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The Development, Use and Performance of the Cropico Electronic Standard Cell

The Weston Standard Cell

The maintenance of the volt has traditionally been based on the Weston Standard Cell which has a temperature coefficient of about - 40 μV/°C at 20°C. The manner of use is determined by the level of accuracy generally required which can fall into three categories.

1) For accuracy levels between ± 10 ppm and ± 100 ppm, an oil filled twin cell enclosure provided with a thermometer suffices.

2) At ± 5 ppm, temperature controlled single cell enclosures are satisfactory.

3) For accuracy levels of ± 1 ppm to ± 3 ppm, a ten or twelve cell bank in an enclosure, temperature controlled at about 30°C to within a few millidegrees, is fairly standard practice. Such banks are usually maintained in conjunction with a portable temperature controlled four cell bank for transfer purposes, and some buffer cells for working.

A single standard cell is useless as a reference source in this context. The standard cell deteriorates at an unpredictable rate with age; it shows random changes in its value, and is very sensitive to mechanical disturbance. This behaviour is well understood and for work of the highest accuracy the use of the controlled twelve cell bank has proved very successful. However the bank of cells must always be held at its correct temperature and must not be mechanically disturbed. If the cells are regularly intercompared they will show individual random variations, but it is hoped that the average value of the group will remain reasonably constant. A true value can be attributed to the average by regularly sending a portable bank to the nearest standardising laboratory. Generally at least one year must elapse and two or three certifications are necessary before confidence can be established in a particular cell bank. Cases are known where all the cells drift together and the establishment of a drift pattern with time is essential.

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The multiplicity of cells in the bank is necessary because of the hazard of rogue cells. Occassionally cells show rapid changes in value and cease to be of use. A twelve cell bank can suffer the loss of three or four cells before replacement of the defectives is necessary.

The most difficult problem is in transferring the value of the volt with a four cell unit. The transfer unit needs very careful handling; some time has to be allowed for stabilization after movement and a successful transfer may take some weeks to effect.

The situation in the U.K. is such that outside the N.P.L., two laboratories have a capability in the region of ± 1 µV, a few are at ± 2 µV and a figure of ± 3 µV is typical of good laboratories. The maintenance of a voltage reference to better than ± 5 µV is expensive in supervision time, and generally laboratories prefer to restrict their capability closely to their actual needs because of cost considerations.

The techniques for maintaining standard cells are fully described in British Calibration Service Publications.

The Cropico Electronic Standard Cell

History The Zener diode has been used as a reference source for very many years, and it has always been looked upon as a possible successor to the standard cell. While it has been used extensively as a reference in digital voltmeters, it has been considered to be inferior to the controlled Weston Cell in performance. Experience shows that Zener diodes tend to be noisy, occasionally jump in value and usually ramp, i.e. their reference voltage drifts continuously. These effects have only been significant when accuracies better than 100 ppm were required.

Stable voltage sources using Zener diodes were developed by the Croydon Precision Instrument Co. (Cropico Ltd.) about 20 years ago for use with their d.c. potentiometers, and these devices were developed in the late sixties to the stage where they could be used as sources for state of the art potentiometers. It was noticed that some of these sources were virtually noise-free and appeared to be more stable than standard cell banks. This led to a long study of the stability of Zener diodes resulting in the construction of a very satisfactory mains operated electronic standard cell in 1972. Unfortunately when dealing with possible reference standards there is no substitute for elapsed time, hence the commercial marketing of such devices was delayed until 1979. During this long period techniques for identifying, treating and operating Zener diodes have been established. Very stable diodes are found only in limited numbers and the rejection rate during selection is extremely high. About six months elapses between the preliminary identification of a possible stable device and its adoption. Evidence indicates that such selected devices show no changes whatsoever other than those due to its temperature coefficient, but we have the problem of obtaining a stable usable reference voltage from them without degradation of performance.

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Development of the Cropico Electronic Standard Cell

A selected Zener diode is virtually noise-free and stable at a particular operating current but has a finite temperature coefficient. Operation at the minimum temperature coefficient is not necessarily compatible with other essential criteria.

We decided that a practical device should be reliable, simple to use, robust so that it could be sent anywhere in the world by post after certification, and also could be left inoperative in adverse conditions for protracted periods. We aimed for a yearly stability of ± 2 ppm, equivalent to that of a good laboratory, and a short time transfer capability of ± 1 ppm or better.

The diode has a 6.5V output but every circuit element between the reference and output inevitably degrades its stability. However it is possible to construct extremely stable low range voltage dividers, so steps down to 1 V and 1.01861 V were chosen, these values being compatible with existing standard cell technology. A 10 V device will be introduced shortly with some degradation of performance due to the operational amplifier necessary.

The existence of a finite temperature coefficient in the diode tempted the adoption of a temperature controlled enclosure held at 30°C but operation at the higher temperature increases noise, affects the stability slightly, introduces thermo-electric effects and requires the introduction of a mains supply. Unfortunately a mains supply is also a source of trouble in the guise of unwanted signals and insulation troubles unless a very high degree of isolation is achieved. We have had extensive experience in the design of such supplies, and although the original prototypes were mains operated and have been in successful operation for many years we believed that battery operation was safer and preferable for a portable device normally inactive. Rechargeable batteries are attractive but they do fail, and they are often discharged when needed, and require a charger. We decided to opt for the U2 cell which although bulky is readily available anywhere in the world at a local retailer.

