Frequency Extension of the NIST AC-DC Difference Calibration Service for Current

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Introduction

The NIST calibration service for ac-dc difference of thermal current converters (TCCs) relies on primary multijunction thermal converters (MJTCs), reference, and working-standard thermal converters and thermoelements (TEs). Calibrations are performed by the comparison of the ac-dc difference of a customer's thermal current converter with the ac-dc difference of a NIST standard. Typical artifacts accepted for calibration include single-junction thermoelements, multijunction thermal converters, and transfer shunts for use with thermoelements. This paper describes the standards on which the calibration service is based and the results of the study underway to characterize the NIST standards over the extended frequency range from 10 Hz to 100 kHz at currents up to 20 A.

Primary Standards

The NIST primary standards of ac-dc difference for current are multijunction thermal converters. The primary MJTC group consists of six converters with rated heater currents ranging from 5 to 50 mA. The ac-dc differences of these MJTCs are believed to be below 0.5 ppm at frequencies ranging from 30 Hz to 10 kHz. Detailed descriptions of the primary MJTCs and the results of their intercomparisons have been published previously [1,2].

Extension to 100 kHz

The existing characterization of TCCs for frequencies above the range of the primary MJTCs, i.e. from 10 kHz to 50 kHz, relies on the frequency flatness of the ac-dc difference for selected, specially constructed, single-junction thermoelements. Single-junction TEs are chosen for use in this process of extending the frequency up to 50 kHz, and these methods have been described before [1,3]. Single-junction TEs are also chosen in this project to extend the ac-dc difference characterizations up to 100 kHz because they have a much simpler structure than the MJTCs and can be constructed to have smaller reactances and therefore wider frequency ranges.

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Various TEs, identified as FX_2, FY_2, FA, and FB, have been intercompared up to 100 kHz as current converters by one of two methods. In the first method, the two TEs are connected in series. This arrangement may suffer from possible bead-effect error, as described by Hermach [1], so another method was also used. In the second, the two TEs were connected with two nearly identical 6-kΩ resistors in series with the heaters to form thermal voltage converters and the resistor-TE combination intercompared as such. In this arrangement, the TEs are working as current converters, so ac-dc differences for current are obtained. The series resistors had very small differences in reactance, and by interchanging them and taking the average, even these could largely be eliminated.

Extension to 10 Hz

The methods and current converters used to extend the frequency range from 30 Hz, the lower limit of the NIST primary MJTCs, to 20 Hz has been described elsewhere [1]. For the frequency range of interest in this paper, from 10 Hz to 20 Hz, a significant contribution to the ac-dc difference comes from the failure of the TE to thermally average the input waveform. When the signal levels applied to the TEs are reduced, the temperature of the heater as well as the temperature variations are lower, resulting in smaller ac-dc differences at these low frequencies. Two special thermal converter assemblies were built for low-frequency measurements [5]. These converters consist of either four or six TEs with their heaters connected in series and their outputs connected in series aiding, as shown in figure 1. These special modules, Fe and Ru, allow reasonable output levels to be obtained at low heater temperatures.

Extension of Current Ranges

The characterization of standard TCCs at higher and lower currents is based on a process of build-up and build-down through the current levels. These methods have been described previously [1,3,4] and will only be summarized in this paper. Range-to-range intercomparisons have been made by techniques employing interconnection arrangements essentially the same as those described above for the frequency extension [1,3,6]. For lower current ranges, two TEs were compared in series and then connected in parallel using two nearly identical resistors to make the currents sufficiently in phase. For this method, the TEs are used at or near their rated current so current-level dependence is essentially eliminated from the characterization process. At higher currents, generally greater than 1 A, TEs of different ranges were compared in series at current levels suitable for the lower range TE. Level dependence was tested by making comparisons at multiple levels and by cross checks between different build-up paths.

