

RECENT DEVELOPMENTS IN THE NIST AC-DC DIFFERENCE CALIBRATION SERVICE FOR THERMAL TRANSFER STANDARDS*

Thomas E. Lipe
Electricity Division
National Institute of Standards and Technology[†]
100 Bureau Drive, Mail Stop 8111
Gaithersburg, MD 20899-8111

Phone: (301) 975-4251, FAX: (301) 926-3972, Email: thomas.lipe@nist.gov

ABSTRACT

This paper presents a brief summary of the ac-dc difference calibration service for thermal transfer standards at the National Institute of Standards and Technology in Gaithersburg, MD. Related topics discussed include automated calibration systems, research into a new cryogenic thermal transfer standard, fabrication of thermal converters using semiconductor processing techniques, and a high-voltage comparator system based on a binary inductive voltage divider.

Keywords: ac-dc difference, binary divider, current shunt, thermal converter, thermal transfer, transition edge sensor

INTRODUCTION

Ac voltage and current are most accurately measured by comparing the heating effects of the unknown alternating signal to those produced by a known dc signal of a magnitude equivalent to that of the root-mean-square (rms) value of the ac quantity. The devices generally used to make this comparison are thermal voltage and thermal current converters (TVCs and TCCs) which are useful, with varying uncertainties, from a few hertz to many hundreds of megahertz. These devices usually consist of a heater structure, which alternately carries the ac and dc signals to be compared, and one or more thermocouples spaced along the heater to monitor its temperature. By applying ac and both polarities of dc in a timed sequence, and measuring the thermocouple output, one can use the conventional definition of ac-dc difference, δ , as

$$\delta = 10^6 \times \frac{(Q_d - Q_a)}{Q_d} \quad (1)$$

where Q_d is that value of dc which, when applied with positive and negative polarities, produces the same mean response as the rms ac quantity Q_a .

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[†] Electronics and Electrical Engineering Laboratory, Technology Administration, U. S. Department of Commerce.

THE NIST CALIBRATION SERVICE FOR THERMAL TRANSFER STANDARDS

NIST in Gaithersburg, MD, provides calibration services for ac-dc thermal transfer instruments at voltages from 200 mV to 1000 V, at currents from less than 1 mA to 100 A, and for frequencies from 5 Hz to 1 MHz [1]. Figure 1 shows this parameter space with the appropriate approximate uncertainties. This paper describes only the calibration service at NIST-Gaithersburg; calibrations of thermal converters at frequencies exceeding 1 MHz are performed at the NIST facility in Boulder, CO.

