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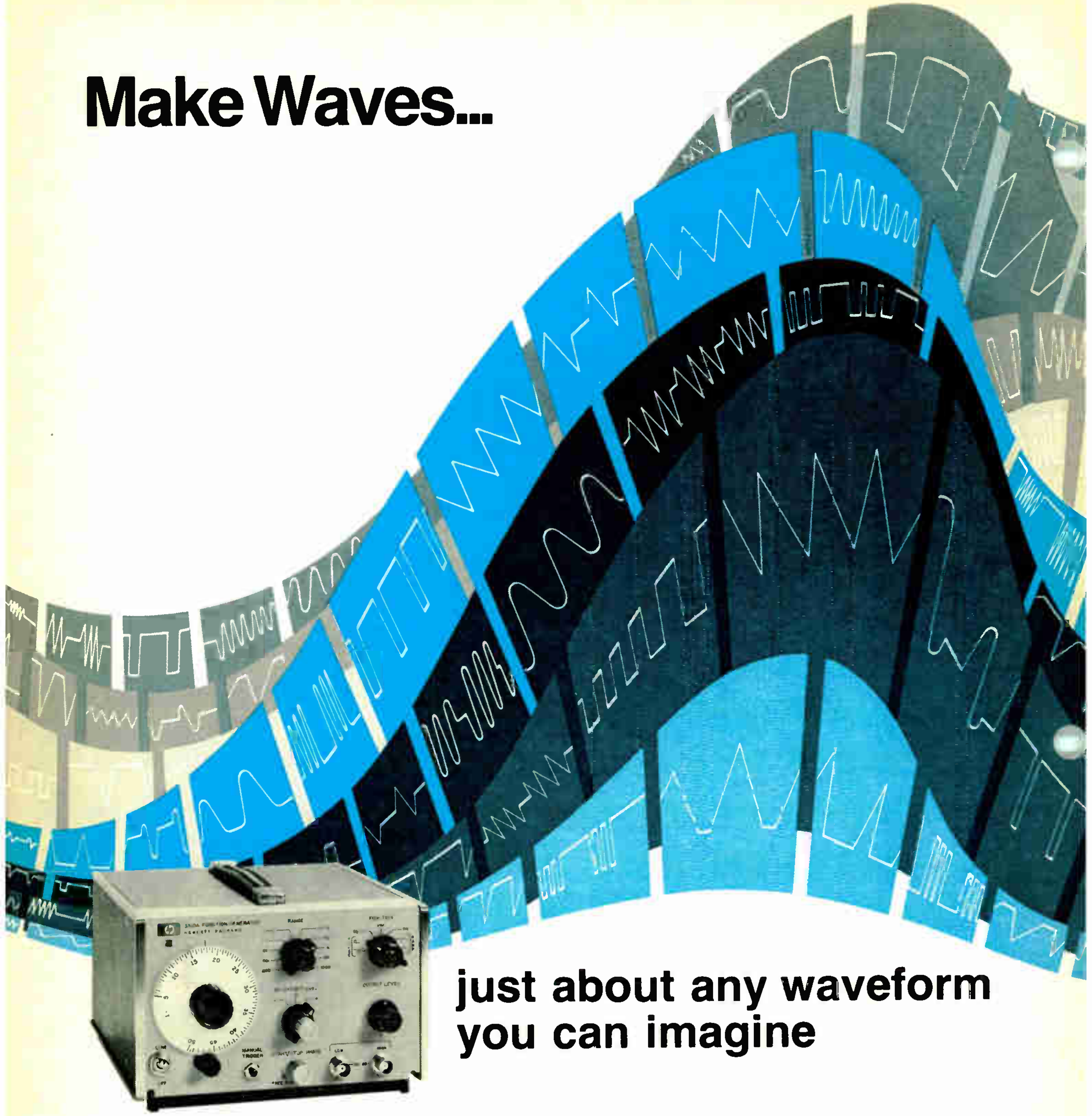
IEEE spectrum

features

Make Waves...



just about any waveform you can imagine

HP's 3310A is the function generator that gives you seven different waveforms—in three different modes—in one inexpensive package.

In its basic form, the 3310A gives you a continuous output of square waves, sine waves, and triangle waves – plus positive and negative ramps and pulses—for only $595.

And for only $140 more, you can get the 3310B, which lets you generate each of these seven waveforms in two other modes – single-cycle and multiple cycle "bursts." These can be triggered either manually or by an external oscillator; starting-point phase can be varied by ± 90°.

In either the "A" or "B" version, the 3310 gives you a choice of ten frequency ranges—from 0.0005 Hz to 5 MHz—and an output voltage range from 15 mV pk-pk to 15 V pk-pk into 50Ω load. Dc offset of ±5 V into 50Ω load is also standard.

Both the 3310A and 3310B can be used in frequency-response and transient-response testing, as a waveform converter, for generating phase-coherent waveforms, and as a frequency multiplier or divider, among other things. Applications include testing television and communications systems, radar systems, and analog or digital circuits.

For further information on the 3310A and 3310B, contact your local HP field engineer, or write to Hewlett-Packard, Palo Alto, California 94304. In Europe: 1217 Meyrin-Geneva, Switzerland.

090/41A

HEWLETT PACKARD

SIGNAL SOURCES

Ecap II—An electronic circuit analysis program

Advances in the use of sparse matrix storage and in methods of numerical integration have brought within practical range the analysis of kilobranch circuits. Ecap II incorporates many of these advances

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Ecap II, a nonlinear dc and transient circuit analysis program, uses a free-format, problem-oriented language for describing circuit parameters and topology. Its computation speed is high enough to make the transient analysis of kilobranch nonlinear circuits feasible. The program includes a nested model feature that permits the user to store circuit descriptions of devices and subcircuits for subsequent recall and insertion into larger circuits. Nonlinearities can be specified by means of tables, built-in functions such as the diode equation, and Fortran subroutines. A diagnostic feature pinpoints errors in the input format or inconsistencies in the circuit description.

During the 1960s, computer programs for circuit analysis became such a widely accepted tool that today many engineers use these programs daily as an indispensable aid in designing circuits of many kinds. A number of these programs are currently available for analyzing circuits up to about 300 branches in size. Some of these programs (for example, Sceptre[1] and Circus[2]) have suffered from the so-called "minimum time constant" problem,[3] which makes the transient analysis of some circuits prohibitively slow. This time-constant barrier has been broken by the use of implicit methods of integration that, though known for years, have only recently been used in circuit analysis programs (for example, Trac[4] and Cirpac[5]).

With the advent of integrated circuitry, demands for the analysis of kilobranch problems have spurred the development of sparse matrix programming techniques[6–8] and improved methods of numerical integration.[9,10]

Ecap II, an electronic circuit analysis program[11] for the IBM 1130 computing system and for machines supporting the operating system (for example, S/360), embodies many of these new analysis and programming techniques.

Input language features

Ecap II, designed for the engineer with little programming familiarity and for the technician without a background in circuit theory, uses a simple input language. In terms of this language the user may readily describe his circuit, define the types of analysis to be performed (dc and/or transient), and specify the desired output variables and their mode of presentation (printed or plotted).

The syntax of the language is patterned largely after that of the Sceptre program, which is familiar to many circuit design engineers, and permits any alphanumeric name to be assigned to the circuit components. Each component is described by its value and name, which

An expanded version of this article, which will contain full mathematical details, will be published in the August 1971 issue of IEEE Journal of Solid-State Circuits, vol. SC-6.

Spectral lines

Engineering in the social context. Two related problems are now of primary concern to scientists and engineers: the present unemployment situation and the unenlightened priorities of a society that has been misdirected away from a technology applicable to the solution of social problems.

In April's "Spectral Lines," Dr. Wilmotte set the stage for a debate as to what IEEE and its members should do—including a recommendation for establishing a center dedicated to clarifying problems of technology. Here are some additional suggestions.

The present generation is the first in history to face the prospect of a planet limited in its ability to support an exponentially growing and polluting human race. Evidently things will change whether we like it or not. We can orient these changes in proper directions if we work on matters while we still have some options.

In earlier eras of modest technology, unlimited mineral and fuel resources, and expanding frontiers, there were always important "clean" problems to solve (a blind-landing system for aircraft, or television technology, or going to the moon). Now many problems are not so clean. (With what objectives do we design a new mass-transit system, or where do we put a power plant so that few will object?) In addition to technological problems, which may not have a "best" answer, there are often mutually opposing social and political pressures that compound the situation.

What to do?

The IEEE has Student members. In the past they chose engineering partly to get away from the sociology they didn't like. Now they must change their attitudes and include many disciplines in their curriculums. They must be taught engineering in a social context.

The IEEE has professors. They are interested in basic research and have chosen "clean" problems about which they might publish definitive papers. Now if they are to be funded, some will have to choose problems of greater political interest to the public.

The IEEE has members in industry doing applied research and engineering with the objective of producing and selling profitable products. If the public is not to be "turned off" from technology, engineers must consider the social acceptability of these commodities.

The IEEE has engineers in management whose orientation has been manufacturing profitable products. There is an increasing demand for services. Keeping in mind technological and social considerations regarding new and future products, management will have to devise new areas where the services of the engineering groups can be marketed.

The IEEE has engineers in government (almost exclusively in the Executive branch) who have responsibilities for defined and funded technical areas. In addition to handling their specific assignments, they must look toward the broader needs of society where engineering skills can be useful.

The IEEE has at least a few members associated with the legislative process. Through them and yet-to-be established groups, technological insights can be prepared for the legislators who are always sensitive to public needs. Legislation can be developed to broaden the constructive impact of technology on society.

Unless these changes in professional emphasis are made, there will be fewer opportunities for engineers, fewer accomplishments, and fewer solutions.

The IEEE as an organization can adapt to suggesting and recommending new areas of application of technology to legislative and executive branches of government, to industry, and to the nation. Only after these areas are perceived, given explicit emphasis in simple language, and sold to the leadership and the public, will necessary funds be available. The people pay for our work, whether as consumers or taxpayers. They are beginning to feel disenchanted with technology. To show how technology can solve many of society's problems, we must communicate with them through lectures, articles in the news media, appearances on television, preparation of educational materials, etc. If our ideas are to get proper exposure, our presentations must be clear, newsworthy, and interesting.

Suitable well-developed ideas are not easily generated, although anyone can make suggestions. Good ideas can be stimulated by holding symposiums and Section meetings on relevant topics; having committees meet, think, talk, write, and recommend; publishing articles and position papers; having direct contact with responsible people in government and industry (a form of lobbying, although I would urge emphasis on information rather than privilege).

All of these new directions for students, professors, industrialists, people in government, and IEEE organizations are uncommon, though not unfamiliar. In the next decade our profession will be different from what it was in the last. Some changes will take time, but we are fortunate in having young engineers who can adapt rapidly; some have done so already. Their example should make it easier for established professionals to move in needed new directions.

