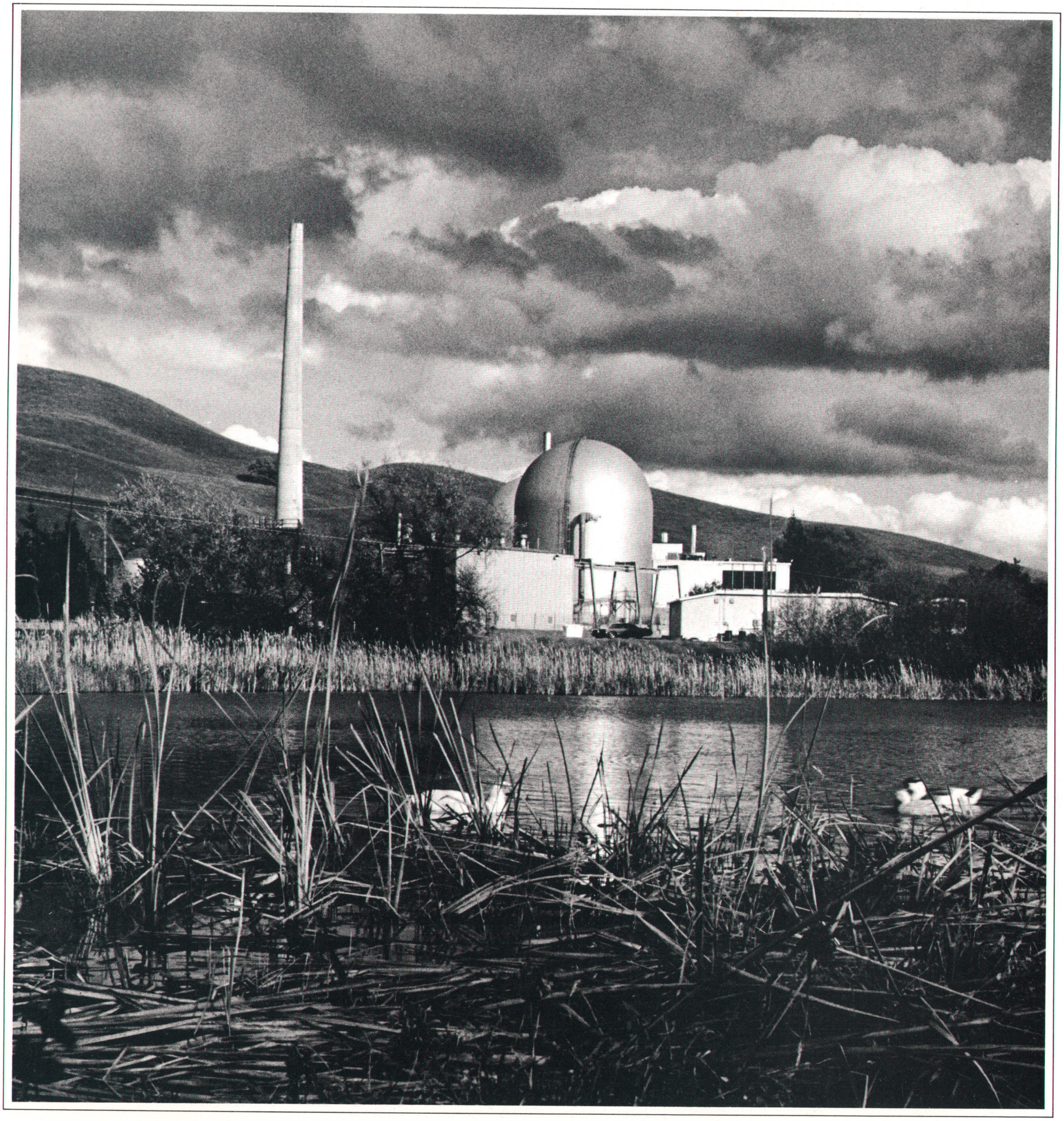
HEWLETT-PACKARD JOURNAL



MARCH 1971

On-Line Data Reduction for Nuclear Analyzers

Sniffing out minute amounts of radioactivity in our environment is just one of the talents of the versatile multichannel analyzer. Here are four multichannel analyzer systems—two of them brand new—that include on-line computing devices capable of anything from straight number crunching to completely automating the analysis.

By Jonathan R. Cross, James A. Doub and John M. Stedman

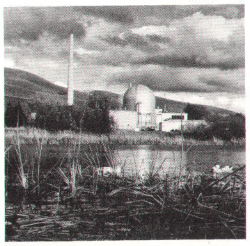
SOME OF THE FIRST 'COMPUTERS' were really pulse-height analyzers. These electronic instruments were developed by nuclear scientists to help identify and classify various radioactive materials. While this is still their principal function, they are also used for a variety of other purposes in medicine, electronics, environmental science, and many other fields.

The contemporary pulse-height analyzer, or multichannel analyzer, is much faster, has much better resolution, and can do much more than those 'rooms full of tubes' of twenty years ago. It collects and analyzes the same kind of data, but it's better data, and there's more of it. Reducing this data—extracting all the information it contains—calls for complex data manipulation on a scale vastly greater than that of the pencil, paper, and slide rule methods of the early days.

Hewlett-Packard is a manufacturer of computers, calculators, and data communications devices as well as multichannel analyzers, and has developed a variety of systems in which analyzers are supported by on-line data reduction facilities. Depending upon his needs, a user can choose a relatively inexpensive system that does data reduction only, or either of two more powerful systems that offer program control of the analyzer along with on-line data reduction, or a super-system which combines the abilities of one or more analyzers with a digital computer. The systems are automatic and easy to use, whether the user is a technician who must repeat an experiment many times for many different samples or a researcher who requires 'hands on' control of the entire data accumulation and reduction process.

Four Types of Systems

The four types of systems and their capabilities are compared in the table on page 3. At the heart of all the systems is the HP 5401B Multichannel Analyzer (or components thereof, in the case of the largest system). The 5401B is a high-speed, high-resolution instrument (200 MHz clock rate analog-to-digital converter, 8192 channels) with very low integral nonlinearity (less than ±0.05%). Readers who aren't familiar with what multichannel analyzers do and how they're used will find more information about them on pages 4 and 6.



Cover: *This is one of the reactors at General Electric Company's Vallecitos Nuclear Center. One of the Hewlett-Packard multichannel analyzer systems described in this issue is used at Vallecitos for nuclear research and effluent monitoring. We thank GE for allowing us to photograph their reactor; we found it a much better model than their tame ducks, which refused to hold still for our cameras. (Their cows weren't very cooperative, either.)*

In this Issue:

Multichannel-Analyzer System Capabilities	5401B/9100 MCA + Calculator	5403A MCA/Calculator System	5402A MCA/BASIC System	5406B Multiparameter Analyzer
DATA ACCUMULATION				
Number of analog-to-digital converters	1	1	1	1–16
Maximum resolution (channels)	8192	8192	8192	24,576
Data accumulation modes:				
Single parameter	x	x	x	x
Multiparameter				x
Multiplex				x
Multichannel scaling	x	x	x	x
Sampled voltage analysis	x	x	x	x
DATA ANALYSIS				
Programming language	calculator	calculator	BASIC	EXECUTIVE
Program storage media	magnetic cards	magnetic cards	paper tape	paper or mag tape
Program console	calculator	calculator	teleprinter	teleprinter
Speed	slowest →			fastest
Software expandability (subroutine language)	calculator	calculator	BASIC, Assembly Language	FORTRAN, ALGOL, Assembly Language
SYSTEM CONTROL				
Analyzer functions programmable?	No	Yes	Yes	Yes
DATA INPUT/OUTPUT				
Calculator peripherals	x	x		
Computer peripherals			x	x
Analyzer peripherals	x	x	x	
Coupler/controller peripherals		x		
PRICE RANGE	$15,300	$19,600	$27,950	$35,000 up

The smallest and least costly of the four systems pairs the multichannel analyzer with the HP 9100A/B programmable calculator. With this system data from the analyzer can be entered directly into the calculator, either under control of a calculator program or at the user's command from the calculator keyboard. After the calculator has performed numerical analysis on the data to extract the useful information, the results can be displayed on the calculator's cathode-ray tube or printed automatically by the calculator printer. A plotter can be added to the system to make permanent copies of the basic analyzer data.

Next come two new and more powerful moderate-cost systems. In the HP 5403A MCA/Calculator System the programmability and computing power are again provided by HP 9100-series calculators, but instead of the one-way interface of the smaller system, there is a two-way interface through the HP 2570A or 2575A Coupler/Controller. The interface gives the calculator random access to the analyzer's memory and control of important analyzer functions, and as a result the system is capable of a much higher degree of automation than the smaller calculator system. Also, the range of peripherals and other instruments that can be added is much wider; besides the calculator peripherals most digital devices than can interface with the coupler/controller can be made part of the system. For example, a teleprinter might be used to produce formatted reports.

Both of the calculator systems are programmed from the calculator keyboard, which is relatively simple to use and requires no previous programming experience. Programs are stored on wallet-size magnetic cards for future use.

