contained enclosures for periodic calibration in the national laboratory. In the not-too-distant future, each of these groups will be compared with a subsidiary maintaining group of cells by this same process, and the results obtained printed at the local computer terminal as a part of the full calibration report on the group of cells submitted for calibration. The idiosyncrasies of individual standard cells in any group in an enclosure after being transported up to 3000 km to the national laboratory will still have to be checked and correlated, and for the future this remains a manual procedure. It is not yet possible for us to program a computer to exercise the considered judgement of a well-trained conscientious metrologist, and the automatic intercomparison of groups of standard cells is meaningful only if each of the members of the groups is a stable well-behaved standard cell in its environment. However, the automatic system will considerably lessen the load of very precise measurements to be made on standard cells.

ACKNOWLEDGMENT

The assistance of J. D. Sankey, who is in charge of the local computer, is gratefully acknowledged, particularly for his appreciation of the extent of the possibilities and his urging of the author to make greater use of the facilities available, and secondly for his diligence in programming the computer and in achieving a high level of computer availability with a minimum of down-time.

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A High-Resolution Prototype System for Automatic Measurement of Standard Cell Voltage

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***Abstract*—The conceptual requirements, the design, and the initial performance of the prototype switching for connecting standard cells to an automatic measurement system are described. Features of the design include random selection of two cells at a time, inversion of connection polarity on command, modular construction for expansion, and less than 10-nV residual uncompensated error voltage.**

Also described briefly are controllers for manual operation of the switches and the rudimentary high-resolution digital potentiometer used to complete the measurement system. Results of tests of the switching and observations of the prototype system performance are presented.

I. INTRODUCTION

SINCE their development late in the nineteenth century by Weston [1], [2], standard cells have been employed in maintaining a standard of voltage throughout the world at the highest attainable levels of accuracy. Testing of these cells has long been the domain of highly skilled and dedicated personnel whose efforts brought the world to the level of the "part-in-a-million" volt. The sheer burden of numbers of cells to be tested in recent years, the desirability of employing advanced test programs with computer aided analysis of the data [3], and the recent development of volt maintenance using the ac Josephson effect [4] have led to the need for automating standard cell measurements. Efforts toward this goal have ranged from the simple obvious use of a high-impedance digital voltmeter to elaborate systems employing scanning and achieving resolution on automatic tests of 1 part in 10^7 [5]–[7].

Recently, a project was initiated at the National Bureau of Standards, Gaithersburg, Md., the long-range objective of which is the automation of all measurements necessary to characterize the performance of both standard cells and their enclosures. Levels of precision and accuracy sought are commensurate with the highest requirement likely to arise in the foreseeable future. The purpose of this paper is to describe the development of the prototype system and to describe the initial experience with the system in testing and use. The goal sought for performance of the prototype system is that the error assignable to it be less than 0.01 μV, or 1 part in 10^8 of standard cell voltage.

Manuscript received July 3, 1974; revised August 28, 1974. This paper is a contribution of the National Bureau of Standards and not subject to copyright

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II. SWITCHING REQUIREMENTS

Required for any highly precise automated measuring system is the switching necessary for scanning or interconnecting the various parts of the total system load. For a system capable of meeting future needs, not only must a high order of electrical performance be achieved, but also a sufficient flexibility must be provided to satisfy demands imposed by test philosophies yet in the throes of creation. To meet these performance criteria, a list of requirements was established for the prototype switching which are enumerated as follows along with the associated reasoning.

1) Random selection of cells, two at a time, with either a normal or an inverted polarity was required.

Random selection insures maximum flexibility. Pairing of cells permits intercomparison by difference measurement and produces a left–right sense for optimum use of statistically derived measurement patterns [8]. Polarity inversion, suitably interlocked for protection of the cells, permits a cancellation of nearly all unwanted parasitic voltages.

2) Modular construction with a provision for local use of the cells connected to any module without disrupting the system was required.

