

Specification for Calibration and Performance Testing of Secondary Current Sensing Coils and Weld Current Monitors used in Single-Phase AC Resistance Welding



American Welding Society



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Specification for Calibration and Performance Testing of Secondary Current Sensing Coils and Weld Current Monitors used in Single-Phase AC Resistance Welding

1st Edition

Prepared by the
American Welding Society (AWS) A10 Committee on Instrumentation for Welding

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This specification sets forth accepted methods for testing and describing the performance of Rogowski-type air core current sensing coils (CSC) and weld current monitors (WCM) used in the measurement of single-phase ac resistance welding currents. A definition of terms relevant to this measurement is included. CSC and system tests and calibration methods are described in detail. Detailed information that shall be made available to the user are prescribed.



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Dedication

Dr. V. Ananthanarayanan

This document is dedicated to Dr. V. Ananthanarayanan (Anthony). Without his vision, leadership, and persistence, neither this document nor the A10 Technical Committee would exist.

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Foreword

This foreword is not part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Secondary Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, but is included for informational purposes only.

Measurement of resistance weld current and calibration of the measurement devices have been performed for many decades. However, the indications, readings, or outputs of devices made by different manufacturers and sometimes, the same manufacturer, while measuring the same current differ from one another significantly. This Measurement and Calibration Specification was prepared to help equipment manufacturers and users take into account some of the common sources of measurement uncertainty and standardize the methods of testing/calibration of these devices. The information that shall be provided to the user upon the completion of the calibration effort is also clearly specified. The goal is to assure consistent weld current measurement results independent of measurement equipment and to provide the user with a quantitative estimate of the total measurement uncertainty.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS A10 Committee on Instrumentation for Resistance Welding, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

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Specification for Calibration and Performance Testing of Secondary Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding

1. Scope

This specification sets forth accepted methods for testing and reporting the performance characteristics of Rogowski-type air core Current Sensing Coils (CSCs) and the Weld Current Monitors (WCMs) used in the measurement of secondary current in single-phase ac resistance welding. CSCs mounted inside transformers are not included in this specification. Traceability of measurements to National Standards as required by this specification is discussed. References regarding traceability concepts and requirements are provided. Sources of measurement uncertainty, methods of combining these uncertainties, and the manner in which the overall uncertainty is to be stated are discussed.

This standard makes sole use of SI units.

Safety and health issues and concerns are beyond the scope of this standard and therefore are not addressed herein. Safety and health information is available from other sources, including, but not limited to, applicable federal and state regulations.

2. Testing

This clause describes the accepted methods that are needed to evaluate common sources of measurement uncertainty. Each test will include a description of the purpose for the test, list the equipment needed, describe the test setup and the test procedure.

2.1 Measurement Standards. The calibration shall be done using appropriate Measurement Standards. The Measurement Standard shall be more accurate than the device being calibrated. The uncertainty of the Measurement Standard used shall be included in the documentation of the calibration. Further, to ensure that adequate calibration is performed, the Measurement Standards must be traceable to NIST or other acceptable national

metrology laboratory or nationally recognized standards. A more detailed explanation of traceability can be found in Annex F. Measurement Standards used must be calibrated and used in the range and type of currents in which they were intended to be used.

For example, to comply with this specification, it is not acceptable that a shunt calibrated by dc continuous current be used in a calibration of pulsed current at 20 kA. The shunt must be calibrated by ac methods at current levels for which the shunt will be used.

It is recommended that multiple sets of Measurement Standards with NIST or National Standards traceability be maintained by all calibrating organizations in order to periodically compare them against one another and assess any changes in the values of the standards.

2.2 Test Categories. There are no firmly established limits of uncertainties for the measurement applications of CSCs, or for the WCM-CSC combination. It is common to group the applications as shown below. The values of uncertainties may vary from one organization to the next, depending on their individual needs, capabilities, and economic considerations. Note that there may be overlap between the ranges of uncertainties. Uncertainties may be expressed as a percentage of full scale, or of reading.

(1) Laboratory Standards: uncertainty typically $\pm 0.25\%$ to $\pm 1\%$,

(2) Working Standards: uncertainty typically $\pm 1\%$ to $\pm 2\%$, and

(3) Production Instruments: uncertainty typically $\pm 2\%$ and greater.

Tests described in this specification are divided into three categories: "Type Tests," "Routine Tests," and "Optional Tests."

(1) Type tests are carried out to characterize the product design and manufacturing process. It is also being done when uncertainty requirements are less demanding.

(2) Routine tests shall be done on every piece of hardware because test results depend on manufacturing differences from CSC to CSC. It is required when uncertainty requirements cannot be met with type tests alone.

(3) Optional tests are conducted when more rigorous estimates of the measurement uncertainties are required.

The categories are shown for 3 typical classes of instruments, namely instruments used as Laboratory Standards, Working Standards, and Production Instruments. Laboratory Standards are usually maintained at a company standards laboratory for the purpose of establishing a uniform and traceable basis of measurements. Working

Standards typically are used to disseminate the calibration from the standards laboratory to the field, shop, or production areas of a company. Production instruments typically are the instrumentation in the field, shops, or production areas of a company.

Table 1 lists all the tests included in this specification and their categories. Under the Test Category columns, there may be a “double listing” of the test category, such as “Type/Routine” or “Type/Optional.” In these instances, the test category may depend on the uncertainty that is trying to be achieved, or conversely, the uncertainty is acceptably large enough so as not to require the test. Furthermore, considerations have to be given to whether the CSC is being tested by the original manufacturer (in which case, Type Testing may be appropriate) or whether the CSC is being tested by a user

Table 1
CSC and WCM-CSC Combination Tests and Their Categories

Test No. (Clause No.)	Test	Test Categories			Comments
		Lab. Std.	Work Std.	Prod. Instr.	
1 (3.1)	Mutual inductance calibration at manufacturer recommended load	Routine	Routine	Type/ Routine	The most important characteristic of the CSC. It is used to describe the relationship between the CSC output voltage and the current it is being used to measure when connected to the WCM for which it was designed.
2 (3.1)	Mutual inductance calibration at no load	Routine	Optional	Optional	The results of this test help evaluate the CSC interchangeability since the manufacturer recommended load might differ from WCM to WCM.
3 (3.2)	Position sensitivity	Routine	Type/ Routine	Type	Often the single highest source of uncertainty in measurements made with Rogowski-type CSCs.
4 (3.3)	Tilt tests for position sensitivity	Routine	Type/ Routine	Type/ Optional	These additional tests are needed to provide a more rigorous estimate of the uncertainties due to position sensitivity.
5 (3.4)	Sensitivity to external magnetic fields	Optional	Type/ Optional	Type/ Optional	These additional tests are needed to provide a more rigorous estimate of the uncertainties due to position sensitivity. Particularly relevant when CSCs are placed in smaller secondary loops.
6 (3.5)	Temperature coefficient of a CSC	Routine	Type/ Routine	Type	It is important to know the temperature coefficient since CSCs are commonly used at temperatures different from where they are calibrated.
7 (3.6)	Frequency Response Testing of a CSC	Type/ Routine	Type	Type	Frequency response of CSC must be evaluated with respect to the spectrum of the current waveform being measured.
8 (4)	WCM-CSC combination calibration	Routine	Routine	Routine	Commonly performed, but the uncertainties and traceability aspects are usually not taken into account.

to verify performance (in which case, Routine or Optional Tests are more appropriate). Comments are provided to clarify the need for each test.

2.3 Physical Environment for Testing. All tests shall be performed with the Unit Under Test (UUT) at a temperature of $20^{\circ}\text{C} \pm 5^{\circ}\text{C}$, except when the temperature coefficient of the CSC is being determined. The relative humidity shall be no higher than 95%.

3. CSC Tests

Rigid closed, rigid hinged, and flexible CSCs are covered by this specification. The common CSC shapes covered are round, oval, and tear-drop. Other shapes, such as square, rectangular, or “racetrack” are not excluded from use. When testing these other shapes, the test methods described in this specification may not be directly applicable. This specification may be used as a guide in these instances.

3.1 Mutual Inductance Calibration. The CSC’s output signal is a function of its mutual inductance, M_{CSC} . The CSC shall be calibrated and the value of mutual inductance provided to the user. It is usually expressed in units of *micro henries* (abbreviated μH ; 1×10^{-6} henries) or *nanohenries* (abbreviated nH ; 1×10^{-9} henries). For CSCs used with weld current monitors, the CSC mutual inductance is typically in the range of $0.2 \mu\text{H}$ to $0.7 \mu\text{H}$. For the purposes of this specification, the mutual inductance of the CSC is considered to be independent of frequency.

The CSC manufacturer needs to know the input impedance of the WCM to which the output of the CSC shall be connected. Only then can the CSC output be properly trimmed to provide the expected effective mutual inductance. It is common practice to adjust the *effective mutual inductance* of a CSC with the use of added resistor(s). These resistors are often physically located in the electrical connector of the CSC’s output cable. Series and/or parallel adjusting schemes are commonly used. The effective mutual inductance of the CSC is dependent upon the external electrical load impedance to which it is connected. The effective mutual inductance at the WCM manufacturer’s recommended load impedance shall be stated. In addition, the effective mutual inductance at no-load impedance may be stated. The no-load impedance is defined as a load equal to or greater than $1 \text{ M}\Omega$.

A value of CSC *transimpedance* may be provided, but shall not be used as a sole characteristic that describes the CSC sensitivity. In all instances, if a *transimpedance* value is given, it shall be accompanied with a value for frequency and load impedance under which it applies.

The value of transimpedance, if used, shall be stated in units of ohms, milliohms, or microohms, as appropriate. This value is commonly expressed as “millivolts per thousand amperes” at a stated frequency which is equivalent to units of microohms. The internationally accepted scientific units of ohms, milliohms, or microohms are preferred over the use of the expression “millivolts per thousand amperes.”

The mutual inductance calibration shall be performed in a 1/R-type magnetic field. A 1/R-type magnetic field is only created by an infinitely long straight conductor with a circular cross section when a current is flowing along the length of the conductor. The field is purely tangential to the single center conductor. The magnetic field beyond the outside of the conductor varies inversely with the distance R to the center of the conductor in a radial direction. Ideally, there are no other field contributions from any other source, especially the return conductor.

It is difficult to generate an ideal 1/R field. A practical, proven and suggested means to implement the generation of a suitable approximation of a 1/R-type magnetic field is with the use of a coaxial cage arrangement. The coaxial cage, which may be cylindrical or comprised of large flat rectangular conductors and a rigid straight center conductor with a round cross section. Sections through typical hexagonal and circular coaxial cages are shown in Figure 1. The coaxial cage geometry shall be such as to develop a suitable 1/R-type magnetic field approximation in the test envelope during the mutual inductance calibration test.

The sizes of the central and return conductors shall be appropriate for the current range used. Typical diameter of the center conductor is 38 mm to 50 mm. Practical cage diameters range from 300 mm to 600 mm, and the inside length range from 300 mm to 900 mm. The thickness of the outer walls and end plates of the cage is typically 6 mm to 12 mm thick. The inside of the cage must be sufficiently large to permit mounting the center of the CSC around the center conductor while maintaining a suitable clearance between the CSC and the inside walls of the cage. The opposing design criteria are to keep the cage small to minimize the insertion impedance of the cage in the high current path, while simultaneously providing sufficient working volume inside the cage to accommodate the CSC being calibrated. Smaller cages are less expensive to fabricate and are more portable. Additionally, the thick outside walls of the cage provides eddy-current shielding from external fields.

The CSC mutual inductance calibration shall be performed in a 1/R-type magnetic field equal to or better than that generated by a coaxial cage as described herein. If a coaxial cage is not used, it is the responsibility of the user to ensure, either through measurement or modeling

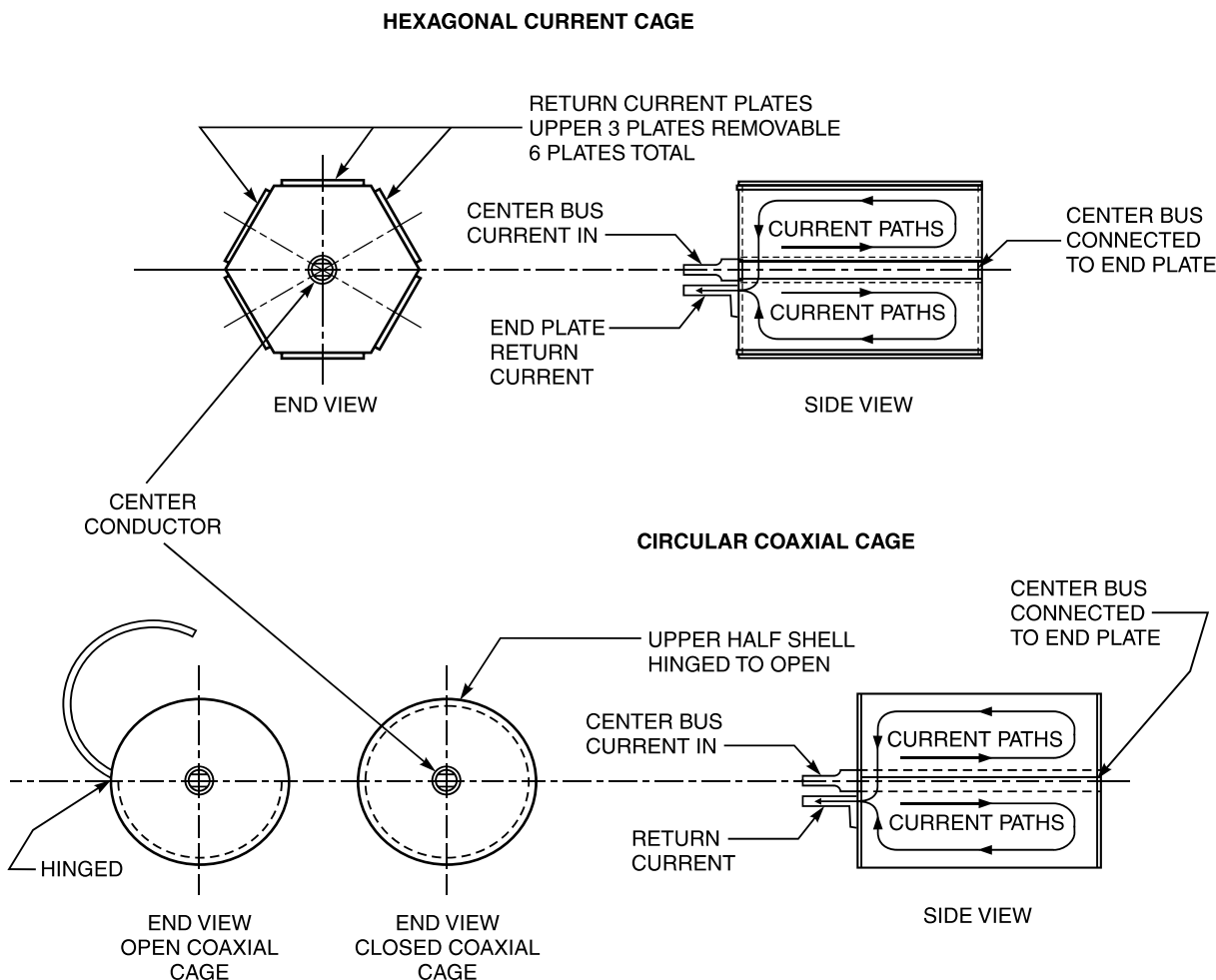


Figure 1—Hexagonal and Circular Coaxial Cages Typically Used for Mutual Inductance Testing of a CSC

of the magnetic field, that the magnetic field is a suitable approximation of the field produced by a coaxial cage, or that of an ideal $1/R$ field.