Seville Chapman
Director, Scientific Staff
New York State Assembly

designates the nodes to which is connected. For example, a 7.5-kilohm load resistance from node VOUT to GND (ground) would be described

RLOAD, VOUT − GND = 7.5K

A model library, which allows multilevel *nesting* of component and circuit models, provides significant notational leverage. This leverage is particularly useful in specifying circuit configurations that involve many hundreds of branches. A complex logic circuit, for example, need only have each basic transistor type described as an equivalent circuit, assigned a name, and its external nodes specified. These notations are then stored in the library. Next, each primitive subcircuit (NAND, NOR, INVERTER) may be delineated by specifying the appropriate components, calling forth each transistor type by name, and indicating terminal connections. This subcircuit is then named, assigned external nodes, and stored in the library.

These individual subcircuits may then be assembled into more complex logic arrays, such as latches or full adders—again by recalling each subcircuit from the library and specifying its terminal connections. In this manner, nested models to a depth of 20 levels can be used to "wire up" a very large circuit with ease. The model library also permits retrieval, modification, renaming, and restorage of any model. A given circuit may be filed away in the library and later recalled for any desired modification and reanalysis.

Whenever a model is retrieved from the library for insertion into a circuit, its standard parameters and/or components (that is, those originally specified) may be modified, respecified, or even deleted without altering the copy of model still in the library. Moreover, since the parameters, as well as the components, may have alphanumeric labels, each transistor may be assigned a different alpha, base resistance, operating temperature, and diffusion constant as it is being plugged into the circuit. In this way, a particular transistor or diode model may be tailored for each instance of its use in a circuit. Specifying the value of various circuit elements requires appropriate units such as PF (picofarads), K (kilohms), or UH (microhenries).

Nonlinear elements may be described by means of tables, built-in functions, or user-supplied subroutines. For example, a diode having a q/kT factor of 28 and a reverse saturation current of 6.5×10^{-9} mA and connected from node B to node E in a circuit would be specified as a dependent current source as

JD5, B − E = DIODE (VJD5, 28, 6.5 E − 9MA)

where JD5 is the name of the element, VJD5 is the voltage across it, and DIODE is the name of a built-in function describing the standard exponential diode characteristic. The following format could be used to describe a diode by means of a table:

JD5, B − E = TAB7 (VJD5)

TAB7, −10, −1E-6 MA, 0, 0, .59, .001MA, .66,

\+ .01 MA, .73, .1 MA, .8, 1 MA .89, 10 MA

Here, the plus sign that appears in column 1 signifies a continuation of the statement.

Any number of circuit elements may be specified as dependent on one or more parameters such as ALPHA, OPTEMP, or TIME. Moreover, any of these parameters except TIME may be made to depend on some other parameter. If, for example, three capacitors C5, C11, and CB are to be scaled simultaneously using different values of the parameter SCALE, the statements would be

C5, 7 − E = SCALE* 7.5 PF

C11, B − GND = SCALE* 50 UF

CB, 18 − FX = SCALE* 1.95 PF

SCALE = 1.0: OR 2.7, OR 10.5

Auxiliary parameters may be defined that depend on the circuit responses. In this way, the power in a resistance RLOAD can be obtained with the statement:

PLOAD = VRLOAD * IRLOAD

In addition, ammeters and voltmeters may be inserted anywhere in the circuit to monitor variables of interest. By combining these capabilities with appropriate Fortran subroutines, the user is able to effect conditional printing of a warning message, or even to terminate the program, whenever the power in a transistor or the voltage across some component exceeds a prescribed level.

To facilitate studying the effects of parameter variations on the dc response of a circuit, Ecap II allows any parameter, as well as the value of any circuit component, to be varied, either by additive (subtractive) or by multiplicative increments. Thus, if the user wishes to study the effect of varying ROUT from 10 to 1000 ohms in 10 percent increments, he would use the statement:

VARY, ROUT = 10, 1000, *1.1

During such a parameter study or during a transient analysis, any desired circuit response variables, parameters, or component values can be *monitored*—that is, printed out concurrently with their computation. Furthermore, any list of output variables may be saved for subsequent study after certain other printed or plotted output data have been examined.

An analysis may be rerun after modifying the circuit by reading in only the necessary changes, not the entire circuit description. What is more, on the 1130 computing system, these changes may be effected using the console typewriter instead of the card reader, so that a useful degree of interactive control over the program can be exercised. Finally, only a single description of a circuit need be entered, whether the analysis to be performed is dc, transient, or both.

Processing and compilation of circuit data

As anyone who has ever carried out the process manually on even a five- or ten-branch problem will attest, circuit analysis is very largely a bookkeeping chore. Indeed, in a program such as Ecap II, roughly 30 percent of the total code is devoted to the tasks of processing the input language, extracting and compiling the circuit data, and identifying and flagging the errors in the input statements or inconsistencies in the circuit description.

The Ecap II language processor utilizes many of the programming techniques used in compilers of languages such as Fortran and PL/I. Ecap II supports a wide range of problem sizes and main storage sizes on different machines. The program adapts to this wide range and yet offers efficient operation on both small and large machines. One effective technique is that of using a tree-structured symbol table for storing the names of all circuit elements, nodes, and parameters. Figure 1 illustrates how five resistor names (RBC, RLOAD, R37, R38Q, and R3XYZ) are stored in the symbol tree. The entire alphabet is stored on the main diagonal. Solid lines to the right represent continuous strings or concatenations of symbols; dotted lines to the left represent alternatives. For example, appended to the character R is the string BC *or* the string LOAD *or* the strings 37, 38Q, or 3XYZ. This structure enables the table to be searched very efficiently for any name in it.

The symbol tree may be segmented so that only one segment need be in main storage at any time, with the other segments stored on disk if main storage space is not available. This provides the capability of operating on a small machine without sacrificing performance on a large system. The symbol tree may also be adapted to the storage of element names within models, with symbol subtrees for each model reference appended to the model reference name. Thus, if RBC, RLOAD, and R37 are three resistor names in a model, and if Q7 and Q19 are the names of two instances of this model in a circuit, the symbol tree would store all these names (compounded) as shown in Fig. 2. The symbol tree for a circuit with nested models would, therefore, be organized into nested subtrees that correspond to the different levels of the models themselves. Keeping the entries for a particular model reference close to each other in the table minimizes both the number of segments needed in main storage and the length of search required to find any given name. Hence, processing of interstatement references is not degraded by the use of models.

Another important programming technique of Ecap II is the separation of the syntax definition from the syntax processing. The programs that process the input statements are not tied to the syntax of the statements they are processing; rather, the syntax definitions are carried in tables, a technique developed originally for programming language compilers. This is analogous to the use of microcode instead of hard-wired circuitry in hardware, and has a similar effect—the amount of actual programming (special logic circuitry) required is much less, and changes can be made to the tables (microcode) with rela-

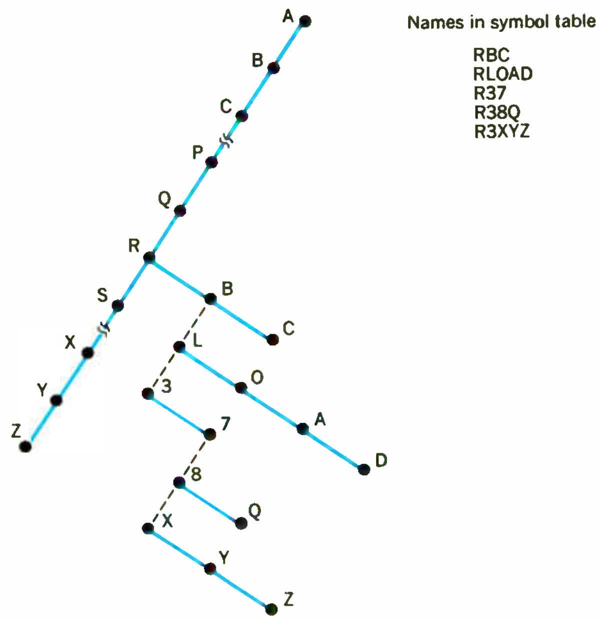
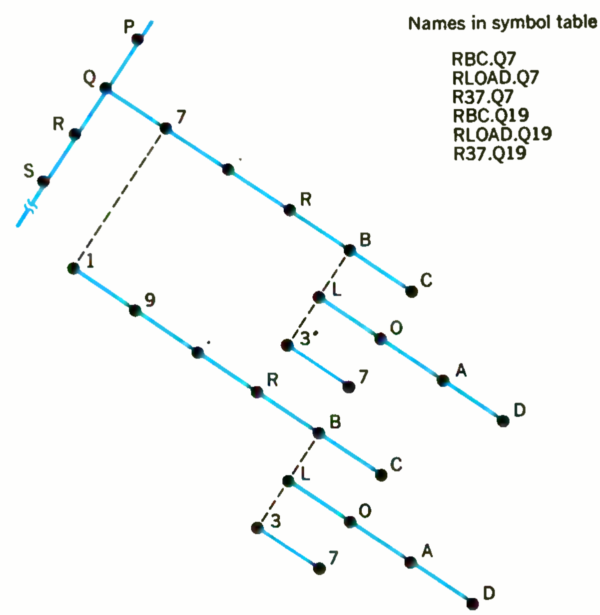


FIGURE 1. Tree-structured table with simple names.

FIGURE 2. Tree-structured table with compound names.



tive ease. If, the input were to be German- or French-oriented the tables could be modified to effect the needed changes. Similarly, the syntax could be modified to use commas rather than dashes between nodes, without modification of any programs. By this same method, a nonelectrical application of network analysis, such as mechanical or structural analysis or fluid flow in pipelines, could be accommodated by modifying the input language syntax appropriately. The addition of new commands and new processing options to the language is also facilitated by the syntax table.

Parallel to the need for efficient compilation techniques is the requirement for meaningful diagnostic messages to help the user identify and correct errors in the circuit specifications and input-language statements. Careful attention has been given to this aspect of the circuit analysis problem. Ecap II provides a variety of diagnostic messages at several different levels of severity during both input processing and analysis phases. These messages range from simple warnings to indications of fatal errors that immediately terminate the analysis. The philosophy of the program is to proceed as far through the analysis as possible—at least up to a fatal error—so that a majority of errors may be detected on the first run of a given problem. In this way the user can identify his easily recognizable mistakes without expending large amounts of computer time for an obviously abortive analysis.

Special programming techniques

The incorporation of sparse matrix programming techniques in Ecap II is one of the keys to a significant increase in problem-size capability; the other is the use of a dynamic storage allocation system, which automatically assigns storage space during execution of the program both in main memory and on disk memory. These two advances permit circuits larger than 100 branches to be handled on the 1130 computer and those larger than 1000 branches on System 360. In most practical circuits, the components are only connected "locally," so that the coefficient matrixes for the algebraic-differential equations that describe these circuits have relatively few nonzero elements. Storing only the nonzero coefficients in these sparse matrixes permits much more efficient use of computer memory. At the same time, a significant reduction in the actual number of computations required to compile and solve the circuit equations results. This, in turn, permits the economical use of implicit integration methods, which are the means of breaking through the time-constant barrier.

Two particular storage formats are noteworthy: *topological* matrixes, whose elements are ±1 and 0 only, are stored entirely as integer arrays; *sparse* matrixes contain both floating-point numbers and integers, the latter used as row–column indexing information to indicate the location of each nonzero element in the matrix.