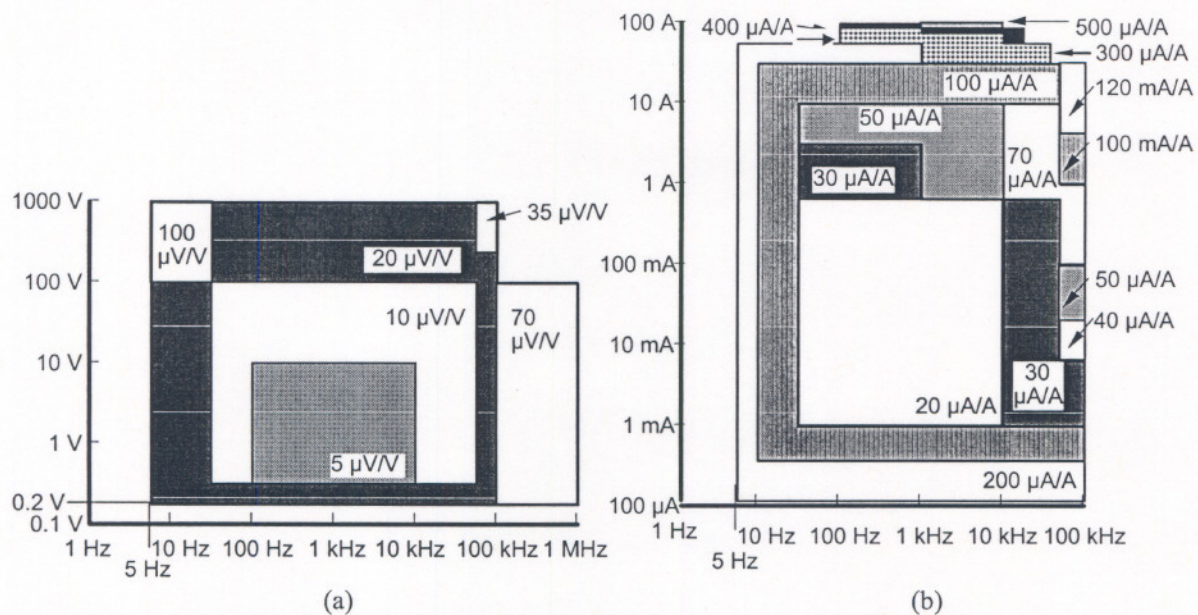


Figure 1. Parameter space for NIST-Gaithersburg ac-dc difference calibrations for voltage converters (1a) and current converters (1b). Approximate divisions in the expanded uncertainty ($k = 2$) available to calibration customers are shown.

The characterizations of thermal transfer standards over the entire parameter space are based on:

- a group of primary standards composed of multijunction thermal converters (MJTCs) [2]
- a high frequency extension procedure based on carefully made coaxial converters
- a low frequency extension procedure based on multiple-thermoelement modules operated at low heater temperatures, and
- range-to-range build-up and build-down bootstrap measurements.

A diagram of the overall process for characterizing NIST thermal voltage converter standards is shown in Figure 2.

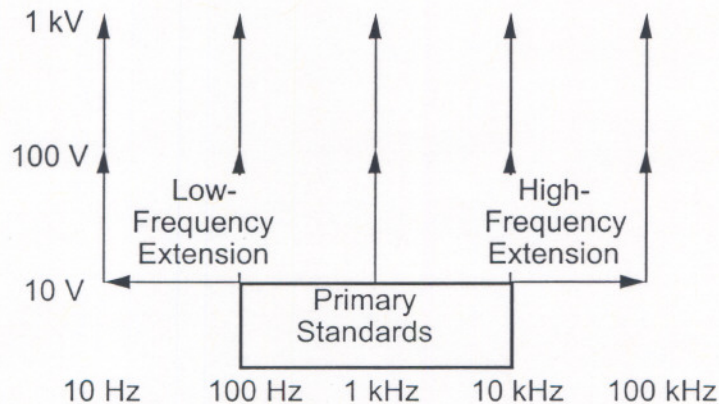


Figure 2. Build-up diagram for voltage, showing the frequency extensions.
The current converter build-up is similar.

The NIST reference standards for ac-dc difference are a group of single-junction thermal converters (SJTCs) [3]. For voltage measurements, these converters consist of single-junction thermoelements (TEs) which are used in series with carefully-made, high-precision multiplying resistors for voltages greater than 1 V. For current, the reference standards are a set of high-current thermoelements [4]. These reference standards are calibrated against the MJTC primary standards once per year.

In general, the reference standards are not used to perform customer calibrations, except for specially requested low-uncertainty points. For customer calibrations, NIST employs a set of working standards for both voltage and current [5]. NIST working standards for voltage are also SJTCs, but the two TEs in the working set have different current ratings, allowing each multiplying resistor in the set to be used at two different voltages. The working standards for current are, again, high-current thermoelements. The working-set standards are checked against the reference standards twice per year. The combination of separate build-up paths for the reference and working converters and crosschecks between the paths offers an excellent method to maintain the quality of the calibration service.

The uncertainty analyses for the NIST standards include contributions (such as the performance of the calibration systems and the errors from the thermal converters themselves) combined using the square root of the sum-of-the-squares (RSS) method [6-8]. For the calibration of customers' TVCs, additional uncertainty elements, depending on the type of converter structure, are combined by RSS with the uncertainties for the NIST standards. Recent re-evaluation of the NIST reference and working standards have prompted a reduction in uncertainties for both voltage and current calibrations, at some points by a factor of five or more.