In the other new system, the HP 5402A MCA/BASIC System, programmability and computing power are provided by a general-purpose digital computer, the HP 2114. The system is programmed in BASIC, a powerful but easy-to-learn conversational language. Users can easily program complex routines without becoming computer experts. Interfaces for all standard computer peripherals plug into the computer mainframe. The analyzer/computer interface is two-way, allowing the computer random access to the analyzer's memory and remote control of the analyzer. Thus the system is capable of a high degree of automation.

The most powerful of the four types of systems is the HP 5406B Multiparameter Analyzer System. This computer-based system has a modular hardware and software architecture which makes it versatile and efficient. As a multiparameter analyzer it can include as many as four analog-to-digital converters like the one used in the 5401B Multichannel Analyzer. It also has a multiplex mode in which as many as sixteen analog-to-digital converters can be interfaced with the computer. Its software, based upon a unique EXECUTIVE system, can easily be expanded by the user to include his own programs.

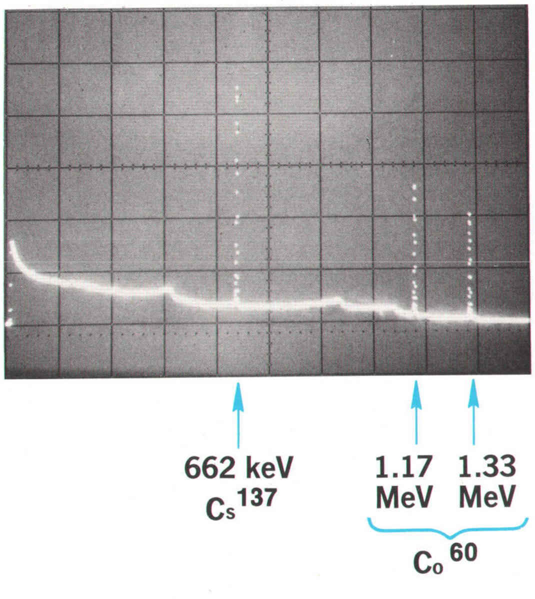
Identifying Radioactive Materials

How multichannel analyzers work and why they need on-line data reduction

Radioactive isotopes may emit many different kinds of radiation, but the kind most useful in nuclear studies is gamma-ray radiation. A gamma-ray photon is emitted by the nucleus of a radioactive atom when a quantum transition takes place between two energy levels of the nucleus. The energy of the photon is the difference between the energy levels involved in the transition. It is a fixed energy, an invariant of nature. A given radioisotope may emit such photons at one or more of these fixed energies, but no two isotopes emit the same combination of energies. Thus each isotope has a distinct gamma-ray energy spectrum, like a nuclear 'fingerprint,' which can be used to identify that isotope if it is present in a sample.

Here's how a multichannel analyzer is used for identifying radioisotopes. The gamma rays emitted by a radioactive sample are sensed by a detector. The detector is a semiconductor diode which emits an amount of charge proportional to the energy of the incident gamma-ray. These solid-state detectors are sometimes cooled to cryogenic temperatures to prevent changes in their structure and to reduce noise. The small amount of charge out of the detector is fed to a charge-sensitive preamplifier which produces a voltage pulse whose height is proportional to the charge. After further amplification and shaping the pulses go to the multichannel analyzer, which measures the height of each pulse, converts it to digital form, and adds one count in whichever memory location, or 'channel', corresponds to that pulse height, or photon energy.

The analyzer, in effect, 'grades' the pulses according to height in much the same way that a truckload of oranges might be graded according to size. If the oranges were allowed to roll down an incline over a series of bins, such that the opening of each bin were a little larger than the opening of the preceding bin, then the smallest oranges would fall into the first bin, those a little larger into the next bin, and so on. One could then plot the number of oranges in each bin as a function of bin number or orange size.



In analogous fashion, after counting pulses for a period of time ranging from minutes to days, depending upon the activity of the sample, the multichannel analyzer displays the gamma-ray spectrum of the sample, which is a plot of total counts versus channel number or pulse height or photon energy. A typical spectrum has one or more peaks in it; the peaks are located at the characteristic energies of the photons emitted by the isotopes in the sample. If an ideal measurement were possible (it isn't), each peak would be very narrow—in fact, it would have no width at all. In real life, limitations of the detector and noise in the electronics, mainly the preamplifier, tend to spread out the peaks into bell-shaped or Gaussian distributions.

A measure of the analyzer's ability to separate closely-spaced peaks is its digital resolution, or the number of discrete channels available to cover the range of energies expected in an experiment. The more channels an analyzer has, the higher is the analyzer's digital resolution. High-resolution analyzers like the HP 5401B have as many as 8192 channels and produce results like the typical spectrum shown here. The peak at 662 keV identifies cesium 137. The two peaks at 1.17 and 1.33 MeV identify cobalt 60. Although the Gaussian shape of the peaks isn't apparent here, the display could be expanded to show it.

Once the analyzer has finished accumulating data, the mean value or centroid of each peak must be calculated to determine the energies of the photons emitted, and the total number of counts under each peak must be found to determine how much of each isotope is present. The latter calculation must be normalized to compensate for varying detector efficiencies and geometries. Thus two apparently simple calculations yield the peak locations and the relative activity at each peak energy.

A closer look at these calculations applied to an actual example shows that the situation is somewhat more complex. Background activity is always present, and this is accumulated along with the data from the sample. The background data may distort the shape of the peak and introduce error into the calculations. To obtain an accurate indication of the activity, the net area of the peak alone must be found. One technique for doing this assumes a straight-line function for the background and subtracts its area from the total, giving the corrected net area. A corrected centroid is calculated using a new peak found by subtracting the background data from the original peak data.

Normalization calculations can also become complex. Detector efficiencies change with energy, so an entire spectrum may need amplitude normalization as a function of energy.

Many more examples of data reduction techniques, such as curve-fitting, normalizing data for nonlinearities in the electronics, peak-to-background (signal-to-noise) enhancement, and so on, appear in current nuclear literature. Many of these calculations can be done quickly and efficiently by an on-line computer or calculator. This is the reason the systems described in this issue were developed.

The Systems In Action

In the following paragraphs each of the four types of multichannel-analyzer systems is described in more detail, and examples are given to illustrate what each system can do.

Analyzer/Calculator System

In the low-cost analyzer/calculator system, a plug-in interface (HP 10667A) makes it possible to read analyzer data into the calculator for processing. Data transfer can be initiated by FORMAT commands from the calculator keyboard or program. All calculator peripherals can be used with the system.

A typical application for an analyzer/calculator system might be found at a nuclear power station. Due in part to increased public concern, tighter standards are being placed on the radioactivity of the effluent from nuclear power plants. The amount of radioactive material that can be released into the environment from such plants is severely restricted, so much so that the most sensitive instruments available are needed to detect and measure any pollution and identify the isotopes responsible. Such instruments include high-resolution solid-state detectors and multichannel analyzers, combined with sophisticated data reduction equipment.

To make certain that radiation limits are not exceeded routine monitoring of gaseous and liquid effluents is necessary. Samples are taken and analyzed for their radioactive constituents by measuring the various types of radiation being emitted. Approximately 50% of the radionuclides of primary concern emit gamma rays. Each sample analysis for these isotopes results in a gamma-ray spectrum on the multichannel analyzer. The analyzer data must then be reduced to determine how much of each radionuclide is present. The efficiency and geometry factors of the radiation detector and the data accumulation time are known factors which are used in the data reduction. The number of counts in a peak in the spectrum, corresponding to the intensity of the gamma-ray radiation at a particular energy from a known isotope, must be converted to suitable units. This information, along with an experiment number, a sample identification number, the time, and detector constants, must be recorded in a standard format.

A simple calculator program recorded on a magnetic card can be used over and over again for both the data reduction and the data recording. Fig. 1 shows such a program. The user simply inserts the program into the calculator via the magnetic card, and enters the proper constants and identification numbers into the calculator via the keyboard. The result is a standard printout for each sample (Fig. 2) showing the required information.

Another experimental record often desired is a normalized plot of the analyzer spectrum, such as the log or square root of the accumulated analyzer data. This plot can be recorded by the HP 9125A Calculator Plotter or its higher-speed relative, the 9125B.