Like all other *data blocks* under the control of the dynamic storage allocation (DSA) system, each matrix has a six-word (integer) header that contains a block identification number, a type code, and row–column dimensions. Following the header are integer words that contain: number of nonzero elements, number of nonzero rows, and, in successive pairs, a row *pointer* and row *index* for each nonzero row. Each of these pointers gives the relative location within the block of the column indexes that corresponds to each nonzero element in the current row of the matrix. For topological matrixes, the column indexes are signed integers corresponding to the ±1 elements of the matrix. For sparse matrixes, all column indexes are positive integers—following them the floating-point values of the nonzero matrix elements are stored in succession as they are encountered in a row-wise scan of the matrix. In addition to topological and sparse matrixes, Ecap II utilizes null and scalar matrixes and full vectors, each with its own block identification number, type code, and row–column dimensions. However, no indexing information is required.

The DSA system automatically administers the allocation, rearrangement, disk storage, and disk retrieval of all data blocks during the execution of an Ecap II run. Before each block is generated, a request is made for DSA to allocate the desired amount of space in a large array (in main memory) called IPOOL. After a search of available spaces (holes) in IPOOL, the block may be assigned space therein. If no single hole is large enough to accommodate the pending request, the existing blocks either will be "squeezed" together or a number of blocks, starting with those of lowest retention priority, will be stored in DPOOL (on disk memory) until enough space is made available.

To keep track of the location of each block in IPOOL or DPOOL, DSA maintains in the low-address portion of IPOOL a *directory* with a three-word entry for each block as follows: a positive (or negative) integer that gives the relative address of the block in IPOOL (or DPOOL), the block size, and the retention priority. A *negative* retention priority means that the block is in *held* status and is not eligible to be stored on disk because it is a necessary ingredient in a current or pending computation. For example, before the execution of an operation that requires blocks A, B, and C, the instructions GET(A), GET(B), and GET(C) retrieve these blocks from DPOOL (if they are not already in IPOOL) and put the blocks in *held* status. After this operation, the execution of a PUT instruction causes the block retention priority to be set to whatever positive value is specified. In this way, the block is removed from held status—but *not* stored in DPOOL. A block is sent to DPOOL only to create space in IPOOL for a pending request.

When a block is no longer needed, it may be released. If the block was in IPOOL, its space now becomes a hole available for reallocation; if the block was in DPOOL, its space is not reused, but the block is deleted from the directory by setting its location word to zero. By managing space allocations in IPOOL and DPOOL in this manner, DSA makes very effective use of both main and auxiliary memory; this permits Ecap II to handle much larger problems than otherwise would be possible.

Although most users of the program will have little need for it, there is a versatile system of diagnostic printing routines for displaying all the data blocks and matrixes and for monitoring the status of storage allocations throughout the execution of the program. In this way, all the numerical details of an analysis can be studied exhaustively to verify the accuracy of the computations. These printout facilities have been an invaluable aid in developing and maintaining the program.

Methods of numerical analysis

The principal breakthrough in the numerical analysis techniques embodied in Ecap II is the use of implicit integration.[3,9,10] The approach taken in solving a differential equation of the form $\dot{x} = f(x,t)$ is to approximate this equation by a difference equation of the general form

$$x_n = a_1x_{n-1} + a_2x_{n-2} + \cdots + h[b_0\dot{x}_n + b_1\dot{x}_{n-1} + b_2\dot{x}_{n-2} + \cdots]$$

where h is the integration step size and where $x_n = x(t_n) = x(nh)$. The coefficients a_i and b_i are usually determined by matching a certain number of terms in the Taylor expansion of $x(t)$ about a point. If the coefficient $b_0 = 0$, the formula represents an *explicit* method of integration, since all the data on the right-hand side are already known from previous integration stops. If, however, $b_0 \neq 0$, the term $\dot{x}_n$, which has not yet been computed, is required to calculate the new value of x_n. In this case, the formula represents an *implicit* method of integration and requires that a system of equations relating $\dot{x}_n$ and x_n be solved at every integration step. If these equations are nonlinear, then an iterative process of solution must be used.

It is characteristic of difference equations whose degree exceeds that of the differential equation they are intended to approximate that certain *parasitic* solutions are always present in addition to the desired solution.[3] Normally, these parasitic solutions can be made small enough to be quite negligible. But with an explicit method of integration, the step size h must not be allowed to become appreciably larger than the smallest time constant in the circuit. Otherwise, the parasitic solutions will grow without bound and completely overwhelm the desired solution. This phenomenon, called "numerical instability," is far less severe a restriction for implicit methods of integration; therefore, step sizes greatly exceeding the minimum time constant can safely be taken.[9]

Although implicit, as well as explicit, methods of numerical integration have been known for years, the fact that implicit methods require the solution of simultaneous equations at every time step was long believed to make these methods impractical. However, the advent of sparse matrix techniques has so greatly speeded up the solution of simultaneous equations[6–8] that implicit integration is now quite feasible. In addition to eliminating the time-constant barrier, the implicit integration method permits algebraic-differential equations for any circuit to be solved simultaneously; that is, it is unnecessary to eliminate the variables associated with the algebraic equations and to derive an equivalent system of purely differential equations, as required by explicit methods of integration. This simplifies the coding considerably.

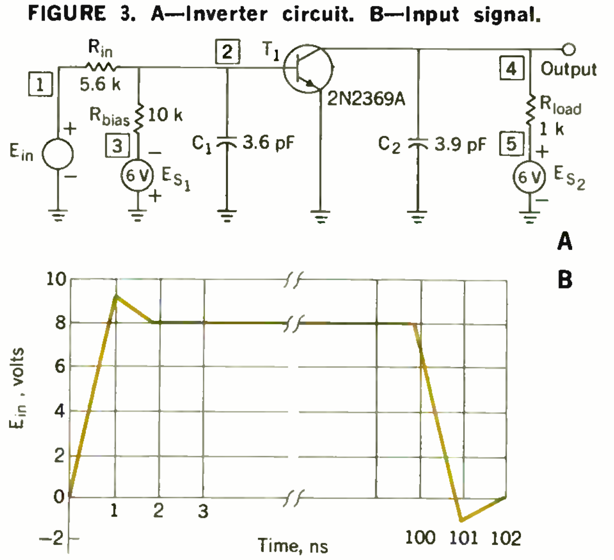
Although these methods of solving the algebraic-differential equations are usually called numerical integration, the implicit methods may also be viewed as numerical *differentiation*. Indeed, this is evident from the fact that the general difference equation can be solved for $\dot{x}_n$ in place of x_n. It then is clearly a general formula for numerical differentiation. Although this is the way the difference formula is actually used in Ecap II, the term *integration* will be retained in the discussion to follow.

In Ecap II, the integration method uses Gear's *variable-order* approach[9] as modified by Brayton, Gustavson, and Hachtel.[10] This approach optimizes the order of the method with respect to step size throughout the integration process. That is, at each integration step the largest step size consistent with the allowed truncation error and with the current order k of the integration process is computed. But periodically, the step sizes corresponding to orders $k - 1$ and $k + 1$ are also computed to determine which order of integration permits the largest integration step. A maximum value of $k = 6$ is assumed by the program, but the user may specify any smaller value. The integration process always starts at first order (with a step size of $10^{-6}\, t_{max}$) and gradually builds up to higher order and larger steps as the integration proceeds. Linear problems tend to level off at fifth or sixth order, except at sharp discontinuities in the transient response. Nonlinear problems seem to favor lower orders—around third, fourth, or fifth. Because the method has excellent stability, even in the presence of small time constants, very large integration steps can be taken when the responses are not changing radically. On the other hand, when a very sharp change in a response occurs, the step size may decrease by several orders of magnitude, if necessary, so that the details of this response can be computed as accurately as the specified truncation error requires. Thus, the integration method is well-suited to the types of problem encountered in modern circuit analysis.

The allowed truncation error, which the user must specify by assigning a value of the parameter TRUNC, represents an upper bound on the accumulated sum of the maxima of the individual truncation errors incurred at each integration step. Ecap II assumes that TRUNC is to be evenly distributed over the entire integration interval $(0, t_{max})$ so that the allowed truncation error at each integration step is equal to the fraction h/t_{max} times TRUNC. The actual truncation error at each step is taken as the (absolute) largest of the individual truncation errors for the capacitance voltages and inductance currents. Adjusting the step size maintains equality between the actual and allowed errors at each step. The user should, therefore, assign to TRUNC a numerical value that represents the maximum accumulated error (in the voltage or current units appropriate to his problem) that can be tolerated in any capacitance voltage or inductance current at the end of the integration process.

Ecap II uses a hybrid formulation of the network equations[12] that is a modification of the usual state-variable formulation; that is, the state vector x contains variables

FIGURE 3. A—Inverter circuit. B—Input signal.



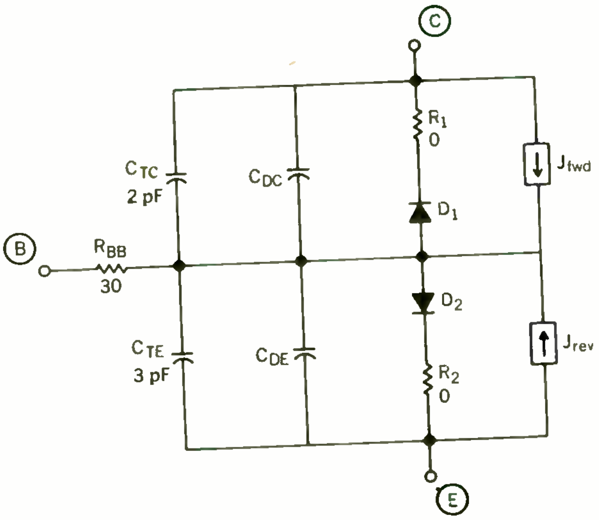
that correspond not only to differential equations (capacitance tree-branch voltages and inductance link currents[3]), but also to algebraic equations (conductance tree-branch voltages and resistance link currents). No attempt is made to eliminate the algebraic variables because the implicit integration algorithm can handle the algebraic equations simultaneously with the differential equations. In point of fact, since the algorithm requires computing the rate vector dx/dt, an iterative process of solving nonlinear algebraic equations is used that is only slightly different from that used in dc analysis. Indeed, much of the same code is exercised for both dc and transient analysis.

The iterative process of solving nonlinear equations in Ecap II is a modification of Newton's method[13] in which the residual error is never allowed to increase from one iteration to the next so that the process cannot diverge. Although this does not always ensure convergence, it results in a larger region of convergence than by some other methods. Generally, this algorithm performs well, converging in five to ten iterations. However, in circuits containing negative resistance—tunnel-diode circuits and flip-flops—the method may get hung up with a nonzero, but irreducible, residual error, unless the initial conditions for the iteration process are correctly chosen to penetrate the region of convergence. A method of circumventing this problem has recently been discovered, but will not be discussed here.[14]

For strictly linear problems, Newton's method is ideal in that it will converge in one iteration if there is no round-off error. Ecap II employs this method for linear problems because it makes use of much of the code that is also used for nonlinear problems. More than this, it permits completely automatic *iterative refinement* of the solution,[15] if this should be necessary in a poorly conditioned linear problem to satisfy the accuracy criterion already included in the program or specified by the user.