NIST Reference and Working Standards

Although NIST does use some current shunt-thermoelement combinations as check standards and transfer standards, essentially all reference and working standards are thermoelements. As standards, TEs are inherently superior to shunts because they have smaller structural reactances and stray impedances. These characteristics yield ac-dc differences which are generally flatter with frequency and less dependent on surrounding structures and operating voltage. Furthermore, in any structure where currents divide, such as a shunt in parallel with a TE, it is never possible to make the ac current division identical to the dc current division at all frequencies since the ac divides according to impedance ratios and the dc according to resistance ratios.

For currents at 250 mA and below, the standards are single-junction, vacuum thermoelements. Many of these TEs are specially constructed with Evanohm heaters. For currents from 500 mA to 20 A, special air-mounted thermoelements with thermally lagged heaters and thermal compensation are used. A diagram of a typical high-current TE is shown in figure 2. For the highest currents, tubular heater structures are used because of skin effect. Electrically insulated, thermal compensation straps between the thermocouple output leads and the heavy terminal blocks on the ends of the heater significantly reduce the variation in output emf due to the thermal drift and warm-up of the heater and ambient temperature variations.

Results

Typical results of the build-up process for the intercomparison of reference standards from 5 mA to 20 A are given in figure 3a for 100 kHz and in figure 4 for 10 Hz. The arrows point to the converter in the 'test' position, and the measured ac-dc differences are given in parts-per-million. Generally the comparisons were made at the rated current for the lower of the two converters. Typical results for the characterization of the working standards, by direct comparison with the reference standards at the rated current, are given in figure 3b for 100 kHz and in figure 4 for 10 Hz.

Uncertainty Analysis

100 kHz

The analysis and combination of uncertainties for this work have been done according to NIST Technical Note 1297 [7]. The uncertainty analysis for both type A errors (those that can be evaluated by statistical means) and type B errors (those which are evaluated by other means) of the TEs used as primary standards at 100 kHz is described in detail in [1]. This analysis includes:

contributions for the NIST primary standard multijuction thermal converters at frequencies up to 10 kHz;

contribution for the characterization of the reference standards up to 50 kHz;

pooled standard deviations for characterization of reference standard thermoelements;

contributions to the variation of ac-dc difference with frequency out to 100 kHz for reference TEs including current definition, skin effect, and bead-effect error.

The summary of the uncertainty analysis applied to the build-up process for the reference standards is given in table 1. It contains contributions for both type A and B errors including:

pooled standard deviations for the comparator;

estimated type B errors for the comparator;

estimated type B errors for each step in the build-up process at each current range.

The summary of the uncertainty analysis for the characterization of working standards is given in table 2.

10 Hz

The characterization of the ac-dc difference for the NIST thermal current converters at 10 Hz relies on the frequency flatness of two specially constructed, cluster thermal converters [5]. The uncertainty for these special low-frequency reference converter modules is given in table 3 and contains contributions for both type A and B errors including:

estimated frequency flatness of thermoelements due to failure to thermally average;

effect on detector circuitry due to residual ac component;

pooled standard deviations for the comparator;

level dependence at 10 Hz.

The uncertainty analysis for the reference standard TEs is also given in table 3. In a manner similar to table 2, the uncertainty at 10 Hz for the working standard converters has been derived and has been summarized in table 4.

Conclusion

The characterization of the NIST thermal current converter standards at 100 kHz and 10 Hz and the related uncertainty analysis are nearly complete. This analysis applies only to the characterization of the NIST standard current converters. The overall uncertainty of the NIST calibration service for converters and transfer shunts is still being determined. Routine calibrations, instead of special calibrations, for ac-dc difference of thermal current converters and transfer shunts at these frequencies are expected to begin later this year.