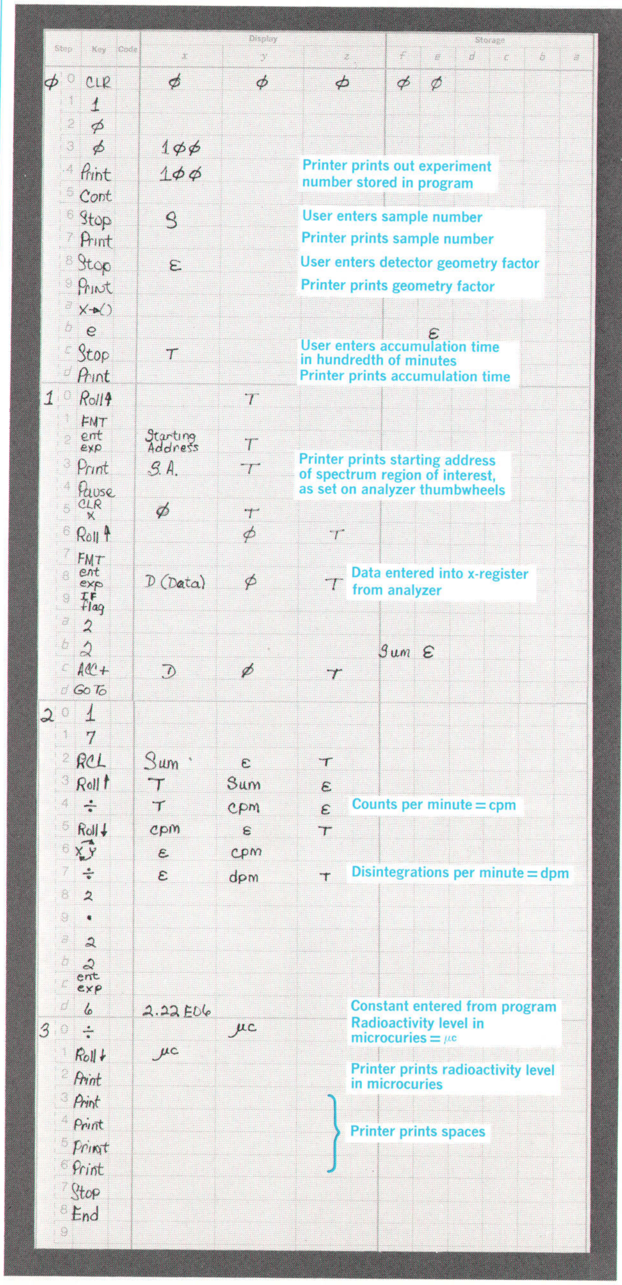


Fig. 1. *Calculator program for calculating isotope radioactivity from the gamma-ray spectrum accumulated by a multichannel analyzer. This program is for the simplest possible analyzer/calculator system, which consists of analyzer, calculator, and interface kit.*

Multichannel Analyzers and People

Multichannel pulse-height analyzers were developed for nuclear research and their principal uses are still in the nuclear field. However, they affect our lives in many other ways, too. Here's a partial list of their applications.

- Radionuclide assay
    - Monitoring nuclear plant effluent
    - Design, test, and construction of nuclear reactor cores
        - fuel-element leakage testing
        - fuel-element scanning to find power-density distribution in reactor core
    - Reactor fuel reprocessing
    - Nuclear materials management and inventory control
    - Nuclear waste disposal control
    - Environmental monitoring and fallout detection
    - Medical diagnosis
        - whole body counting
        - radiopharmaceutical assay
    - Neutron activation analysis (used extensively in pollution studies)
- Nuclear physics research
- High-altitude physics research
- Radiation-shield design
- Reactor physics
- Detector design and test
- Nondispersive X-ray fluorescence
    - Metallurgical surface physics
- Mossbauer spectroscopy
- Magnetic tape testing
- Noise and drift measurements in electronic circuits
- Pulsed-radar return signal analysis
- Particle size analysis (used in pollution studies)
- Medical scintiphotography (organ imaging)
- Time-rate studies
    - Nuclear physics
        - isotope half-life determination
    - Nuclear medicine
        - radioisotope dilution curves
        - hepatic and renal blood-flow measurements
        - liver-function test (external hepatogram)
        - kidney-function test (renogram)
- Prospecting
- Process control
- Communications-link analysis
- Optical transmission analysis.

Several often-used nuclear data reduction programs are available for the analyzer/calculator system. These include routines which calculate the net area under spectral peaks, the full width at half the maximum height (FWHM) of the peak, and the centroid of the peak. Many other routines can be written by the user, of course. For very long programs the HP 9101A Extended Memory may be needed. It increases the number of storage registers in the calculator system by 248; this is enough to store $248 \times 14 = 3472$ program steps.

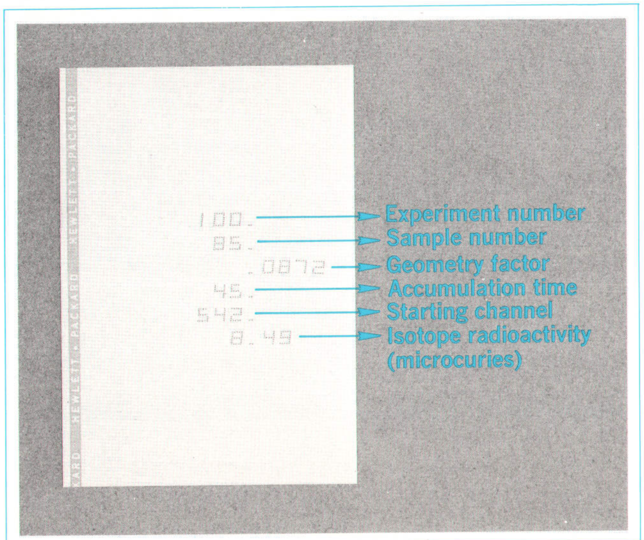


Fig. 2. *Printout from program of Fig. 1.*

HP 5403A MCA/Calculator System

The HP 5403A System consists of an HP Series 9100 Calculator, an HP 2575A or HP 2570A Coupler, an HP 5401B Multichannel Analyzer, and interface boards which plug into the coupler and connect to the calculator and the multichannel analyzer. In addition, peripherals such as teleprinters, high speed paper tape punches and tape readers, digital printers or additional multichannel analyzers can be added to the system by means of interface boards that plug into the coupler. Calculator peripherals such as the HP 9120A Printer, the HP 9125A/B Plotter and the HP 9101A Extended Memory are compatible with the system, as are existing peripheral devices which connect directly to the multichannel analyzer. Fig. 3 is a photograph of a 5403A system.

All of the components in this system can be controlled from the calculator program or keyboard via FORMAT command sequences, or the PRINT command in the case of the HP 9120A Printer. Multichannel analyzer functions which can be controlled from the calculator include the ERASE, ACCUMULATE, DISPLAY, Serial Output, Parallel Output, Serial Input, and TRANSFER modes, and START and STOP. In addition, the calculator can access any memory channel in the analyzer and read or write data into the channel, can transfer data between the analyzer and a coupler peripheral or the calculator, and can check the operat-

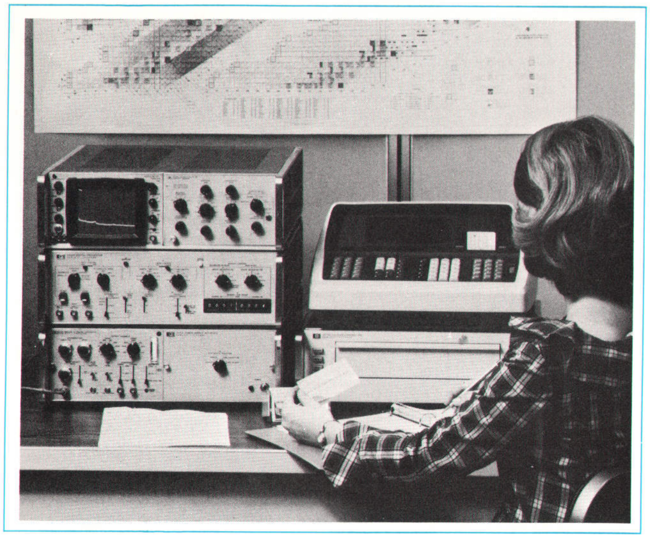


Fig. 3. *HP 5403A MCA/Calculator System consists of analyzer, coupler/controller, and calculator. This system is capable of a higher degree of automation than the minimal analyzer/calculator system. The two-way coupler permits calculator control of analyzer functions as well as transfers of data among the analyzer, the calculator, and peripheral devices.*

ing status of the multichannel analyzer.

As an example of what the system can do, take the nuclear-power-station monitoring problem again. With the small analyzer/calculator system the analyzer had to be set up manually by the user. The calculator program had to be rerun for each peak in the resulting spectrum, and the user had to enter the time, the detector constants, and other parameters manually.

The 5403A system, on the other hand, can do the entire job automatically, with the calculator program controlling the data accumulation, processing, and recording. Little training is required to operate the system once the program is written, since the program can be stored on wallet-size magnetic cards.

In the typical situation, repeated measurements are required on the activity of effluent samples. The data accumulated must be analyzed to determine what the activity of several isotopes in the sample are, and the data must be recorded on a peripheral device in a suitable form. If the activity of the source exceeds a certain value, an indicating device is to be triggered.

