An Improved Transportable DC Voltage Standard

BRUCE F. FIELD, MEMBER, IEEE, AND MICHAEL R. MCCALEB

***Abstract*—Zener-diode-based dc voltage standards can be excellent transport standards for the unit of dc voltage because of their resistance to physical shock and temperature changes. The problems of transporting a unit of voltage and the properties of available Zener standards were studied to develop a set of characteristics we consider essential for an optimum transport standard. We report some of the results of this requirements study, explain the design of our improved transport standard, discuss our efforts to select Zener diodes for the standard, and present data obtained from prototype Zener reference modules to be used in the standard.**

I. INTRODUCTION

OVER THE past six years we have examined the performance of nearly all high-quality commercially available Zener voltage standards for possible use as a transport standard of voltage with transport accuracies of 0.5 ppm or better. While calibrators and digital voltmeters are best calibrated at the 10-V level, traditional instrumentation, potentiometers, standard cells, etc., require a 1.018-V standard. A dual-voltage transport standard is thus required to determine not only the value of the unit of voltage but also the capability of the laboratory to accurately scale between the two voltage levels.

Standard cells are less than optimum as a transport standard because they produce only a single voltage (unless they are connected in series) and are difficult to use because of their sensitivity to physical shock and temperature changes. Also, problems and lack of certain essential features in presently available commercial standards have led us to design our own Zener standard to be used exclusively as a transport standard. Our standard contains four independent references and has been designed specifically for good predictability, minimum power consumption, maximum allowable transportation time, and minimum size and weight.

This paper describes some of the major requirements for a transportable standard and the reasoning behind them based on our experience with similar standards. It details the procedures used to test and select Zener diodes, discusses the design of our standard, and presents performance data on one of the two Zener reference modules that have been constructed.

II. REQUIREMENTS STUDY

The purpose of a voltage transport standard is to determine the difference between the units of voltage at two laboratories. This usually entails calibrating the standard at laboratory A, physically transporting the standard to laboratory B where it is compared to B's unit of voltage, and finally returning it to A where it is recalibrated. The entire process can often be completed in a few weeks. Since a good standard cell group can be used to determine the laboratory voltage difference with an uncertainty of 0.15 ppm (1σ) at the 1.018-V level, a useful Zener standard must be able to determine the difference with better accuracy, at different voltage levels, or with less logistic difficulty. When used as described above, we consider the following characteristics to be essential requirements for a Zener transport standard (see also [5] for greater detail).

A. Predictability of the Output Voltages

It is important that the changes in the standard can be modeled correctly (e.g., a linear drift) during the time of the transfer. Since the transport standard is not being used to maintain a unit of voltage, high stability (zero drift) is not required. Typically Zener standards will exhibit variations about a drift line which will introduce uncertainty in the determination of the voltage difference between laboratories.

B. Multiple Independent Outputs

It is absolutely necessary to use multiple standards, or preferably a transport standard containing multiple independent reference devices, to evaluate the errors associated with transporting the standard. Changes in the relative differences between the multiple references, as measured at both laboratories, can be used as a statistical check of the transportation uncertainty.

Care should be taken in the design of a standard with multiple references to ensure that the outputs are statistically independent of one another, even though they are housed in the same enclosure and probably share some common circuitry. If independence is not achieved between the outputs, the true uncertainty of the transfer will be larger than the value estimated by most common statistical procedures.

C. Battery Operation

Although Zener standards have the potential for being shipped unpowered, thus placing no limits on the time

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The authors are with the National Bureau of Standards, Electricity Division, Gaithersburg, MD 20899.

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required for shipment, most standards (and diodes) exhibit a change in voltage that is of indeterminate magnitude and direction (though possibly zero) caused by the temporary removal of power. Some standards consistently showed small random shifts, less than 0.1 ppm, with repeated power interruptions. This value can be used for those individual standards as a reliable estimate of the uncertainty caused by power interruptions. However, a battery power source capable of supplying power for 48–72 h of operation is generally recommended for shipment.