To ensure that the floating-point calculations have adequate precision, Ecap II uses extended precision (48-bit words) on the 1130, which is significant to more than nine decimals, and long precision (64-bit words) on S/360, which is significant to more than 15 decimals. On both machines, however, the normal convergence criterion corresponds to only six-decimal accuracy. The accuracy of the iterative process of solving both linear and nonlinear equations is, therefore, adequate for most applications. It is certainly much greater than is required by the integration method, where accuracy of one percent or less is usual.

FIGURE 4. Transistor equivalent circuit (2N2369A).



Sample problems

Problem 1. Figure 3(A) illustrates a simple logic inverter circuit that contains a single transistor and is driven by a pulse of the waveform in Fig. 3(B). The Ebers–Moll equivalent circuit of Fig. 4 represents the transistor. The parameters for the transistor model are

1. For the diode characteristics

$$J_{be} = 3.5745 \times 10^{-9}(e^{28V_{be}} - 1) \text{ mA}$$

$$J_{bc} = 7.3801 \times 10^{-9}(e^{32V_{bc}} - 1) \text{ mA}$$

2. For the emitter junction capacitance

$$C_{TE} = 3.0 \text{ pF}$$

$$C_{DE} = 6.72 \times 10^{-9} J_{be} \text{ pF}$$

3. For the collector junction capacitance

$$C_{TC} = 2.0 \text{ pF}$$

$$C_{DC} = 185 \times 10^{-9} J_{bc} \text{ pF}$$

4. For the base resistance

$$R = 20 \text{ ohms}$$

FIGURE 5. A printout that shows the complete circuit to be analyzed. This listing was generated when the ANALYZE statement was read and processed for Problem 1.

```
                                ECAP EXECUTION                                   RUN NO    43
CIRCUIT , JCNDIODE      STANDARD DIODE MODEL
J1 , 2 - 1 = DIODE(VJ1,K,PISAT)    DIODE CURRENT, AMPS
K = 28    Q/KT FACTOR, PER VOLT
PISAT = 1.0E-12      REV SAT CURRENT, AMPS
STORE , EXT = 2 - 1 , DES = 'STANDARD DIODE MODEL'
CIRCUIT , 2N2369A      TRANSISTOR MODEL
RBB , B - 4 = 30     BASE RESISTANCE
R1 , 5 - C = 0     DUMMY, TO MEASURE JBC
R2 , 6 - E = 0     DUMMY, TO MEASURE JBE
CTE , 4 - E = 3.0PF
CDE , 4 - E = 6.72E-9*IR2
CTC , 4 - C = 2.0PF
CDC , 4 - C = 185E-9*IR1
J2 , 4 - 6 = DIODE(VJ2,28,3.5745E-12)    DEFINES D2
D1 , 4 - 5 = JCNDIODE , K = 32 , PISAT = 7.3801E-12

     J1 , 4 - 5 = DIODE(VJ1,K,PISAT)    DIODE CURRENT, AMPS
     K = 32    Q/KT FACTOR, PER VOLT
     PISAT = 7.3801E-12     REV SAT CURRENT, AMPS

JREV , E - 4 = 0.474*IR1    REVERSE ALPHA*JBC
JFWD , C - 4 = 0.978*IR2    FORWARD ALPHA*JBE
STORE , EXT = E - B - C , DES = 'TRANSISTOR MODEL FOR HIGH SPEED SWITCHING APPLICATIONS'
CIRCUIT
ES1 , 0 - 3 = 6
ES2 , 5 - 0 = 6
EIN , 1 - 0 = TAB1(TIME)      TAB1 DEFINES INPUT WAVEFORM
TAB1 , 0 , 0 , 1NS , ? , 2NS , 8 , 100NS , 6 , 101NS , -1 , 102NS , 0 , 11 NS , ?
C1 , 2 - 0 = 3.6PF
C2 , 4 - 0 = 3.9PF
RIN , 1 - 2 = 5.6K
RBIAS , 2 - 3 = 10K
RLOAD , 5 - 4 = 1K
T1 , 0 - 2 - 4 = 2N2369A , RBB = 20      TRANSISTOR MODEL WITH RBB ?

      RBB , 2 - 4.T1 = 20     BASE RESISTANCE
      R1 , 5.T1 - 4 = 0     DUMMY, TO MEASURE JBC
      R2 , 6.T1 - 0 = 0     DUMMY, TO MEASURE JBE
      CTE , 4.T1 - 0 = 3.0PF
      CDE , 4.T1 - 0 = 6.72E-9*IR2
      CTC , 4.T1 - 4 = 2.0PF
      CDC , 4.T1 - 4 = 185E-9*IR1
      J2 , 4.T1 - 6.T1 = DIODE(VJ2,28,3.5745E-12)    DEFINES D2
      D1 , 4.T1 - 5.T1 = JCNDIODE , K = 32 , PISAT = 7.3801E-12

           J1 , 4.T1 - 5.T1 = DIODE(VJ1,K,PISAT)    DIODE CURRENT, AMPS
           K = 32    Q/KT FACTOR, PER VOLT
           PISAT = 7.3801E-12     REV SAT CURRENT, AMPS

      JREV , 0 - 4.T1 = 0.474*IR1    REVERSE ALPHA*JBC
      JFWD , 4 - 4.T1 = 0.978*IR2    FORWARD ALPHA*JBE

SAVE1 , VC1('BASE VOLTS') , VC2('OUT VOLTS')
PRINT1 , VC1 , VC2 , CDE.T1 , CDC.T1 , TIME
PRINTERPLOT1 , SAVE1 , VS = TIME , TITLE = TITLE1
TITLE1 , 'DIGITAL LOGIC INVERTER' , 'VC1=BASE VOLTAGE' , 'VC2=OUTPUT VOLTAGE'
TSTOP  = 200NS
TRUNC  = 0.50
ANALYZE , DC , TR
```

5. Forward and inverse current gains

$$\alpha_N = 0.978$$

$$\alpha_I = 0.474$$

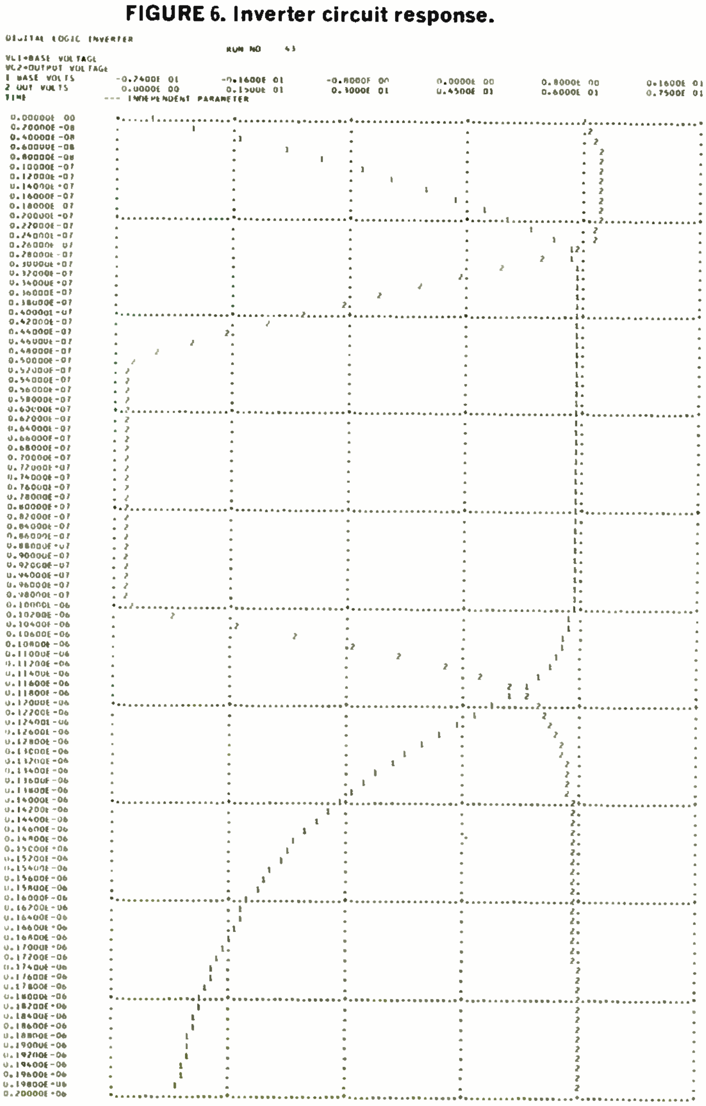
The dummy resistors R_1 and R_2, both of value zero, are used to monitor the emitter and collector diode currents J_{be} and J_{bc}, respectively, and are used in defining both C_{DE} and C_{DC}, as shown, and the current sources J_{fwd} and J_{rev}, according to the equations

$$J_{fwd} = \alpha_N J_{be}$$

$$J_{rev} = \alpha_I J_{bc}$$

To illustrate the use of Ecap II input language in describing this circuit, assume that the base-collector diode D_1 in Fig. 4 is represented by a model already stored in the model library under the name JCNDIODE. This model is simply a nonlinear dependent current source whose V-I characteristic is the exponential diode function with reverse saturation current and whose q/kT factor has assigned values different from those required by the definition of J_{bc}. To define this model first, the following Ecap II statements would be needed:

FIGURE 6. Inverter circuit response.