THE NIST AUTOMATED COMPARATOR SYSTEMS

The present generation of NIST automated thermal transfer standard calibration systems was inaugurated by a prototype system designed and assembled in the early 1980s [9]. Although intended for testing new thermal sensors, it became obvious that this automated system was also ideal for routine ac-dc difference measurements as part of the regular NIST calibration service for voltage converters. Accordingly, it was employed for some routine calibrations in early 1984. As a result of the success of this system, a second automated system was assembled and used for routine voltage calibrations beginning in 1985. A third automated system, initially intended for current calibrations, was assembled in 1998. Because of the recent availability of high-performance transconductance amplifiers, all three automated systems can be used for both voltage and current calibrations.

Although these three automated systems differ in their exact details, the systems have several common attributes. All have highly stable and precise sources of ac voltage or current and dc voltage or current, an arrangement for switching between the ac and dc signals, and a method of monitoring the outputs of the thermal converters with adequate precision. In the NIST systems, the ac and dc signals are provided by separate sources, although in principle, a multifunction calibrator might serve as a single signal source, and the measurement signals are switched using relays. The millivolt-level output electromotive forces (emfs) of the thermal converters are monitored using sensitive, low-noise digital nanovoltmeters. Various arrangements of ac and dc voltmeters and frequency counters are used to monitor the performance of the systems.

The calibration systems are controlled by desktop computers running a commercially available graphics-oriented system control package, which acts as a "virtual instrument" during the calibration procedure. Data and results are displayed in real time as the measurements proceed. A large part of the system control is performed by recursive calls to subroutines from a main calibration program. The software has extensive native error trapping and file handling routines for archiving data, and is easily modified to accommodate new types of instrumentation and new program structures. Data is written to defined sections of the screen, so that the calibration information is readily available to the user. A photograph of one of the NIST automated systems is shown in Figure 3.

THIN-FILM MULTIJUNCTION THERMAL CONVERTERS

Multijunction Thermal Converters have long been used as primary standards for ac-dc difference measurements because of their extremely small ac-dc differences in the audio frequency range. However, MJTCs fabricated from wire are generally unavailable except to national laboratories, are very expensive, and can be difficult to use. In the last decade, research projects at both NIST and the Physikalisch Technische Bundesanstalt (PTB) have focused on using semiconductor fabrication techniques to design and construct thin-film MJTCs (FMJTCs). The latest design [10], the result of a joint collaboration between NIST and Sandia National Laboratories, features