D. Physical Size and Weight

A transport standard should be of a size and weight that can be easily handled by one person. A Zener standard should thus be no heavier than a typical standard cell enclosure which weighs about 11 kg (13.6 kg with the shipping container).

Standards designed for transport require substantial protection against high g-force shocks, and heavier standards need more protection. As a test, we shipped a number of existing standards in foam-lined shipping containers with ball-and-spring type shock indicators securely fastened to the standards. The combined weight of the standards and shipping containers ranged from 27 to 36 kg. During almost all shipments forces of at least 60 g were encountered, and during one shipment a force of greater than 120 g was recorded. Standards and shipping containers should be designed with this in mind.

E. Sensitivity to Applied AC

Diodes and other nonlinear elements in the circuitry can rectify ac noise introduced at the output terminals of the standard. Noise can come from external sources such as digital voltmeters and can produce a substantial dc shift in the output voltage of the standard whenever the noise source is connected. These shifts have been observed by monitoring changes in a Zener standard with a passive measuring system while the noise source in question is alternately connected and disconnected from the Zener standard under test. A number of commercial standards were tested using a commonly available digital voltmeter as the noise source. These standards showed changes in the range of <0.01–30 ppm when the input of the digital voltmeter was connected to the standard. In each case the outputs immediately returned to their original values when the digital voltmeter was disconnected. We have found that the dc changes produced by individual instruments (e.g., voltmeters) are extremely reproducible from day-to-day and thus reproducible measurements cannot be taken as a sign that there is no problem.

Therefore, the standard must provide adequate protection against applied ac at the outputs. Specifically, common digital voltmeters produce 8 mV of noise peak–peak in the 1 kHz–5 MHz frequency band; all voltage standards should exhibit a change of less than 0.01 ppm when such a digital voltmeter is connected to any output.

F. Temperature Coefficient of the Voltage Outputs

The transportable standard is intended to be measured only in a laboratory environment (23 ± 2°C); its value during shipment is not of interest. The standard should be designed to have a temperature coefficient of any voltage output of less than 0.01 ppm/°C change of laboratory temperature.

G. Quality of the 1.018-V Output

Presently the most stringent transport accuracy requirements result from a need to calibrate standard cells, and this will continue to be true for some time. Therefore, the 1.018-V output should be of at least the same quality as the other output voltages. Since the 1.018-V output is usually obtained using a voltage divider, dividers in transport standards should be of a type that are able to withstand significant physical shock without changing their ratio. For example, traditional wire-wound resistors may be unsuitable; one needs to investigate other techniques: film-resistor dividers, time-division dividers, transformers, etc.

III. DIODE TESTING AND SELECTION

The quality of the voltage output of a standard will be dependent mostly on the characteristics of the Zener diode used as the reference. We have found that all diodes, even those from the same manufacturing lot, exhibit individual characteristics such as day-to-day random scatter, stability, and temperature coefficient. Therefore, selection of a diode to be used in a quality voltage standard requires 100-percent testing of all candidate diodes.

We have identified three diode characteristics that require testing—sensitivity to abrupt temperature changes and/or power interruptions (temperature shock and retrace), change in diode voltage with temperature (temperature coefficient), and noise and stability (day-to-day scatter and drift).

A. Temperature Shock Experiments

It is well known, and some of our early tests have quantitatively determined, that substantial permanent shifts in diode voltage can occur when glass-packaged diodes are subjected to abrupt temperature changes. We tested specially mounted 1N829 diode chips for possible use in our standard. Each chip was hermetically sealed in a TO-100 metal-can package using typical integrated circuit techniques with the internal connections between the chip and the package leads made with fine gold wires. The chip was bonded to the case using conductive epoxy. This type of mounting reduces the stresses usually incurred with chips in glass packages and will presumably reduce the effect of abrupt temperature changes.