3.1.1 Equipment

(1) Current source. *This is either a calibrated current source, or an uncalibrated current source used with the calibrated current sensor listed next. In either instance, the source or the sensor must be calibrated in the frequency and current ranges used for the tests. The current waveform must be nominally a full-wave sinusoid. Waveforms other than sinusoidal will introduce frequency dependant errors.*

(2) Reference Current Sensor and Display. *Not required if the current source is calibrated.*

(3) Coaxial cage as in Figure 1.

(4) Frequency counter.

(5) AC voltmeter capable of measuring the output of CSC with an input impedance of 1 megohm or greater.

(6) Load resistor, value recommended by the WCM manufacturer, typically 1000 ohms $\pm$ 1% low inductance resistor. (Recommend the use of a metal film resistor; avoid using a wire wound resistor.) When the mutual inductance is being determined for a “no load” test condition, this load resistor is not used.

3.1.2 Setup. For the mutual inductance calibration, the CSC shall be placed in the coaxial cage during testing so that the following conditions are met. The distance from the end plates to any part of the CSC shall be no

less than 5 cm or 10% of the coaxial cage length, whichever is greater.

(1) The distance from the return current plate(s) (i.e., circular shells) to any part of the CSC shall be no less than 1 cm or 5% of the shortest distance between the center bus and the return current plate, whichever is greater.

(2) If a hexagonal coaxial cage is used, the CSC shall be placed inside a circular envelope in which the radial distance from the center of the bus is no greater than the shortest radial distance less 1 cm or 5% of the shortest distance. The shape of the CSC should not be deformed when it is placed in the coaxial cage for testing.

(3) For CSCs having a circular shape, the CSC shall be placed radially in the coaxial cage such that the center of the CSC coincides with the center conductor of the cage and that it is oriented with the plane of the CSC perpendicular to the center conductor.

(4) If the CSC has a tear-drop or elliptical shape, it shall be centered on the intersection of its two axes (for example, see Figure 3).

(5) Ensure that the CSC cable connector is accessible from the outside of the cage.

Figure 2 is a photograph of a typical hexagonal coaxial cage. The top plate has been removed to facilitate a view of the CSCs placed inside the coaxial cage for testing. The CSCs placed inside the coaxial cage may be Reference CSCs, UUTs, or both. Figure 3 shows a “tear-drop” shaped CSC and the intersection of the two axes which defines the “center” of the CSC.

Figure 4 shows a schematic of the required test setup. The test procedure is described below. Allow sufficient warm up time for all instruments and the CSC to provide required stability. CSCs transported from one location to another must be given sufficient time to stabilize to the test temperature.

3.1.3 Procedure

NOTE: The temperature sensitivity of the CSC may adversely affect the results of the calibration. It has been observed that certain CSCs have relatively large temperature coefficients as large as 0.2% per degree Celsius (°C). In such instances, a few degrees temperature change may alter the calibration results significantly. These effects must be taken into account when assigning a value of uncertainty to the calibration. A method for determining the CSC temperature coefficient is provided in 3.5.

(1) Pass a sinusoidal test current through the coaxial cage from the current source. Record the voltage from AC voltmeter “E.” The test current shall be high enough

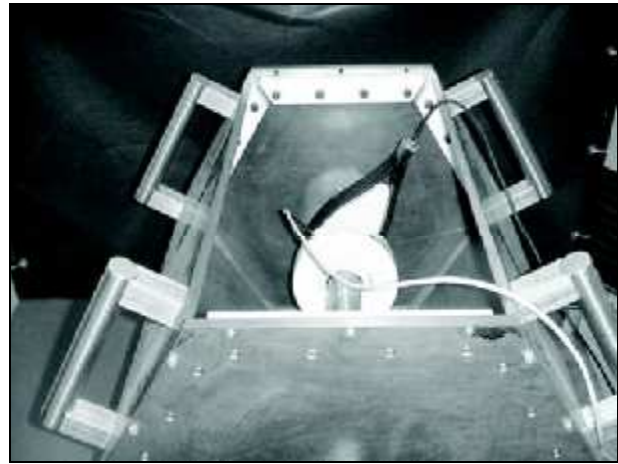


Figure 2—View of Hexagonal Coaxial Cage for Mutual Inductance Measurement and Calibration Showing a Round White CSC and a Black Tear-Drop Shaped CSC Placed Around the Central Conductor

to generate CSC outputs sufficient to overcome the effects of noise on the measurement results.

(2) Record the current from the current sensor “B” and the frequency from frequency counter “D.”

(3) Calculate Mutual Inductance of the CSC using the following formula:

$$M_{\text{CSC}} = V / (2 \pi f I),$$

where

M_{CSC} = the CSC mutual inductance in henries;

V = the CSC output voltage in volts;

π = 3.1416 ...;

f = 55 Hz the test frequency (see Note below); and

I = current passing through the conductor, amperes rms.

NOTE: A frequency of 55 Hz is recommended when a variable frequency source is being used. It is recognized that this is not always possible when the current is being derived from the power line. A source other than one that depends on the power line generally will provide better current stability. A frequency other than line often will reduce the bothersome and error causing effects of beat-frequency interference.

(4) Repeat the measurement 5 times and record each test. The final test result shall be taken as the mean of the set of 5 measurements. Determine the standard deviation

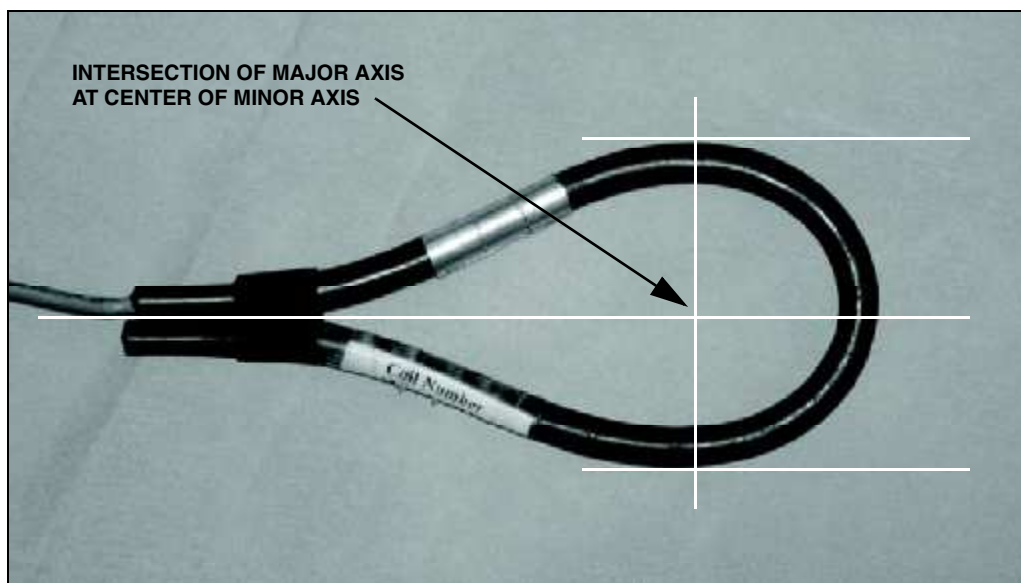


Figure 3—Centering Location for a Tear-Drop Shaped CSC

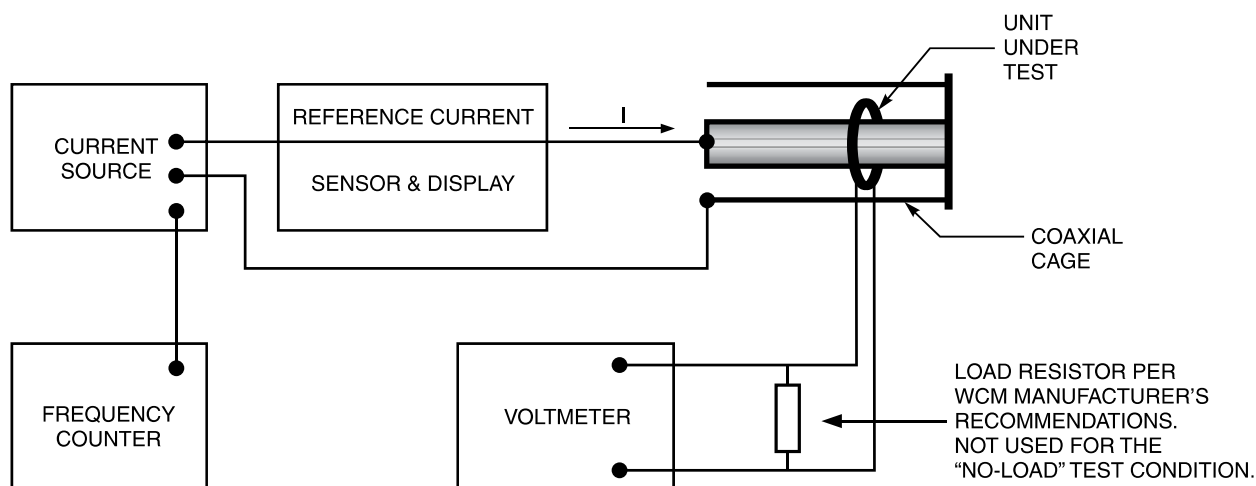


Figure 4—Equipment Setup for Determining the Mutual Inductance of Current Sensing Coils

for each set of 5 measurements. Record the value of two times the standard deviation (2σ) for later use in determining the measurement uncertainty for the test. Refer to Annex C for details and further information.

3.2 Tests for Position Sensitivity. The most common and typically, the largest source of uncertainty in high current measurements used in resistance welding is the

sensitivity of the CSC output voltage to its position in the current path. The lack of awareness of the “position sensitivity” issue and the absence of standard test methods have hindered accurate high current measurements and resulted in less reliable calibration efforts. It is the purpose of this subsection to provide a standard test method that minimizes the measurement uncertainties due to position sensitivity of the CSC.

fields given in 3.3 and 3.4. Forced air-cooling may assist in maintaining the UUT and Reference Sensor at the desired range of temperature.

The output voltages of common belt-type CSCs have been found to have temperature coefficients in the range 0.1% to 0.2% per °C. Consequently, it should be recognized that a 10°C change in CSC temperature may result in a measurement uncertainty of 1% to 2% of its output. If the temperature effects are too great, it will influence the results of the CSC position testing.

3.2.3 Procedure

(1) Place the UUT around the conductor as shown in Figure 5. A Reference Sensor is placed in a fixed position at any location of the test loop (preferably around the top conductor). The Reference Sensor is rigidly fixed in its position throughout the Position Sensitivity test. A test current shall be passed through the bus. The magnitude of the current shall be such that the output signals may be measured without undue influences of noise and readout resolution.

(2) This test may be performed using sinusoidal waveform currents or those produced by a typical resistance welding machine control. If a resistance-welding machine is used, the conduction angle shall be at least 120°. If the current in the test loop is not continuous (i.e., not steady state), the voltage measuring apparatus shall be triggered to acquire its measurements while the current is flowing. The outputs of the UUT and the Reference Sensor shall be measured concurrently.

(3) The UUT shall be placed at Position A and rotated through eight equal rotational positions (i.e., every 45° in rotation). At this test position, the UUT shall be hung from the conductor in each test position. The plane of the coil shall be kept perpendicular to the axis of the conductor during the entire test. For an openable CSC, one of the rotational test positions shall place the CSC split at position 5 as shown in Figure 5. When a rigid hinged CSC is tested, both of the splits shall be tested at the most upward position with the split in the “throat” of the test loop during the above test.

(4) At each rotational position of the UUT, the output voltages of the UUT and Reference Sensor shall be recorded. Alternatively, integrated values of the output voltages of both the UUT and the Reference Sensor at each position (as read by a WCM) may be recorded. (If a WCM is used, it should have sufficient resolution to measure the change. The threshold level at which the WCM is triggered should also be low enough to permit triggering during each test.)

(5) For the CSC in position A, at each rotational position, the ratio of the outputs of the UUT and the

Reference Sensor shall be determined. The maximum, minimum and the average of these ratios shall be determined.

(6) Repeat the above test procedure to arrive at the Position Sensitivity value of the UUT at Position B in Figure 5. At this position, the UUT shall be centered around the conductor at each test position using a non-conducting holder/fixture, typically made of wood or foam. If the CSC is *oval* in shape or has a *tear-drop* shape, it shall be centered at the intersection of its long axis with its axis at its maximum width (see Figure 3).

(7) For the CSC in position B, at each rotational position, the ratio of the outputs of the UUT and the Reference Sensor shall be determined. The maximum, minimum, and the average of these ratios shall be determined.

(8) The Position Sensitivity of the UUT = $100 * \frac{[\text{Maximum ratio from steps (5) and (7) above}] - [\text{Minimum ratio from steps (5) and (7) above}]}{[\text{Grand Average ratio calculated from averages in steps (5) and (7) above}]}$.

3.3 Tilt Test for Position Sensitivity. This test is meant to provide a more rigorous evaluation of the uncertainties due the position sensitivity of the CSC. This test should be considered essential if the CSCs are meant to be used as Calibrating Standards. This test should also be considered essential for obtaining a rigorous estimate of the total measurement uncertainty.

3.3.1 Equipment. The equipment for this test is the same as for the position sensitivity test as described in 3.2.1.

3.3.2 Setup. The CSC shall be centered on a 25 mm diameter bus in the same 250-mm by 250-mm loop used for Position Sensitivity (3.2) testing above. This test may be performed with only the CSC, or with a CSC connected to a WCM.

3.3.3 Procedure

(1) Place the UUT around the conductor as shown in Figure 6. A Reference Sensor is placed in a fixed position at any location of the test loop (preferably around the top conductor). The Reference Sensor is rigidly fixed in its position throughout the Position Sensitivity test. A test current shall be passed through the bus. The magnitude of the current shall be such that the output signals may be measured without undue influences of noise and readout resolution.

(2) The CSC will then be “tilted” to the extreme angles of tilt in a clockwise and counter clockwise direction as shown in Figure 6.

