\pm 3$ ppm and $\pm 9 \mu$rad. Note that the previously discussed sources of error produce larger effects in the phase angle and are related to the variations in $(Z_2 + Z_B)/Z_m$.

5. In the window-type transformers, an uncertainty is caused by the position of the conductor in the window. The geometry of the primary winding affects both the primary and the secondary leakage inductance, thus causing an uncertainty in the ratio correction and, to a lesser extent, in the phase angle. The estimated values in table 6 are based on previous observations.

6. Finally, the electromagnetic interference from the supply transformer, the power lines in the building, and ground currents can also cause measurement errors. The estimated instabilities tabulated in table 6 will lead to a lack of repeatability or long-term random error as the transformer is recalibrated. It is instructive to compare such predicted lack of repeatability with actual performance of a transformer with similar electrical characteristics. Such a comparison was made using a current transformer that had been calibrated 15 times over a 55-month period. The calibration data are shown in table 7, with the standard deviation of 14 ppm for the ratio correction and of 25 $\mu$rad for the phase angle.

The estimated errors of table 6 are combined as if they were true, independent random errors. A uniform distribution is assumed for each of them. For a uniform distribution

$$s = \frac{d}{\sqrt{3}}$$

where $s$ is the standard deviation, and $d$ is the maximum value of the estimated error.

The combined standard deviation is the square root of the sum of the squares of the individual standard deviations. It is calculated for the values of table 6 using the mean value of the magnetization effect ($\pm 10.5$ ppm, $\pm 32 \mu$rad). Such a calculation yields 15.2 ppm for the ratio correction and 25.6 $\mu$rad for phase angle.

The transformer whose calibration data are shown in table 7 has a fixed primary winding and it was calibrated without an external burden and at relatively high secondary current, thus, the items 2, 4, and 5 of table 6 do not apply. Calculating
Table 7. Calibration History of a Typical Laboratory Grade Current Transformer, Marked Ratio 10 A:5 A.

Mean values and standard deviations are the cumulative values to and including the date of calibration.

<table>
<thead>
<tr>
<th>Date</th>
<th>Measured Value</th>
<th>Mean</th>
<th>Std Dev.</th>
<th>Measured Value</th>
<th>Mean</th>
<th>Std Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 Nov 81</td>
<td>125</td>
<td>—</td>
<td>—</td>
<td>453</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>20 Jan 82</td>
<td>156</td>
<td>140.5</td>
<td>21.9</td>
<td>470</td>
<td>461.5</td>
<td>12.0</td>
</tr>
<tr>
<td>22 Feb 82</td>
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<td>16.6</td>
<td>434</td>
<td>452.3</td>
<td>18.0</td>
</tr>
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<td>135.5</td>
<td>13.9</td>
<td>439</td>
<td>449.0</td>
<td>16.1</td>
</tr>
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<td>12.8</td>
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<td>439.8</td>
<td>24.9</td>
</tr>
<tr>
<td>17 Jan 83</td>
<td>161</td>
<td>141.3</td>
<td>14.9</td>
<td>437</td>
<td>439.3</td>
<td>22.3</td>
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</table>

The standard deviation for the remaining items yields 9.1 ppm for the ratio correction and 22.2 μrad for the phase angle. The calculated standard deviations from the estimated error components are in reasonable agreement with the actually observed long-term standard deviation of the transformer indicating that the instabilities of a transformer can be predicted from its characteristics.

4.4 Overall Measurement Uncertainties

In estimating the overall uncertainty, the random and systematic uncertainty components are combined using the guidelines of the BIPM Committee [10]. The two components are combined on a root-sum-squared basis at the three sigma level. A uniform distribution is assumed for systematic uncertainties:

\[ U = \left( 9s^2 + 3d^2 \right)^{\frac{1}{2}}, \]  

where \( U \) is the overall uncertainty, \( s \) is the long-term standard deviation, and \( d \) is the systematic uncertainty of NIST equipment.

In the absence of sufficient data to determine long-term standard deviation, it
is estimated from the type of information in table 6 computed for the specific transformer.

Consider an example. The mid-range compensated current comparator is used with the test set having the total systematic uncertainty of 6 ppm and 10 μrad. Using the cumulative standard deviations from table 7 (June 1986 values), we obtain

\[ U_r = 43.3 \text{ ppm}, \]
\[ U_p = 77.0 \mu \text{rad} \]

as the uncertainties in ratio correction and phase angle.