Shown in Fig. 4 is a flow chart indicating how the 5403A system would solve this problem. Once the instruments are set up and the program is entered into the calculator via a magnetic card the operation is automatic. The crystal-controlled timer in the analyzer can be preset from the calculator for any accumulation time up to 9,999 minutes, in 0.01-minute increments. The

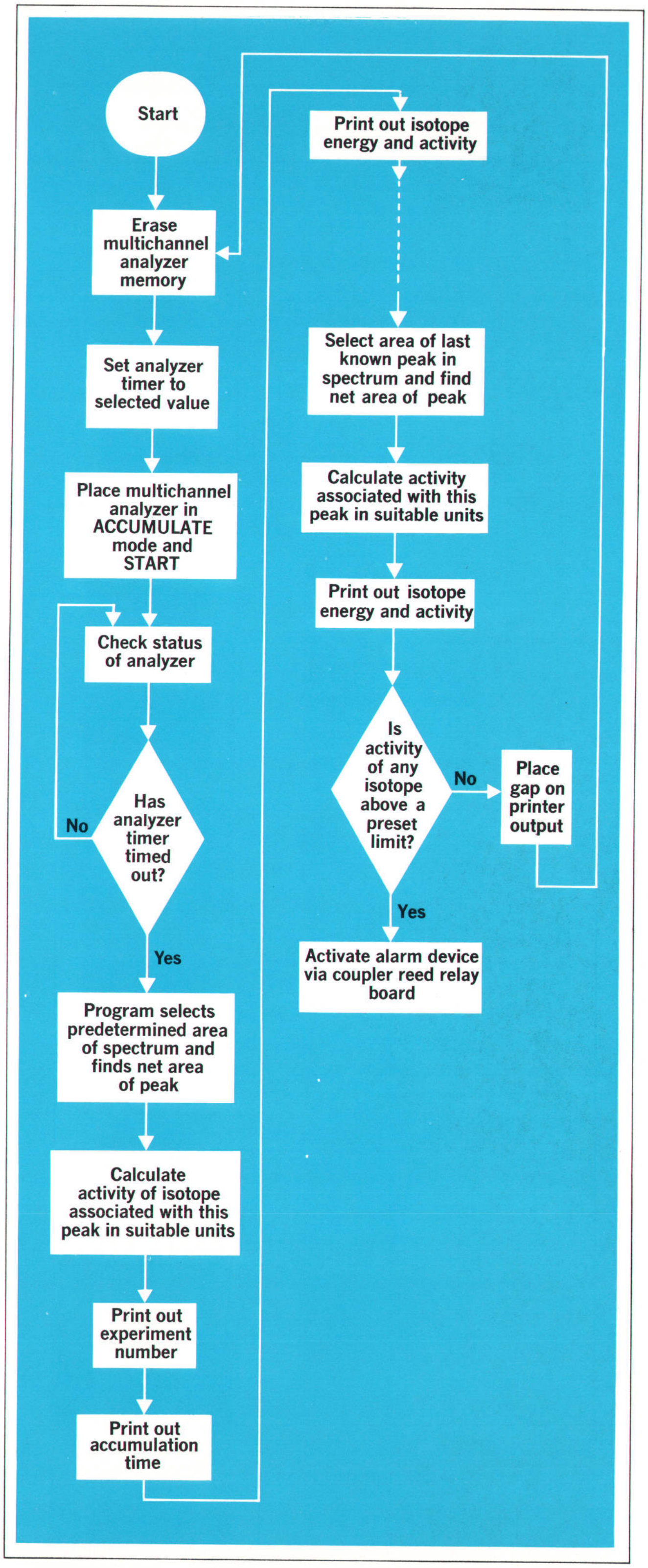


Fig. 4. *Flow chart of calculator program for analysis of gamma-ray spectrum by HP 5403A MCA/Calculator System. The calculator controls the analyzer, computes the activity of all known isotopes in the sample, and triggers an alarm if the activity of any isotope is above a limit.*

random-memory-access feature of the multichannel analyzer allows the calculator to take data from selected portions of the accumulated spectrum for data reduction and analysis. The data is then recorded in a suitable format on the data recording device. If the data indicates isotope activity higher than is allowed, the calculator can command the coupler to trigger an alarm.

There are many other applications for the 5403A System, for on-line data reduction as well as automatic control of experiments. Several application programs have been written to help reduce analyzer data. One of these is for spectrum stripping. Here a known spectrum is multiplied by a constant for normalizing, and is subtracted point by point from a measured spectrum. The result is then written back into the analyzer memory in place of the measured spectrum. This type of data reduction technique is useful in lower-resolution systems to identify the various isotopes represented in an unknown spectrum. Two address registers are provided on the analyzer/coupler interface for ease in programming such routines as spectrum stripping and integration.

HP 5402A MCA/BASIC System

The HP 5402A MCA/BASIC System combines the capabilities of the 5401B Multichannel Analyzer with the versatility of a general-purpose digital computer. BASIC-language programming guarantees that the user does not have to become involved in how the computer operates.

The HP 5402A System (Fig. 5) consists of an HP 5401B Multichannel Analyzer, an HP 2114 Computer with 8192 words of core memory, a teleprinter, and interfaces. The computer and the analyzer can perform either as stand-alone instruments, or together as a system with the computer controlling the analyzer and doing data reduction. For larger applications, several analyzers can be controlled by one computer.

With the analyzer's FUNCTION switch in the EXTERNAL position, major functions of the analyzer can be controlled by the computer. These include START and STOP, and the ERASE, ACCUMULATE, DISPLAY, Serial Output, Parallel Output, Serial Input, and TRANSFER modes. In addition, the computer can randomly access any channel of memory in the analyzer and transfer a word of data between that analyzer channel and the computer, or transfer blocks of data between the analyzer and a computer peripheral. The operating status of the analyzer can also be monitored by the computer's BASIC program.

HP Instrument BASIC is a computer language which

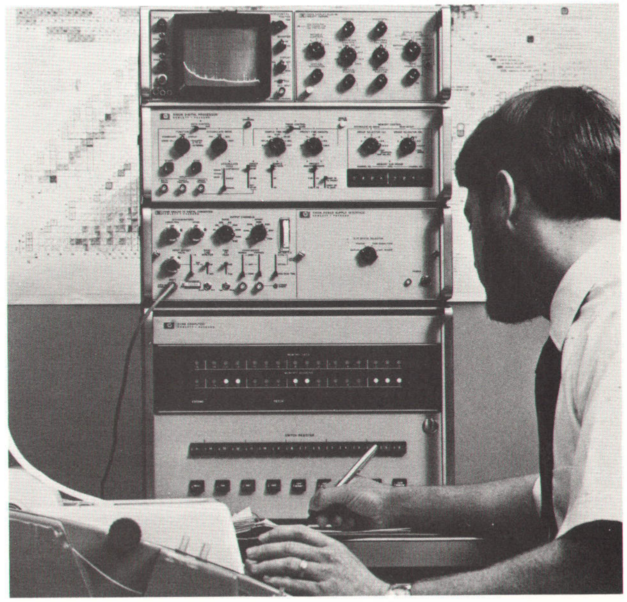


Fig. 5. *HP 5402A MCA/BASIC System consists of analyzer, general-purpose digital computer, teleprinter, and interfaces. BASIC-language programming makes the system easy to operate. The analyzer and computer can be used separately or together as a system with the computer controlling the analyzer and doing data reduction.*

is well-suited as the man-machine interface in a multichannel-analyzer system. It is simple to learn and use, yet powerful enough to perform nearly all desired computations. Analyzer functions are controlled by means of simple CALL program statements.

The nuclear power examples discussed in connection with the calculator-based systems can also illustrate what the MCA/BASIC System can do. In addition to all the functions performed by the calculator in those examples, the computer-based system can perform more complex routines. For example, it can compare the calculated spectral peak energies with known values to find peaks that would otherwise be unrecognizable due to spectral noise or statistical fluctuations. Fig. 6 shows the BASIC program required to do this. The technique consists of correlating a characteristic spectral peak with the experimental spectrum.[1] At points of high correlation a peak is said to exist. Fig. 7 shows a typical experimental spectrum and the correlation spectrum resulting from the BASIC program. Peaks in the correlation spectrum have the same mean values and proportional intensities (areas) as the original spectrum. The program computes these means and areas and prints them on the teleprinter.

HP 5406B Multiparameter Analyzer System

The HP 5406B is a modular computer-based single-

```
1  PRINT
2  PRINT
3  PRINT
10  CALL ERASE                                              Accumulation
20  CALL ACCUM                                              of data
30  CALL STAT(L)
40  IF L=1 THEN 30
50  PRINT "KEV PER CHANNEL";                                Calibration
60  INPUT R                                                 of system
70  PRINT "FWHM (CHANNELS)";                                Width of
80  INPUT S                                                 search peak
90  LET M=3*S
100  PRINT
110  PRINT
120  PRINT "   PEAK LOCATION","TOTAL COUNTS"                 Setup of
130  PRINT "(CHANNELS)";"    (KEV)";"           IN PEAK"     printout
140  PRINT
150  LET V=0
160  LET W=0
170  LET Z=0
180  DIM G[50]
190  LET G=0
200  FOR T=1 TO M                                           Computation of
210  LET G[T]=EXP(-((2*T-M-1)/S)↑2*LOG(2))                  search function
220  LET G=G+G[T]
230  NEXT T
240  FOR I=0 TO 4095-M
250  LET A=0
260  LET Q=0
270  FOR T=1 TO M
280  CALL READ(I+T-1,D)
285  CALL DISPB
290  LET A=A+D/M                                            Calculation of
300  LET Q=Q+G[T]*D                                         correlation
310  NEXT T                                                 spectrum
320  LET C=Q-G*(A+SQR(A))
330  IF C>0 THEN 500
340  LET C=0
350  GOTO 540
360  CALL WRITE(4096+I+(M-1)/2,C)
370  CALL DISPB
380  NEXT I
390  PAUSE                                                  Repeat
400  GOTO 1                                                 experiment
500  LET Z=1
510  LET V=V+C
520  LET W=W+C*R*(I+(M-1)/2)                                Printout
530  GOTO 360                                               subroutine
540  IF Z=0 THEN 570
550  PRINT W/V/R;W/V,V/.9162
560  LET Z=0
570  LET V=0
580  LET W=0
590  GOTO 360
1000  END

READY


RUN


KEV PER CHANNEL?.305043
FWHM (CHANNELS)?7

   PEAK LOCATION                   TOTAL COUNTS
(CHANNELS)     (KEV)                 IN PEAK

 43.0735      13.1393              1.50533E+06
 96.001       29.2844              1202.86
 115.409      35.2046              312196
 132.859      40.5276              82459.3
 165.047      50.3466              1688.97
 243.56       74.2964              161.844
 309.582      94.4359              10624.8

 3843.57      1172.46              451292
 3946.8       1203.94              3657.75
PAUSE
```