References

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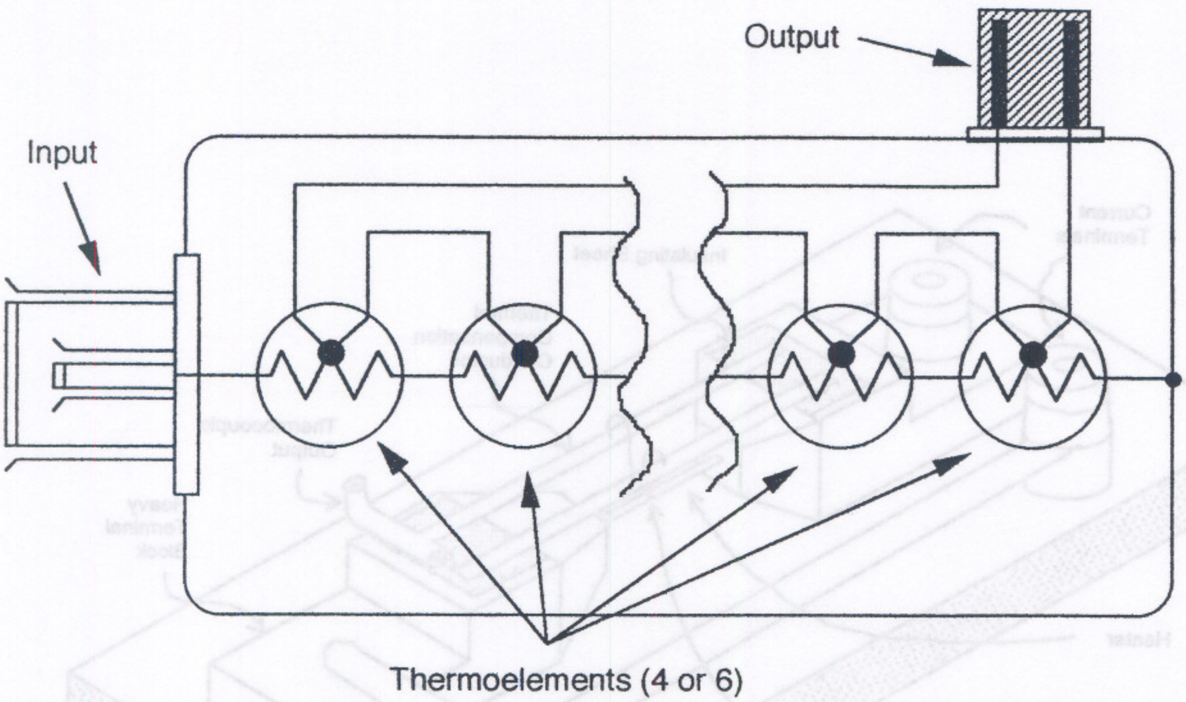

Figure 1. Diagram of low-frequency thermal converter module, consisting of either four (for Fe) or six (for Ru) thermal elements with their inputs and outputs connected in series.