CIRCUIT, JCNDIODE:STANDARD DIODE
+ MODEL

J 1, 2-1 = DIODE (VJ1,K,PISAT):DIODE
+ CURRENT, AMPS

K=28:Q/KT FACTOR, PER VOLT

PISAT = 1E − 12:REV SAT CURRENT, AMPS

STORE, EXT = 2 − 1, DES = 'STANDARD
+ DIODE MODEL'

The first statement starts the definition of the circuit and labels it. The second statement defines the nonlinear dependent current source J1 by means of the built-in diode function whose arguments are the voltage VJ1 across the diode, the q/kT factor K, and the reverse saturation current PISAT. The parameters K and PISAT are then assigned "standard" values, which will always be used in this model unless otherwise specified. Finally, the STORE statement causes this circuit to be added to the model library under the name JCNDIODE with external terminals 2 and 1 and with the description 'STANDARD DIODE MODEL.' Note that each statement may have comments following it, separated by a colon. The following statements may be used to define the transistor model:

CIRCUIT, 2N2369 A:TRANSISTOR MODEL

RBB, B-4 = 30:BASE RESISTANCE

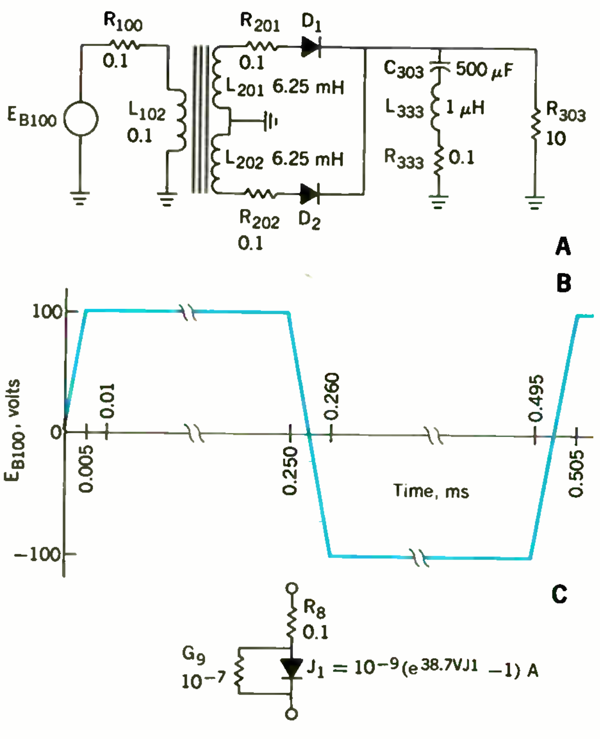
R1, 5-C = 0:DUMMY, TO MEASURE JBC

R2, 6-E = 0:DUMMY, TO MEASURE JBE

CTE, 4-E = 3.0 PF

CDE, 4-E = 6.72E-9*IR2

FIGURE 7. A—Full-wave rectifier. B—Input signal. C—Diode equivalent circuit.



```
CTC, 4-C = 2.0 PF

CDC, 4-C = 185E-9*IR1

J2, 4-6 = DIODE(VJ2,28,3.5745E-12):DEFINES D2

D1, 4-5 = JCNDIODE,K=32, PISAT=7.3801E-12

JREV, E-4 = 0.474*IR1:REVERSE ALPHA*JBC

JFWD, C-4 = 0.978*IR2:FORWARD ALPHA*JBE

STORE, EXT = E-B-C, DES = 'TRANSISTOR
+ MODEL FOR HIGH SPEED SWITCHING
+ APPLICATIONS'
```

Here, the label or name of the circuit, which only later becomes a "model" upon execution of the STORE command, is 2N2369A. Notice that R_{BB} equals 30 ohms in this definition of the circuit; later, when the model is plugged into the circuit of Fig. 3(A), R_{BB} will be respecified as 20 ohms. The J2 statement defines the base-emitter diode D_2 of Fig. 4 and D_1 is defined by means of the diode model JCNDIODE, previously stored in the library. Since the values of K and PISAT as originally defined for JCNDIODE are not suitable for D_1, these parameters are respecified in the D1 statement. Finally, the STORE statement causes the circuit 2N2369A to be stored on the model library with external nodes E, B, and C and with the accompanying description.

It is now possible to describe the entire circuit of Fig. 3(A) using the 2N2369A transistor model—which, of course, has the JCNDIODE model nested within it. The necessary statements are

```
CIRCUIT

ES1, 0-3 = 6

ES2, 5-0 = 6

EIN, 1-0 = TAB1(TIME):TAB1 DEFINES INPUT
+ WAVEFORM

TAB1, 0,0, 1NS,9, 2NS,8, 100NS,8,
+ 101NS,-1, 102NS,0, 110NS,0

C1, 2-0 = 3.6 PF

C2, 4-0 = 3.9 PF

RIN, 1-2 = 5.6 K

RBIAS, 2-3 = 10K

RLOAD, 5-4 = 1K

T1, 0-2-4 = 2N2369A, RBB=20:TRANSISTOR
+ MODEL WITH RBB=20
```

Two points are worth noting in this definition of the circuit: first, the input voltage, as a function of time, is defined by the table TAB1 in which the units NS (nanoseconds) are affixed to the abscissa values; second, the transistor model, with RBB changed to the desired value of 20 ohms, is of type 2N2369A and has its emitter, base, and collector nodes (labeled E, B, C in the original definition) connected to nodes 0, 2, and 4 in the circuit. The node 0 or GND is taken as the datum or ground node in all Ecap II circuits.

The circuit description is now complete and it remains only to define the desired output and analysis options. Suppose that the outputs VC1 and VC2 are to be saved and renamed 'BASE VOLTS' and 'OUT VOLTS' when plotted. Suppose also that VC1, VC2, and the values of the capacitances CDE and CDC in the model T1 are to be listed (printed) as a function of TIME. The required output statements for this purpose and for entitling the output plot are

```
SAVE1, VC1('BASE VOLTS'), VC2('OUT VOLTS')

PRINT1, VC1, VC2, CDE.TL,CDC.TL,TIME

PLOT1, SAVE1, VS=TIME, TITLE=TITLE1

TITLE1, 'DIGITAL LOGIC INVERTER,'
+ 'VC1=BASE VOLTAGE,' + 'VC2 = OUTPUT
+ VOLTAGE'
```

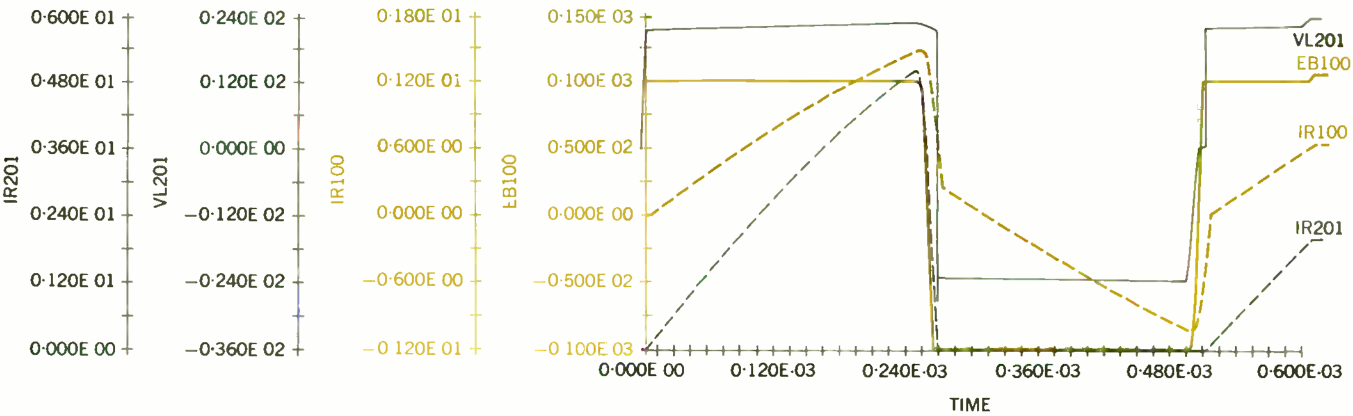
Finally, suppose that it is desired to perform a transient analysis for 200 ns, after first finding the dc initial conditions, and set an upper bound of 0.5 on the accumulated truncation error in the integration process. The statements to effect this are

```
TSTOP = 200 NSEC

TRUNC = 0.5

ANALYZE, DC, TR
```

FIGURE 8. The responses of Problem 2 as a function of time. The drawing from which the original waveforms were taken were reproduced by an IBM 1627 plotter.



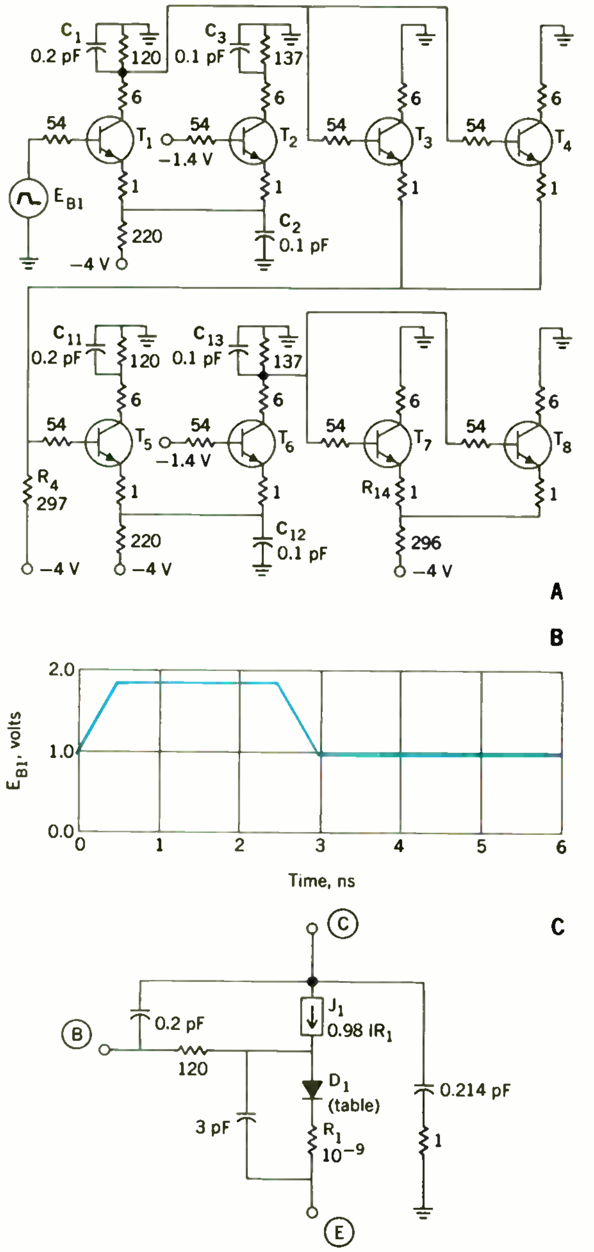


FIGURE 9. The eight-transistor logic circuit (A) of Problem 3, driven by a trapezoidal pulse (B), with the transistors represented by the model of (C).

When the ANALYZE statement is read and processed, a listing (Fig. 5) is generated that shows the complete circuit to be analyzed, including all its models. The model definitions are indented according to the corresponding level of nesting, and the actual parameter values (RBB = 20 in T1, K = 32 in D1.T1) are shown in each instance. Also, the nodes E, B, and C within the model T1 have been renamed. Figure 6 illustrates the printer-plotted output.