Fig. 6. *BASIC program for HP 5402A. The system accumulates a spectrum, then correlates it with the spectra of isotopes known to be present. This gets rid of background data that might otherwise mask small peaks and make it impossible to measure their activities.*

parameter or multiparameter multichannel analyzer system. Its modular hardware and software give the user optional system configurations that include as many as sixteen analog-to-digital converters, a display subsystem, most computer peripherals including paper tape, magnetic tape, disc, line printer, and others, and a variety of computer mainframe configurations with as many as 24,576 words of data storage. Modular software makes it easy for the user to generate efficient real-time systems which may include programs supplied with the system, or programs written by the user, or both. Many often-used routines are supplied; examples are Gaussian curve fitting and multiparameter accumulate. User-written programs can be in FORTRAN, ALGOL, or HP Assembly Language.

Fig. 8 is a photograph of a 5406B system. All of its

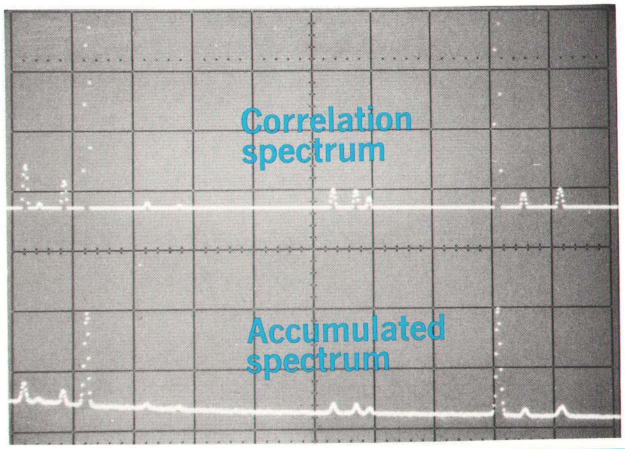


Fig. 7. *Analyzer displays of portion of raw spectrum (bottom) and same portion of spectrum after correlation by program of Fig. 6. Correlation spectrum peaks have same mean values and same relative activities (areas) as peaks of original spectrum.*

functions are controlled from the teleprinter keyboard by means of 5406 EXECUTIVE-language commands.

An example of the use of a 5406B system is nuclear-reactor fuel-rod scanning. The rods have been used in an operating reactor core, and the analyzer system measures their power densities as a function of position. The rods are extremely 'hot,' so data rates are high. Four analog-to-digital converters are used; each views the rod from a different side. Using the analyzer's multiplex mode, the four 'views' are accumulated in four different segments of memory. Then the area of each peak in the

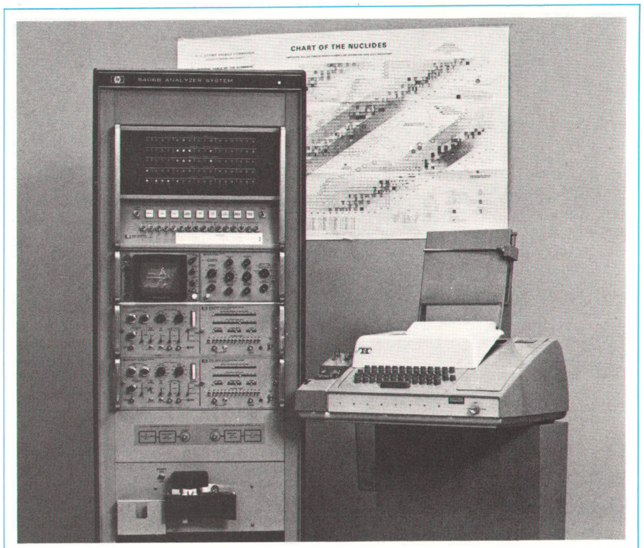


Fig. 8. *HP 5406B Multiparameter Analyzer is a powerful, modular, computer-based nuclear analysis system. It can include as many as 16 analog-to-digital converters and most computer peripherals.*

resulting spectra is computed for each view as an indication of power density. The results are printed on the teleprinter and the original four spectra are stored on magnetic tape for future reference.

Fig. 9 shows the 5406B EXECUTIVE program for this task. The operations MOVE and ANALYZE were written by the user in FORTRAN. Also shown in Fig. 9 is the tabular format of the output.

```
; ROD                          Subroutine ROD
REWIND                         Rewind mag tape
SET,R=0                        Initialize rod counter
SET,L=0                        Initialize position index
MOVE,L,R                       Position fuel rod
MEASURE                        Perform measurement subroutine
SET,L=L+1                      Increment position index
COMPARE,L,M                    Has last position been reached?
IF,COMPARE,-4                  No, re-execute loop
SET,R=R+1                      Increment rod counter
COMPARE,R,N                    Have all rods been measured?
IF,COMPARE,-8                  No, get next rod
STOP                           Yes, stop

;MEASURE                       Subroutine MEASURE
ERASE                          Erase region Ø
ACCUMULATE                     Accumulate data into region Ø
ANALYZE                        Analyze data in region Ø
WRITE                          Write region 1 to mag tape
WAIT,ACCUMULATE                Wait for accumulation to end
TRANSFER                       Transfer data from region Ø to region 1
RETURN                         Return to calling program

SET,M=20                                              }
SET,N=1                                               }  User types
SET,P=17                                              }  this
ROD                                                   }

FUEL ROD POWER DENSITY MEASUREMENT

ROD NO. =        17

                 RELATIVE  POWER  DENSITY                        }
POS   VIEW 1        VIEW 2       VIEW 3       VIEW 4             }
                                                                 }
1   .  1997         2009.5       2009.51      1997.04            }
2      1997.15      2010.06      2011.45      2003.67            }  System
3      2019.53      2009.59      2007.28      2007.92            }  responds
4      2007.49      1999.16      2003.04      2001.28            }  with this
5      2005.86      1999.14      2017.6       2013.87            }
                                                                 }
18     2021.75      2018.9       2018.16      2014.33            }
19     1998.06      2009.95      2002.6       2001.6             }
20     2011.66      2006.11      2007.19      2013.64            }

AVERAGE POWER DENSITY = 1997.01
STANDARD DEVIATION =       12.64

              VIEWS EXCEEDING AVG+-TWO STD. DEVIATIONS

                   POSITION           VIEW

                       N    O    N    E
```

Fig. 9. *5406B EXECUTIVE-language program and typical printout for fuel rod power density measurement using four analog-to-digital converters.*

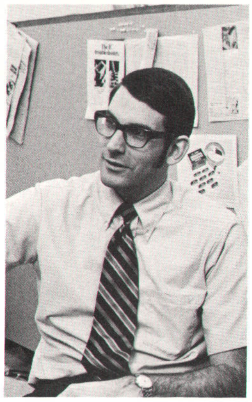
Acknowledgments

Of the many people who contributed to the development of the systems described in this article, several are deserving of special credit. Bob Wagstrom was project leader for the 5406B. Ed Muns developed the BASIC software system concepts for the 5402A, and Ken Fox lent assistance with instrument BASIC. Dave Snyder and John Harpootlian made extensive contributions to the concept and execution of the 5406 EXECUTIVE. Tom Bendon and Al Low did product design and lent technical assistance. Norm Marschke, Bob Tinnen, and Gibson Anderson all contributed heavily to the development of the calculator-based systems.

Reference

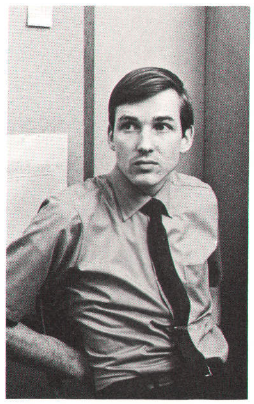
1. W. W. Black, 'Application of Correlation Techniques to Isolate Structure in Experimental Data,' Nuclear Instruments and Methods, Vol. 71, 1969, pages 317–327.

Jonathan R. Cross



Jon Cross is project leader for the 5401B Multichannel Analyzer and related instruments and systems. He received his BSEE degree in 1965 from Purdue University, where he was elected to Tau Beta Pi. Jon joined HP in 1965 and, after helping to design the 5415A, 5416A, and 5416B Analog-to-Digital Converters, assumed his present project-leader responsibilities early in 1970. A member of the Sierra Club, Jon likes to spend a lot of his spare time camping and skiing, but his talents also include playing folk guitar and designing and building FM stereo receivers.