To test our assumption about diode packaging, we subjected several groups of 1N829 diode chips, 30 in glass packages and 11 in metal cans, to several temperature shock tests. The first test involved ten glass-packaged diodes that were operated in a temperature controlled oil bath at 30°C ± 0.002°C. The diode voltages were measured once a day for approximately five days, then the temperature of the oil bath was lowered to 10°C over a two-hour period and left at that temperature for 24 h. The diodes were then returned to 30°C, and measurements were resumed for an additional five days. This process was repeated three times and the change in each diode voltage was calculated by subtracting the mean value of the five measurements obtained after the temperature disturbance from the mean value measured before the disturbance. These data are summarized in Table I as tests $1A$, $1B$, and $1C$. A second test was done using 20 diodes of the same type, but the diodes were in a less well controlled air chamber (±0.1°C). The chamber temperature was lowered from 25°C to 10°C, held there for 24 h, and then raised back to 25°C. The changes were calculated as before and are listed in Table I as test 2. A third test using 11 metal-can mounted diodes was conducted in such a manner as to closely simulate the first test and the changes observed are also included in Table I as test 3.

At best, the range of the voltage changes was always quite large. Further, during tests $1A$–$1C$ the changes for any individual diode were not reproducible from test to test. For each group we report the minimum and maximum changes observed, the average value of the group (respecting the sign of the change), and the average magnitude of the change (the average of the absolute values of the changes).

B. Temperature Coefficient

One characteristic of all the diodes we have tested has been their adherence to a model, relating the diode voltage to temperature that was first proposed by Eicke [6]. He reported that

$$\frac{dV}{dT} = \alpha(T - T_0) + \beta(T - T_0)^2 \tag{1}$$

where V is the voltage of the diode, T is the temperature, T_0 is a nominal temperature, β is a constant, and α is a function of the diode current. The relationship between α and the diode current (I), where

$$\alpha = k \log\left(\frac{I}{I_0}\right) \tag{2}$$

is important because it demonstrates that there exists an intrinsic value of current I_0, different, for each diode, where the value of α is equal to zero. If β is also zero then the temperature coefficient will be zero for all values of temperature; if not, then I (and thus α) can be adjusted to obtain a zero temperature coefficient at a particular temperature. We exploit this characteristic in our standard, determining I_0 for each candidate diode, and then setting the diode current during final assembly to a composite value to make the temperature coefficient of the total voltage of the two series-connected diodes nearly zero. For the vast majority of diodes we tested, β was equal to zero to within the measured error.

TABLE I

CHANGE IN DIODE VOLTAGE (IN ppm) CAUSED BY TEMPERATURE SHOCK

	package type	minimum change	maximum change	average change	average magnitude
test 1A	glass	+0.1	+6.0	+3.6	3.6
test 1B	glass	+0.3	+8.0	+4.2	4.2
test 1C	glass	+0.5	+9.0	+4.1	4.1
test 2	glass	-1	+13	+4.7	4.8
test 3	metal	-1.5	+1.8	+0.2	0.7

C. Stability Tests

Noise and stability tests were done in a constant temperature oil bath (39°C ± 0.002°C) with the diodes mounted in sockets and powered by a quasi-constant-current source consisting of a constant voltage source and an individual dropping resistor for each diode. The diode voltages were measured using a version of the NBS Zener calibration system which has a basic accuracy (1σ) of 0.11 ppm [7]. For one group of diodes no pretest aging was done and the diode voltages exhibited exponential drifts that stabilized to mostly linear drifts after about 120 days. To determine if this stabilization period could be shortened artificially, other groups of diodes were subjected to various elevated temperatures, typically 100°C for 20 days, and the temperature was then gradually reduced to room temperature or rapidly changed back and forth several times. These actions did not substantially change the stabilization period required.