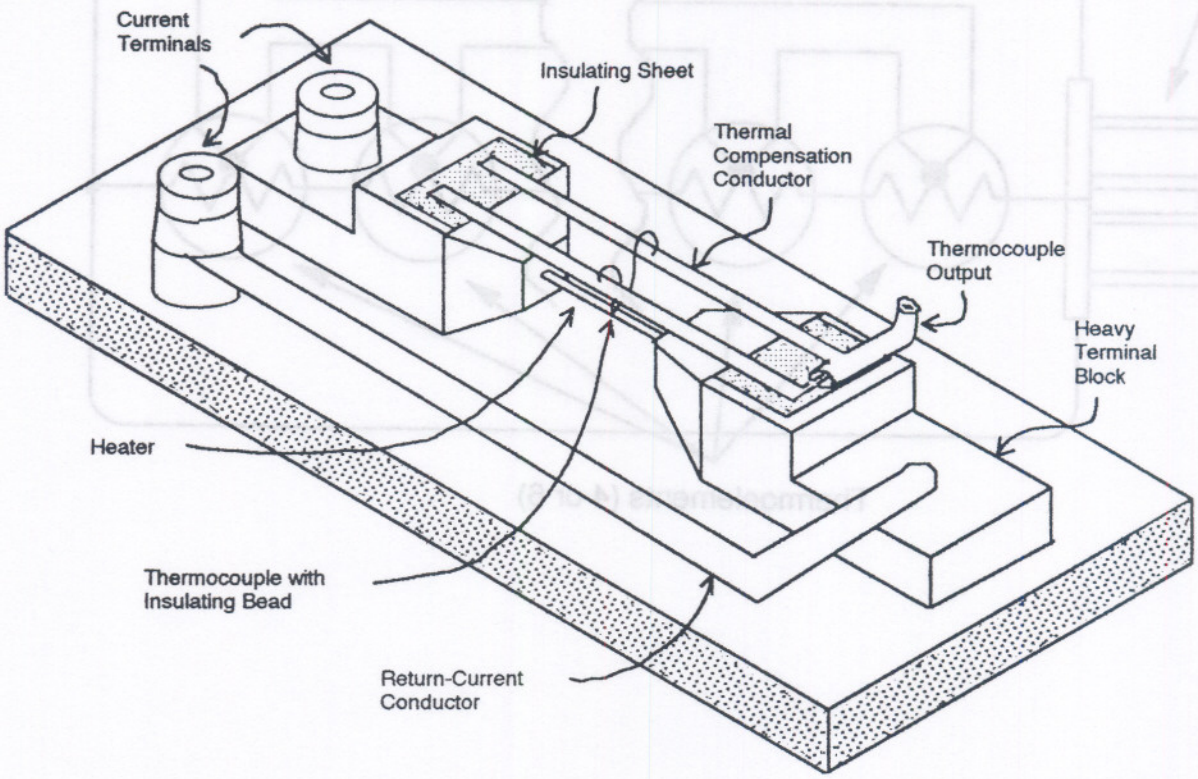

Figure 2. Typical construction of high-current thermoelement, showing the heavy terminal blocks and return-current conductor.