Modular arrangement, besides permitting the switching function to be accomplished near the cells involved in the test, also permits a simple change of the system size. Cells may be conveniently addressed by their location within the module complement, the module identifier, the output line identifier, and the polarity identifier. This pattern of operation is readily interfaced to computer control, and a simple highly reliable interlock is possible to preclude accidental switching of cells in parallel or with opposite polarity.

3) Simplified connection within the system using only two pairs of guardable coaxial cables was required.

Use of only two lines to interconnect modules and measuring apparatus permits simplified system wiring and minimizes loading of cells by line impedance. Formation of each of the two lines by a pair of coaxial cables adds shielding and permits a further reduction in impedance loading by driving the shields as guards at the center conductor potential. The use of two contacts per line not only isolates cells which are not being tested, but, by proper arrangement of the switches, permits cancellation of most of the thermoelectric voltage generated in switching.

4) There were several miscellaneous performance requirements:

a) uncompensated thermoelectric voltages must be less than 3 nV;
b) leakage resistance must be greater than 10 GΩ;
c) expected life must be greater than 10 years; and
d) cell circuits must open during power failure.

An evaluation of the available switching methods and hardware showed that many switch designs might be adapted to meet a majority of the requirements. However, the multiple-level individually actuated crossbar switch most nearly met the total requirement. The crossbar switch is advantageous in consideration of the actuating power level and offers a life expectancy of 10^7 actuations, which might approach 100 years in this application. Finally, the crossbar switch is amenable to modification to overcome its major fault which is the level of possible thermoelectric voltage.

III. Construction of the Prototype Switching

To demonstrate the feasibility of the selected crossbar switch, a prototype system has been constructed consisting of three modules each capable of servicing 10 cells. One of the modules is expanded to permit use of a local semiautomatic cell selection. These modules employ commercially available crossbar switches that are modified both in the switch structure and in the materials used in the conducting circuit. Fig. 1 is a simplified diagram of the 6-level switching used for each cell. Levels 1 and 3 are used to guard the voltage switched on level 2; similarly, levels 4 and 6 are used to guard the voltage switched on level 5. Cell leads are connected to levels 2 and 5, and the guards are also switched to minimize possible interaction in the system and unwanted noise pickup. Addition of electrically actuated sections to the switch may be employed to expand the switching for a local or special function. There is also a simple local switch that connects the cell lines to output terminals and disables the automatic switching function.

In any system intended for use in scanning standard cell voltages with high precision, consideration of thermoelectric voltage effects is mandatory and is often the limiting criterion on the level of precision achieved. Briefly, the ideal thermoelectrically quiet system would be entirely of copper. Only slightly less elegant would be a system employing copper, silver, and gold, which can produce thermoelectric effects of 100 nV/K and for which a passive thermal shield is normally adequate. Such materials are not available on crossbar switches now made. Thus modification of the switch structure and careful design of the module are necessary to achieve the design requirements.

The crossbar switches employed are modified to use only beryllium–copper conductors and gold–silver–platinum contacts which are thermoelectrically matched to each other with less than 250 nV/K. This modification limits the critical junctions to the two necessary connections to copper lead wires in each circuit. In addition to connecting pairs of switches in a bucking configuration and using cadmium–tin (low thermoelectric voltage) solder, two methods are employed to minimize thermoelectric effects. These may be most readily understood by reference to Fig. 2, which shows the internal switch construction, and Fig. 3, which shows the switch actuators.

The first method employs a heavier than usual lagging of the switch environment against laboratory temperature. Visible behind the 10-cell switch module in Fig. 2 is the containing case formed of two nested aluminum boxes separated by a layer of foam insulation. The thermal masses of these boxes and of the switch mounting plate, and the low conductivity of the foam insulation, are used to reduce thermal gradients that might be troublesome.