IV. DESIGN OF THE TRANSPORTABLE STANDARD

To satisfy the requirement of multiple independent references, our standard has four plug-in reference modules. Each module consists of a printed circuit board that contains all the circuitry required to convert raw dc power into two regulated outputs of 10 and 1.018 V (see Fig. 1). The entire module is only 18-cm long by 8-cm wide by 2.5-cm high and contains the preregulator circuitry, a relay to switch between battery and line operation, a temperature controlled oven, the temperature-control circuitry, and a final regulator stage consisting of two Zener diodes in series and associated resistance networks. Fig. 2 is a simplified schematic of the module. Power to the circuitry is provided by an edge card connector but the stabilized 10- and 1.018-V outputs are wired directly from the card to the output terminal posts. Separate supplies are used for the stabilized output circuitry and the temperature controller.

This design has several advantages over presently available standards: there are no active components in the final stage (other than the Zener diodes themselves) to introduce additional noise, double components (2 diodes in series and 2 resistive dividers in parallel) are used to reduce noise and drift by averaging, and the modules are completely independent of one another.

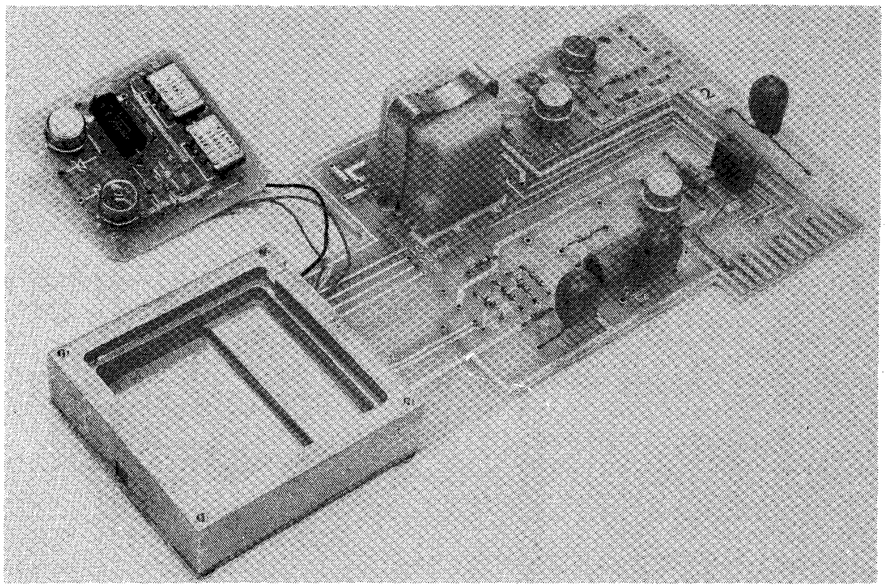

Fig. 1. Photograph of the reference module with the final regulator stage removed from the oven.

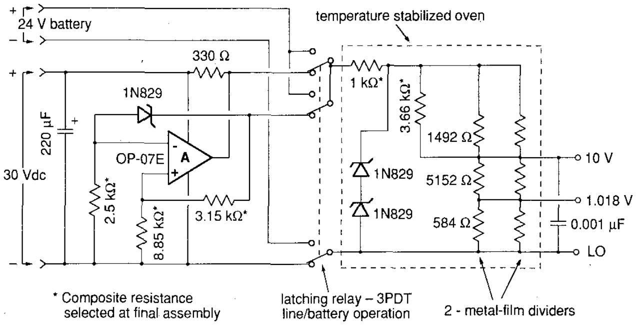

Fig. 2. Simplified schematic of the reference module showing the preregulator and final regulator stage. The temperature controller is not shown.

A. DC Power Supply

A power transformer containing a shielded primary winding and five independently shielded secondary windings is used as the primary power source. Four of the secondary windings are used to power the voltage regulation circuitry on the modules while the fifth winding supplies power for all the temperature control circuits. The shields on the secondary windings are carried through the modules as a guard. Using separate windings helps ensure that the voltage outputs are completely independent from one another and allows them to be freely connected in series or series opposition as desired.