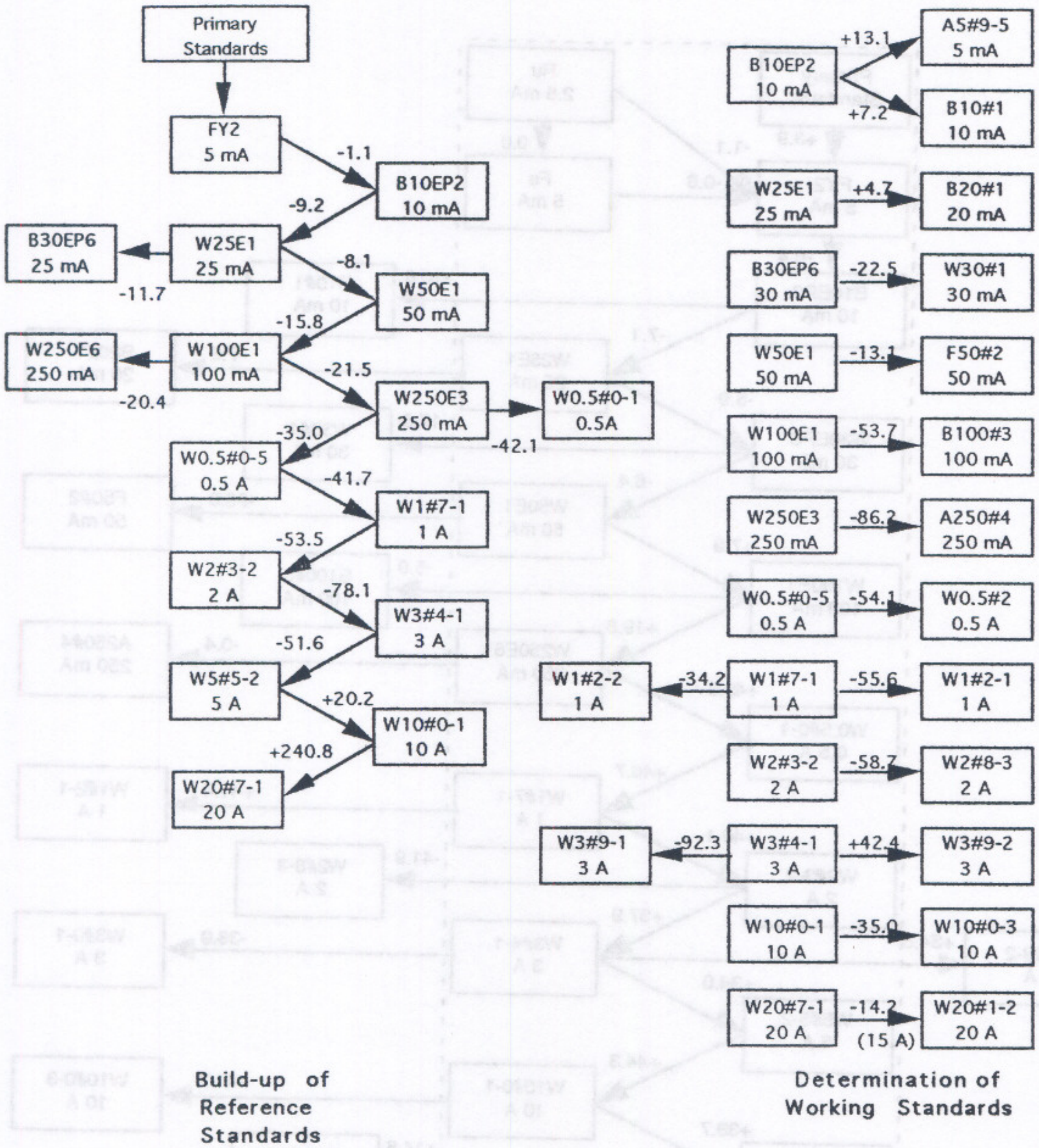

Figure 3.

Figure 3a (left) shows the build-up chain for reference standard thermal current converters at 100 kHz for currents from 5 mA through 20 A. The arrows point to the TCC in the 'test' position and the numbers are the ac-dc differences of the 'test' TCC relative to the 'standard' TCC in ppm.

Figure 3b (right) shows the determination of the working standard TCCs from the reference standards at 100 kHz. A build-up of the working standards is currently underway.