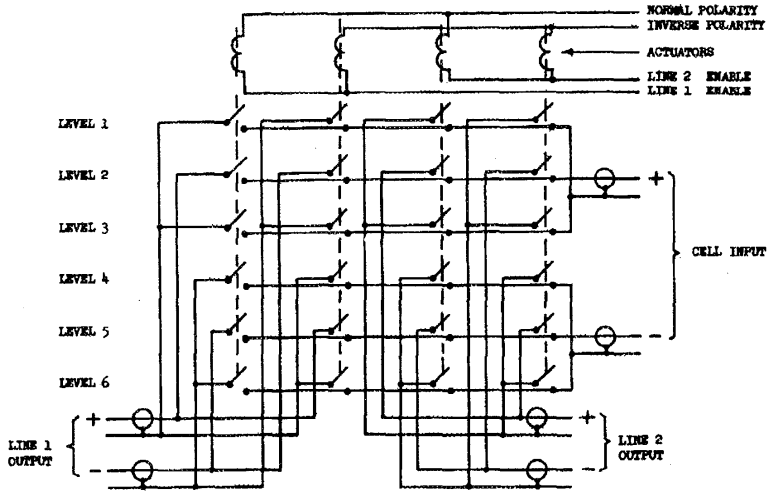

Fig. 1. Simplified switching diagram for each cell.

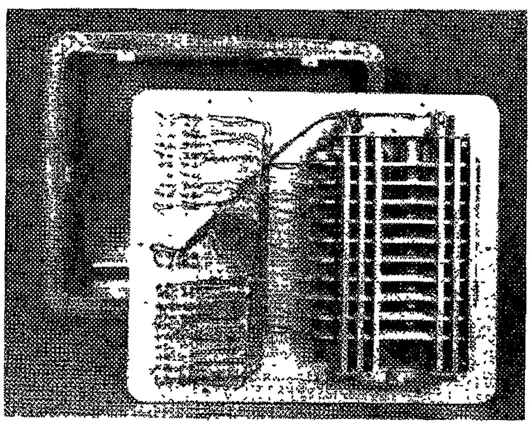

Fig. 2. Internal switch construction.

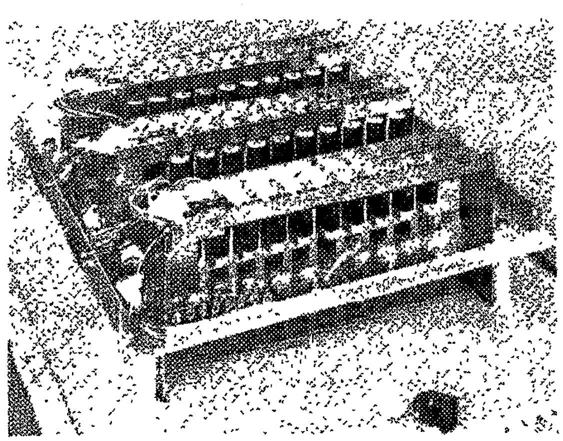

Fig. 3. Switch actuators.

Aiding the filtering action is the high thermal conductivity of the aluminum.

Additionally, critical junctions are heat-sinked inside close-fitting copper sleeves so that the effects of thermal transients are minimized. The added thermal mass also helps to equalize temperatures in the switches. These sleeves can be seen in Fig. 2, as can the rotary switch used to set the local system function of the module.

The final method used is to remove nearby heat sources from the vicinity of the circuitry and to shield them by interposed thermal reflectors. Fig. 3 shows the actuators, which are made remote from the switch proper to minimize heat input from this source. The switch mounting plate and the actuator base plate serve as heat reflectors. Heat from apparatus outside the switch is limited by the lagging and by the physical spacing required by the case. In the particular module shown in Fig. 3, an extra actuator set is used to provide a local/automatic-selection mode.

Fig. 4 shows an assembled switch module. A warning signal is generated when an attempt is made to call a cell and the module has been placed in the local mode. This signal is used to illuminate an indicator light in this particular module. In the local mode, however, an exclusive lockout function is performed and cells cannot be addressed by the system. Shown also are the rows of coaxial connectors used to input the cell voltages to the module, to output these voltages in the local mode, and to interconnect the module to the system. Fig. 5 shows the coaxial connector parts. The core is of copper to minimize thermoelectric voltages, insulation is of Teflon® and noncritical parts are of more common materials. The connector is designed to permit direct connection to a coaxial cable and to preserve the guarding feature.