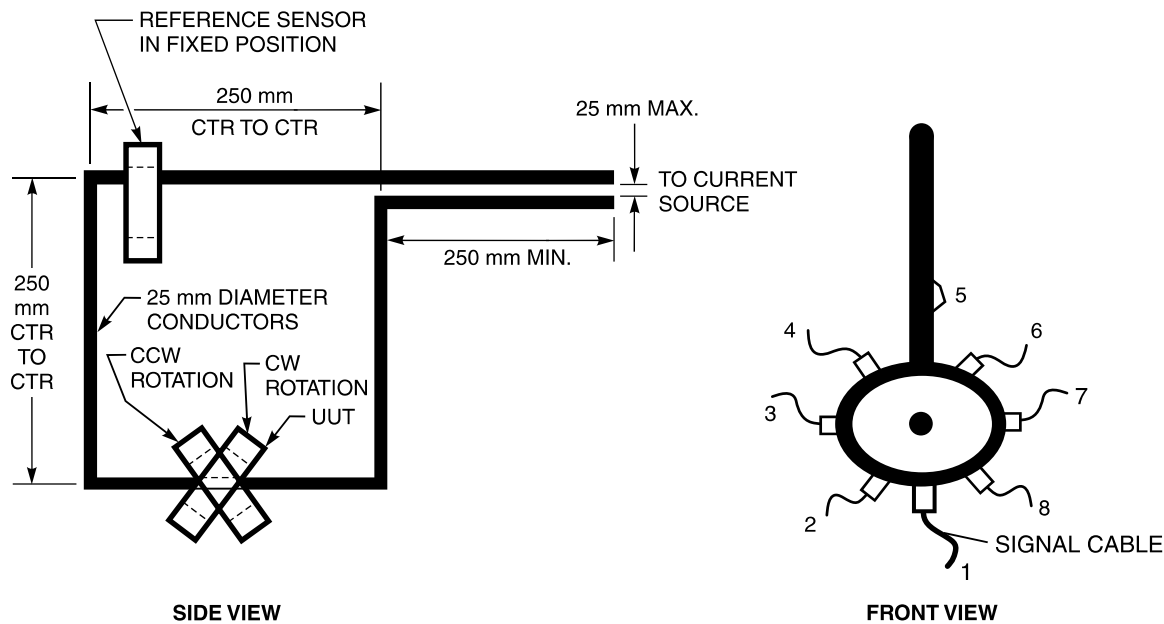


Figure 6—CSC Plane Tilt Test

(3) The CSC or WCM output readings are taken at both of the extreme angles of tilt. The UUT and the Reference Sensor readings must be taken concurrently. The values of the two readings shall be recorded.

(4) The CSC shall then be rotated about its axis in 8 equal angles (i.e., 45°) and the tilt test repeated.

(5) Calculate the ratio of the UUT reading divided by the Reference Sensor reading for each of the 8 rotational positions for each of the “tilted” directions.

(6) The maximum difference of the two sets of 8 measurements (a total of 16 measurements), expressed as a percent change, shall be the value used for the tilt test. This is calculated as $100 * [(Maximum\ ratio) - (Minimum\ ratio)] / (Grand\ Mean\ ratio)$.

(7) For an openable CSC, one of the rotational test positions shall place the CSC split at position 5 as shown in Figure 6. When a rigid hinged CSC is tested, both of the splits shall be tested at position 5 during the above test. For an openable CSC, one of the rotational test positions shall place the CSC split at position 5 as shown in Figure 6. When a rigid hinged CSC is tested, both of the splits shall be tested at the most upward position with the split in the “throat” of the test loop during the above test.

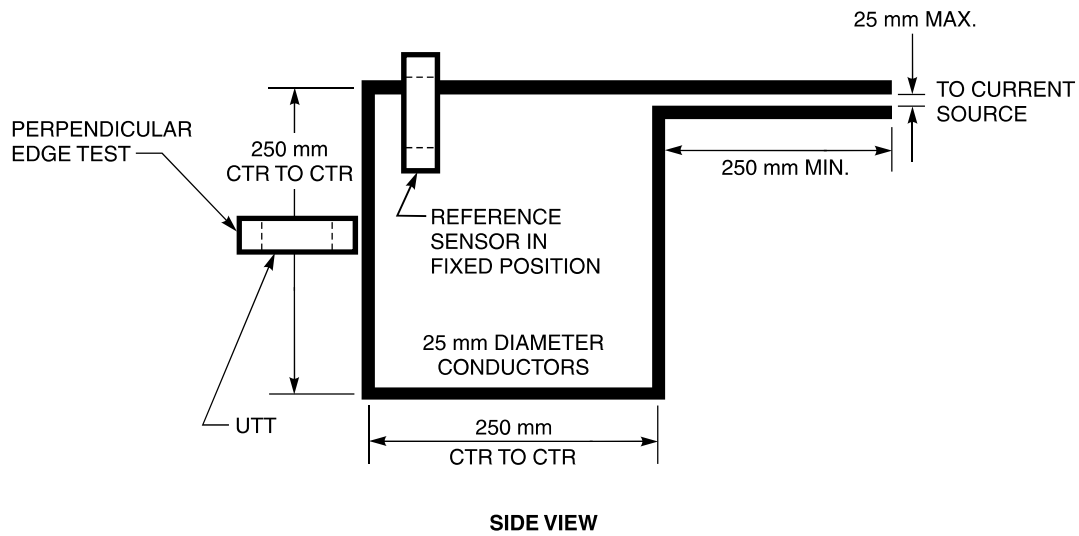
3.4 Test for Sensitivity to External Magnetic Fields. This test is meant to provide a rigorous evaluation of the

uncertainties due the sensitivity of the CSC to external magnetic fields, which should be theoretically equal to zero for a Rogowski-type CSC. This test should be considered essential if CSCs are meant to be used as Laboratory Standards. This test should also be considered essential for obtaining a rigorous estimate of the total measurement uncertainty.

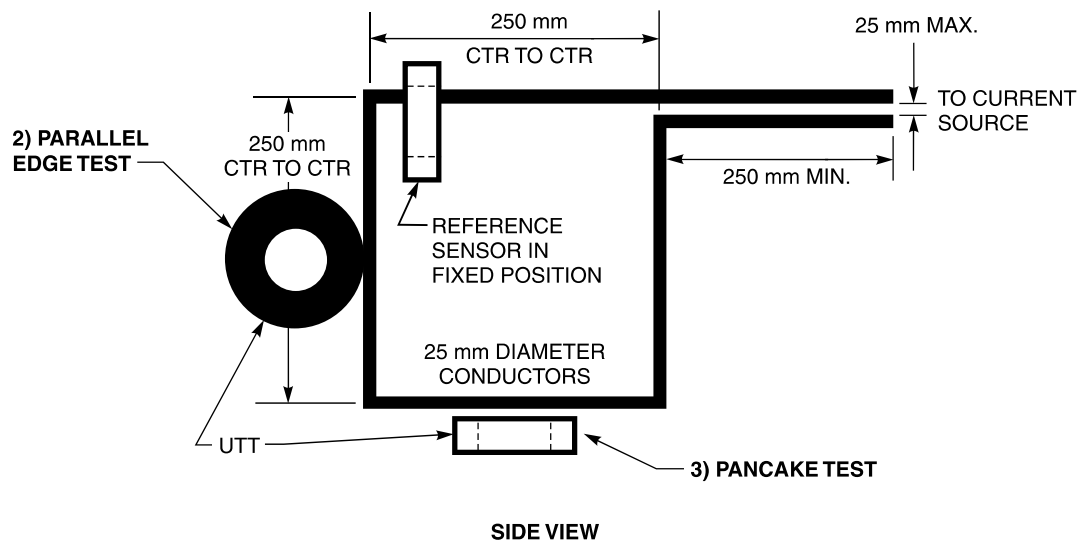
3.4.1 Equipment. The equipment for this test is the same as for the position sensitivity test as described in 3.2.1. Rarely will a WCM have sufficient resolution or sensitivity to perform this test. A sensitive voltmeter or digitizer will be required.

3.4.2 Setup. The CSC is placed next to or against the current carrying rectangular loop as shown in Figures 7 and 8. The rectangular loop does not pass through the CSC. The CSC is positioned so that it can be rotated through 360°. A common WCM may not have sufficient sensitivity to measure CSC output. Therefore, a voltage output in a steady-state test shall be used. The result is the CSC’s sensitivity to an external field under these test conditions. It is often expressed as a percentage.

(1) **Edge Test—Perpendicular:** The CSC is placed so that the plane of the CSC is perpendicular to the rectangular loop (see Figure 7);



**Figure 7—CSC Testing for Sensitivity to External
Magnetic Fields (Perpendicular Edge Test)**



**Figure 8—CSC Testing for Sensitivity to External Magnetic Fields
(Parallel Edge Test and Pancake Test)**

(2) Edge Test—Parallel: The CSC is placed so that the plane of the CSC is parallel to the rectangular loop (see Figure 8); and

(3) Pancake Test—The CSC is laid flat on the rectangular loop (see Figure 8).

These tests may be performed using sinusoidal waveform currents or those produced by a typical resistance weld machine control. If a resistance-welding machine is used, the conduction angle shall be at least 120°. If the current in the test loop is not continuous, (i.e., not steady state), then the voltage measuring apparatus shall be triggered to acquire its measurements while the current is flowing. The output of the UUT and the Reference Sensor shall be measured concurrently.

3.4.3 Procedure

(1) Place a reference CSC in a fixed position at any location of the test loop (preferably around the top conductor). The reference CSC is rigidly fixed in its position throughout the External Magnetic Field Sensitivity test. A test current shall be passed through the bus. The magnitude of the current shall be such that the output signals may be measured without undue influences of noise and readout resolution.

(2) The UUT shall be placed at the appropriate position against the conductor. It then shall be rotated through eight equal rotational positions (i.e., every 45° in rotation) about its own axis. The plane of the UUT shall be kept constant with respect to the conductor during the entire test.

(3) At each rotational position of the UUT, the output voltages of the UUT and Reference Sensor shall be recorded. Alternatively, integrated values of the output voltages of the UUT and the Reference Sensor at each position (as read by a WCM) may be recorded. However, when using a WCM as a current readout device, difficulty may result if insufficient UUT output is produced. The WCM may not register any output. In this instance, a suitable voltmeter must be used rather than the WCM.

(4) UUT test positions shall include placing any CSC split or cable exit point directly against the conductor. This may make it necessary to test at more than the prescribed eight rotational positions. At each rotational position, the ratio of the outputs of the UUT and the Reference Sensor shall be determined and recorded.

(5) The Sensitivity to External Magnetic Field of the UUT is determined by the following expression:

$$\text{External field sensitivity} = 100 * (\text{Maximum ratio}) * (M_r/M_{\text{uut}}),$$

where M_r is the mutual inductance of the Reference Sensor and M_{uut} is the mutual inductance of the UUT CSC.

(6) If the Reference sensor is an alternate sensor such as a shunt, the external field sensitivity may also be determined by the following expression:

$$\text{External Field Sensitivity} = 100 * (\text{Maximum ratio of } I_{\text{UUT}}/I_{\text{Ref.}}),$$

where I_{UUT} is the indicated current from the CSC under test when exposed to an external field and $I_{\text{Ref.}}$ is the test current flowing through the high current circuit.

(7) Repeat the above test procedure to arrive at the External Magnetic Field Sensitivity value of the UUT at the other positions as shown in Figure 7 or 8.

(8) Repeat steps (1) to (6) above for the three positions shown in Figures 7 and 8, namely perpendicular edge, parallel edge and pancake test positions. The External Magnetic Field Sensitivity of the UUT is the highest of the values at the three test positions.

3.5 Test for Measuring the Temperature Coefficient of the CSC. The purpose of the test is to determine the temperature coefficient of the mutual inductance of a CSC. The temperature coefficient of a CSC may be a significant contributor to the overall uncertainty in the mutual inductance of the CSC. The temperature coefficients of the CSCs may result in output voltage variances on the order of 0.01% per °C to 0.2% per °C. Consequently, there can be large errors resulting from the change in temperature of the CSC. Carrying out this test will help evaluate the measurement uncertainty because of temperature effects.

The temperature coefficients of a CSC may be significantly different at high temperatures than at very low temperatures. The properties of materials used in CSC construction and the fundamental physics of the CSC at very low temperatures can be very different from those at ambient or elevated temperatures. Temperature coefficients are seldom evaluated for low temperatures. However, if the CSC performance specifies use over a temperature range that includes low temperatures, it shall be evaluated to determine the temperature coefficients over the specified temperature range.

The test procedure given below evaluates only the CSC (and an unspecified portion of its output cable) being subjected to the change in temperature. The procedure does not include any temperature effects that the cable connector or those of the readout instrumentation may exhibit. (The cable connector often contains CSC sensitivity trimming resistors that may contribute to apparent temperature coefficient of the CSC.) If the intended specification or use subjects the connector and/or readout

instrumentation (i.e., a WCM combination) to the altered temperature, then the procedure may have to be modified to also include those items in the test temperature environment.

3.5.1 Equipment

(1) Sinusoidal current source. *Either the current source or the current sensor listed next shall be calibrated in the frequency and current ranges used in the test.*

(2) Current sensor for measuring current. *(Not required if the current source is calibrated.)*

(3) Temperature chamber. Provides an elevated temperature for testing greater than room ambient temperatures. Must include a refrigeration capability for testing at temperatures less than room ambient temperatures.

(4) Frequency counter.

(5) AC voltmeter capable of measuring output of CSC.

(6) Load resistor, value recommended by the WCM manufacturer, typically 1000 ohm 1% tolerance low inductance resistor. (Recommend the use of a metal film resistor; avoid using a wire wound resistor.)

(7) Temperature sensor for sensing CSC temperature to a resolution of at least 1°C.

3.5.2 Setup. Figure 9 shows a schematic of a typical test setup. The elevated or reduced temperature tests are done at the maximum and minimum temperatures that are specified for the CSC. If this temperature is not specified or known, several tests are recommended to find linearity or nonlinearity of the temperature coefficient and repeatability of the test results. The testing temperature range is to be reported.

The CSC should be mounted around the current carrying conductor in the temperature chamber and fixed so that it can not move during the test. Ensure that the CSC cable exiting the temperature chamber cannot inadvertently change the CSC position. Make sure that the output connector of the coil is accessible from outside the chamber.

3.5.3 Procedure

(1) Turn on the measurement equipment and allow sufficient warm up time for all instruments to provide required stability.

(2) At room temperature, apply the test current. Record the current from the current sensor, the frequency from frequency counter, voltage from AC voltmeter, and temperature of the CSC from sensor. The test current shall be high enough to generate CSC outputs sufficient to overcome noise effects.

(3) Turn the current off temporarily to avoid undue heating of the current carrying conductor.

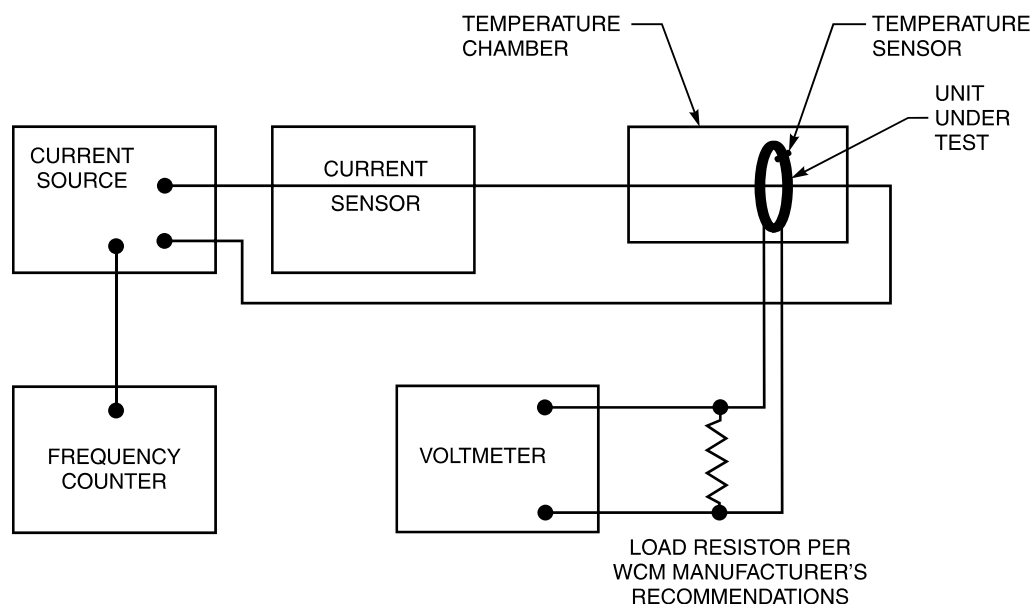


Figure 9—Equipment For Determining the Temperature Coefficient of Current Sensing Coils

(4) Change the temperature in the chamber to the maximum temperature for which CSC performance is specified. If not specified, elevate the temperature between 25°C to 30°C above the initial room temperature and allow thermal equilibrium to be achieved. This could require several hours. Alternately, decrease the temperature to the minimum temperature for which the CSC performance is specified. If not specified, reduce the temperature between 25°C to 30°C below the initial room temperature and allow thermal equilibrium to be achieved.