These considerations led to the adoption of temperature compensation using the base emitter voltage of a transistor. When correctly set this gives a parabolic temperature characteristic somewhat similar in shape to that of a manganin resistor. The flat portion of the curve can be set by the manufacturer at 20°C or 23°C. If set at 20°C the output is within about ± 0.2 ppm between 19°C and 21°C and would be about 3µV low at 17°C and 2µV low at 23°C.

Operation and Performance

The electronic standard cell should be kept in a reasonably stable temperature environment for 6 hours before use. At switch on, the output is about 30µV high and will be within ± 2 ppm of its final value 15 to 20 minutes later and at its final value within 60 minutes. In an environment of 20 ± 0.5°C one may expect the output to remain within ± 0.2 ppm for some time, but there may be a slow drift due to residual ageing in the output resistor network. We expect such changes to be within ± 2 ppm per annum and to reduce with time.

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If the ambient temperature is several degrees higher than the set temperature the output will rise slowly with time, and the converse is true. Slow variations in output indicate varying ambient temperatures. It must be emphasized that we are talking of a few parts in a million; one would not expect measurements to within ± 5 ppm to be carried out in an environment swinging between say 17°C and 23°C.

The Cropico reference consists of a mains operated unit about 7 years old and two battery units 2 years and 1 year old respectively. These are kept in a laboratory controlled to 20° ± 1°C although variations of ± 2°C are experienced. Measurementsare taken when the temperature of the units is within 20°± 0.5°C, a period of several hours every afternoon. The three units can be intercompared within ± 0.1 ppm and never show differences exceeding ± 0.2 ppm, this being the experimental error. The noise level is negligible. Regular certifications from approved laboratories give an uncertainty of ± 1.5 µV in the knowledge of the volt, but subject to this there is no evidence of any change in the value of these units.

Production and Test Procedures

Large numbers of diodes are examined and the most promising selected. These are then subjected to an ageing procedure taking some months. A further selection is carried out and selected diodes are incorporated into the final units. The output is adjusted and the temperature compensation set. The completed devices are left in the uncontrolled factory and may swing in temperature between 5°C and 23°C. It is known that the devices will drift initially, mainly due to ageing of the resistance network. Approximately once a week each unit is brought into the controlled room at about 9 a.m. its value is measured at 3 p.m. and it is then returned to the open factory. This is repeated until each unit agrees with the reference bank within ± 0.2 ppm for some weeks. Generally a period of six months may elapse between first construction and dispatch. An annual stability expected to be within ± 2 ppm represents a change of less than ± 0.2 ppm per month, and elapsed time is an essential part of testing.

Great care has been taken to design out every possible source of instability and drift and we expect any drift to lessen with time. Random changes in output are not expected; such changes have been observed in some devices early in the long test period and have been found to be due to defective components and mechanical defects, however such events lead to continuing improvements in design. Many of these electronic cells have been sent all over the world by means of the normal postal and transport system; none has been damaged in transit.

Causes of Error

Thermo-electric e.m.fs are a serious hazard in state of the art voltage measurements. The electronic standard cell suffers very little from these and having copper terminals, provided copper leads are used and external switch work is of a high quality, no serious problems arise if temperature gradients are avoided. However the device has a long thermal time constant and the

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temperature compensation depends upon the whole device being at the same temperature. If the device is subjected to a sudden step in temperature say of the order of 3°C its output may deviate up to 5 µV and take several hours to settle; slow changes have less effect. Such conditions are rather extreme but rapid air circulation even in a controlled environment can cause troublesome local temperature gradients. It is a well known fact that temperature conditions throughout a large laboratory where people are working may differ substantially; the controller really only controls the temperature at the sensors. For absolutely optimum performance the device can be kept in a cabinet controlled at 20°C ± 0.5°C.

A single electronic standard cell is an almost ideal transfer device. We have found that we can transfer the volt between laboratories in two days with a reproducibility within ± 0.2 ppm. In demonstrating these devices throughout Europe we have taken them directly from the car and switched on, and we have found that the value of the volt given 1 hour later has been without fail within the capability of the laboratory and within extreme limits of ± 2 µV.

The single unit is an ideal buffer or working device because it cannot be damaged by the operator. N.B. When comparing against a Weston standard cell, the electronic standard cell must not be switched off before disconnecting the Weston cell, otherwise the latter will be loaded.

Three of these cells can be used as a reference standard and this has many attractions mainly on the basis of cost effectiveness, they cannot be damaged or overloaded and any one can be used as a portable transfer or working standard. Naturally some time must elapse before sufficient confidence is established in Zener based references for them to wholly supplant standard cell banks but we believe this will come.

We have already made a large number of these devices and do not issue them until we are certain they are well within our specification. However the output is subject to the usual statistical variations; some are extremely good, some are good and the remainder within specification. They are improving steadily.

Acknowledgements

Although this paper has been written by Dr. F. C. Widdis (Director of Cropico Ltd.) it actually describes the work of many people who have been involved in this fascinating project over the years. In particular his fellow directors of Cropico Ltd., Mr. F. W. Dye and Mr. C. W. Potter and the directors and staff of associated companies.

N.B. The information given in this paper is based on experience with the electronic standard cell and is believed to be typical. It does not constitute or supplant the specification which is given in leaflet ESC1/2 April 1980, and the operators Handbook.