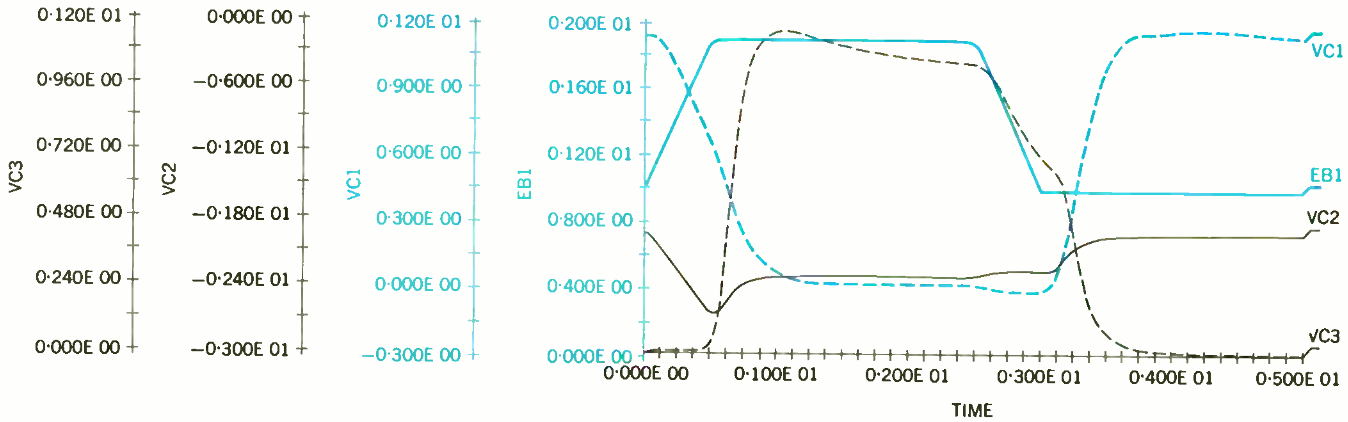
Problem 2. The full-wave rectifier circuit of Fig. 7(A) is driven by a 2-kHz trapezoidal wave, Fig. 7(B). The model used for the high-current diodes D_1 and D_2 is shown in Fig. 7(C). Only a transient analysis was requested for this circuit with initial condition VC303 equal to 21 volts, and with everything else equal to zero.

The interesting feature of this problem is that the small leakage inductance of the transformer causes a very sharp negative voltage spike to appear across L_{201} just after D_1 ceases to conduct at TIME = 0.268 ms (Fig. 8). This drawing was originally produced by the IBM 1627 plotter attached to the 1130 computing system. With the specified truncation error, this analysis required 172 integration steps. The minimum step size in the vicinity of these spikes was about 1 ns. Repetition of the analysis with a tenfold smaller truncation error resulted in 466 integration steps, with a minimum step size of 0.3 ns. In the first case, the spike width was about 100 ns, but in the second run, only 5 ns. The difference is due, of course, to the smaller allowed truncation error in the second run.

Just prior to the appearance of this "glitch" in VL201, however, the integration had been proceeding at the maximum step size of 30 μs (TSTOP/20) for eight successive steps. Thus, the step-size-control algorithm was able to respond to more than three orders of magnitude change in the first run and to five orders of magnitude in the second. The first run took 60 minutes, the second, 190 minutes.

Problem 3. A logic circuit driven by a trapezoidal pulse, Figs. 9(A) and (B), contains eight transistors, all represented by the simple model of Fig. 9(C). This model contains a small stray capacitance from collector to a resistive substrate. The overall circuit contains 60 nodes and 105 branches and gives rise to 30 differential and 62 algebraic equations. From zero initial conditions, con-

FIGURE 10. The responses of Problem 3 as a function of time. The drawings from which the original waveforms were taken were reproduced by an IBM 1627 plotter.



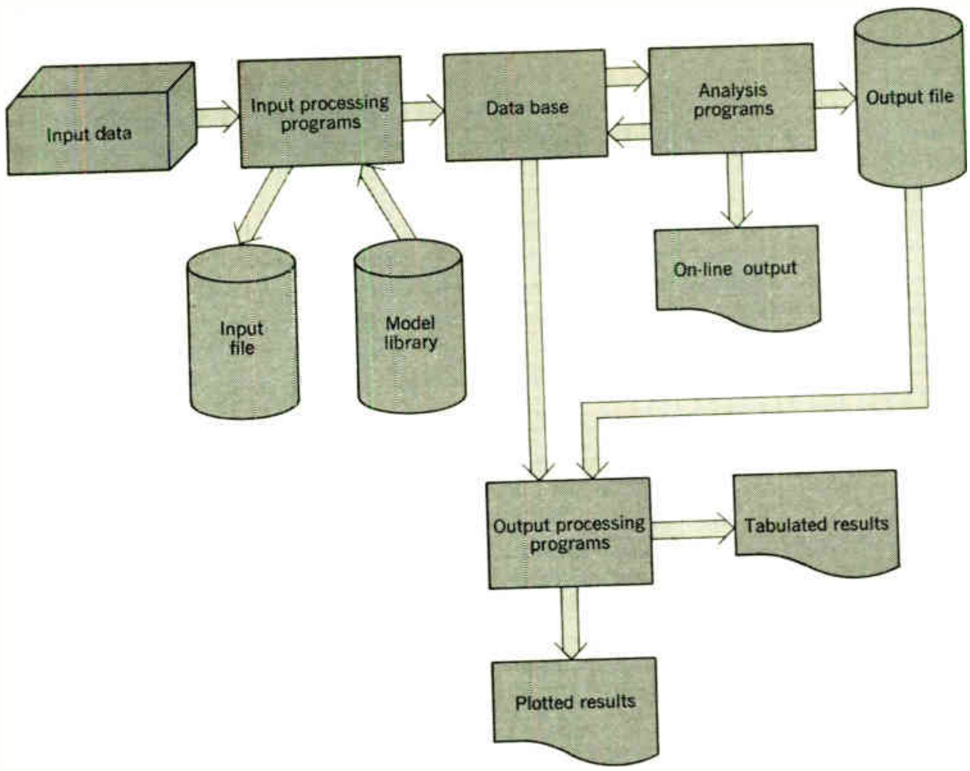


FIGURE 11. Overall program organization.

vergence to the dc equilibrium solution was obtained in six iterations. The transient analysis, with a specified integration time of 5 ns, took 324 integration steps to produce the responses of Fig. 10. The entire problem required 320 minutes of computer time on the 1130 (11 minutes for the input processing and dc analysis).

The same problem was run on System/360, Model 65, under the multiprogramming, variable number of tasks (MVT) option of the operating system, with three different values of TRUNC. Table I lists the program statistics and central processing unit (CPU) times for transient analysis only. The CPU time for input processing and dc analysis was 52 seconds; region size was 250 kilobytes.

To demonstrate that the Ecap II integration algorithm is free of the time-constant limitations of explicit integration methods, C_3 was reduced from 0.1 pF to 0.1 × 10^{-6} pF, and the analysis was repeated. With this change, the ratio of largest to smallest time constant was greater than a million to one. The integration proceeded with exactly the same step sizes as in the original problem for the first 30 steps because the voltage across C_3 was quiescent up to this point. As soon as V_{C3} began to change, however, it did so much more rapidly than in the original problem, which forced the step sizes to become noticeably smaller. But when V_{C3} settled down again, the integration proceeded at essentially the same rate as in the original circuit.

By contrast, when this problem was run using the fourth-order Runge–Kutta option of the Sceptre program (an explicit method of integration), the program stopped at less than 3 percent of the requested integration time, after taking more than 22 000 integration steps. It would have taken more than 800 000 steps to complete the analysis.

Implicit integration methods are free of the minimum-time-constant restriction as long as the responses associated with these small time constants are quiescent. But when these responses begin to exhibit a significant contribution to the overall response of the circuit—as in the case of V_{L201} in Fig. 8, or in the case just discussed—then the integration-step size must be decreased to trace out these responses within the prescribed limits of accuracy. Accordingly, the time-constant limitations inherent in implicit integration are related to considerations of accuracy whereas those of explicit integration are related to questions of numerical stability, which have nothing to do with accuracy.

A tenfold replication of the circuit of Fig. 9, coupled together with ten additional resistors, was also analyzed. This problem, consisting of 1060 branches, 300 differential equations, and 630 algebraic equations, was run under MVT on System/360, Model 65, with a region size of 700 kilobytes. Input processing and dc analysis took 6.8 minutes of CPU time and the transient analysis (TRUNC = 0.5, 95 integration steps) took an additional 37 minutes. The results were, of course, identical to those obtained for the prototype problem. But a greater than tenfold increase in CPU time per integration step was required primarily because of the extra movement of data

I. Program statistics and CPU times for Problem 3 (eight-transistor logic circuit, 105 branches)

Specified Truncation Error	Number of Integration Steps	Number of Iterations	CPU Time (seconds)
1.0	73	115	150.7
0.5	95	124	170.7
0.1	282	318	457.3

blocks in core during DSA "squeeze" operations and also because of the ten extra algebraic equations resulting from the ten coupling resistors.

Program structure

Figure 11 illustrates the overall structure of Ecap II. The program is divided into three major phases: input, analysis, and output. Input statements are read by the input processing program (*input phase*). Each statement is checked for validity, saved in the input file, converted into internal storage format, and stored in the data base. If the statement is a model reference—that is, if it represents a subnetwork previously defined and stored in the model library—the corresponding statements are read from the model library and included in the data base. If the statement is a command—that is, a request for a particular process to be performed—it is checked for validity, converted to internal data format, and the requested process is performed.

When the command requesting an analysis is read, control is passed to the analysis programs (*analysis phase*). These programs use the data base both as input (the circuit description) and as intermediate storage (for matrixes and tables). At each step of the analysis, output data are generated and placed in the output file, printed on-line, or both.

When the analysis is complete, control passes to the output processing programs (*output phase*). These programs, as directed by user input, produce various tabular listings or plots of the solution data. Control passes back to the input phase when all output has been processed. Additional input can then be processed. At this point, the user has a variety of options: changing the circuit description, saving the circuit in the model library, loading a previously saved circuit or subcircuit, reanalyzing the circuit after changes have been made, or studying in more detail the output previously generated. These program functions are requested by use of the Ecap II command statements: to control entry and modification of a circuit, to maintain the model library, and to control program execution.

Interaction with the circuit description. As noted, the input data are automatically stored in the input file. This file contains what is referred to as the current circuit. A variety of commands are supplied to provide the user with the facility to interact with this file (Table II). An additional means of interaction with the input file (current circuit) is the automatic replace feature. Any statement previously entered can be replaced by entering a complete replacement with the same name. For example, if R17, 4 – GND = 20K had been entered within the scope of the current circuit, then entry of R17, 4 –24 = 4.3*PAR4 would replace the previous R17. Thus, both the topology and the method of value specification can be changed.

Interaction with the model library. The model library contains descriptions of subcircuits or entire circuits. The means of entering these circuits into the model library is, first, to put a circuit description into the input file (normally from input data, or alternatively by the LOAD command), and second, to enter the STORE command. A field on the STORE command contains the name of the circuit or subcircuit. Table III lists the commands that provide entry into and maintenance of the model library.

Program control commands. Table IV lists three commands that provide control of program execution.

II. Commands that provide interaction with the input file

Command	Function
CIRCUIT	Clears the input file and data base in preparation for reading a new circuit description. The current circuit, if one is in the file, is lost.
LOAD	Clears the input file and loads it with a previously stored circuit or subcircuit. The function of LOAD is similar to that of CIRCUIT, except that the input file and data base are initially loaded with the saved circuit.
REMOVE	Removes one or more statements from the input file and data base.
LIST	Lists the contents of the input file. This is particularly useful, after a series of changes, to check the current circuit description for validity.
STORE	Copies the current circuit into the model library as a new entry. This entry can then be used during this or later runs as a model in larger circuits, or loaded via a LOAD command as the current circuit. (The STORE–LOAD combination can be used to save the current status of a circuit for additional study during a later run, thus saving the time of reentering the original description and any changes that have been made.)