(5) At this altered test temperature, apply the test current. Record the current from the current sensor B, the frequency from frequency counter D, voltage from AC voltmeter E and temperature of the CSC from temperature sensor G.

(6) Record and calculate the mutual inductance of the CSC using the following formula at room temperature and at the altered test temperature.

$$M = V / (2 \pi f I),$$

where

- M = mutual inductance in henries;
- V = coil output voltage in volts, rms;
- π = 3.1416...;
- f = 55 Hz (*see Note below*); and
- I = current passing through the conductor in amperes, rms.

NOTE: A frequency of 55 Hz is recommended when a variable frequency source is being used. It is recognized that this is not always possible when the current is being derived from the power line. A source other than one that depends on the power line generally will provide better current stability. A frequency other than line often will reduce the bothersome and error causing effects of beat-frequency interference.

(7) Calculate the temperature coefficient of the CSC as:

$$S = \text{Temperature coefficient } (\%/^{\circ}\text{C}) = \left[\frac{\left(\frac{M_{TT}}{M_{RT}} \right) - 1}{T_{TT} - T_{RT}} \right] \times 100$$

where

- M_{TT} = CSC mutual inductance at the altered test temperature,
- M_{RT} = CSC mutual inductance at the room temperature,
- T_{TT} = CSC altered test temperature, and
- T_{RT} = CSC room temperature.

3.6 Frequency Response Testing of a CSC. The purpose of this test is to provide a method that may be used to determine the frequency response of a CSC. This test is useful for determining if the CSC has adequate performance to be used in single-phase ac resistance welding current measuring and control applications. Typical weld current waveforms contain a spectrum of frequencies. The CSC must have a sufficiently wide bandwidth to preserve the waveform “fidelity” within established limits in order to achieve a desired measured uncertainty. The effect of bandwidth on measurement uncertainty is discussed below. Additional information may be found in Annex E.

The CSC equivalent lumped parameter circuit, for the purposes of these tests, is considered to consist of a simple R-L (i.e., resistance and coil self-inductance). The resistive elements include the CSC resistance and CSC trimming resistors, if present. The load resistance is considered as a pure resistance. In this lumped parameter model, the load resistor forms a voltage divider with the CSC impedance. The CSC impedance is considered as the CSC self-reactance, the CSC resistance, and any trim resistances that may be in use.

The effective mutual inductance of CSCs is commonly adjusted (often referred to as “trimming”) by the use of one of two methods:

- (1) *Series* trimming
- (2) *Shunt* (or *parallel*) trimming

Figure 10 illustrates the two trimming methods. For the simple series trimmed configuration, shown in Figure 10(A), a resistance is selected such that the load resistance of the subsequent electronic equipment or instrumentation forms a voltage divider between the sum of the CSC impedance and the series trimming resistance, and the load resistance. When the shunt (or parallel) trimming arrangement is used, as shown in Figure 10(B), a voltage divider is formed between the CSC impedance and the trimming resistance in parallel with the load resistance.

Two test methods have been provided below. The first is simpler and may be used to determine the frequency response for *only* an untrimmed CSC, or a *series* trimmed CSC. It uses a simple “voltage insertion” method that does not require the generation of high frequency, high currents. A second method is provided that will work with either the *series* or *parallel* trimmed CSC. It does require the use of high frequency, high currents as well as a reference CSC with known frequency response characteristics. Generally, the bandwidth of the reference CSC must be greater than the CSC being tested.

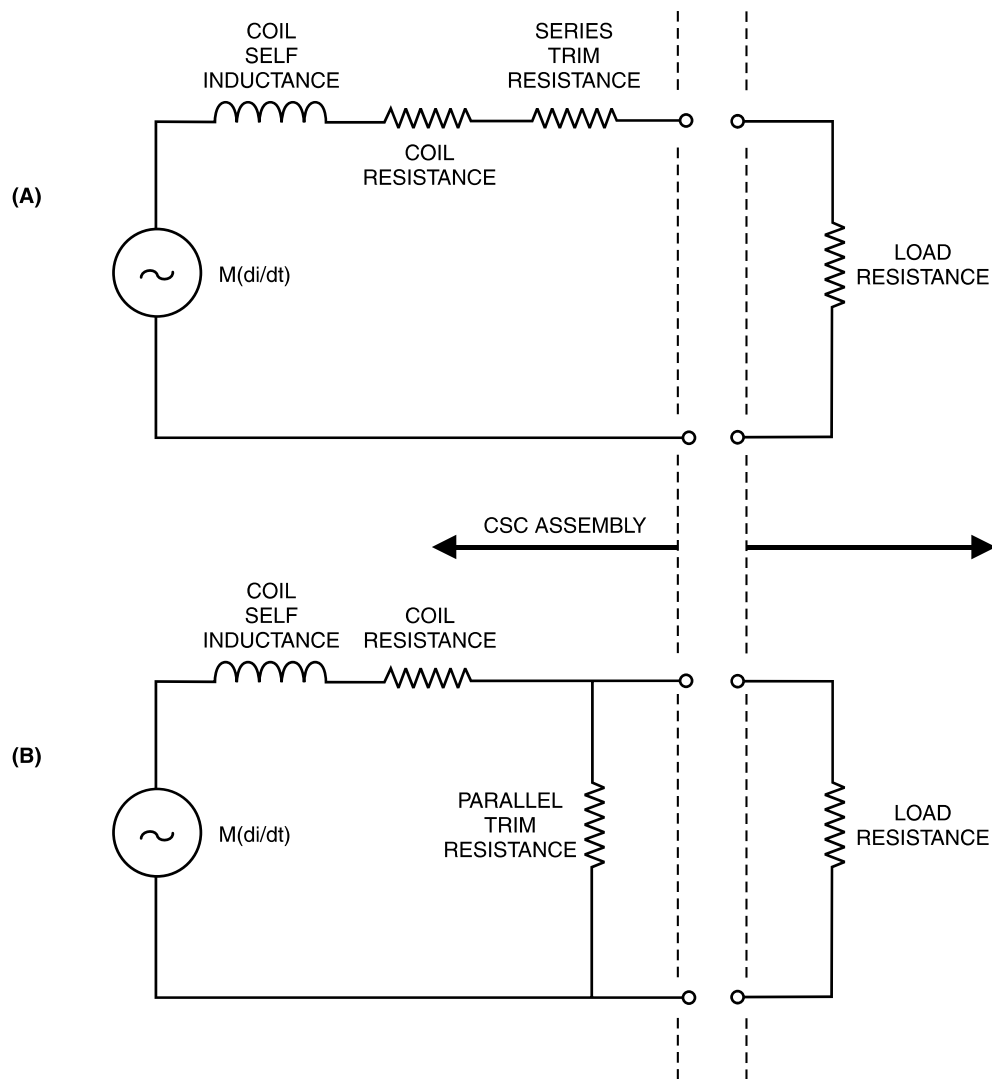


Figure 10—CSC Testing for Frequency Response
(A) Series Trimmed CSC, (B) Parallel Trimmed CSC

3.6.1 Voltage Insertion Method

3.6.1.1 Equipment

(1) Variable Frequency Voltage Generator: sinusoidal waveform, 45 Hz to 5 kHz or greater, 0 Vac–5 Vac or suitable voltage ranges consistent with the voltmeters and the phase meter being used.

(2) AC Voltmeters, V1 and V2: 0 Vac–5 Vac or consistent with the voltage generator being used, uncertainty of $\pm 0.1\%$ or better.

(3) (Optional) Phase Meter: uncertainty of $\pm 0.1^\circ$ or better, frequency range consistent with the other test equipment.

(4) Load Resistor: low-inductance resistor, nominally $1 \text{ k}\Omega \pm 1\%$, unless otherwise specified. A value other than $1 \text{ k}\Omega$ may be used, depending on the application. The value of this resistor is critical to the measurement and must be known and specified. For example, when the CSC is intended to be used with a specific monitor or controller that has an input impedance of $2 \text{ k}\Omega$, then this

value should be used during this test. The resistance value must be reported with the test results.

3.6.1.2 Setup. The block diagram in Figure 11 shows the arrangement of test equipment. The *Variable Frequency Voltage Generator* is connected in series with the CSC and the *Load Resistance*. The generator should be connected to the “low” side of the CSC. The “low” side may be connected to a cable shield and possibly to an internal shield within the CSC. It may be difficult to determine the “low” side. For unshielded cables and coils, it is generally unimportant which CSC lead is chosen to connect to the generator. This generator is substituted in place of the CSC’s equivalent voltage source provided by normal coil action when it is excited to a current flowing through the CSC window. This test setup does not require the use of high currents.

In some instances, making connections to the CSC will require improvising because of the electrical connector that might be part of the cable assembly. If an electrical connector is present, it should *not* be disassembled for this test. The connector often contains CSC trimming resistor(s) that could be disturbed, causing a change in the calibration of the CSC.

The use of the *Phase Meter* is optional. Its use provides a check on the measurement process and verifies that the CSC is behaving as properly modeled.

3.6.1.3 Procedure. This subclause provides a suggested procedure by which the frequency response of a CSC may be determined. A sample of the data needed to determine the CSC bandwidth is shown in Table 2. The final results may be reported in the form of a table giving frequency, response ratio, and phase angle. Or alternatively, the data may be reported in the form of two graphs, namely, response ratio vs. frequency, and phase angle vs. frequency.

(1) Set the frequency of the Voltage Generator to a value at or below the lowest frequency that will be measured. This will usually be 50 Hz or 60 Hz.

(2) Set the voltage output of the Voltage Generator to a value between about 2 V and 5 V. It should be set such that it is about 10% less than the full-scale range of the Voltmeter, V1, range being used.

(3) Set the appropriate range settings on the Phase Meter for proper operation. *Precaution:* Some phase meters will show an apparent change of phase reading as a function of the voltage levels being used. This is due, in part, to such factors as noise, dc-offsets, and waveform distortion. A simple test to determine if the phase meter is sensitive to voltage levels is to temporarily decrease the voltage of the Voltage Generator to about one-half its value. The indicated phase angle should not change significantly. If a change is observed, then increase the volt-

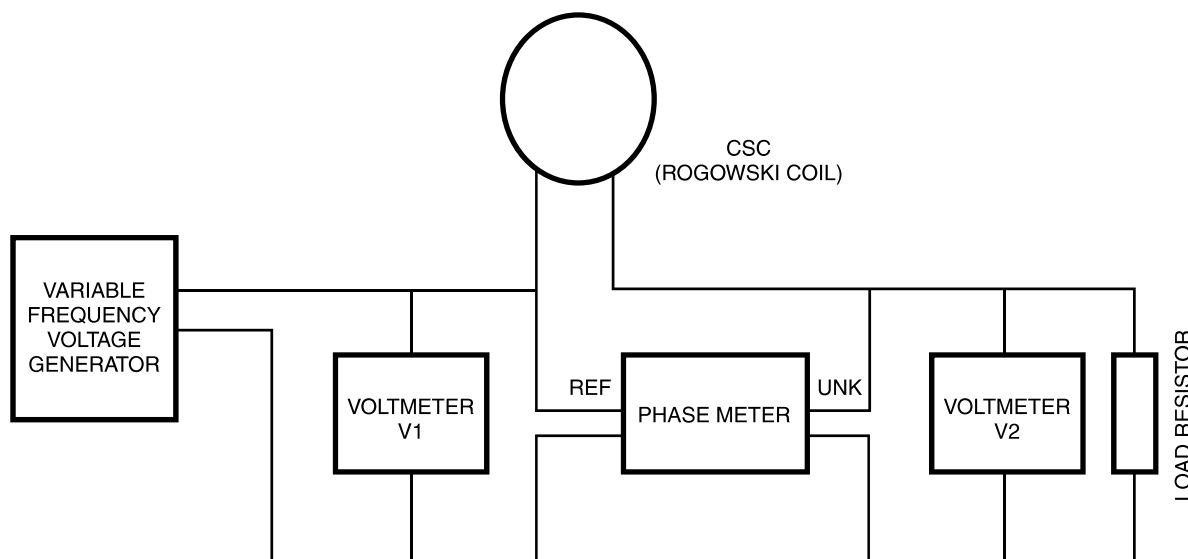


Figure 11—Equipment for the CSC Frequency Response Test Setup for an Untrimmed CSC, or a Series Trimmed CSC

Table 2
Sample of the Data Needed to Determine the CSC Bandwidth (Voltage Insertion Method)

Frequency Hz	Voltmeter V1 Volts	Voltmeter V2 Volts	Ratio V2/V1	Normalized Response	Phase Meter Degrees
50	1.903	1.898	0.997	1.000	-0.4
100	1.902	1.892	0.995	0.998	-0.8
250	1.904	1.894	0.995	0.998	-2.1
500	1.910	1.894	0.992	0.995	-4.1
1000	1.905	1.875	0.985	0.988	-8.2
2500	1.903	1.782	0.936	0.939	-19.9
5000	1.902	1.535	0.807	0.809	-35.9
6950	1.902	1.341	0.705	0.707	-45.0
10 000	1.901	1.076	0.566	0.568	-55.5

age levels at which the test is being done, and repeat this process until no significant change is observed.

(4) Record the value of frequency, voltage V1, V2, and the Phase Meter reading. At this frequency, the two-voltmeter readings should be nearly equal, and the measured phase angle should be small, usually less than a few degrees.

(5) Increase the frequency setting of the Voltage Generator. A typical set of frequencies is provided in an example of typical data provided in Table 2.

(6) Repeat steps 4 and 5 above until data at all of the frequencies have been collected and recorded.

(7) Calculate the ratio of V2/V1 for each of the frequencies; record the result of the calculation. Divide each of these ratios by the value of the ratio obtained for 50 Hz or 60 Hz. Record these values as the "Normalized Response" as shown in Table 2.

(8) The bandwidth of the CSC is defined as the frequency at which the Normalized Response, as calculated above, equals 0.707. Alternatively, the frequency of the Voltage Generator may be varied until the Phase Meter indicates a phase angle of -45.0° . This is shown in Table 2 in bold-faced type.

NOTE: The above test may be performed without the use of the phase meter. However, its use verifies the ratio data and also verifies that the circuit is behaving as a single pole network. As an alternative procedure, after setting the first voltage level, the frequency may simply be increased until the phase meter indicates an angle of -45° . This will be the -3 dB bandwidth value. It is good practice to verify this value with comparison to the normalized voltage ratio value of 0.707.

3.6.2 High Frequency, High Current Method

3.6.2.1 Equipment

(1) Variable Frequency Current Source: sinusoidal waveform, 45 Hz to 5 kHz or greater, with a suitable current output consistent with the CSC and voltmeters and the phase meter being used.

(2) A CSC used as a reference that has a known frequency response. Generally, the bandwidth of the reference CSC must be greater than the CSC being tested.