John M. Stedman



John Stedman earned his BSEE degree at Walla Walla College in 1966, and spent the next three years with NASA providing electrical engineering support for plasma research and other research projects. In 1969 he received his MSEE degree from San Jose State College and shortly thereafter joined HP's Santa Clara Division as a development engineer. Parts of the 5401B Multichannel Analyzer and several of the interfaces used in HP multichannel-analyzer and signal-averager systems are John's handiwork. He's a member of IEEE and the Sierra Club, and whenever he can, he likes to head for the hills for a little skiing, camping or hiking.

James A. Doub

Jim Doub is engineering group manager for nuclear instruments and signal averagers. He came to HP in 1965 and was assigned project leader for the 5415A Analog-to-Digital Converter. Later, he was project leader for the 5401A Multichannel Analyzer. Before coming to HP, he had worked on magnetic devices for three years at Bell Telephone Laboratories. Jim holds a BSEE degree from the University of California at Berkeley (1963) and an MSEE degree from Rutgers University (1965), and is working for an MBA degree at the University of Santa Clara. He's a member of Tau Beta Pi and Eta Kappa Nu. His leisure-time activities reflect a broad range of interests—he's an accomplished photographer, a builder of furniture, and a fledgling sailor of no mean enthusiasm.

Very High and Very Low Resistances—Why and How They are Measured

These extremes of the resistance range can tell a great deal about properties of materials and the quality of semiconductor contacts.

By Yoshihisa Kameoka and Jean E. Bonhomme

THE RESISTOR, the simplest passive element, was first defined by an obscure German physicist, Georg Simon Ohm. His pamphlet, published in 1827, is entitled "Die galvanische Kette mathematisch bearbeitet." In it are the results of his efforts to measure currents and voltages, and to describe and relate them mathematically. One of his results is the fundamental relationship called Ohm's Law.

The same result is said to have been discovered 46 years earlier by a brilliant recluse, Henry Cavendish. But Cavendish's works were not discovered until long after both he and Ohm were dead.

Ohm's law states simply that the voltage across various types of conducting materials is directly proportional to the current flowing through the material. Stated another way, if the same potential difference is applied across a material, different currents will result. Thus, the relationship familiar to all electrical engineers:

$$R = \frac{E}{I} \text{ or} \qquad (1)$$

$$R = mL^2t^{-1}Q^{-2} \qquad (2)$$

Where R, the resistance, is the parameter responsible for the differences in current or voltage mentioned above. In Eq. 2, m = mass, L = length, t = time and Q = charge.

Accurate and convenient resistance measuring instruments based upon Ohm's Law are in common use. Measuring resistance over a wide range, from less than one ohm to several megohms, is generally easy. Much more difficult have been applications where very low resistance, less than 1/100 ohm and very high resistance, a million megohms and higher, must be measured. Relay contact and semiconductor resistance are among the applications requiring low resistance measurements. Insulating and dielectric materials, and high-voltage components are tested for high-resistance characteristics. Two Hewlett-Packard instruments, the HP Model 4328A Milliohmmeter and the HP Model 4329A High Resistance Meter aim at making measurements at these extreme ranges easier and more accurate than in the past.

Low-Resistance Measurements

The HP Model 4328A, Fig. 1, is a solid-state instrument with a range from 1 mΩ to 100 Ω. It uses the 4-terminal (Kelvin) principle by which constant current is applied to the device under test, and the voltage drop is measured. A special probe is used, so that only two leads need be connected across the unknown. Errors due to contact potential and thermoelectric effects are substantially eliminated by the use of a low level ac (1 kHz) measuring signal. Excessive voltage could change the surface characteristic of the sample under test.

An IEC (International Electrotechnical Commission) standard recommends that when contact resistance is measured by ac, the frequency should be 1 kHz ±200 Hz, the rms value of current be 1 A or less, peak values of voltage be 20 mV or less, and instrument accuracy be ±10% or better. The Model 4328A meets these requirements. Voltage drop across the unknown is less than 200 μV peak on all ranges and does not exceed 20 mV under any condition. Power dissipation in the devices under test is so low (23 μW max) that the instrument is commonly used to check explosive devices such as fuses and squibs.

A phase detector circuit is used in the Model 4328A which detects only the voltage drop in phase with the current through the device, and rejects the reactive com-

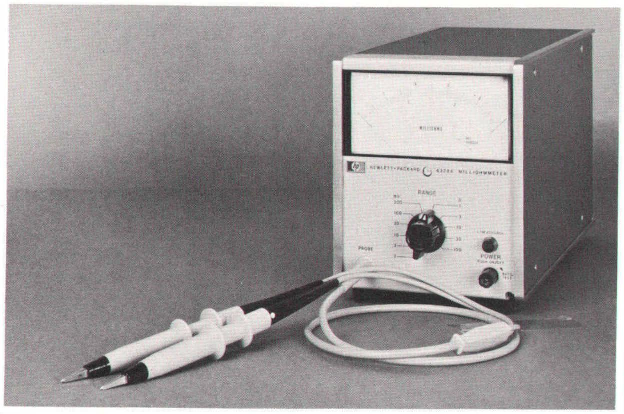


Fig. 1. *This Hewlett-Packard Model 4328A Milliohmmeter measures low resistances from 1 milliohm to 100 ohms full scale with a resolution of 20 μohms.*

ponent. Thus accurate measurements may be made of unknown resistances having reactance up to twice the full scale of the range in use.

Principle of Operation

The Model 4328A may be divided into two major sections, Fig. 2. A 1 kHz oscillator section serving as a constant current source to the sample, and a voltmeter section with a phase-discriminating circuit which amplifies the voltage drop across the sample, synchronously detects it, and deflects the ohm-calibrated meter.

Assume that an unknown with an impedance Z_x is connected between the current terminals of the probes. A closed loop is formed by the reference resistance R_s of the instrument, Z_x and transformer T2 secondary winding. A positive feedback loop is formed as both ends of R_s are connected to the input terminal of high impedance amplifier, the power amplifier of the next stage and output transformer T1. The circuit starts to oscillate at 1 kHz $\pm$100 Hz, the frequency determined by capacitance C_o and inductance L_o of T1 primary.

The value of R_s is selected by the range switch so as to be 500 times the value of the selected range. As a result the oscillator is a constant current source to Z_x. Voltage across the reference resistance R_s is always 100 mV peak, thus when the value of Z_x is equal to the full-scale value, the voltage applied to Z_x is 200 μV peak. The input impedance of the high-input-impedance amplifier is sufficiently high so that voltage changes across R_s become negligible. If the probe leads are open, oscillation stops to prevent excessive voltage across the sample, and in the absence of oscillations, a Schmitt trigger in the circuit causes the meter to read towards infinity (full scale).

The 20 mV peak limiter, connected to the tip of the current terminals, limits the ac voltage applied to the sample to 20 mV peak even if the range setting is incorrect. This is done by comparing the 1 kHz output level to a reference diode. When a certain level is exceeded, the signal is amplified, rectified and the resulting dc level is used to reduce the oscillator gain.

The voltage drop across Z_x is applied to the ac amplifier via transformer T2, and the amplified signal fed to one input of the phase detector. The other input is connected to a flip-flop driven by the 1 kHz oscillator. Because the output of the ac amplifier is synchronously rectified, the detected voltage is in phase with the current flowing through the reference resistance R_s.

An unknown sample can be defined as $Z_x = R_x + jX_x$, and the resulting voltage drop V across the sample will be $V = V_R + jV_x$. But the phase detector detects only the voltage drop V_R which is in phase with the current through R_s. Therefore, errors due to jX_x will be less than 1% as long as its reactance value at 1 kHz is not more than twice the set range of the Model 4328A.

Some Applications

A typical circuit for measuring dynamic resistance of various semiconductor devices is shown in Fig. 3. Devices commonly measured include switching diodes, power diodes and point contact diodes. Resistivity of a semiconductor wafer is easily measured using a four-point probe.

High-Resistance Measurements

Related to resistance is resistivity ρ, which is the characteristic of a material rather than of a particular specimen of that material. The resistivity of copper, for example, is 1.7×10^{-6} ohm-cm, and that of quartz is about 10^{14} ohm-cm. Resistivity is of importance when considering the fundamental behavior of materials, as in solid-state physics. It is also important when investigating the interior behavior of irregularly-shaped objects.