III. Commands that provide interaction with the model library

Command	Function
STORE	Creates a new entry in the model library by copying the contents of the input file (current circuit).
DELETE	Deletes a named entry from the model library. All record of it is lost.
LIST	Provides three options: (1) List a named entry (a particular model). (2) List the name only of all entries in the file table of contents. (3) List the file in its entirety, that is, all statements of all models.

IV. Commands that control program execution

Command	Function
ANALYZE	Causes the current circuit to be analyzed by either the dc or transient programs.
OUTPUT	Causes reexecution of the output processing programs to produce additional tabular or plotted output.
EXIT	Transfers control of Ecap II back to the computing system at the end of an analysis session, or can cause a user program to be executed and to return control to Ecap II when it is complete.

Further details on the structure of the Ecap II input language may be found in Ref. 11, which describes the format and usage of circuit description statements, analysis controls, and output options.

During the past few years, several substantial breakthroughs have been made in methods of numerical analysis and programming techniques that are of great importance in the field of computer analysis of circuits. The most significant advances have been the use of sparse matrix storage and computation techniques coupled with implicit integration. These two developments are responsible for completely demolishing the long-standing "time-constant barrier," and for bringing within practical range the analysis of kilobranch circuits. Ecap II incorporates a number of these recent advances and provides a tool better equipped to satisfy the growing demands of circuit designers.

The authors express their appreciation for the collaborative efforts of Anita Ford, R. Boe, M. Goldberg, D. Goodwin, A. C. O'Hara, I. Jhangiani, R. A. Payne, and E. F. Sarkany in developing Ecap II. Thanks are also due Dr. K. U. Wang of the University of Cincinnati, D. A. R. Zein of Northwestern University, and G. Martin of the Université Libre de Bruxelles, Belgium, for their contributions to the program.

REFERENCES

1. "Automated digital computer program for determining the response of electronic systems for transient nuclear radiation (Sceptre)," AFWL-TR-69-77, Air Force Weapons Lab., Research and Technology Div., Air Force Systems Command, Kirtland, N.Mex.

2. Milliman, L. D., Massena, W. A., and Dickhaut, R. H., "Circus—A digital computer program for transient analysis of electronic circuits—User's guide," Boeing Co., Harry Diamond Laboratories, Rept. AD-346-1, Jan. 1967.

3. Branin, F. H., "Computer methods of network analysis," *Proc. IEEE*, vol. 55, pp. 1787–1801, Nov. 1967.

4. Johnson, E. D., Kleiner, C. T., McMurray, L. R., Steele, E. L., and Vassallo, F. A., "Transient radiation analysis by computer program (Trac)," Automatics Div., North American Rockwell Corp., Anaheim, Calif., Tech. Rept. issued by Harry Diamond Laboratories, June 1968.

5. Schichman, H., "Integration system of a nonlinear network analysis program," *IEEE Trans. Circuit Theory*, vol. CT-17, pp 378–386, Aug. 1970.

6. Tinney, W. F., and Walker, J. W., "Direct solutions of sparse network equations by optimally ordered triangular factorization," *Proc. IEEE*, vol. 55, pp. 1801–1809, Nov. 1967.

7. *Proc. Sparse Matrix Symp.*, IBM Rept. RA-1, Mar. 1969.

8. Hachtel, G. D., Brayton, R. K., and Gustavson, F. G., "The sparse tableau approach to network analysis and design," *IEEE Trans. Circuit Theory*, vol. CT-18, pp. 101–113, Jan. 1971.

9. Gear, C. W., "The automatic integration of stiff ordinary differential equations," *Information Processing 68*, A. J. H. Morrell, ed. Amsterdam: North Holland Publishing Co., 1969, pp. 187–193.

10. Brayton, R. K., Gustavson, F. G., and Hachtel, G. D., "The use of variable-order variable-step backward differentiation methods for nonlinear electrical networks," *Mem. Mexico 1971 Internat'l IEEE Conf. on Systems, Networks, and Computers*, Oaxtepec, Mexico, pp. 102–106.

11. *Ecap II Application Description Manual (GH 20-0983)*, IBM Corp., Mechanicsburg, Pa.

12. Branin, F. H., and Kugel, L. E., "The hybrid method of network analysis," *Proc. IEEE Symp. on Circuit Theory*, San Francisco, Calif., Dec. 1969.

13. Branin, F. H., "A controlled-step Newton method for solving nonlinear equations," *Proc. ACM-SIAM-IEEE Conf. on Math. and Comp. Aids to Design*, Anaheim, Calif., Oct. 1969.

14. Branin, F. H., "Solution of nonlinear dc network problems via differential equations," *Mem. Mexico 1971 Internat'l IEEE Conf. on Systems, Networks, and Computers*, Oaxtepec, Mexico, pp. 93–101.

15. Forsythe, G. E., and Moler, C. B., *Computer Solution of Linear Algebraic Systems*. Englewood Cliffs, N.J.: Prentice-Hall, 1967.

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Richard L. Lunde was born in Watseka, Ill., on October 21, 1939. He received the bachelor of science and master of science degrees in mathematics from the University of Illinois, Urbana, in 1961 and 1964, respectively. He joined the IBM Corporation in 1964 and is presently a staff programmer with the Data Processing Division, Des Plaines, Ill., where he is working on the Ecap II system. Mr. Lunde is a member of the Association for Computing Machinery.

Switching in vacuum: a review

Vacuum interruption devices are considered to be a relatively recent development from the point of view of power system applications; however, their underlying principle was discovered more than 150 years ago

Amos Selzer **Cutler-Hammer, Inc.**

The growing use of vacuum interruption devices by the power and control industries in the past decade has introduced these mechanisms to many people to whom the area of vacuum switching is somewhat new. It is felt that a review of vacuum switching from a historical and technological standpoint will facilitate a more general understanding of this important subject.

The advantages of vacuum interruption were recognized by scientists as early as the 19th century. However, the lack of theoretical understanding of low-pressure-arc physics on one hand and insufficient practical know-how of vacuum technology on the other prevented the construction of a commercial type of vacuum interrupter.

With advances in the understanding of plasma physics and improving techniques in the areas of vacuum contact metallurgy, metal-to-glass or metal-to-ceramic bonding, and vacuum sealing of envelopes, the vacuum interrupter as a commercial device became a reality. In the 1950s vacuum interrupters and relays were introduced and slowly adopted by power and control industries; recently, vacuum triggering devices and vacuum contactors joined them on the commercial scene.

The potential of vacuum interruption devices can be fully realized only by acquiring an understanding of both the physical characteristics of the vacuum arc and the functions of contacts in vacuum.

Historical remarks

The January 1971 issue of *Scientific American* contains an article entitled "Circuit Breakers" by Werner Rieder, in which many types of interrupters are described. The author ends his discussion by presenting the "newcomer" (which is, of course, the vacuum interrupter) and predicts a bright future for it. With this in mind, it will probably surprise even the people working in research and development in the area of vacuum interruption to know that only one year after the discovery of the electric arc an experiment was performed in vacuum to study some of the arc characteristics in that environment; furthermore, the discovery of the arc and the vacuum experiment were made about 160 years ago.

Revised text of a paper presented at the 21st Electronic Components Conference, Washington, D.C., May 10–12, 1971.

In a lecture delivered on November 16, 1809, before the Royal Institute, Sir Humphrey Davy stated that when current was sent through potassium vapor between platinum electrodes, over nitrogen gas, a vivid white flame arose. "It was a most brilliant flame, of from half an inch to one and a quarter inches in length." Sir Humphrey Davy's laboratory notes for the years, 1805–1812, are preserved in two volumes in the Royal Institute library. Two paragraphs of these notes are of interest to us from a historical point of view.

April 20, 1808—"A given quantity of muriatic acid gas was acted upon by a dry charcoal; there was a continued vivid light in the galvanic circuit."

August 23, 1809—"An experiment to ascertain whether any heat sensible to the thermometer is produced by the electric flame in Vacuo."

Davy published his work later (1812) in *Elements of Chemical Philosophy*.

Extensive work in research and development was done on the electric arc, electric discharge, and vacuum technology during the 19th century and the beginning of the 20th century.

In the areas of the electric arc and electric discharge:

1. In 1889, Paschen first discovered the relationship of the breakdown voltage between two contacts, in uniform electric fields and in gaseous environment, to the product of the gap distance between the electrodes and the pressure (Paschen's law).[1]

2. The first study of the topic of high-voltage breakdown between two electrodes in vacuum was made by R. W. Wood in 1897.[2]

3. In 1918, Millikan and Sawyer discovered that electrodes in vacuum can be conditioned to support higher electric fields. They found that if a vacuum gap is continuously sparked over, the breakdown voltage increases until it reaches a "plateau"; this plateau is the highest voltage the gap will support.[3]

The potential of vacuum interruption was demonstrated by these contributions and according to Rittenhouse[4] the first patent on vacuum switching was registered in 1893.

Vacuum interrupter devices could not be developed without an advance in vacuum technology. The need to obtain knowledge at pressures lower than atmospheric initiated the development of vacuum technology. Torricelli is known to be the first man who succeeded in evacuating a space by building his mercury barometer in 1644. In the 17th century vacuum pumps were built by Otto von Guericke in Germany (1650) and by Robert Boyle in England (1660), which were capable of reducing the system pressure by a considerable amount. In the 19th century, lower pressures were obtained by piston-type pumps or by water-jet suction pumps, which were capable of pumping down to 0.25 torr.* Better vacuum was obtained by using the Toepler pump, which worked on the same principle used by Torricelli. Bessel Hagen, in 1881, described a pump of this type capable of pumping down to about 10^{-2} torr.

A need for production of lower pressure arose with the development of incandescent filament lamps. In 1905, a rotary mercury pump was developed by Gaede. Shortly thereafter, the oil rotary pump was introduced and adopted by the lamp industry. In 1913, Gaede invented a "molecular" pump that could reduce the pressure to 10^{-4} torr; however, Gaede's largest contribution to the development of vacuum technology came in 1915 when he introduced his "diffusion" pump.[5] Pressures down to 10^{-6} torr and lower could be achieved with these mercury pumps. Pressures of about 10^{-6} torr were attainable by the use of a mechanical pump in conjunction with absorbent material. Millikan[6] used a charcoal trap immersed in liquid air to obtain lower pressure; the pressure in his experimental systems probably approached 10^{-7} torr. However, the best gauge available to Millikan at this time, the McLeod gauge, could measure pressure only down to 10^{-5} torr.

The limited knowledge and technology did not prevent the Swedish Birka Company[7] from constructing the first commercial vacuum switch in 1921. These switches were used to interrupt very low power. However, in 1926 Sorensen and Mendenhall[8] published a paper that summarized a series of experiments in which they successfully interrupted 926 amperes rms and 41 500 volts. This work was the beginning of a new era in power interruption.

In 1963 a historical review of the development of vacuum interrupters covering the period between 1926 and 1962 was published by J. D. Cobine.[9] It is one of Cobine's many excellent contributions toward the development and understanding of vacuum interruption.