(3) Voltmeters for measuring V1 and V2; 0 Vac–5 Vac or consistent with the current and coil's mutual inductance being used, uncertainty of $\pm 0.1\%$ or better. At the lower frequencies, the CSC voltages will typically be in the range of a few millivolts.

(4) (Optional) Phase Meter: uncertainty of $\pm 0.1^\circ$ or better, frequency range consistent with the other test equipment.

(5) Load Resistor: low-inductance resistor, nominally $1\text{ k}\Omega \pm 1\%$, unless otherwise specified.

3.6.2.2 Setup. The block diagram in Figure 12 shows the arrangement of test equipment. The *Variable Frequency Current Source* is connected in series with the *Reference CSC* and the *CSC Under Test*. It is important to terminate each CSC with a *Load Resistance* for which the respective CSC is to be used. In some instances, making connections to the CSC will require improvising because of the electrical connector that might be part of the cable assembly. If an electrical connector is present, it should *not* be disassembled for this test. The connector often contains CSC trimming resistor(s) that could be disturbed, causing a change in the calibration of the CSC.

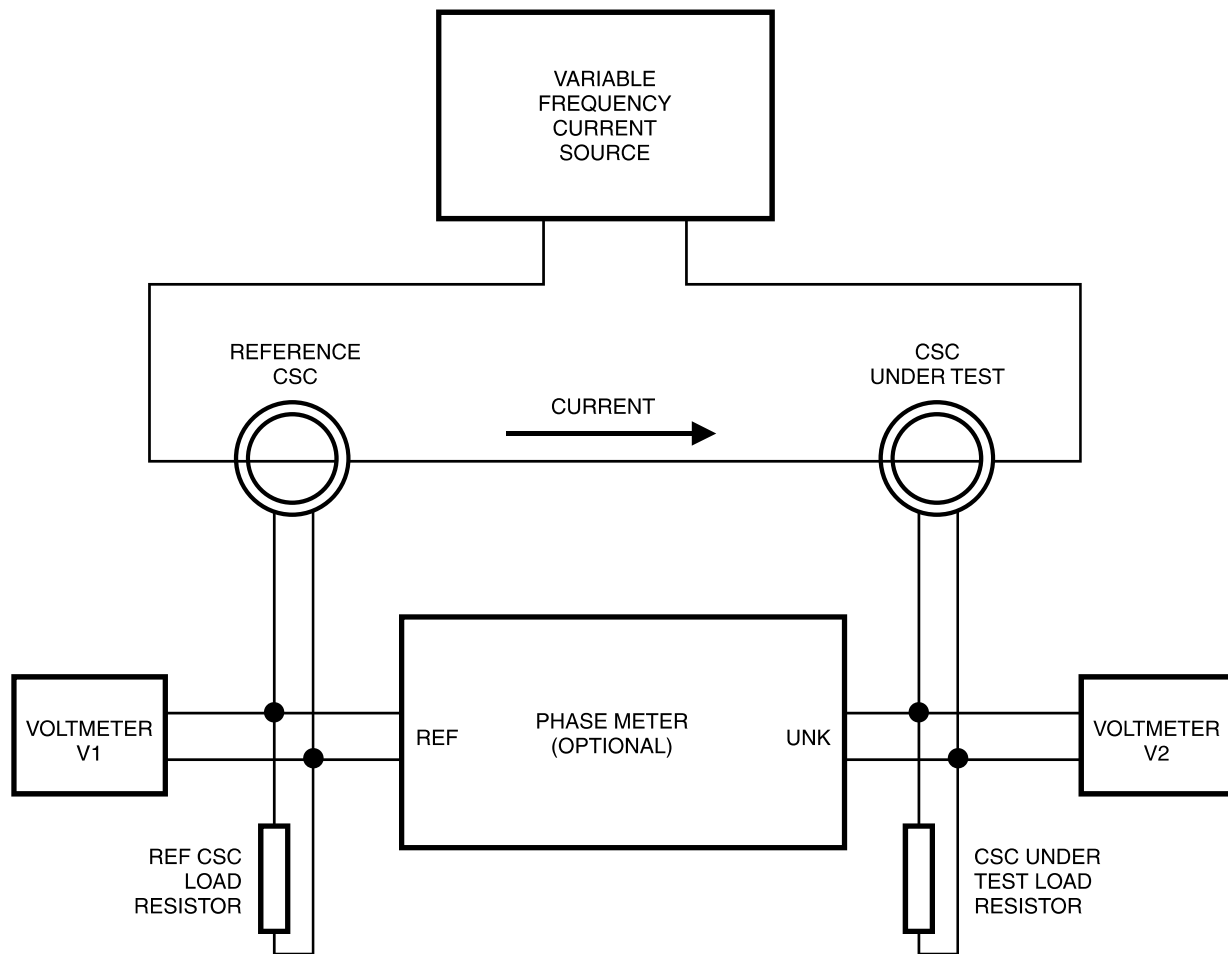


Figure 12—Equipment for the High Frequency, High Current Frequency Response Test

3.6.2.3 Procedure. This subclause provides a suggested procedure by which the frequency response of a CSC may be determined. A sample of the data needed to determine the CSC bandwidth is shown in Table 3. The final results may be reported in the form of a table giving frequency, response ratio, and phase angle. Or alternatively, the data may be reported in the form of two graphs, namely, response ratio vs. frequency, and phase angle vs. frequency.

(1) Set the frequency of the *Current Source* to a value at or below the lowest frequency that will be measured. This will usually be 50 Hz or 60 Hz.

(2) Select the voltmeter ranges to obtain suitable readings. During the testing at a constant current, the voltmeter readings will increase as the test frequency is

increased. This will require that the voltmeter ranges be changed accordingly to obtain suitable readings.

(3) (Optional) Set the appropriate range settings on the Phase Meter for proper operation. If the Phase Meter indicates an angle near 180° , it will be necessary to reverse the leads of either the Reference CSC, or the CSC Under Test to obtain a phase angle near zero degrees. *Precaution:* Some phase meters will show an apparent change of phase reading as a function of the voltage levels being used. This is due, in part, to such factors as noise, dc-offsets, and waveform distortion. A simple test to determine if the phase meter is sensitive to voltage levels is to temporarily decrease the voltage of the Voltage Generator to about one-half its value. The indicated phase angle should not change significantly. If a change is observed, then increase the voltage levels at

Table 3
Sample of the Data Needed to Determine the CSC Bandwidth
(High Frequency, High Current Method)

Frequency Hz	Voltmeter V1	Voltmeter V2	Ratio V2/V1	Normalized Response	Phase Meter Degrees
50	15.67 mV	16.13 mV	1.029	1.000	-0.4
100	31.35 mV	32.10 mV	1.024	0.995	-0.8
250	78.39 mV	80.24 mV	1.024	0.995	-2.1
500	156.7 mV	160.0 mV	1.021	0.992	-4.1
1000	313.4 mV	317.8 mV	1.014	0.985	-8.2
2500	783.5 mV	754.9 mV	0.963	0.935	-19.9
5000	1.567 V	1.302 V	0.832	0.809	-35.9
6950	2.172 V	1.581 V	0.727	0.707	-45.0
10 000	3.134 V	3.134 V	0.584	0.567	-55.5

which the test is being done, and repeat this process until no significant change is observed.

(4) Record the value of frequency, voltage V1, V2, and the Phase Meter reading. The measured phase angle should be small, usually less than a few degrees at the lower frequencies.

(5) Increase the frequency setting of the Current Source. A typical set of frequencies is provided in an example of typical data provided in Table 3.

(6) Repeat steps (4) and (5) above until data at all of the frequencies have been collected and recorded. Note that the CSC voltages will increase as the test frequency increases.

(7) Calculate the ratio of V2/V1 for each of the frequencies; record the result of the calculation as the Ratio V2/V1. Divide each of these ratios by the value of the ratio obtained for 50 Hz or 60 Hz. Record these values as the “Normalized Response” as shown in Table 3.

(8) The bandwidth of the CSC is defined as the frequency at which the Normalized Response, as calculated above, equals 0.707. Alternatively, the frequency of the Current Source may be varied until the Phase Meter indicates a phase angle of -45.0° . Note the frequency at which the phase angle equals -45° . This is shown in Table 3 in bold-faced type at a frequency of 6950 Hz.

3.6.3 A Guide to General CSC Bandwidth Requirements. Table 4 provides a general guide to the CSC bandwidth requirements for a range of measurement uncertainties. This range of uncertainties applies to CSCs used for reference standards through those used for “routine” measurements. These uncertainties pertain only to the CSC and do not include any subsequent errors due to signal processing or display electronics. The val-

Table 4
A Guide for CSC Bandwidth Requirements
as a Function of the Desired Uncertainty

Uncertainty Due to CSC %	Minimum Required -3 dB Bandwidth kHz
±0.1	5.2
±0.2	3.6
±0.5	2.2
±1	1.5
±2	1.0
±5	0.6

ues apply only to typical current waveforms produced by single-phase ac resistance weld equipment. Further, this guide is restricted to the measurement of rms currents.

The *Minimum Required -3 dB Bandwidth* limits shown in Table 4 are a “worst case” instance where the maximum anticipated harmonic current is present for conduction angles equivalent to *20% of current* as set by the weld controller. CSCs having the minimum bandwidth or greater will be suitable for the indicated *Measurement Uncertainty*. The errors due to band-limited conditions will *always* result in a negatively biased measurement uncertainty where the measured current always will be less than the actual current.

These criteria do not apply for measurements of peak or average current, or to waveforms such as those that are generated by inverter type weld equipment.

4. Calibration of WCM-CSC Combination

This clause describes the calibration of a WCM combined with a CSC as a current measuring system. The calibration of the WCM-CSC combination is the most accurate method of calibration, as contrasted to a CSC and a WCM being calibrated separately. Calibration of the combination is sometimes referred to as a *system calibration*. This method compares the current measured by the combination of the CSC and the WCM to the actual weld current measured by a Measurement Standard.

4.1 Equipment

(1) Current Source producing waveforms similar to those in a single-phase ac resistance welding machine (see Figure 13).

(2) Reference Standard traceable to NIST or other National Laboratory. The reference current sensor may be a CSC and WCM, or a CSC with a digitizer as shown in Figure 14(A) or a separate reference current sensor, as a shunt, with a digitizer or other suitable readout, shown in Figure 14(B). The performance of the Reference Standard(s) shall be verified over the range of currents and conduction angles for which it will be used.

(3) Coaxial Cage as in Figures 1 and 2.

Figure 13 shows the test reference waveform to be used for rms current calibration. The weld time shall be 13 cycles at each current level at which calibration is being done. The fourth through the twelfth cycles shall be used for measurement and calibration purposes. Data from the first three cycles and the last cycle shall not be included in the calculations. In cases where the WCM is not capable of blanking the first three and the last cycle, a simple

9-cycle current burst may be used. It is important that the same portion of the test current waveform be used for both the Reference Standard and for the WCM-CSC Combination being calibrated. The waveform shows a large conduction angle, but the actual conduction angle in the calibration test will depend on the current value at which the calibration is being done.

NOTE: The Reference Standard shall use a signal analysis method equivalent to the signal analysis method performed by the WCM being calibrated. For example, if the WCM provides only one current value for the weld current heating stage with first cycle blanking and this value is determined by the rms value method, then to be meaningful, the Reference Standard needs to perform the calculation of current using the same method.

4.2 Setup. Figure 14 shows two typical equipment setups that are suitable for the calibration. Figure 14(A) uses a Reference Standard that contains a reference CSC and a readout for the Reference Standard. The readout may be a suitable digitizer that can be gated to capture the current burst or the readout may be a WCM having sufficient resolution and accuracy to serve as a standard. It may be necessary to use a predetermined load resistor, as shown, in order for the calibration of the Reference Standard to be valid.

Figure 14(B) shows a second setup wherein a reference current sensor other than a CSC is used to obtain a measurement of the test current. It shall have a traceable calibration over the range of current and current conduction angle for this test to be acceptable for this specification.

Each CSC is placed in a coaxial cage (such as in Figure 2) during this test in order to minimize the return conductor effects. Mount the UUT CSC in the coaxial cage such that the plane of the CSC is normal to the axis of the