IV. PROTOTYPE SYSTEM

Assembly of the switch modules into a prototype system requires addition of both system controllers and measuring apparatus. To permit operation of the switching, a manually operated system controller and a local controller were constructed. An exclusive lockout is provided so that

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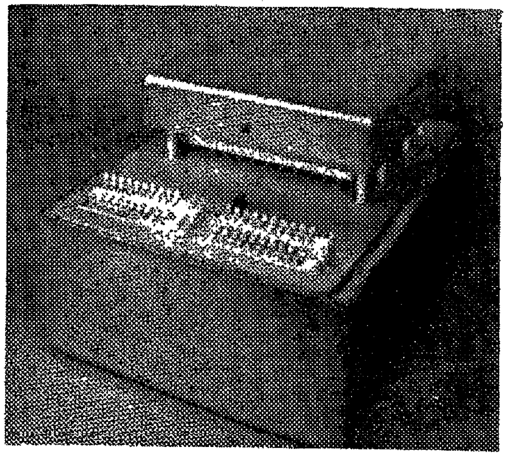

Fig. 4. Expanded 10-cell switch module.

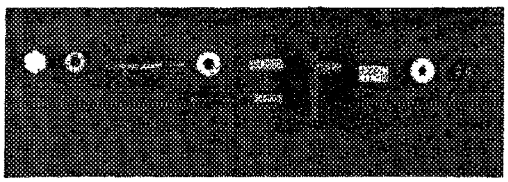

Fig. 5. Guarded coaxial connectors.

when any cell in the system is addressed on a line, no operation. Such a limited life is unacceptable. Thus a additional cell may be addressed on this line until an intentional release has been accomplished. In the manual controllers this function is accomplished by sets of interlocking pushbuttons, but in the computer-controlled operation the exclusive interlock will be generated in the interface.

Logic employed in operation of the prototype system is of the "address-then-wait-and-see" variety. After a cell is addressed, a callback from the switch indicates completion of the switching task. In the manual controller, this callback is used to illuminate an appropriate light. Release of the cell is also indicated as the light extinguishes. Polarity of cells addressed on either line is set by a master polarity switch with a slow-action center-off pattern. All necessary system power is supplied by the controllers. Except for its simpler switching task, the local-automatic controller is identical in operation to the system controller. After assembly of the total automated system, it is anticipated that these controllers will be invaluable in diagnostic testing of individual modules.

The design of a system for high-precision cell voltage measurement entails many considerations, and effort on this phase of the project has been addressed only toward solving some of the more critical problems. One major problem is the switching, which, by the nature of the measurement process, is actuated much more often than that associated with scanning. For example, as might occur in a null-balancing mode of operation, a switch actuated at a rate of 1 per second might exhaust an expected lifetime of 10^7 actuations in only 100 days of measuring logic was chosen in which a null-balance is not obtained and switching is done only to provide 10-μV increments of the voltage difference between the two cells under test. The remaining difference voltage is amplified and digitized directly using a solid-state conversion with an essentially unlimited life expectancy. Such an approach, which is similar to the older deflection methods, requires that the amplifier have a high input impedance to minimize cell loading to a negligible level and provide for accurate measurement.

To complete the prototype of the automated standard cell measuring system, a rudimentary measuring facility was assembled using a precision potentiometer to supply the 10-μV increments. A commercial precision amplifier with digitized output was obtained and modified so that the resolution approaches 10 nV. The input impedance of this amplifier transiently starts at 8 kΩ and rises rapidly to significantly greater than 10 MΩ. This impedance level is sufficient to offer negligible cell loading, lower in fact than can be achieved with a normal light-beam galvanometer and a careful approach to near null-balance.

V. RESULTS

At the time of writing, over a year's experience has been gained in daily use of the prototype standard cell test facility described. Operation has been in the manual mode with visual readout from the digital display because the computer-controller facility is not yet available. During this period, problems have been due to 1) unfamiliarity with the equipment and with provided operational modes, 2) adjustment problems with the crossbar switches associated with the modified structure, and 3) difficulties with ancilliary equipment used to complement the rudimentary measuring system and with cabling interconnections. All of these problems are in the category of expected difficulties, and none has been major.