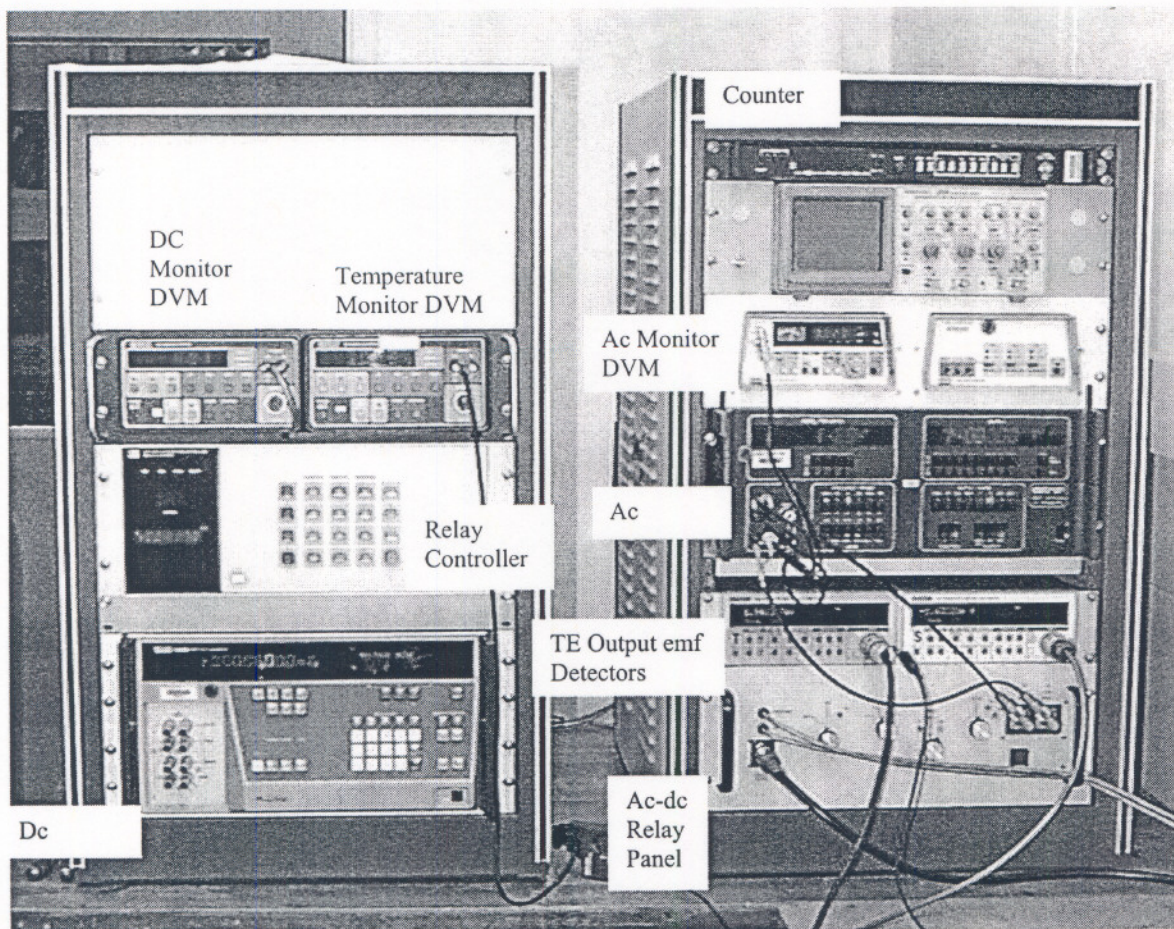


Figure 3. A NIST automated calibration system, showing the various components.

heaters composed of a NiCrAlCu alloy (for voltage converters) or gold (for current converters) deposited over a low-stress silicon nitride membrane. All devices fabricated employ 100 thermocouples of CuNi alloy for the negative leg and NiCr alloy for the positive leg. Deep Reactive Ion Beam etching is used on the backside of the wafer to leave a thin membrane beneath the heater; this creates an isothermal region where the temperature is sensed. A NIST/Sandia thin-film MJTC is shown in Figure 4.