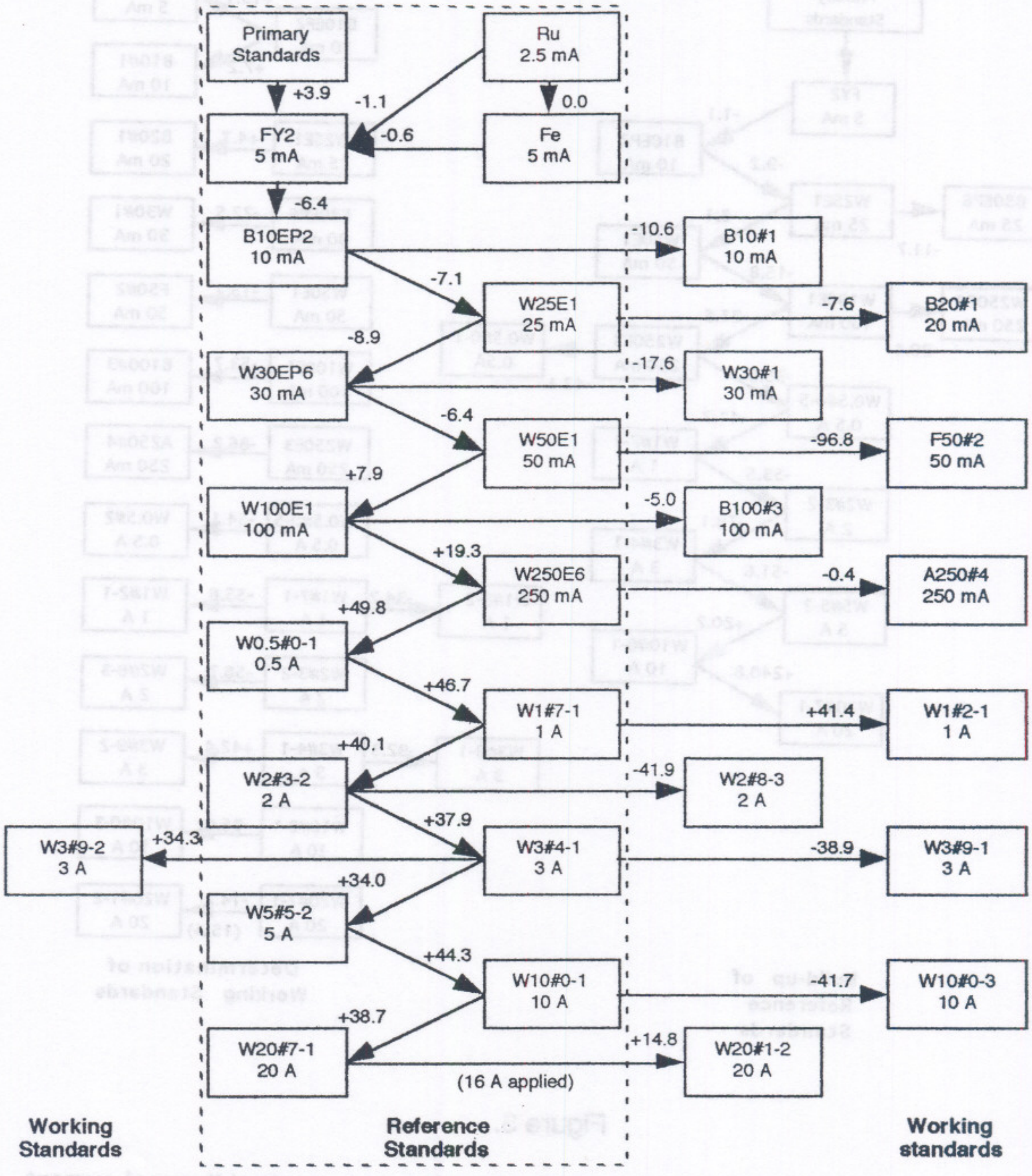

Figure 4. Build-up of reference TCCs from 5 mA to 20 A at 10 Hz and determination of working standards relative to the reference standards. The reference standards build-up is shown enclosed in the dashed box. The arrows point from the reference TCCs to the working TCCs and the numbers indicate the ac-dc difference of the test unit in ppm.

Table 1.

Summary of Uncertainty Analysis
for Reference Standards at 100 kHz

Primary Standards: $$U_{primary} = 1.4\,ppm$$

Each build-up step from 5 mA through 1 A: $$U_{0'} = 6.8\,ppm$$

5-mA Level: $$U_{5mA} = \left(U^2_{primary} + U^2_{0'}\right)^{1/2} = 6.9\,ppm$$

10-mA Level: $$U_{10\,mA} = \left(U^2_{5mA} + U^2_{0'}\right)^{1/2} = 9.7\,ppm$$

$$\vdots \qquad \vdots$$

1-A Level: $$U_{1A} = \left(U^2_{500\,mA} + U^2_{0'}\right)^{1/2} = 20.4\,ppm$$

Each build-up step from 2 A to 20 A: $$U_{0''} = 8.8\,ppm$$

2 A Level: $$U_{2A} = \left(U^2_{1A} + U^2_{0''}\right)^{1/2} = 22.2\,ppm$$

$$\vdots \qquad \vdots$$

20 A Level: $$U_{20A} = \left(U^2_{10\,A} + U^2_{0''}\right)^{1/2} = 28.4\,ppm$$

The uncertainty for the 100-kHz primary standards is given as $U_{primary}$. The contribution for each build-up step from 5 mA to 1 A is $U_{0'}$, and from 2 A to 20 A is $U_{0''}$. Uncertainties listed are for 2σ.