B. Preregulator

The preregulator accepts 30 V ± 0.05 V from the dc power supply and regulates it to within ±0.0002 percent at a voltage of approximately 24 V. It uses a single low-noise op-amp with a Zener diode in the feedback loop to produce a regulated voltage output and simultaneously regulates the diode current. Combinations of fixed-value metal-film resistors are chosen to operate the diode at its zero-temperature-coefficient current as the preregulator is not temperature controlled. This arrangement produces good line regulation; we measured a 40-μV (1.7 ppm) change in the output for a one volt change in the input.

C. Final Regulator

The final regulator is a shunt type of regulator comprised of two Zener diodes in series. All the components of the final regulator are soldered to a small printed circuit board that is mounted in the oven. A resistance network, consisting of a 1-kΩ wire-wound resistor shunted by two series-connected trim-resistors (not shown), connects the diodes to the preregulator. The two fixed-value metal-film trim-resistors are selected to fix the diode current to obtain an overall temperature coefficient of the diode voltage of less than 1 ppm/°C. Two 3-resistor metal-film dividers in 8-pin dual-in-line packages are connected in parallel and driven by the series connected diodes to produce the 10- and 1.018-V outputs. The temperature coefficients of the divider ratios have been measured and they are all under 1 ppm/°C. The top resistor of the divider has been deliberately specified to be too large and is shunted during final assembly with fixed-value metal-film resistors to adjust the outputs to be very close to 10 and 1.018 V. All fixed resistor values are calculated based on the initial Zener diode selection tests and measurements of the divider resistances.

D. Temperature Controlled Oven

The oven is a small, a 51 mm × 51 mm × 15 mm aluminum box mounted on the module PC board and stabilized at 39°C ± 0.005°C by the controller circuitry. The printed circuit board of the final regulator stage sits in a milled ridge around the top of the oven with the components facing down (see Fig. 1). To ensure that both the diodes and dividers are in good thermal contact with the bottom of the oven, the surface has been milled to two different depths to accommodate the different component heights, and silicon grease is used. A piece of Mylar tape is attached to the bottom of the oven to insulate the diodes (which are electrically connected to their cases) from one another.

The oven temperature is controlled by a simple proportional-control circuit consisting of a lower-power Wheatstone bridge with a thermistor as the temperature sensing element feeding a single op-amp dc amplifier which in turn controls two transistors and four metal-film resistor heaters. The heater resistors are small-sized resistors mounted in holes drilled in the sides of the oven. One interesting feature is that the transistors are mounted in holes in the sides of the oven near the resistors. With this mounting arrangement, the power dissipated in the transistors which would normally be conducted to the surroundings is used to heat the oven. This reduces the power consumption and extends the battery operating time.

Special care has been taken to reduce any variable temperature gradients within the oven. The transistors and resistors are mounted on opposite sides of the oven and the components of the final regulator stage are mounted symmetrically about the center line estimated by the heaters. An experiment was performed to measure the change in the temperature gradient within the oven by disabling the heaters on one side of the oven, changing the ambient temperature, and observing the change in the gradient. From these measurements and some simple calculations we estimate that the temperature change of any of the components due to gradient variations should be less than 0.001°C for a 2°C change in ambient.