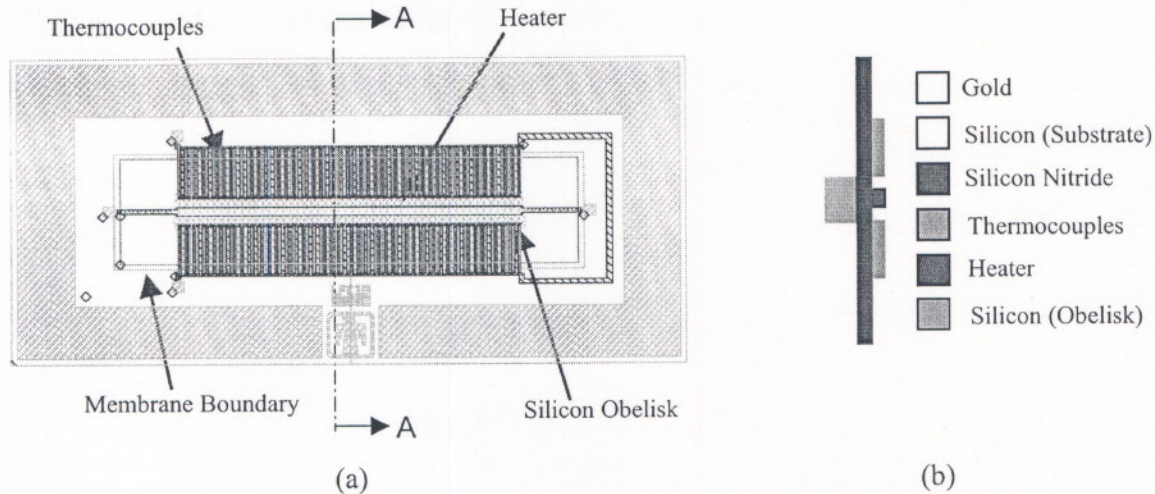


Figure 4. A NIST/Sandia FMJTC (4a) and a representation of the cross-section of the FMJTC (4b) through A-A.

Preliminary data for both an FMJTC with a small obelisk and an FMJTC without the silicon obelisk depicted in Figure 4 are shown in Figure 5. The obelisk is intended to reduce the ac-dc differences at low frequencies by increasing the time constant of the device. This data compares favorably with traditional TVCs at mid- and upper- audio frequencies. Further development of these devices includes provision for mounting the FMJTCs in vacuum. This should facilitate operating the converters at current levels of several amperes or more, a regime presently available only by using current shunts or special thermoelements, and will further reduce the low-frequency error.

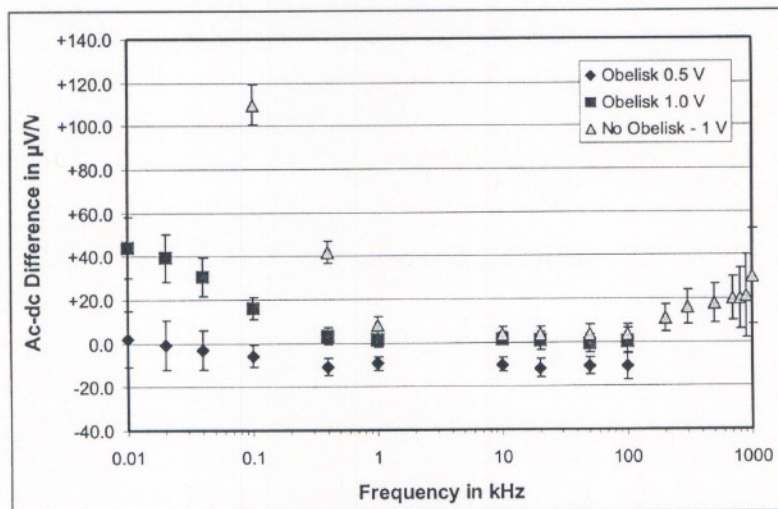


Figure 5. Ac-dc Differences of FMJTCs without a sub-heater obelisk and with a small obelisk at 0.5 V and 1 V applied. Note the reduced low-frequency error of the FMJTC with the obelisk. Error bars are the k = 2 uncertainties of the measurements.

NEW CRYOGENIC TRANSFER STANDARD

The limiting factors for the accuracy of thermal converters at low voltages and audio frequencies are, to a great extent, thermal and thermoelectric effects that are temperature dependent. NIST is developing a thermal transfer standard that operates at temperatures below 10 K, where these thermal effects are expected to be quite small. The Cryogenic Thermal Transfer Standard (CTTS) [11] is especially suitable for use at extremely small input power levels, where an accurate primary standard does not as yet exist.

The CTTS uses a NbTa resistive transition-edge device as its thermal sensor. The critical temperature of the sensor is about 6 K, with a transition region some 3 mK wide. The transition-edge sensor (TES) is deposited on a 1 cm² chip (Figure 6) along with an integrated signal heater and trim heater resistor. The chip is mounted on a temperature-stabilized platform. The resistance of the TES is monitored by a room-temperature resistance bridge, and is maintained in the TES transition region by the closed-loop application of feedback voltage to the trim heater. The input signal is conducted through the vacuum jacket of the cryostat, and through the internal liquid nitrogen (N) and helium (He) shields via a superconducting transmission line, fabricated from crystalline YBa₂Cu₃O_x (YBCO) deposited on a lanthanum aluminate substrate. Since the YBCO is well below its 90 K critical temperature, this transmission line greatly enhances the thermal isolation to the experimental platform while providing better electrical properties than the earlier twisted pair manganin or normal-metal coaxial input leads. A photograph of the cryostat interior is shown in Figure 7.