Consider another example where the long-term standard deviation is not available, but instead the combined uncertainties from table 6 are used (15.2 ppm and 25.6 μrad). The overall uncertainties become

\[ U_r = \left[ (3 \times 15.2)^2 + (\sqrt{3} \times 6)^2 \right]^{1/2} = 46.7 \text{ ppm}, \]
\[ U_p = \left[ (3 \times 25.6)^2 + (\sqrt{3} \times 10)^2 \right]^{1/2} = 78.7 \mu \text{rad}. \]

For this type of transformer the uncertainties quoted in NIST reports are ±100 ppm and ±100 μrad. In both cases the quoted uncertainty for ratio correction is somewhat larger than the observed value, while the phase angle uncertainty is about the same magnitude as the observed value. There is a certain advantage to keeping accuracy statements simple and as inclusive as possible. Hence, the rounded off figure of 100 ppm (or μrad) is used for both error components.

### 4.5 Special High-Accuracy Transformers

The discussion in this chapter so far has dealt with the transformers that constitute the majority of the NIST calibration workload. These are relatively old designs having corrections within 0.1% and 1 mrad and stabilities about an order of magnitude better. Advances in technology enable the construction of simple, two-winding transformers that are about an order of magnitude more accurate. Two-stage transformers can be constructed that have corrections and instabilities within a few ppm (or μrad).

The sources of error as listed in table 6 are greatly reduced or even eliminated. The accuracy of these specialized transformers is comparable to that of NIST standards. Calibration of high-accuracy ratio devices on a Special Test basis is provided. The charges are based on the actual cost rather than a fixed fee. Special Tests are subject to constraints due to scheduling and availability of equipment. The accuracies for such tests are evaluated on an individual basis. Uncertainties in the range of ±5 to 10 ppm (or μrad) are possible.
4.6 International Comparisons

When a laboratory, such as NIST, attempts to verify the accuracy of its current ratio standards, a vast amount of time and effort is required. One has to be always cautious in guarding against undetected errors. Inasmuch as possible, redundant techniques are employed to reduce the possibility of undetected errors. Interlaboratory comparisons among the national standards laboratories of other countries provide excellent means for checking the highest accuracy measurements. Two international comparisons have been conducted over the past 25 years in which NIST directly participated.

In 1965 a comparison was conducted between NIST and the National Research Council (NRC), Canada. Two multirange, audio-frequency current transformers were used [11]. The nominal ratios ranged from 1:1 to 6:1. The tests were conducted between 400 Hz and 10 kHz. At the frequencies of the primary interest, 400 and 1000 Hz, the agreement was within 0.4 ppm and 5.4 μrad at 400 Hz, and 0.3 ppm and 6.1 μrad at 1000 Hz. The greater than expected phase angle difference at 400 Hz was attributed to the magnetization of the core.

During 1984–1985, NIST, NRC, and three European laboratories participated in calibrating a multi-range, power frequency transformer at 50 and 60 Hz [13]. A range of current ratios from 5:1 to 200:1 was checked. The secondary currents ranged from 200% of rated to 1% of rated. At the rated current the agreement of all participants was within 1 ppm and 1.9 μrad. At very low currents, 1% of rated, the spread was 3 ppm and 5 μrad. The spread at low currents was partly attributed to the electromagnetic pickup in the transformer under test.

The above direct interlaboratory comparisons and others that have been indirect (e.g., NRC with European laboratories) confirm that the state of the art is well within the 100 ppm/100 μrad uncertainty which is used by NIST in routine work. At the 5 ppm/5 μrad level there are differences. Such uncertainties are given by NIST only in special cases in which there is ample evidence through independent checks that the data are valid. Also the transformer under test must exhibit adequate stability.

5 ACKNOWLEDGMENTS

The authors would like to express their appreciation to the following staff members: Mr. T. M. Souders who, on many occasions, guided and consulted in matters regarding current transformers, Mrs. E. A. Matthews and Mr. Robert Palm who prepared portions of the graphical data, and Mrs. R. Cummings, Mrs. D. Williams, Mrs. B. Meiselman, Mrs. R. Von Feldt, and Mr. J. Greenberg who helped prepare the manuscript.
INFORMATION REGARDING THE NIST CALIBRATION SERVICE FOR INSTRUMENT CURRENT TRANSFORMERS

A1 Technical Information

Only metering-type or laboratory-standard current transformers (including current comparators) will be accepted for test. These tests determine the current ratio correction factor and phase angle of the transformer "as received." NIST does not undertake the cleaning of transformers and does not knowingly begin tests on faulty transformers.

Before a test can be started, the test conditions must be completely specified by the user. The current ratio (primary to secondary) available on a routine basis ranges from 0.25:5 to 12000:5. Tables 1 to 3 in the body of this document give specific ratios that are routinely available. Ratios other than those listed may be available by special arrangements at an additional fee. Normal secondary current levels for testing are 0.5, 1, 2, 3, 4, and 5 A. Over-current tests, up to but not exceeding 10 A, are generally available within the limitations of NIST equipment. Burdens should be specified either as:

1. Series resistance in ohms and inductance in millihenries,
2. ANSI/IEEE C57.13–1978 standard burdens,
3. VA load at specified power factor, or
4. The user supplied burden and connecting leads.