Surface and volume resistivities of solids such as printed circuit board materials, plastics, resins, refractories, semiconductor materials, oils, solvents and fabrics require high-resistance measurement capability. Other more common applications include measurements of capacitor insulation, and relay coil resistance. Accurate high-resistance measurements are needed to examine effects of temperature, humidity, and surface conditions on a variety of insulating devices and materials. More important, most high-resistance materials have non-linear characteristics, i.e. voltage versus resistance. Thus

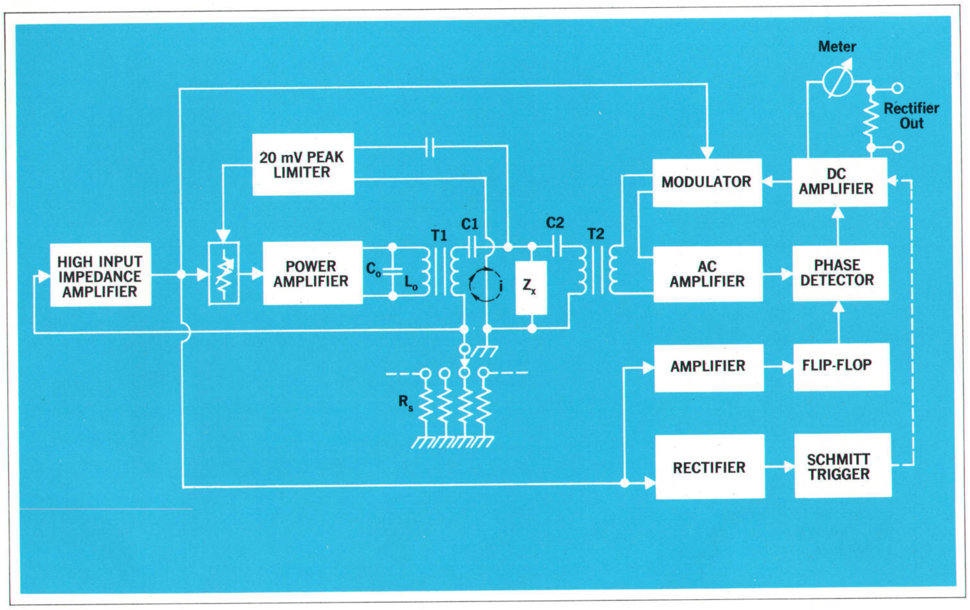


Fig. 2. *Functional block diagram of the Model 4328A shows how a feedback loop is formed when Z_x is plugged in. Inductance of the primary winding of T1 and C_o determine the frequency of oscillation. The modulator prevents the meter voltage (V_r) from varying in the presence of small changes in feedback loop or oscillator output.*

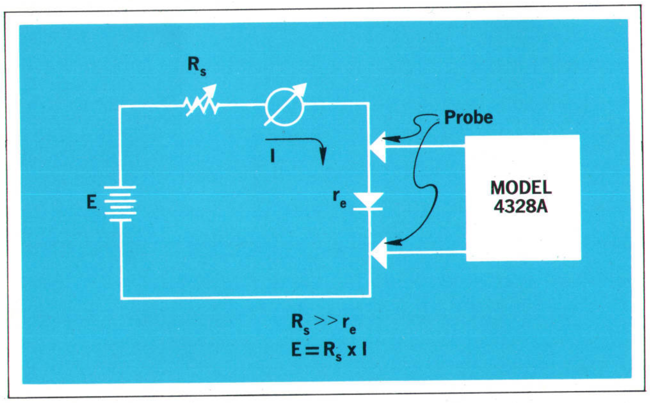


Fig. 3. *A typical circuit used to measure the dynamic resistance of a diode.*

voltage measurement is very important.

Measuring of high resistance is essentially a problem in measuring extremely small currents. Until recently the vacuum-tube electrometer, the vibrating reed capacitor and the field effect transistor have been the only devices available to provide the high input impedances required.

Further, it has been necessary to design dc to ac converters to provide ac amplification of the outputs of tubes and transistors used in electrometers. These converters (usually choppers) are required to eliminate the errors inherent in dc amplification of such low-level signals. The combined inherent instabilities, drift, leakage currents, grid currents and converter problems have justified devising an entirely new principle in this type of measurement.

As used in the HP 4329A High-Resistance Meter, Fig. 4, this principle is called the 'self-oscillating parametric impedance converter', Fig. 5. This circuit provides both a high-input impedance and an ac output available for stable, drift free amplification. A variable-capacitance diode (varicap) bridge serves as the parametric element.

These diodes are variable capacitance diodes designed to have a known junction capacity versus voltage characteristic variable with applied voltage. Normally this characteristic is non-linear and increases with increasing forward bias. Here the diodes are used as variable-capacitors since the applied forward bias does not extend into the conduction region of the diode.

Fig. 6 illustrates the diode characteristic curve showing the capacity of the depletion layer or 'operating region' as a function of applied diode voltage.

Principle of the Parametric Converter

A parametric amplifier is defined as a network capable of transferring energy from a high frequency source to an applied signal at a lower frequency by virtue of a periodically varying energy storage element. The time varying element need not be linear.

The Model 4329A parametric converter circuit can be simplified to a basic bridge circuit, Fig. 7. C1 and C2 are diode capacitors; the two resistance arms are equal. The bridge unbalance voltage is the input to an amplifier, the amplifier's output is the 'supply' for the bridge.

To understand the parametric converter, consider the result of making a very small change in the value of C_T. If for example, C_T is raised in value, the net C in the lower arm now is greater than that of C1. Thus the

Fig. 4. *High resistances to 2×10^{16} ohms are measured with the Hewlett-Packard 4329A High Resistance Meter. Automatic range and multiplier indicators are lighted to make them easy to read.*

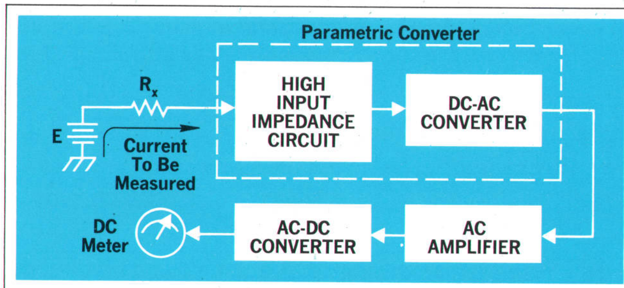


Fig. 5. *Basic principle of the measuring technique used for high resistance measurements.*

voltage across the lower arm will tend to decrease to a value less than that across C1. Point 1 tends to become more negative. This represents a bridge unbalance, and the amplifier sees this as a net negative-going signal at its input.

This signal is inverted and amplified and the bridge 'supply voltage' changes. This change in the net voltage between point 3 and 4 is seen by C1 as an increase in forward bias, and by C2 as a decrease in forward bias. C1 therefore tends to increase its capacitance, and C2 tends to decrease its capacitance. Thus the effect of the fed-back voltage is to cancel the initial unbalance due to the change in C_T.

However, the circuit constants *(R, L, C)* determine the speed at which the response can catch up with the initial unbalance, and by the time the bridge is re-

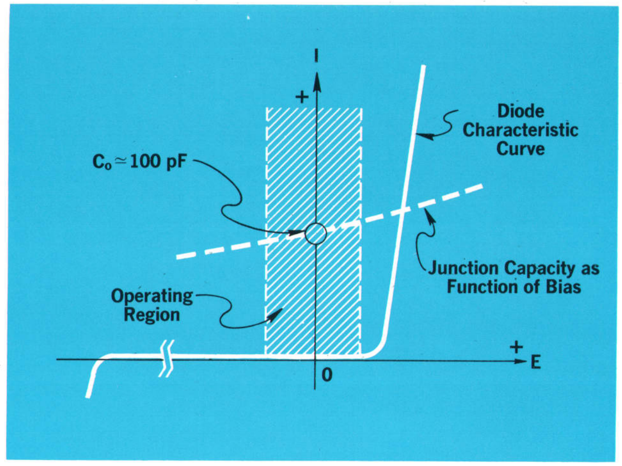


Fig. 6. *Characteristic of the variable capacitance diode used in parametric converter. The diode used in this instrument has a C_0 of 100 pF.*

balanced and quiescent, the total *C* value of the upper arm is greater than that of the lower and the cycle repeats with all polarities reversed. This action continues as a normal oscillator, at a frequency and amplitude determined by the initial change in C_T and by other component values. This type of oscillation is called a parametric oscillation, in that the modulation of the reactance parameter *(C)* determines the behavior of the oscillator.

In applying this concept to a practical high-resistance measuring circuit, only a few simple changes are necessary. Point 1, the junction between C1 and C2 can be considered the input point, where a voltage to be measured is applied to the circuit.

Any change in voltage at this point will be seen as a further unbalance in the bridge. This additional unbalance will increase the signal to the amplifier and result

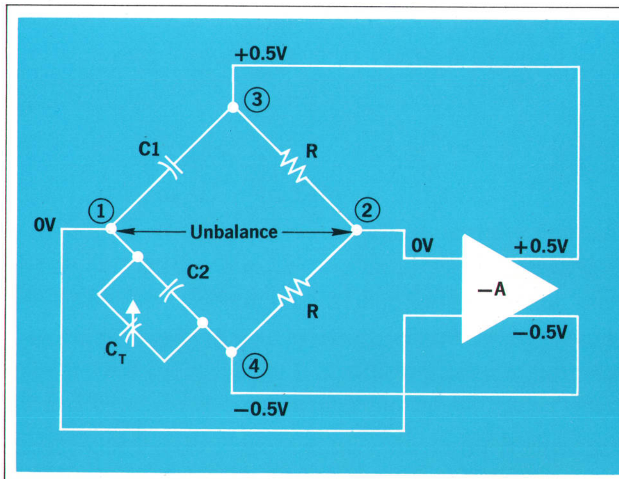


Fig. 7. *Basic parametric converter bridge circuit.*

in an increase in the amplitude of oscillations.

It remains only to develop a dc voltage proportional to the increase in oscillation amplitude, suitable to drive a meter circuit. The high-impedance input is developed by the non-conducting variable-capacitance diode, aided in a practical circuit by suitable isolating capacitors, high resistance circuit mountings, and augmented by negative feedback. The stable gain characteristic of the Model 4329A is accomplished in the standard ac feedback-controlled amplifier manner, made possible by converting the dc input current to a change in the amplitude of converter oscillations. The actual circuit used in the HP 4329A, Fig. 8, operates like the analogous circuit.