Estimates of the switching capability based on the testing of component parts indicated that a residual uncompensated thermoelectric voltage level of 1 nV/K had been achieved. Extrapolating to use in a laboratory environment with uncontrolled but modest nearby heat sources indicated that the 3-nV performance level of the design goal had been met. Shown in Fig. 6 is a bar-graph plot of the results of an offset voltage measurement on all active positions of the prototype system in the use condition. Contributions to the plotted figures come from the switching, the interconnecting cabling, and, not insignificantly, the equipment used to perform the special test. It is significant that the mean assignable offset to these measurements is only about 3 nV.

Data obtained using the prototype system indicate that the overall error in measurement that can be assigned to the system proper is less than 10 nV, within the design goal. Also demonstrated in operation of the system is the flexibility of the scanning in fulfilling its intended function. Thus a system can be built which displays measure-

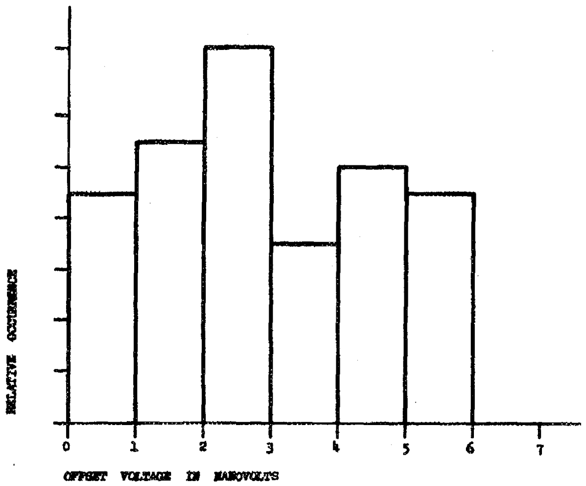

Fig. 6. Magnitude of measured offset voltages in prototype system.

ment capability at the limit of that now envisioned, which is readily flexible, and which is adaptable to new approaches. It should be pointed out that not all of the provisions of the system to ensure measurement excellence have been employed. Specifically, the guarding feature has not been activated and has been employed only as a shield. As the system expands and the workload is increased, however, such a feature can be used to ensure that highest measurement accuracy is maintained.

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A Review of 12 Years of Performance of an Automatic Standard Cell Test Facility

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***Abstract*—Operating experience and difficulties encountered in a 12-year use of the automatic standard cell test facility are reviewed. The facility was designed to accommodate 40 cells on test and to resolve the difference between the voltage of each test cell and that of a reference cell to 0.1 μV. The large amount of data obtained has led to a more complete characterization of cell performance and has identified an unexpected impulse-type response in unsaturated standard cells exposed to a varying thermal environment.**

Difficulties of various types have been expected over the operating period. An unexpected type of failure occurred, however, with snap-action switches used on low-voltage logic lines, and similar failures may be anticipated in new designs.

I. INTRODUCTION

USE OF THE Weston standard cell, which was developed before the turn of this century [1], [2], has undergone a significant increase during the last three decades. Because of the large number of these cells requiring calibration, an automatic standard cell test facility was built at Sandia Laboratories and placed in service in 1961 [3]. This facility offers 0.1-μV resolution, the capability of measuring the voltage of one of 40 cells each 10 min, and an increase in the data obtained leading to a more nearly complete characterization of cell performance [4]. At the present time, when many laboratories are seriously contemplating building automated standard cell test facilities, the extended experience with this early effort should prove useful. Included in this paper are 1) a brief description of the system, 2) a survey of some of the results achieved by use of the system, and 3) an analysis of the various failures experienced during the systems operational history.

Manuscript received July 3, 1974. This work was supported by the Atomic Energy Commission.
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II. AUTOMATIC STANDARD CELL TEST FACILITY

Shown in Fig. 1 is the automatic standard cell test facility. On the extreme left side in one of the ovens used to house unsaturated standard cells during test, and on