When the current in the signal heater is switched from ac to dc or vice versa, the resistance of the TES changes slightly. A temperature controller driven by the resistance bridge varies the feedback voltage to return the TES resistance to its initial value. By monitoring the feedback voltage, the ac-dc difference of the CTTS can be determined. Since the sensitivity of a TES to small changes in heater current is roughly 3000 times that of a traditional thermoelement, the CTTS has the potential to be developed into a very sensitive new primary standard of ac-dc difference, particularly at the very low signal levels to which it is well suited. The performance of the CTTS is presently limited by the magnetic fields from the signal and trim heaters, which affect the critical temperature (T_c) of the TES. The result of this T_c suppression is an ac-dc difference that is proportional to the input signal level. A new TES chip, incorporating bifilar heater structures and magnetic shielding to eliminate magnetic pickup, is in the design stage.

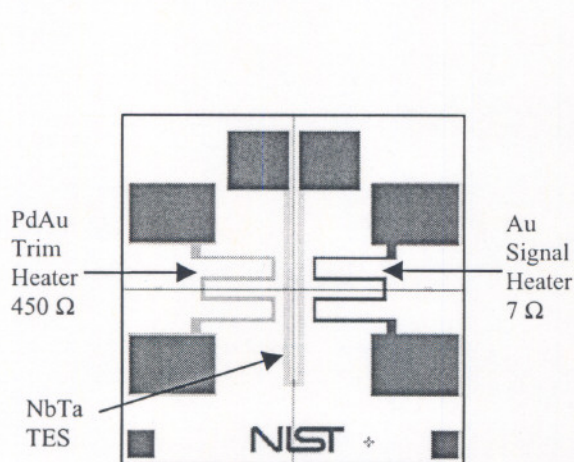


Figure 6. The TES chip.

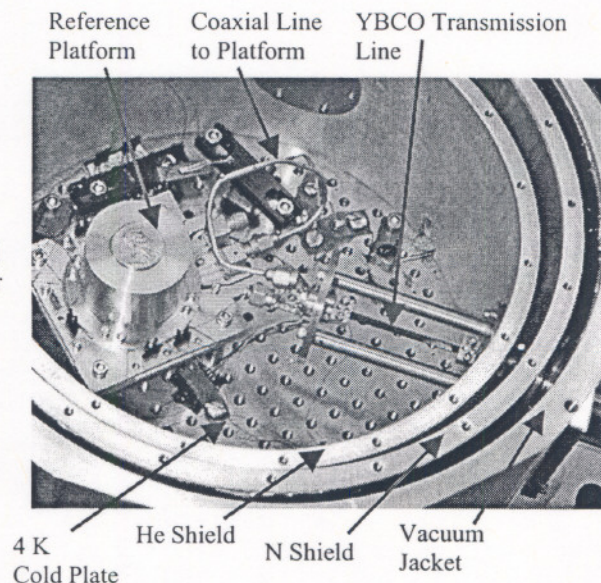


Figure 7. Interior of the cryostat, showing the reference platform and high- T_c input transmission structure.