Table 2.

Summary of Uncertainty Analysis
for Working Standards at 100 kHz

Each comparison from 5 mA through 1 A: $W_{0'} = 6.9\,ppm$

5-mA Level: $$W_{5mA} = \left(U_{5mA}^2 + W_{0'}^2\right)^{1/2} = 9.6\,ppm$$

10-mA Level: $$W_{10\,mA} = \left(U_{10\,mA}^2 + W_{0'}^2\right)^{1/2} = 11.8\,ppm$$

$\vdots$

1-A Level: $$W_{1A} = \left(U_{1A}^2 + W_{0''}^2\right)^{1/2} = 21.5\,ppm$$

Each comparison from 2 A through 20 A: $W_{0''} = 8.8\,ppm$

2-A Level: $$W_{2a} = \left(U_{2A}^2 + W_{0''}^2\right)^{1/2} = 23.9\,ppm$$

$\vdots$

20-A Level: $$W_{20A} = \left(U_{20A}^2 + W_{0''}^2\right)^{1/2} = 29.7\,ppm$$

The uncertainty for each comparison from 5 mA to 1 A is $W_{0'}$, and from 2 A to 20 A is $W_{0''}$. Uncertainties listed are for 2σ

Table 3.

Summary of Uncertainty Analysis
for Reference Converters at 10 Hz

Primary Standards: $$Y_{primary} = 0.8\,ppm$$

Cluster converter characterization at 5 mA $$Y_0 = 5.1\,ppm$$

Each build-up step through 250 mA $$Y_{0'} = 5.0\,ppm$$

10-mA level $$Y_{10\,mA} = \left(Y_0^2 + Y_{0'}^2\right)^{1/2} = 7.1\,ppm$$

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250-mA level $$Y_{250\,mA} = \left(Y_{100\,mA}^2 + Y_{0'}^2\right)^{1/2} = 13.5\,ppm$$

Each build-up step through 20 A $$Y_{0''} = 9.1\,ppm$$

500-mA level $$Y_{500\,mA} = \left(Y_{250mA}^2 + Y_{0''}^2\right)^{1/2} = 16.3\,ppm$$

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20-A level $$Y_{20\,A} = \left(Y_{10\,A}^2 + Y_{0''}^2\right)^{1/2} = 27.6\,ppm$$

The uncertainty for the cluster converter is given as Y_0. The contribution for each build-up step from 5 mA to 250 mA is $Y_{0'}$, and from 500 mA to 20 A is $Y_{0''}$.

Uncertainties listed are for 2σ.

Table 4.

Uncertainty Analysis for Working Standard Current Converters at 10 Hz

Each comparison from 5 mA through 250 mA: $Z_{0'} = 3.0\,ppm$

5-mA Level: $$Z_{5mA} = \left(Y_{5mA}^2 + Z_{0'}^2\right)^{1/2} = 3.1\,ppm$$

10-mA Level: $$Z_{10\,mA} = \left(Y_{10\,mA}^2 + Z_{0'}^2\right)^{1/2} = 7.7\,ppm$$

$\vdots$

250-mA Level: $$Z_{250\,mA} = \left(Y_{100\,mA}^2 + Z_{0'}^2\right)^{1/2} = 13.8\,ppm$$

Each comparison from 0.5 A through 20 A: $Z_{0''} = 4.4\,ppm$

0.5-A Level: $$Z_{0.5\,A} = \left(Y_{0.5\,A}^2 + Z_{0''}^2\right)^{1/2}$$

$\vdots$

20-A Level: $$Z_{20\,A} = \left(Y_{20\,A}^2 + Z_{0''}^2\right)^{1/2} = 27.9\,ppm$$

The contribution for each comparison from 5 mA to 250 mA is $Z_{0'}$, and from 500 mA to 20 A is $Z_{0''}$. Uncertainties listed are for 2σ.