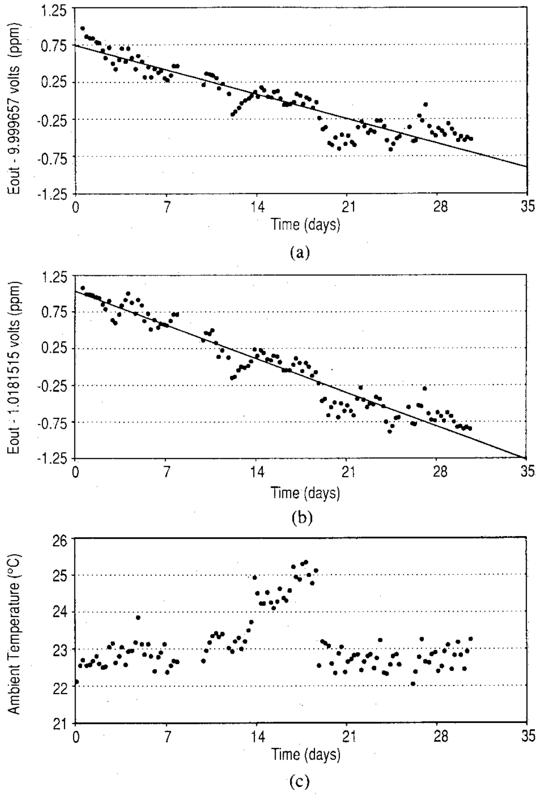

Fig. 3. (a) The 10-V and (b) 1.018-V outputs of one of the reference modules, and (c) Ambient temperature plotted versus time.

The oven was deliberately designed to be as small as possible to minimize power consumption and also to minimize the size of the standard. With a 2.5-cm thickness of surrounding polystyrene insulation, only 22 mW/°C of temperature rise (oven temperature minus ambient temperature) is required to power the oven. In a 23°C environment the Zener diodes and resistors of the final regulator stage provide most of the power required to heat the oven. This prevents us from substantially improving the insulation (and thus reducing the power consumption) as the oven will then overheat.

E. Battery Operation

Under normal operating conditions the standard (modules) operates with power supplied by the ac lines through the shielded power transformer. A latching relay on each module connects the preregulator output to the final regulator stage. When the standard is to be shipped the relays are pulsed (and latched) to disconnect the preregulator and connect the batteries directly to the final regulator stage. Another relay is used to connect the battery to the temperature controllers to provide continuous temperature control.

This arrangement minimizes the battery power used during transportation; however, it does mean that accurate measurements cannot be made under battery operation. Although it is often desirable to operate the standard under battery power while making measurements, we feel that the doubly shielded power transformer provides sufficient isolation for nearly all applications. 24-V batteries are used so that the current through the final regulator diodes under battery power is nearly equal to that normally supplied by the preregulator. The small shift in current that occurs when switching to battery power does not appear to affect the diode voltage permanently once ac line power is restored. We calculate that a 72-watt-h batter (approx. 2.7 kg) will provide 42 h of operation for the complete standard in a 23°C ambient and 19 h in a 0°C ambient.

V. CONCLUSIONS

We have shown that the type of diode package used is important to minimize diode temperature shock or retrace effects, and that the metal-can mounted devices we tested are generally superior to glass-packaged devices. The limited accelerated aging tests we performed did not substantially reduce the stabilization time or improve the drift rate.

We have not as yet completed construction of the entire standard. However, two modules have been assembled and tested for stability. The 10- and 1.018-V outputs of the two modules have been compared to a laboratory Zener standard which in turn was calibrated daily in terms of the NBS volt. The 10- and 1.018-V outputs of one of the modules and the ambient temperature are plotted versus time in Fig. 3. These data were taken starting the first day the modules were powered so the initially high drift rates are not unexpected. Straight lines fitted to the values of the four outputs show standard deviations in the range of 0.17–0.21 ppm, somewhat larger than we had hoped. No corrections have been made for the day-to-day variations of the laboratory Zener used as a reference, and this inflates the observed scatter slightly. Most importantly, the variations in the outputs of the two modules do not appear correlated. On the other hand, there is high correlation between the day-to-day scatter of the 10- and 1.018-V outputs for each individual module, indicating that the noise source is probably the Zener diodes and not the output divider. The observed scatter in Fig. 3 is also consistent with measurements made on the same bare diodes in the oil bath during our stability tests. Therefore, we attribute almost all of the scatter to the quality of the diodes.

From the data of Fig. 3 and similar data from the other module, we estimate that the minimum transfer uncertainty at either the 10- or 1.018-V level for a standard containing four modules will be 0.06 ppm, assuming no transportation effects.

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