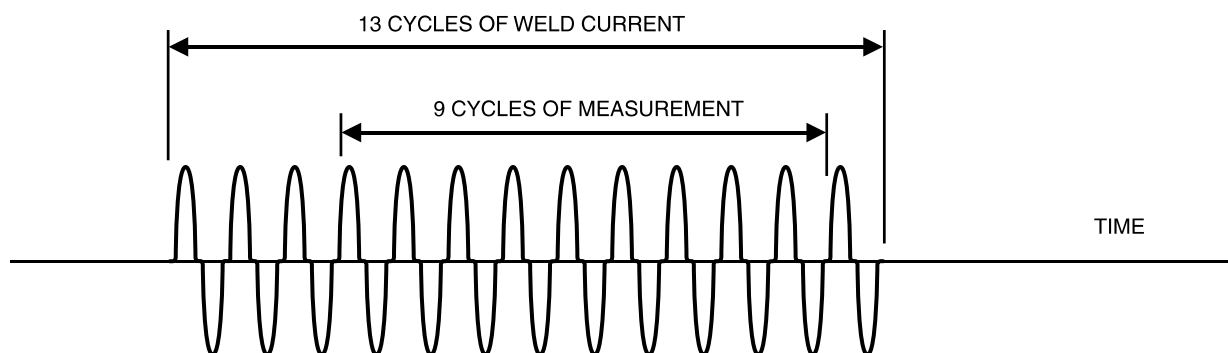


Figure 13—Test Reference Waveform to be used for rms Current Calibration

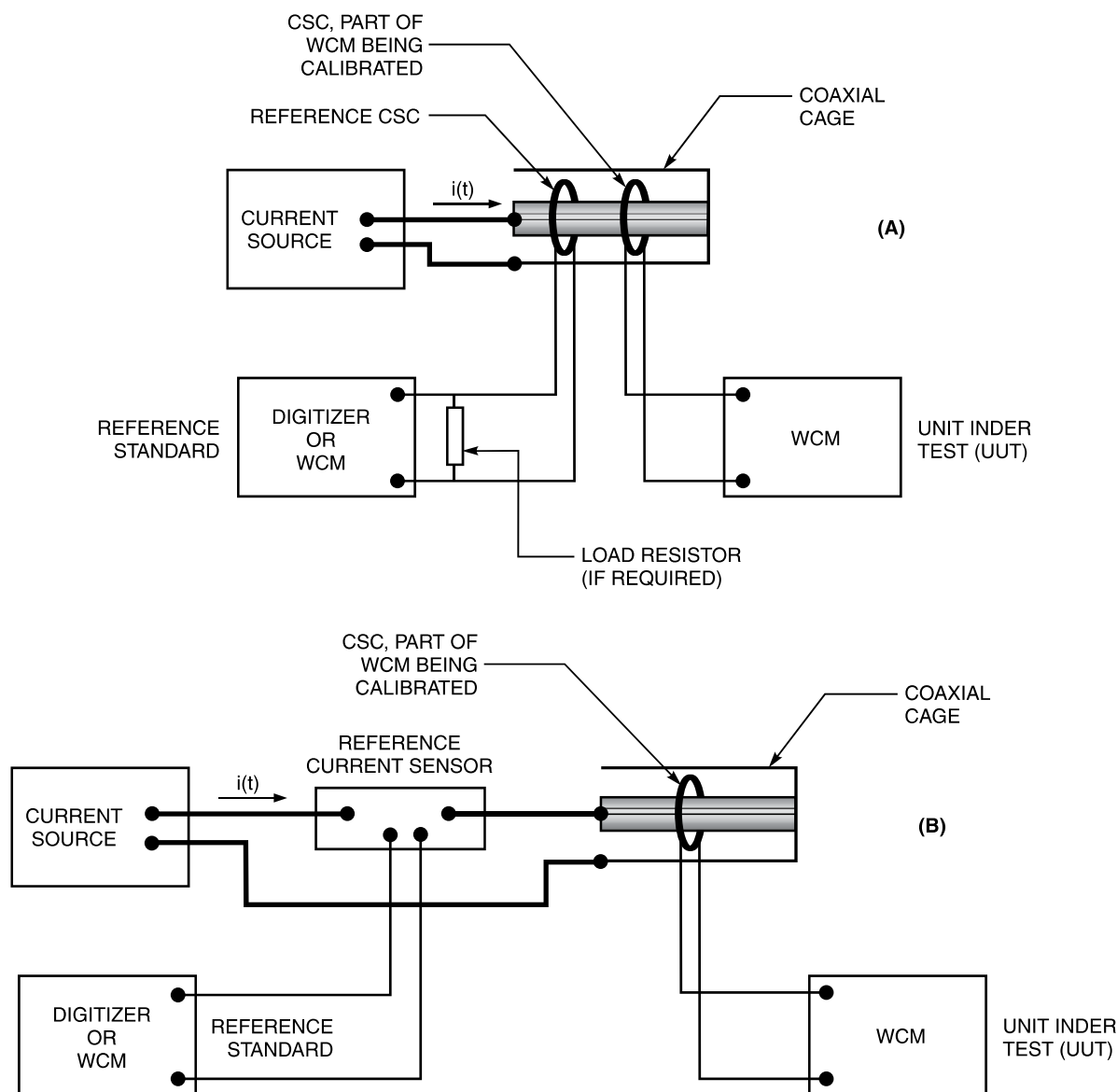


Figure 14—Equipment for the WCM-CSC Combination Calibration

conductor around which it is mounted. Center it radially. If the CSC has a tear-drop or elliptical shape, it shall be centered on the intersection of its two axes (see Figure 3). Make sure the output connector of the coil is accessible from outside the coaxial cage.

Allow sufficient warm up time for all instruments and the CSC and WCM to provide required stability. CSCs and WCMs transported from one location to another must be given sufficient time to stabilize to the test temperature.

4.3 Calibration Procedure

NOTE 1: A single point calibration on one measurement range is not adequate to evaluate the uncertainty of a WCM-CSC combination and is not acceptable for compliance to this specification. The calibration is valid only over the range of currents and conduction angles for which the performance of the Reference Standard has been verified.

NOTE 2: The temperature sensitivity of the CSC may adversely affect the results of the calibration. It has been

observed that certain CSCs have relatively large temperature coefficients as large as nearly 0.2% per °C. In such instances, a few degrees temperature change may alter the calibration results significantly. These effects must be taken into account when assigning a value of uncertainty to the calibration. A method for determining the CSC temperature coefficient is provided in 3.5.

(1) Pass a test current through the coaxial cage from the current source. The testing shall be performed at a minimum of 5 current values distributed in the entire measurement range. For example, consider a WCM having two measurement ranges—10 kA and 50 kA (full scale). On the 10-kA range, the nominal test currents might be 1, 3, 5, 7, and 9 kA. The test currents might be 5, 15, 25, 35, and 45 kA for the 50-kA range. These current values are provided only as a guide and are not mandated by this specification. Calibration at only a single conduction angle is not acceptable for compliance to this specification.

(2) Record the test conditions and the indicated current as obtained from the Reference Standard. The test current shall be high enough to generate CSC outputs sufficient to overcome noise effects.

(3) Record the test conditions and the current obtained from WSC-CSC Combination being calibrated.

(4) Calculate and record the error of reading of the WCM-CSC Combination. The error is determined as:

Error = (WCM-CMC Comb. Reading) – (Ref. Std. Reading), in A or kA

% Error = $\{[(\text{WCM-CMC Reading})/(\text{Ref. Std. Reading})] - 1\} * 100\%$

(5) Repeat the measurement 5 times for each test condition. The final result for this test shall be the mean of the 5 error calculations. Determine the standard deviation for each set of 5 readings and record the value of two times the standard deviation (2σ) for later use in determining the measurement uncertainty for the test. Repeat steps 1 through 5 for the remaining test conditions. Refer to Annex C for details and further information.

5. Uncertainty Statements

When a quantity is measured, only an approximation of the actual value is measured. The measurement error is the difference between the measured value and the actual value. Since the actual value is not known, the error can not be determined. However an uncertainty statement, which describes the possible range of the measurement error, can be determined. The measured value is not

meaningful without this statement of the uncertainty associated with the measurement. To determine the uncertainties of a measurement the sources of uncertainties must be estimated and presented in an understandable way. An uncertainty value is determined for each source of error in the measurement. These uncertainties are then statistically added resulting in a combined uncertainty statement, which is reported along with the measured value. The following will describe this process and how it applies to resistance welding current measurements.

5.1 Combined Uncertainty. A combined uncertainty value shall be provided for the mutual inductance of the CSC and for the measured current as indicated by the WCM. The calculation of the uncertainty shall utilize statistical summation (root sum of squares) of the individual sources of uncertainty. The sources of uncertainty must be included at the 95% level of confidence (2-sigma). The use of National Standards Laboratory (such as NIST) traceable electronic instruments alone, without the estimation and use of measurement uncertainties at each step of the traceability trail shall be considered insufficient.

5.1.1 Sources of Uncertainty for the Mutual Inductance of the CSC. To determine the uncertainty of the mutual inductance value, the following sources of error shall be evaluated and the resultant measurement uncertainty shall be stated with the stated mutual inductance value:

- (1) Temperature coefficient error over a stated temperature range,
- (2) Position sensitivity of the CSC,
- (3) Uncertainties of the voltage value V ,
- (4) Uncertainties of the current value I , and
- (5) Uncertainty of the frequency f .

5.1.2 Sources of Uncertainty for the Measured Current as Indicated by the WCM. To determine the uncertainty of the measured current, the following sources of error shall be evaluated and the resultant measurement uncertainty shall be stated:

- (1) Temperature coefficient error over a stated temperature range,
- (2) Uncertainty of the Standards used to conduct the calibrations,
- (3) Position sensitivity of the CSC,
- (4) Resolution of the displayed values,
- (5) Linearity of the measured values, and

(6) Measurement process randomness (repeatability).

The measurement process randomness is determined by carrying out five successive tests to measure values of current. The difference between the maximum and minimum values divided by the average value, expressed as a percentage, represents the randomness of the measurement process.

The most common sources of error have been included in the above list. Other sources of error may be present. If such other sources of error are found, they should be included.

6. Format for Reporting Test Results

The subclauses below summarize the information that shall be provided for this specification listed under the headings of “Required Information.” In addition, supplemental information that may be useful to users is listed.

6.1 Current Sensing Coil (CSC)

6.1.1 Required Information

- (1) Manufacturer, model, and serial number.
- (2) Effective mutual inductance at the manufacturer recommended load impedance.
- (3) Mutual inductance at no load, if test was performed.
- (4) Manufacturer recommended load impedance.
- (5) Uncertainty at a 2-sigma confidence level of the value of mutual inductance at the manufacturer recommended load impedance, expressed as a percentage.
- (6) Coil position sensitivity, expressed as a percentage.
- (7) External field sensitivity results of optional tests, if any, expressed as a percentage.
- (8) Frequency response of the CSC at the manufacturer recommended load impedance (from “Type Test”), or the –3 dB bandwidth may simply be stated.
- (9) CSC temperature coefficient (from “Type” or “Optional” Test). This may be provided in the form of graphical information or in the form of a chart.

6.1.2 Supplemental Information

- (1) General description of CSC type and shape, i.e., belt, flexible, rigid, round, rectangular, *tear-drop*, *worm*, etc.
- (2) Statement whether CSC is fixed, or openable, split, hinged, etc.
- (3) Dimensions (thickness, width, and diameter, etc.).

(4) Weight.

(5) Manufacturer recommended operating conditions and/or restrictions.

(6) Connector type with a schematic diagram for connection.

(7) dc resistance of the CSC at the output cable/connector connections (may include trimming resistances).

(8) Cable length.

(9) If CSC is intended to be used with specific equipment, provide information relative to this equipment.

6.2 Weld Current Monitor (WCM)

6.2.1 Required Information. This specification has no requirements for information that applies only to the WCM.

6.2.2 Supplemental Information

- (1) Manufacturer recommended operating conditions.
- (2) Clearly marked by manufacturer, model, and serial number.
- (3) Input impedance at the CSC input terminals with a typical tolerance that applies to this impedance.
- (4) Input and output terminal or connector connections.
- (5) Current amplitude ranges with a clear indication of the units of measure, i.e., amperes, kiloamperes, rms, peak, etc. If the WCM is autoranging, this should be so indicated with the nominal range-switching points.
- (6) Resolution on each range (Example 21.16 kA (0.01-kA resolution) vs. 21.2 kA (0.1-kA resolution)).
- (7) External power requirements. Battery requirements if portable.
- (8) Size and dimensions.
- (9) Weight
- (10) If WCM is intended to be used with specific CSC, provide information relative to the CSC or CSCs that are appropriate.

6.3 WCM-CSC Combination

6.3.1 Required Information

- (1) Measurement error for each range. Error to be reported in percent of reading, or alternatively, percent of full-scale range.
- (2) Uncertainty (2-sigma confidence level) of error provided above.

(3) Description of the WCM and CSC Combination by manufacturer, model numbers, and respective serial numbers.

6.3.2 Supplemental Information. Information provided in 6.1.2 and 6.2.2. In some instances, additional information may be provided in the form of a graph.

7. Calibration Certificate

Any Calibration Certificate shall include the following information:

(1) Date calibration was performed.

(2) Person responsible for the calibration.

(3) The full identification of the company or organization performing the calibration.

(4) Conditions of test.

(5) Measurement Standards used in the calibration and their certification expiration dates.

(6) Full and unique identification of WCMs and CSCs, such as model and serial numbers of the items being certified.

(7) (Optional item) How the test results compare to the specifications set forth by the manufacturer.

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Annex A (Normative)

Terms and Definitions

This annex is part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, and includes mandatory elements for use with this standard.

calibration certificate. A document that presents calibration results and other information relevant to a calibration.

calibration. The comparison of a Unit Under Test (UUT) with specified tolerances but of unknown accuracy to a Measurement Standard system of specified capability and of known uncertainty in order to detect, correlate, report, or minimize by adjustment or correction factor, all deviation from specified tolerance limits. External cleaning, minor adjustment, and the production/revision of correction charts/tables or software are included when necessary to meet specified tolerances.

coaxial cage. A conductor cage that develops a 1/R-type. It is used for calibration of CSC and WCM. Cages are typically circular, hexagonal or square in cross section (see Figures 1 and 2).

conduction angle. See **conduction time**.

conduction time. Portion of a half-cycle during which current is flowing. This is typically expressed in degrees, where a half-cycle equals 180°. Also commonly called conduction angle (see Figure A.1).

CSC temperature coefficient. The change in CSC mutual inductance as a result of a change of CSC temperature. The *temperature coefficient* for the CSC is expressed in terms of *percent change of the mutual inductance per °C*.

current off-time. The portion of a half-cycle during which current is not flowing. This time can be defined as the interval between the turn off time of one half-cycle and the start of current flow in the next half cycle (see Figure A.1).

current readout device. The collection of electronics that allows the display or printout of weld current values and measurement time interval. It may also contain the integrator and signal processing required to calculate the current values.

current sensing coil (CSC). A Rogowski-type air core coil used to sense weld current. The CSC is usually connected to a display unit (current readout device) that provides information about the current being measured. See **Rogowski coil**.

cycle blanking. The elimination of a fixed number of half cycles from being included in any analysis or determination of a current value.

effective mutual inductance. The adjustment of the CSC *mutual inductance*, usually with the use of resistors, to obtain an effective value for a specific application or use with a specific WCM. See **mutual inductance**.

error (or measurement error). Result of a measurement minus a true value of the Measurand.

measurand. Particular quantity subject to measurement. In this specification, we are concerned with the proper measurement of the current measurand.

measured value. See **result of measurement**.

measurement. The set of operations having the object of determining the value of a quantity.

repeatability (of results of measurements). The closeness of the agreement between the results of successive measurements of the measurand carried out under the same conditions of measurement.

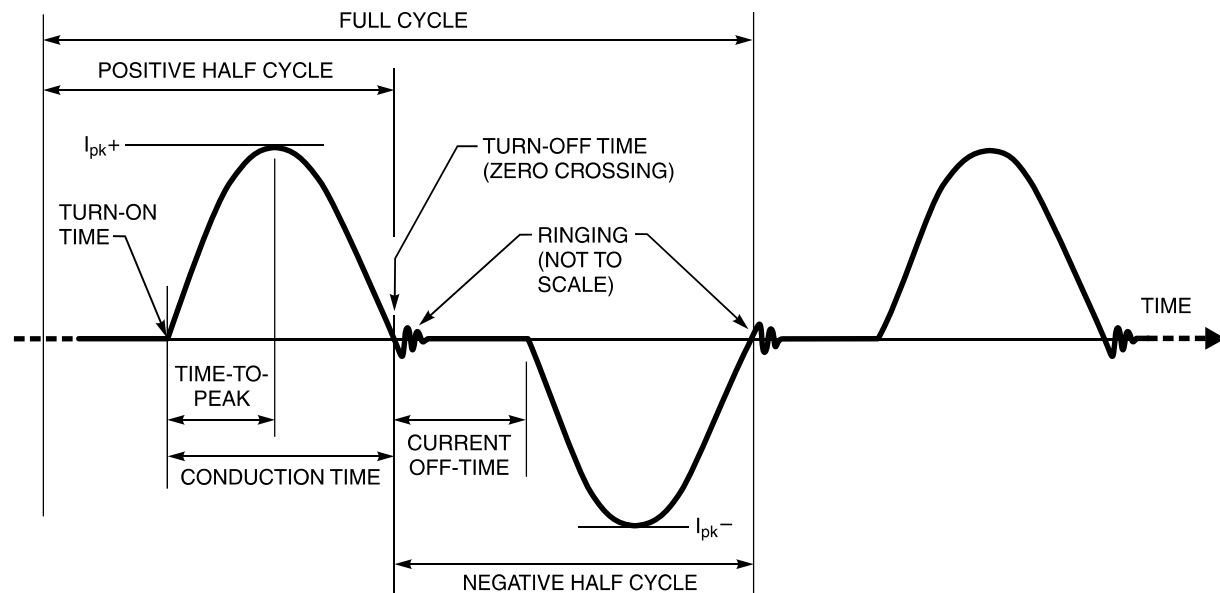


Figure A.1—1.5 Cycles of a Typical Secondary Weld Current Waveform

Measurement Standard or Reference Standard. The highest level reference used to establish and maintain the accuracy of calibrations. Normally, calibrated by sources outside the calibration organization.

measurement uncertainty. See **Uncertainty (of measurement)**.

measurement uncertainty, random. A category of potential uncertainties which do not remain constant or vary in an unpredictable way that biases results in an inconsistent and random manner.

measurement uncertainty, systematic. A category of potential uncertainties that remain constant or vary in a predictable way that biases results/data in a consistent and systematic manner.

mutual inductance. The common property of two electric circuits whereby an electromotive force (i.e., voltage) is induced in one circuit by a change of current in the other circuit. See **Effective Mutual Inductance**.

national standards laboratory. National laboratory responsible for deriving and disseminating units of measurements.