BINARY INDUCTIVE VOLTAGE DIVIDER

High-voltage thermal converters (HVTCs) are used as standards of ac-dc difference and for the measurement and calibration of ac voltage up to 1000 V and 100 kHz. The build-up procedure illustrated in Figure 2 is used to determine the ac-dc differences of these HVTCs. Assuming that the ac-dc difference of the higher-range HVTC is independent of voltage level, this comparison will yield the values for that HVTC, to within the measurement uncertainty. However, the ac-dc difference of the multiplying resistors used in HVTCs may vary as a function of input voltage level, creating significant errors in the build-up process. Formal and informal international intercomparisons of HVTCs have revealed disturbing variations among some of the participating laboratories. As a result, some National Measurement Institutes are developing calibration methods that are independent of the build-up process. NIST has recently developed a system for comparing high-voltage converters to lower-voltage converters using a binary inductive voltage divider (BIVD) [12]. This system takes advantage of the accurate 2:1 scaling ratio of the BIVD to compare an unknown high-voltage converter to a known lower-voltage converter. This method will complement the traditional build-up procedure to more accurately determine the ac-dc difference of HVTCs.

A circuit diagram of the BIVD system is shown in Figure 8. The system consists of an ac source connected to the top of the divider, and separate ac and dc sources, and nanovoltmeters for the

two TVCs being compared. The TVCs measure the output of the ac sources in terms of the dc sources, and the ratio of the ac sources in terms of the BIVD is also measured using two high-performance digital voltmeters (DVMs), which are used only as transfer instruments. Given the measured output voltages of the ac sources in terms of the dc sources, the ratio error of the ac sources determined by the BIVD, and the departure from nominal ratio of the two DVMs, the ac-dc difference of the higher-voltage TVC relative to the known lower-voltage TVC can be determined. Preliminary measurements on a 500-V HVTC indicate that data taken using this approach agree quite well with values of ac-dc difference determined by the build-up process. Planned improvements to the system include compensation for the variations in loading on the divider, and improvements in the control software.

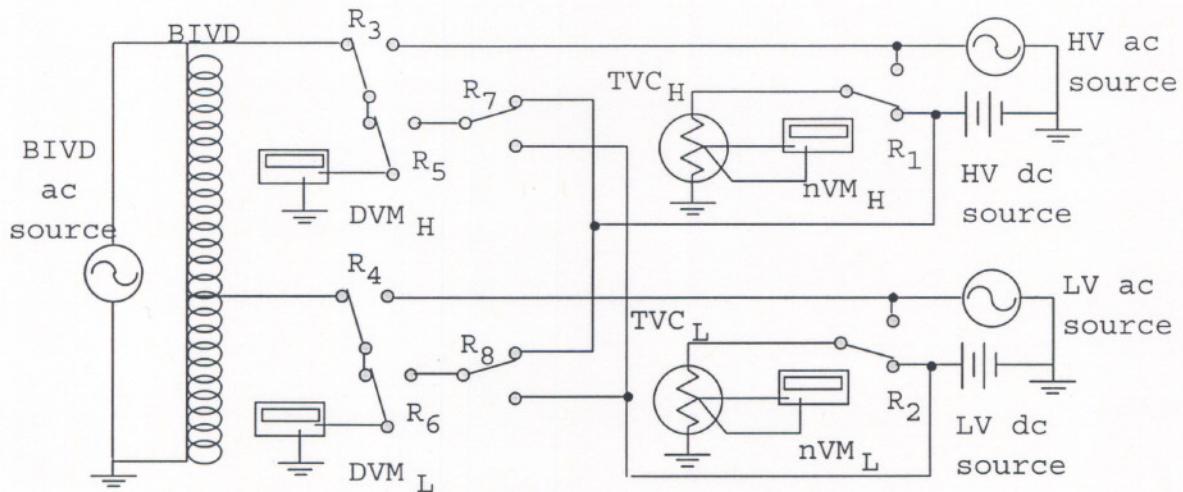


Figure 8. Schematic of the BIVD-based calibration system.

CONCLUSION

The NIST calibration service for thermal current and voltage converters performs calibrations for customers at U.S. National Laboratories, Department of Defense laboratories, and for manufacturers of electronic instrumentation and aerospace equipment. Generally, this calibration service tests some 50 to 75 instruments per year, with an average calibration income of about \$150 000. This paper has presented an overview of this calibration service, including several areas of ongoing research into new and novel thermal transfer instruments and measurement methods.

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