Normal test frequencies are 50, 60, and 400 Hz. Other frequencies may be available and inquiries should be made regarding special tests.

Uncertainties of the measurement are stated on the Report of Calibration (or Report of Test) which is issued for each instrument calibrated.

A2 Calibration Request, Transformer Shipping, Insurance and Risk of Loss

A formal purchase order for the calibration or test should be sent before or at the time the transformer is shipped. This should provide clear identification of the apparatus being submitted and give separate instructions for the return shipment, mailing of the report, and billing. To minimize the time during which equipment is out of service, arrangements can be made to delay shipment to NIST until shortly before the test is scheduled to begin.
Requests for calibrations or tests from Federal and state agencies, must be accompanied either by a purchase order, or by a letter or other document authorizing the costs to be billed to the agency. The NIST agreement to perform the calibration does not imply acceptance of any provisions set forth in the order contrary to the policy, practice, or regulations of the NIST or the U. S. Government. The purchase order should clearly state the desired test conditions.

NIST staff will provide assistance for individual measurement problems where they can. The NIST headquarters is located in Gaithersburg, Maryland, approximately 25 miles northwest of Washington, D. C. The calibration of instrument transformers is performed at the Gaithersburg site by the Electricity Division (811) of the Electronics and Electrical Engineering Laboratory of NIST. Inquiries may be made by direct correspondence to:

National Institute of Standards and Technology
Electricity Division (811)
Metrology Building, Room B344
Gaithersburg, MD 20899

The reader is encouraged to obtain a copy of the NIST Special Publication 250, Calibration and Related Measurements Services of the National Institute of Standards and Technology. This publication is available from the following sources:

Superintendent of Documents
Government Printing Office
Washington, DC 20402

National Institute of Standards and Technology
Office of Physical Measurement Services
Physics Building, Room B354
Gaithersburg, MD 20899

The appendix of SP 250 listing current services and fees is issued twice yearly (usually in June and December) and is available at no charge from the above sources.

Scheduled work assignments for calibrations and other tests generally will be made in the order in which confirmed requests are received. However, work for U.S. Government agencies 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 not be more than 45 days. Some types of instruments may require a longer calibration 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 shipment of his instrument to NIST in time to meet the scheduled start of calibration. Generally, the acknowledgment of the purchase order gives the expected completion date.

NIST staff does not undertake repair services. 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.

A report is issued upon the calibration of each current transformer. This report contains the measured values of the transformer and their uncertainties. Reports of Calibration for current transformers are discussed in section 3.8 of the body of this document and an example of a typical report is given.

NIST neither requires nor recommends intervals between NIST calibrations for current transformers. 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 determined to be necessary for such instruments.

Shipment of apparatus to NIST for calibration or other test should be made only after the customer has accepted the estimate of cost and the tentative scheduling. Apparatus not in good condition will not be calibrated. If defects are found after calibration has begun, the effort may be terminated and data will be issued summarizing information collected to that point. A fee may be charged in accordance with the amount of work done.

The customer should carefully pack apparatus sent to NIST to minimize the likelihood of damage in shipping 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. The customer must pay shipping charges to and from NIST; shipments from NIST will be made collect. The method of return transportation should be stated and it is recommended that return shipments be insured, since NIST 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 NIST, but without insurance coverage. When no
Shipping or insurance instructions are furnished, return shipment will be made by common carrier collect and uninsured.

Shipments of transformers to NIST for calibration should be directed to:

National Institute of Standards and Technology
Electricity Division, MET B165
Rt. I-270 and Quince Orchard Road
Gaithersburg, MD 20899
7. REFERENCES


REFERENCES
A calibration service at the National Institute of Standards and Technology (NIST) for laboratory-quality current transformers is described. The service provides measurements of the current ratio and the phase angle between the secondary and primary currents. In the Report of Calibration or Test, the measured ratio is reported as the product of the marked (nominal) ratio and the ratio correction factor. The measured phase angle is reported directly in milliradians (mrad) and is positive if the secondary current leads the primary. The range of primary-to-secondary current ratios that can be measured with the equipment at NIST extends from 0.25 A:5 A to 12 000 A:5 A. The maximum current at the present time is about 20 000 A. Estimates of calibration uncertainties, including their sources, are given and quality control procedures are described. For routine calibrations, uncertainties of ±0.01% for the ratio and ±0.1 mrad for the phase angle are quoted. However, lower uncertainties—to ±0.0005% or 5 parts per million (ppm) for ratio and ±0.005 mrad or 5 μrads for phase angle—are possible under the provisions of Special Tests.