NIST. National Institute of Standards and Technology—the national standards laboratory of the United States.

on-time. A nonstandard term for weld current **conduction time**.

peak to turn-off time. Difference in time between the turn-off time and the time at the current peak (see Figure A.1).

position sensitivity. The change in the output of a CSC caused by changes in the CSC position relative to the current carrying conductor through the coil window, a change in welder geometry (i.e., current path), or any other factor that changes the magnetic field distribution in the vicinity of the CSC.

RMS current or rms current. The root-mean-squared current value is defined by the following equation:

$$I_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T i(t)^2 dt}$$

where

T = the measurement period in seconds corresponding to an integral number of half cycles, and
 $i(t)$ = the instantaneous current as a function of time.

For half-cycle rms current measurement, “ T ” in the above formula is defined as equal to one half the period of the power line voltage. In cases where the power line frequency varies significantly relative to the desired measurement accuracy, this approach may yield significant measurement errors since the term T will be in error.

resolution. The smallest incremental value that can be generated, modified, measured, or displayed. This is

not equal to the measurement uncertainty even though it is included in the uncertainty calculations.

result of measurement. Value attributed to a Measurand, obtained by measurement.

Rogowski coil. Air core type mutual inductor that has appropriate compensation for the pitch advance in its winding. The core permeability is considered equal to that of air or free space. Its output voltage is the product of the time-rate-of-change of the current being measured and the mutual inductance of the CSC. A Rogowski coil (CSC) used for a weld current measurement may be of rigid or flexible construction, and may be openable (split) or solid (unopenable). The coil is intended to completely surround the current carrying bus or conductor. The CSC is sometimes referred to as a “toroidal coil,” or simply as a “toroid.” The CSC has an output cable so it may be connected to a weld current monitor, a current readout device, or a weld current controller.

single-phase AC resistance welding current. For purposes of this document, single-phase AC resistance welding current is of an alternating nature and is of the same frequency as the primary source.

Standard. See **Measurement Standard**.

time-to-peak. The time from the start of the current pulse to its maximum value for a given half cycle (see Figure A.1).

threshold level. A level below which the current is considered to be zero.

tolerance. The total permissible variation of a quantity from a designated value.

toroid, toroidal coil. A term sometimes used for **Rogowski coil**.

total RMS current. The effective heating value of a current pulse or a series of current pulses. This may or may not include cool times. The rms value can be determined over the integral number of half cycles or from the rms values of individual half-cycles. When the total rms value is determined using individual half-cycle rms values, the following formula shall be used:

$$I_{\text{rms}} = \sqrt{\frac{I_{\text{rms},1+}^2 + I_{\text{rms},1-}^2 + I_{\text{rms},2+}^2 + I_{\text{rms},2-}^2 + \dots + I_{\text{rms},n+}^2 + I_{\text{rms},n-}^2}{n}}$$

where

n = the number of half cycles over which the rms value is calculated,

$I_{\text{rms},n}$ = the rms value of the n th half cycle of current, positive or negative in polarity as indicated by + or –, and

I_{rms} = the rms value of current calculated over n half cycles of current.

NOTE: Some WCMs may produce a total current value that is the mean of the individual half-cycle rms values. This is a different value than given by the above equation.

traceability, traceable measurement. Documented measurements that provide an unbroken chain of documentation, a paper trail, for the equipment used for the measurement back to a National Standards Laboratory, a physical law, or nationally recognized Measurement Standard. For the purposes of this specification, “National Standards Laboratory” is intended to mean the National Institute of Standards and Technology, NIST, or other National Standards Laboratories. Uncertainty of the measurements is also an integral part of a traceable measurement.

transimpedance. The ratio of output voltage from a CSC to input current being measured by the CSC. However, it only applies to undistorted sinusoidal waveforms of a single frequency. The unit of transimpedance is ohms, or microohms, as appropriate. This value is commonly expressed as “millivolts per thousand amperes” at a stated frequency.

turn-off time. The time at which the current is assumed to turn off or cease flowing. This time can be defined as the time at which the final slope of the current intersects with the zero-current level (see Figure A.1).

turn-on time. The time at which the current begins. This can be defined as the intersection of the zero current level and the initial slope of the current (see Figure A.1).

Uncertainty (of measurement). Parameter, associated with the result of a measurement, that characterizes the dispersion of the value that could reasonably be attributed to the Measurand.

unit under test (UUT). The CSC, WCM, or the combination of the CSC with the readout (WCM) being tested.

weld current conduction time. Refers to the current conduction time on a half cycle basis. The conduction time is the difference in time between the turn-off time and the turn-on times. Often, welding current conduction time is expressed as an angle, in degrees.

weld current monitor (WCM). The current readout device used to provide the measured current value, measurement time intervals, or other information. This can be a portable unit or integrated into a welding system. If the WCM is a part of a resistance weld controller, then it is defined as that part of the controller that processes the data from the CSC to arrive at the weld current value.

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Annex B (Informative)

Positional Sensitivity Testing for Current Sensing Coils

This annex is not part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, but is included for informational purposes only.

In general, the largest single contributing factor that establishes the errors in current measurement using a CSC (i.e., Rogowski coil) is its positional sensitivity. The positional sensitivity of a CSC occurs when position, location, or orientation of the CSC changes relative to the current carrying conductor(s) (busses), which as a result, changes the electrical output of the CSC. CSCs are more sensitive to these positional changes when they are in close proximity to the current carrying bus. This is true for not only the bus about which the coil is placed, but also for the near proximity of a return conductor, for example.

In normal operation of the CSC, each individual coil turn is electrically connected in series with the next turn all the way around the coil. Each individual coil turn forms a voltage generator that contributes to the overall coil output by the sum of the voltages all of the turns. This is the principal output voltage of the CSC. The turn-to-turn *pitch advancement* from the beginning of the coil winding to the end of the winding forms a large one-turn loop normal to the axis of the plane of the coil. The cross-sectional area of the *pitch-advancement loop* is nominally the internal area enclosed by the diameter of the CSC. Any varying magnetic flux that couples to this large loop will produce a significant voltage, which represents a large error component. To counter act the effects of this undesired voltage, a *counter turn* is connected in series with the coil. The *counter turn* is ideally the same size as the effective *pitch advancement turn*. The same flux that generates an undesired voltage in the *pitch-advancement turn* then generates an equal and opposite voltage in the *counter turn*. Being connected in series, the two voltages sum to zero. The *counter turn* may be a simple “return lead” placed around the circumference of the coil which progresses in the opposite direction of the *pitch-advancement turn*, or it may be in

the form of a second layer of coil winding. The two-layer coil is a popular design and is very often used in “belt-type” coils.

Combinations of one or more of the following factors cause CSC positional sensitivity:

- (1) Any cross-sectional area variation of individual coil turns. These variations are formed by turn-to turn dimensional deviations of the individual coil turns. In most instances, the effects of these localized variations tend to average out over the whole coil.
- (2) Any variation in the turn-to-turn pitch, i.e., variation in the turn-to-turn spacing.
- (3) Any variation in the individual turn orientation or turn-shape.
- (4) The absence of any coil turns. This is common in coils that open so that they may be placed around a bus conveniently. In belt-type coils, there are “missing turns” on each side of the “buckle” location where the coil opens for mounting. This leaves a “hole” in the response of the coil for this region of the coil. In some designs, extra turns are added near each end of the winding to help make up for the missing turns. However, in the very near field conditions, perfect compensation for the missing turns is not achievable.
- (5) Lack of *pitch-advancement* compensation. It is not possible to perfectly compensate a coil for pitch advancement. There is always a small difference in the effective areas formed by the pitch advancement and the effective compensation turn.
- (6) Small undesired loop areas formed by the leads where the output cable is attached.
- (7) Signals induced in the output cable.

The combined effects listed above can lead to significant errors in the measurement of electrical current. For coils commonly used to measure weld currents, the positional sensitivity may contribute errors of several percent or more. For CSCs used as reference standards, this error ranges from 0.1% to several percent in those commonly available.

If a CSC has a split, a number of these factors are prevalent close to the split and measurement uncertainties can be significantly influenced by the position of the split with respect to the position sensitivity test loop. Particularly, whether the CSC split (or cable exit point) is placed inside the loop in the plane of the test loop would influence the positional sensitivity test results.

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Annex C (Informative)

Sample Uncertainty Calculations

This annex is not part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, but is included for informational purposes only.

The following information may be used as a guide in determining the combined uncertainty of the CSC and the WCM.

The statistical analysis contained in these examples summarize the data collected at the time of test for the WCM. It does not contain statistical analysis to predict the performance of the WCM over a period of time, i.e., until the next time the WCM is calibrated. The error analysis assumes that the error in the mean value is negligible.

To simplify the analysis of errors, the standard deviation is not corrected by the Student's t-factor.

C1. Example for Calculating the Combined Uncertainty for the Measured Value of the Mutual Inductance of the CSC

Assume that the following information has been collected for the CSC.

The temperature coefficient of the mutual inductance for the CSC, when it was heated from 20°C to 50°C, was found to be +0.050%/°C. A change of 30°C in temperature results in a change of 1.5% in the mutual inductance of the CSC. Hence the uncertainty due to temperature is 1.5%.

It is noted that the temperature test is a type/optional test per Table 1. If the temperature sensitivity test is not done for the CSC for which the combined uncertainty is being estimated, the results of its type test must be used. If no temperature sensitivity data is available, measurement uncertainty of the order noted in the above paragraph may go unaccounted for.

The uncertainty of the voltage measurement has been determined to be, for example, ±1.0%.

The uncertainty of the current measurement has been determined to be, for example, ±1.2%.

The uncertainty of the frequency measurement has been determined to be, for example, ±0.5%.

NOTE: The Measurement Standards must have adequate resolution, accuracy, and repeatability so as to not adversely influence the measurements of the CSC being tested.

The position sensitivity of the CSC was found to be 3.4%.

The standard deviation from a set of 5 repeated measurements as found to be 0.08%. To achieve a confidence level of 95%, twice the value of the standard deviation is used as $2\sigma = 2 * 0.08\% = 0.16\%$.

The combined uncertainty for the CSC is determined as follows by statistically adding the individual error sources.

$$\epsilon_{\text{tot}} = \sqrt{\epsilon_1^2 + \epsilon_2^2 + \dots + \epsilon_n^2}$$

where

ϵ_{tot} = the combined uncertainty for the CSC under the stated conditions of use,

ϵ_n = the error of the nth contributing source at the 95% confidence level.

$$\epsilon_{\text{tot}} = \sqrt{\epsilon_{\text{temp}}^2 + \epsilon_{\text{posn}}^2 + \epsilon_{\text{voltage}}^2 + \epsilon_{\text{current}}^2 + \epsilon_{\text{frequency}}^2 + \epsilon_{\text{repeatability}2\sigma}^2}$$

For the error sources in this example the errors are added per the following:

ϵ_{temp}	= 1.5% = the error from temperature sensitivity of the CSC,
ϵ_{posn}	= 3.4% = position sensitivity error of CSC,
$\epsilon_{\text{voltage}}$	= 1.0% = the uncertainty of the voltage measurement at the 95% confidence level,
$\epsilon_{\text{current}}$	= 1.2% = the uncertainty of the current measurement at the 95% confidence level,
$\epsilon_{\text{frequency}}$	= 0.5% = the uncertainty of the frequency measurement at the 95% confidence level, and
$\epsilon_{\text{repeatability } 2\sigma}$	= 0.16% = twice the standard deviation from a set of 5 repeated measurements.

$$\epsilon = \sqrt{1.50\%^2 + 3.4\%^2 + 1.0\%^2 + 1.2\%^2 + 0.5\%^2 + 0.16\%^2}$$

$$= \pm 4.065\% \cong \pm 4.1$$

The combined uncertainty of the CSC is then found to be $\pm 4.065\%$ of reading, and may be rounded to $\pm 4.1\%$, for the stated conditions of use of 0°C to 50°C and in a welding current path no smaller than 250 mm by 250 mm. Based on this information it can be stated that the CSC mutual inductance has a 95% probability of being the “true value” of mutual inductance $\pm 4.1\%$ of the indicated value.

All units must be consistent at the point of entering them in the above equation whether they are expressed in percent of reading, kiloamperes, or percent of full scale. The individual errors shown above must include the contributions from the resolution, stability, environment, and the errors of the standards used to support each of the individual measurands.

C2. Example for Calculating the Uncertainty for the CSC-WCM Combination

The information from C1 is used in the following example for calculating the combined uncertainty for a CSC-WCM combination relative to the “true value” of the weld current.

The uncertainty due to temperature is calculated using the CSC mutual inductance temperature coefficient of 0.050% per $^\circ\text{C}$. If the temperature range is 0°C to 50°C the uncertainty over the temperature range will be 1.5%.

The position sensitivity of the CSC was found to be 3.4%.

The unit being calibrated had a scale or measurement range of 2 kA to 10 kA. The resolution for this unit is 0.01 kA for this range. This value will be accounted for in the final uncertainty statement since it affects the ability of the meter to determine the current. For the example shown below, the WCM-CSC combination was being calibrated over a range from 20% to 96% of its full-scale range. The *percentage resolution* is calculated therefore from the ratio of $(0.01 \text{ kA}/2 \text{ kA}) \times 100$. This results in a resolution of 0.5%. The value of 2 kA in the denominator is a result of the 20% of 10 kA full-scale range.

The uncertainty of the Current Reference standard has been determined to be, for example, $\pm 1.0\%$ of reading.

NOTE: The Measurement Standards must have adequate resolution, accuracy, and repeatability so as to not adversely influence the measurements of the CSC-WCM combination being tested.

As an example, a linearity test was performed at five current levels on the range and the readings were found as shown in Table C.1.

The mean error is 0.26% and the 2-sigma standard deviation is 0.81% about the mean value. Both the mean error and 2-sigma values will be used in stating a combined uncertainty for the WCM.

The combined uncertainty for the WCM is determined as follows by statistically adding the individual error sources.

$$\epsilon_{\text{tot}} = \sqrt{\epsilon_1^2 + \epsilon_2^2 + \dots + \epsilon_n^2}$$

where

ϵ_{tot}	= the combined uncertainty for the WCM under the stated conditions of use,
ϵ_n	= the error of the nth contributing source at the 95% confidence level.