Practical Circuit

The converter consists of a transformer bridge. Diodes CR1 and CR2 are two arms, and the two halves of center-tapped T1 primary winding are remaining two arms. C6 and C7 block dc from the transformer windings. C_T is the variable capacitor providing a slight unbalance to the bridge and is used to set the 'no-input' oscillation amplitude. Bridge unbalance is taken from the junction of C_T and C_o to the oscillator/amplifier circuit through series resonant circuit C_o/L_o, which sets the oscillation frequency at approximately 100 kHz.

Output of the amplifier is fed back to the bridge by transformer action (from M3 to M2, M1). Oscillations are also transferred by transformer action to the input of meter amplifier circuit rectified, and the resultant direct current drives the meter. The meter circuit current is set such that 200 mV at the converter input gives full-scale deflection.

DC negative feedback through the RC network to the pair of 2 MΩ resistors stabilizes the circuit against variations in circuit parameters, particularly the variable-capacitance diode characteristics. DC feedback to the guard at the input point adds to the total effective insulation resistance of the insulator which isolates the converter input lead from the leakage resistance of the printed circuit board.

This feedback equals the input voltage itself, and is applied to the conducting surface around the periphery of the insulating cylinder containing the input junction point. Since the voltage at the inner surface of the cylinder is equal to that at the outer surface, no leakage occurs through the teflon cylinder and its insulating qualities are enhanced.

Covering a resistance range of 500 kΩ to 2×10^{16} Ω, the Model 4329A, also has seven discrete test voltages from 10 to 1000 V. Test voltages are selected by a front-panel switch.

Resistivity Cell

Volume and surface resistivities can be measured by the Model 4329A using a standard mercury cell. An accessory Model 16008A Resistivity Cell is more convenient, although a little less accurate. The cell's main electrode is coated with conducting plastic and is surrounded by a guard ring. Spring loading the upper electrode provides pressure to measure unknown samples up to 7 mm thick, and a switch selects volume or surface measurement. Contact between the conductive plastic and the surface of the device under test may not be as good as the mercury cell contact, however.

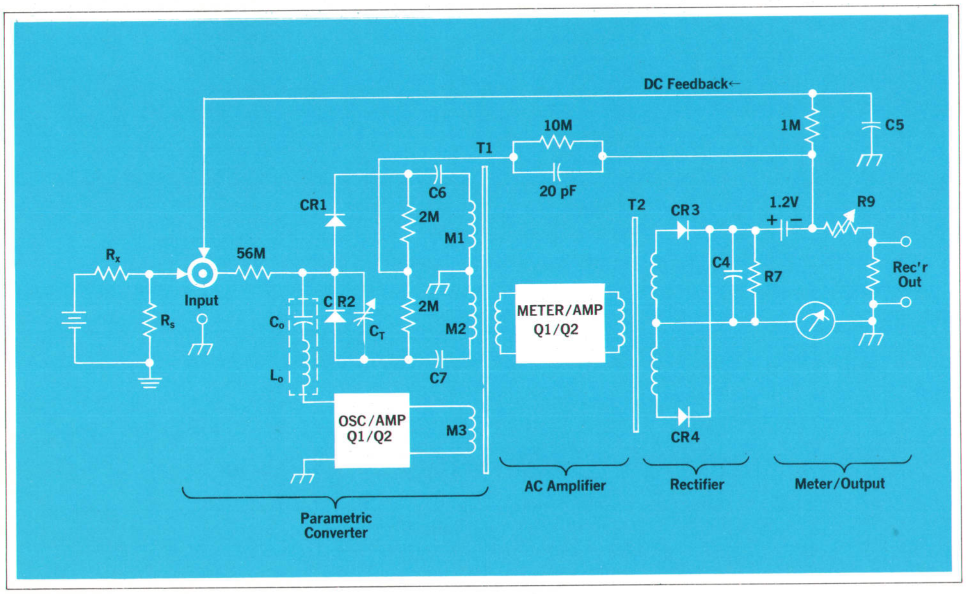
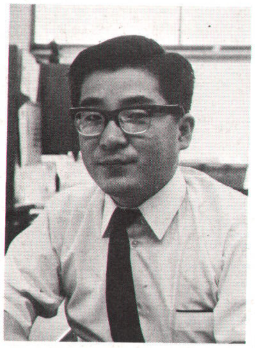


Fig. 8. *A simplified circuit of the Model 4329A High Resistance Meter. Capacitor C_T is the electrical zero adjust. It adjusts the oscillator output level to cancel the ±1.2 volt dc bias.*

Acknowledgments

As with any project, many people have contributed their ideas and efforts. Invaluable contributions were made by Nobuo Numasaki, Giichi Yokoyama, and Haruo Ito. Model 4328A design effort was shared with Yoshito Ichinomiya. The industrial and mechanical designer for the 4328A was Kimijiro Kikuchi. Much of the engineering on the 4329A was by Kenichi Sugimoto (project leader). The industrial designer for the Model 4329A was Kazunori Shibata and the mechanical designer was Toshio Manabe.

Yoshihisa Kameoka



Yoshihisa Kameoka received his BSEE from Iwate University in 1962, then joined Yokogawa Electric Works (YEW) as a research and development engineer.

He joined Yokogawa-Hewlett-Packard in 1964 and worked on the design of a photoelectric tachometer and a dc volt-ammeter. He then joined the 4328A and 4329A project as project leader.

Jean E. Bonhomme

Born in Haiti, Jean Bonhomme started his schooling in France. In 1962 he received his BS in Physics from Brooklyn College in New York and completed work equivalent to an MS in Physics at New York University.

Jean's experience includes work in computer technology, and in medical electronics. He worked in biomedicine at the New York Medical College, Columbia University, and at Albert Einstein College of Medicine. In addition Jean is a licensed high school teacher in New York City. Before joining Yokogawa-Hewlett-Packard, he taught science and English in Japan. Jean has been with YHP since early 1970 and is an engineering publications writer. He is the author of several technical articles published in U.S. magazines.

PARTIAL SPECIFICATIONS

Model 4329A
High Resistance Meter

RESISTANCE RANGE: 500 kΩ to 2×10^{16} Ω.

CURRENT RANGE: 0.05 pA–20 μA.

RECORDER OUTPUT: 0 to 100 mV dc, proportional to meter deflection, output impedance 1 kΩ.

POWER: 115/230 V, ±10%. 50 or 60 Hz, 3 W.

DIMENSIONS: 6.5 in high × 7.8 in wide × 8 in deep (166 × 198 × 204 mm).

WEIGHT: 7.7 lbs (3,5 kg).

PRICE: Model 4329A High Resistance Meter **$750.00**

ACCESSORIES FURNISHED

16117A Low Noise Test Leads, composed of insulated BNC to Alligator clip lead, and banana plug to Alligator clip lead. On BNC lead, outer conductor comprises guard shield. Guard isolated from low resistance alligator clip sleeve.

Model 16008A
Resistivity Cell

RANGE: For sample thicknesses approx 1 mm, up to 4×10^{18} Ω — cm in volume resistivity. Up to 4×10^{17} Ω in surface resistivity.

TEST LEADS: Provided; cell top cover interlocks with test voltage.

MAIN ELECTRODE: 50 mm diameter, conductive-plastic coated.

UPPER ELECTRODE: 100 × 120 mm.

GUARD RING: 70 mm diameter.

MAX TEST VOLTAGE: 1000 V.

DIMENSIONS: 1.9 in high × 7.7 in wide × 6 in deep (48 × 195 × 152 mm).

WEIGHT: 3.7 lbs (1,8 kg).

PRICE: $200.00

MANUFACTURING DIVISION: YOKOGAWA-HEWLETT-PACKARD, LTD.
9-1, Takakura-cho
Hachioji-shi
Tokyo 192, Japan

PARTIAL SPECIFICATIONS

Model 4328A
Milliohmmeter

RANGE: 0.001 to 100 ohms full scale in a 1, 3, 10 sequence.

RESOLUTION: Max resolution 0.02 on 0–1 scale, 0.05 on 0–3 scale.

ACCURACY: ±2% of full scale. Accuracy is unaffected by series reactance of samples with magnitude of up to 2 times full-scale resistance value.

MEASURING FREQUENCY: 1000 Hz ±100 Hz.

VOLTAGE ACROSS SAMPLE: 200 μV peak at full scale.

MAXIMUM VOLTAGE ACROSS SAMPLE: 20 mV peak in any case.

SUPERIMPOSED DC: 150 V dc max may be superimposed on samples from an external source.

RECORDER OUTPUT: 0.1 V dc output at full scale meter deflection. Output resistance approx. 1 kΩ.

POWER REQUIREMENT: 115/230 V ±10%, 50 to 60 Hz, 1.5 W.

PRICE: Model 4328A $495.00. Option 001, rechargeable battery operation, add $25.00.

MANUFACTURING DIVISION: YOKOGAWA-HEWLETT-PACKARD, LTD.
9-1, Takakura-cho
Hachioji-shi
Tokyo 192, Japan

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