For the error sources in this example the errors are added per the following:

$$\epsilon_{\text{tot}} = \sqrt{\epsilon_{\text{temp}}^2 + \epsilon_{\text{std}}^2 + \epsilon_{\text{csc posn}}^2 + \epsilon_{\text{linearity mean}}^2 + \epsilon_{\text{linearity 2sigma}}^2 + \epsilon_{\text{resolution}}^2}$$

ϵ_{temp}	= 1.5% = the error from temperature sensitivity of the CSC,
ϵ_{std}	= 1.0% = the uncertainty of the Measurement Standard at the 95% confidence level,
$\epsilon_{\text{csc posn}}$	= 3.4% = position sensitivity error of CSC,
$\epsilon_{\text{linearity mean}}$	= 0.26% = the mean error for the WCM over the current and % Heat range,

Table C.1
A Typical Example of Linearity Test Results for a WCM on a 10 kA Full-Scale Range

%Heat ^a	Nominal Current kA	Standard Reading kA	UUT Reading kA	Error % Reading	Group Mean Error % Reading
30	2	2.011	2.02	0.50	0.58
		2.012	2.03	0.89	
		2.011	2.02	0.45	
		2.010	2.04	1.49	
		2.009	2.00	−0.45	
50	4	4.128	4.14	0.29	0.30
		4.126	4.15	0.58	
		4.127	4.13	0.07	
		4.128	4.12	−0.19	
		4.129	4.16	0.75	
75	6	6.017	6.04	0.38	0.24
		6.015	6.02	0.08	
		6.017	6.04	0.38	
		6.014	6.02	0.10	
		6.015	6.03	0.25	
84	8	8.088	8.10	0.15	0.10
		8.086	8.13	0.54	
		8.089	8.08	−0.11	
		8.085	8.08	−0.06	
		8.091	8.09	−0.01	
95	9.6	9.605	9.63	0.26	0.06
		9.607	9.63	0.24	
		9.606	9.59	−0.17	
		9.608	9.60	−0.08	
		9.603	9.61	0.07	
Mean					0.26
2-sigma Std. Dev. ^b					0.81

^a The choice of parameters depends on the particular weld current controller that is being used, for example, % Heat or % Current.

^b The value of standard deviation is obtained from the entire set of values for the “error of reading” column.

$\epsilon_{\text{linearity}2\text{sigma}} = 0.81\% = \text{the 2-sigma value from the linearity test,}$

$\epsilon_{\text{resolution}} = 0.5\% = \text{the display resolution for the WCM for the measurement range being evaluated,}$

$$\epsilon = \sqrt{1.5\%^2 + 1.0\%^2 + 3.4\%^2 + 0.26\%^2 + 0.81\%^2 + 0.5\%^2}$$

$$= \pm 3.97\% \cong \pm 4.0\%$$

The combined uncertainty of the system is then found to be $\pm 3.97\%$ of reading from 20% of full scale to 100% of full scale for the stated conditions of use of a CSC temperature range of 0°C to 50°C and in a welding current path no smaller than 250 mm by 250 mm. In practice, this may be rounded to $\pm 4.0\%$. Based on this information it can be stated that the current value displayed on the

WCM has a 95% probability of being the “true value” of current $\pm 4.0\%$ of the indicated value.

All units must be consistent at the point of entering them in the above equation whether they are expressed in percent of reading, kiloamperes, or percent of full scale.

In the example given above, the temperature coefficient of the WCM has been considered to be zero. Experience has shown that its temperature coefficient is typically small in comparison to that of the CSC. A more rigorous analysis would have to include the WCM’s temperature coefficient if the other contributions to the error become small.

A similar analysis is needed for each measurement range. Note that the determination of the position sensitivity and the temperature coefficient for the CSC would not need to be repeated for the other current ranges.

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Annex D (Informative)

Reference Documents for Optional Additional Information

This annex is not part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, but is included for informational purposes only.

Dieck, R. H., "Measurement Uncertainty: Methods and Applications," Instrument Society of America, 1992, ISBN 1-55617-126-9. Available through the ISA, 67 Alexander Drive, P.O. Box 12277, Research Triangle Park, NC 27709.

Ananthanarayanan, V. et al., "Unrecognized Errors in the Calibration of Current Coils," presented at the Sheet Metal Welding Conf., Detroit, MI, Oct. 16, 1998. Available through American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

Destefan, D. E. and Ramboz, J. D., "Uncertainty Analysis for High-Current Measurements," presented/published at Natl. Conf. of Stand. Lab. Workshop and Symposium, July 19–23, 1998, Albuquerque, NM. Available through NCSLI, 1800 30th Street, 305B, Boulder, CO 80301-1236.

Ramboz, J. D. and Destefan, D. E., "Establishment of Traceability for Pulsed-Current Measurements to Greater than 60 kA," presented/published at Natl. Conf. of Stand. Lab. Workshop and Symposium, July 19–23, 1998, Albuquerque, NM. Available through NCSLI, 1800 30th Street, 305B, Boulder, CO 80301-1236.

Simmon E. D., Rose, A. H., and FitzPatrick, G. J., "An Optical Current Transducer for Calibration Studies," 8th International Symposium on High Voltage Engineering, Yokohama, Japan, August 23–27, 1993. Contact NIST Electricity Division at 100 Bureau Drive, Gaithersburg, MD 20899.

Taylor, B. and Kuyatt, C. E. "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," NIST Technical Note 1297 NIST, Gaithersburg, MD 20899.

Ward, D.A. and Exon, J. La T., "Using Rogowski Coils for Transient Current Measurements," Engr. Sci. and Ed. Journ. June 1993, pp. 105–113.

Ferguson, H. S., "The Measurement of Electrical Variables in Resistance Welding," Application Note #1, Duffers Scientific Inc., December 1964. Available from Dynamic Systems Inc., P.O. Box 1234, Poestenkill, NY 12140.

Ramboz, J. D., Destefan, D. E., Stant, R. S., "The Verification of Rogowski Coil Linearity from 200 A to Greater than 100 kA using Ratio Methods," IEEE Instru. and Meas. Technology Conf., Anchorage, Alaska, USA, May 21–23, 2002, pp. 687–692. Available through IEEE, 3 Park Avenue, 17th Floor, New York, NY 10016-5997.

General requirements for the competence of testing and calibration laboratories, ISO/IEC 17025 1999. This reference can be obtained from www.iso.ch.

U.S. Guide to the expression of uncertainty in measurement, October 1997, available from the National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301, ph. 303-440-3339.

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Annex E (Informative)

Information Relating to the Testing for CSC Frequency Response

This annex is not part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, but is included for informational purposes only.

Typical weld current waveforms contain spectra of frequencies. The CSC must have a sufficiently wide response bandwidth to preserve the waveform “fidelity” within established limits in order to achieve a desired measured uncertainty. The bandwidth dependence due to measurement uncertainty is discussed below.

CSC electrical characteristics that will characterize the frequency response of a CSC for use in single-phase ac resistance weld applications are:

- (1) CSC self-inductance, usually specified in units of millihenries.
- (2) CSC winding dc-resistance, specified in units of ohms.
- (3) Any sensitivity trimming resistors, either in shunt and/or series with the coil winding. Resistance to be given in units of ohms.
- (4) The input resistance to any signal processing equipment (i.e., weld current monitor, weld current controller, or any circuit used to process and analyze the coil output voltage). A typical value of input resistance is 1 k Ω to 3 k Ω .

Sensitivity trimming resistors may or may not be present. If they are present, then the circuit arrangement and typical values should be provided. Additionally, if trim resistors are present, then the nominal value of input resistance that the coil is intended to work into must be given.

The effects of the distributed capacitance across the coil and the cable capacitance are considered to be zero. Except in rare instances, this is a valid assumption over the frequency range that the coils are expected to experi-

ence for single-phase ac resistance welding applications. Using the above CSC characteristics, the CSC’s performance may be predicted by applying standard electrical engineering principles.

The coil may be tested as an “untrimmed” (i.e., coil without trimming resistor(s) for sensitivity adjustment), or a coil that has trimming resistors included. Both the amplitude and the phase angle of the response may be determined by the given method. From this data, the bandwidth of the CSC, under “loaded” conditions, may be obtained.

The self-inductance of the CSC and the circuit resistances generally establish the limits of the frequency response. The effects of the self-inductance and resistance cause both a phase shift and an amplitude change of the output signal as the maximum usable frequency of the CSC is approached. Nominally, the CSC output voltage signal has a phase shift of -90° with respect to the current being measured. This is the result of the induced voltage in the CSC being proportional to the rate of change of current (di/dt). The “derivative function” causes the quadrature phase shift. The voltage injection employed in the method described here does not require that the quadrature phase shift be considered. The method evaluates additional phase shift due to the CSC and other circuit elements as a function of frequency.

The amount of response roll-off and phase shift that is acceptable depends on the measurement uncertainty that is required in a typical or specific application. This document does not set limits on the response or phase angle. A guide is provided in Table 4 (3.6.3) that gives the CSC minimum bandwidth for values of measurement uncertainty for the CSC. It requires that the measured response

and phase angle are provided as a function of frequency and that the value of the load resistance used during the test is also provided. Further, this method does not evaluate the effects of any subsequent signal processing, such as an integrator, for example. This method and criteria apply only to the measurement of rms currents derived from typical single-phase resistance weld control equipment. It is not to be used for the measurement of peak or average values of current, nor for such applications as inverter controlled weld currents.

Fundamentally, the uncertainty for currents measured in single-phase ac resistance weld applications depends on two factors. First, the amplitudes of the harmonic frequency components (spectra) that are present in the current waveform, and second, the bandwidth (i.e., the frequency response [amplitude and phase]) of the CSC.

The harmonically related spectrum varies widely from welder-to-welder. The spectrum is a function of the conduction angle, the physical geometry of the secondary current loop, the workpiece being welded, and to a lesser extent, the power-system impedance. Therefore, only typical values of harmonic content can be provided as a guide when trying to establish limits of measurement uncertainty or CSC bandwidth requirements. The CSC bandwidth requirements have to consider the harmonic content of the current being measured and the desired measurement uncertainty. The bandwidth requirement for a CSC that is being used for routine measurements of weld currents is far less stringent than for a CSC that is being used as a calibration reference standard. A guide is provided in Table 4 (3.6.4) that gives typical values of CSC bandwidth related to the measurement uncertainty being sought.

Annex F (informative)

Information Relating to Equipment Traceability

This annex is not part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, but is included for informational purposes only.

Traceability is defined in ANSI Z540 as:

“Traceability is the property of a result of a measurement whereby it can be related to appropriate standards, generally national or international standards, through an unbroken chain of documented comparisons.”

Additional details regarding traceability can be found in the references provided. The concept of traceability, for the purpose of this document, is simplified in the following. Traceability relates to proper calibration standards, ancillary equipment, trained personnel, procedures, and the measurement process used. However, to provide adequate calibrations, many things must be present including proper methods, proper environment, appropriate equipment, calibrated and traceable equipment, trained personnel, and scientifically sound statistical analysis to assess uncertainty.

All measurement standards must be appropriate for the intended measurements, must be calibrated using traceable standards, and only used over the range of measurement for which they have been calibrated. Further, WCMs being calibrated can only be certified over the range of currents where they have been tested—no excessive extrapolation. Traceability also carries with it the concept that the equipment being calibrated is tested over the entire range and conditions for which it is being certified as a result of the calibration. As an example,

traceability does not exist for a WCM if it is tested at only 99% heat at 2.5 kA on a 20-kA range if it is used to measure a 17 kA current at 66% heat even though the calibration was done with traceable equipment.

Another example of a violation of the concept of traceability is the following. A WCM is tested with *standards* calibrated only at 2 kA and only at 99% heat. The WCM under test however is tested from 2 kA to 20 kA and from 20% heat to 99% heat on the 20-kA measurement range. The WCM 20-kA range is certified by the calibrating entity. The concept of traceability is violated since, even though the WCM was calibrated over the entire measurement range, the accuracy of the measurement standards beyond 2 kA are unknown.

Traceability may also be violated if standards have been certified to manufacturer specifications. Typically, test equipment manufacturer specifications included an accuracy specification limited to a specifically stated range of temperature. If the test equipment is used outside of the specified temperature range, measurement traceability is violated.

This specification contains testing methods to aid in assuring traceability of measurements. However, it is still important that the persons and entities conducting testing and certification of WCMs and CSCs not lose sight of the concepts of traceability.

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Annex G (Informative)

Guidelines for the Preparation of Technical Inquiries

This annex is not part of AWS A10.1M:2007, *Specification for Calibration and Performance Testing of Current Sensing Coils and Weld Current Monitors Used in Single-Phase AC Resistance Welding*, but is included for informational purposes only.

G1. Introduction

The American Welding Society (AWS) Board of Directors has adopted a policy whereby all official interpretations of AWS standards are handled in a formal manner. Under this policy, all interpretations are made by the committee that is responsible for the standard. Official communication concerning an interpretation is directed through the AWS staff member who works with that committee. The policy requires that all requests for an interpretation be submitted in writing. Such requests will be handled as expeditiously as possible, but due to the complexity of the work and the procedures that must be followed, some interpretations may require considerable time.

G2. Procedure

All inquiries shall be directed to:

Managing Director
Technical Services Division
American Welding Society
550 N.W. LeJeune Road
Miami, FL 33126

All inquiries shall contain the name, address, and affiliation of the inquirer, and they shall provide enough information for the committee to understand the point of concern in the inquiry. When the point is not clearly defined, the inquiry will be returned for clarification. For efficient handling, all inquiries should be typewritten and in the format specified below.

G2.1 Scope. Each inquiry shall address one single provision of the standard unless the point of the inquiry involves two or more interrelated provisions. The provi-

sion(s) shall be identified in the scope of the inquiry along with the edition of the standard that contains the provision(s) the inquirer is addressing.

G2.2 Purpose of the Inquiry. The purpose of the inquiry shall be stated in this portion of the inquiry. The purpose can be to obtain an interpretation of a standard's requirement or to request the revision of a particular provision in the standard.

G2.3 Content of the Inquiry. The inquiry should be concise, yet complete, to enable the committee to understand the point of the inquiry. Sketches should be used whenever appropriate, and all paragraphs, figures, and tables (or annex) that bear on the inquiry shall be cited. If the point of the inquiry is to obtain a revision of the standard, the inquiry shall provide technical justification for that revision.

G2.4 Proposed Reply. The inquirer should, as a proposed reply, state an interpretation of the provision that is the point of the inquiry or provide the wording for a proposed revision, if this is what the inquirer seeks.

G3. Interpretation of Provisions of the Standard

Interpretations of provisions of the standard are made by the relevant AWS technical committee. The secretary of the committee refers all inquiries to the chair of the particular subcommittee that has jurisdiction over the portion of the standard addressed by the inquiry. The subcommittee reviews the inquiry and the proposed reply to determine what the response to the inquiry should be. Following the subcommittee's development of the response, the inquiry and the response are presented to

the entire committee for review and approval. Upon approval by the committee, the interpretation is an official interpretation of the Society, and the secretary transmits the response to the inquirer and to the *Welding Journal* for publication.

G4. Publication of Interpretations

All official interpretations will appear in the *Welding Journal* and will be posted on the AWS web site.

G5. Telephone Inquiries

Telephone inquiries to AWS Headquarters concerning AWS standards should be limited to questions of a general nature or to matters directly related to the use of the standard. The *AWS Board Policy Manual* requires that all AWS staff members respond to a telephone request for an official interpretation of any AWS standard with

the information that such an interpretation can be obtained only through a written request. Headquarters staff cannot provide consulting services. However, the staff can refer a caller to any of those consultants whose names are on file at AWS Headquarters.

G6. AWS Technical Committees

The activities of AWS technical committees regarding interpretations are limited strictly to the interpretation of provisions of standards prepared by the committees or to consideration of revisions to existing provisions on the basis of new data or technology. Neither AWS staff nor the committees are in a position to offer interpretive or consulting services on (1) specific engineering problems, (2) requirements of standards applied to fabrications outside the scope of the document, or (3) points not specifically covered by the standard. In such cases, the inquirer should seek assistance from a competent engineer experienced in the particular field of interest.