Most of the papers published after 1962 will be mentioned in the following parts of the discussion. In order to complete the historical review of the development of vacuum interruption devices, two papers published after 1962 introducing relatively new practical devices will be mentioned here. The first, by Lafferty[10] in 1966, deals with triggered vacuum gaps, and the second, by May[11] in 1968, describes vacuum contactors.

Vacuum interruption devices

Many types of low-power vacuum switches have been built, but only a few will be mentioned here. In 1934, Rankin *et al.*[12] reported on a vacuum switch with three ratings: 10 A, 230 V ac; 15 A, 115 V ac; and 10 A, 250 V dc. Kling[13] and Teare[14] described a switch with similar ratings. Other low-power devices include the vacuum relays. The first vacuum relay was produced by Federal Telegraph Co. before 1930[15] and was rated 4 kV at 5 A dc. Such relays are used today for switching high voltage in radio, radar, and television transmitters. These applications usually utilize ranges in the tens of kV and low currents. The vacuum reed switch is another member of this group rated at up to 10 kV and below 0.5 A, and it is used in control of communication networks.

Vacuum interrupters. The use of these devices commercially was first reported in 1955.[16,17] These interrupters were built jointly by two companies: the Jennings Radio Co. and the Schwager Wood Co. Their development and construction are described by Jennings *et al.*[18] and later developments by Ross.[19,20] These interrupters were rated at 15 kV, 200 A, 60 Hz; however, in 1955 a switch was constructed with four of these devices in series, and it successfully switched a single-phase transmission line 240 km long at 230 kV.

A three-phase switch was built in 1959 in which eight vacuum interrupters were connected in series on each phase. The switch ratings were 230 kV, 600 A, and it was used successfully on a transmission line in Arizona.[21]

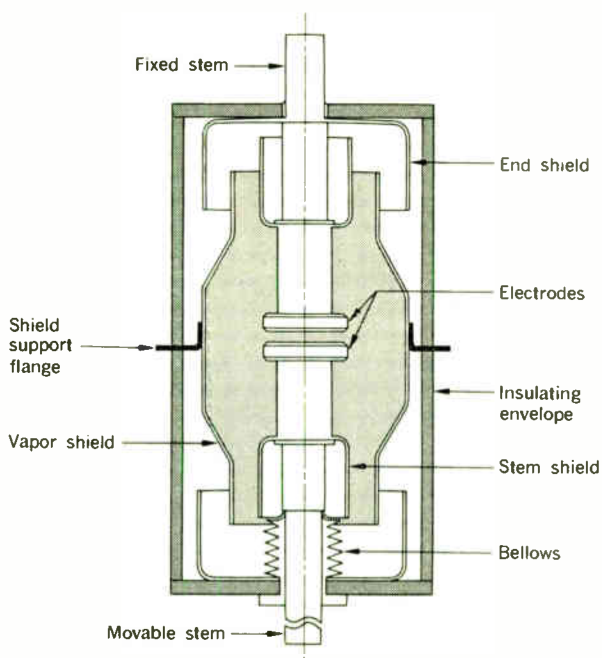
A schematic representation of a vacuum interrupter is given in Fig. 1.[22] The materials usually employed for the respective components are as follows:

Envelope. Alumina ceramic, glass, or glass ceramic.
Bellows. Stainless steel, beryllium copper, monel.
Stem. OFHC (oxygen-free high-conductivity) copper.
Shields. OFHC copper, stainless steel.
Envelope cover. Kovar, stainless steel.

All these materials are characterized by a low vapor pressure, which is necessary in a sealed device at low pressures. The contact materials vary from one manufacturer to another; however, copper–bismuth alloy is commonly utilized.

Extensive work in research and development in the 1960s resulted in upgrading the ratings of vacuum interrupters. Compared with 15-kV 4000-A interruption capabilities before 1960, devices today are capable of interrupting 15 kV and 31 000 A, and by connecting two in

FIGURE 1. Vacuum interrupter schematic diagram.



* 1 torr = 1 mm Hg = 133.3 n/m².

series a 34.5-kV 1500-MVA rating is achieved.[23]

To satisfy most interruption requirements, an interrupter should be developed that is capable of interrupting 50 kA and has a voltage rating greater than 15 kV to minimize the number of units required in series.

Vacuum triggering gap. Vacuum gaps were utilized by Hull as lightning arresters as early as 1927.[9] In 1960, vacuum triggering gaps were employed to discharge capacitor banks.[24,25] Other vacuum triggering devices available were operating in the 10^{-3}-torr range or on systems that were being continually pumped down, and some even depended on gas presence for successful triggering.[26] In 1966, Lafferty[10] reported on a sealed-off triggering vacuum gap capable of carrying large powerline currents. The device is shown schematically in Fig. 2.

The breakdown voltage of a vacuum gap depends on the gas adsorbed on the electrode's surfaces and on the surface condition. Because the contact surfaces will change after every arc, it is not practical to control the breakdown by the gap spacing. In the device described by Lafferty, the trigatron method is used to break the gap. This method utilizes a third trigger electrode, labeled "trigger lead" in Fig. 2. To operate the device a positive voltage pulse is applied to the trigger lead; a breakdown occurs between the lead and its adjacent electrode. This produces a burst of plasma, which fills up the gap between the two main electrodes and causes a complete breakdown of the gap that energizes the electric circuit. This method is also used in gaseous mediums. The ratio between the voltage the gap can withstand and the level at which a trigger can initiate a breakdown is 4 to 1 in gases compared with ratios of 1000 to 1 in vacuum.[23] The device has the following advantages: small size, rapid deionization time, operation possible over a wide range of gap voltages, operation possible in strong radiation environment, no major gas clean-up problems, no audio noise or shock waves, no explosion hazard.[10]

Vacuum contactors. Many different vacuum contactors with different ratings are available on the market today. These devices are usually employed to control motors. Voltage ratings range from 1.1 kV to 7.5 kV and current ratings vary between 200 A and 900 A. Ranheim *et al.* reported on one type of contactor capable of interrupting 1.5 kV at 9000 A rms. A schematic representation is shown in Fig. 3.[11] The vacuum contactor is very similar to the vacuum interrupter. Its lower voltage rating makes it possible to use a smaller volume. It is also possible in this case to connect the shield electrically to one contact up to certain power ratings. The practical requirements of vacuum contactors differ from those of the vacuum interrupter. The vacuum contactor has to repeat its function many more times than does the interrupter. In addition, the arc of this device must be stable for a duration of half a cycle and exist down to low values of current. If the arc is not stable, overvoltages may damage the motor's insulation. (See the section on arc stability.)

The requirement of repetitive operation calls for a bellows with a long lifetime and contacts with low erosion characteristics. The requirement for a stable arc was first tackled by Reece,[27] who suggested the use of auxiliary metals with high vapor pressure and low thermal conductivity in order to improve contact life and arc stability.

The vacuum medium

The term *vacuum* refers to every medium that has a pressure below atmospheric pressure (760 mm Hg). The

FIGURE 2. High-voltage triggered vacuum gap for microsecond-pulse operation.

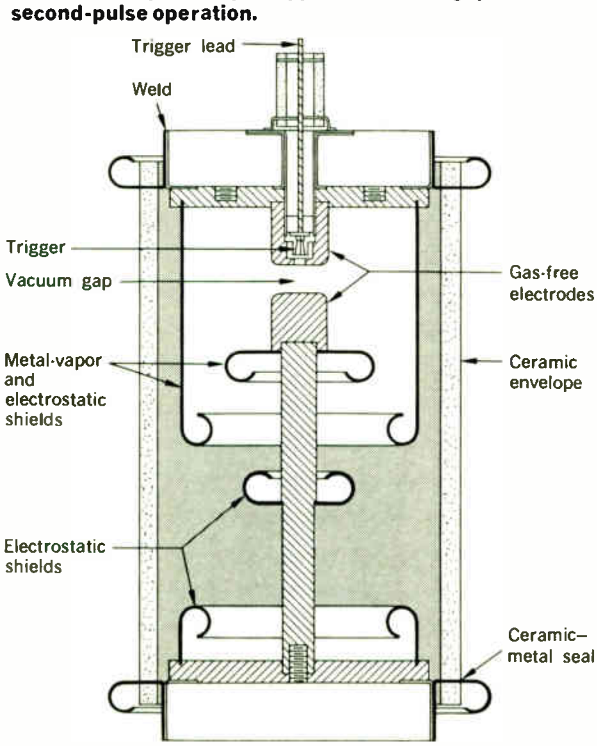
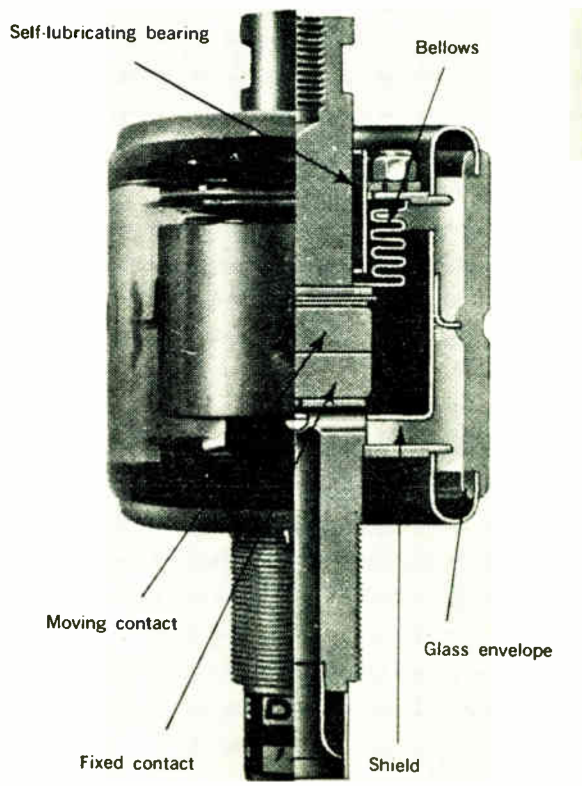


FIGURE 3. Section through a typical vacuum switch showing the principal components.



I. Gas kinetic data for N_2 at 25°C

Pressure, torrs	Density, molecules/ cm^3 at 25°C	Mean Free Path, cm
760	2.5×10^{19}	6.3×10^{-6}
10^{-3}	3.3×10^{13}	4.8
10^{-4}	3.3×10^{12}	48
10^{-5}	3.3×10^{11}	480
10^{-6}	3.3×10^{10}	4.8×10^{3}
10^{-7}	3.3×10^{9}	4.8×10^{4}

most commonly used unit of pressure in the vacuum discipline is the *torr*, defined previously.

The concept of the mean free path is important to anyone interested in evacuating a confined space to very low pressure. The *mean free path* is defined as the average distance that a gas molecule, atom, ion, or electron will travel in a gaseous medium before colliding with another gas molecule or atom; that is, $L_e = 5.64/n\pi d^2$, where L_e is the electron mean free path, n is the density of the medium, and d is the atomic or molecular diameter.

In the high-pressure ranges of the vacuum system, the mean free path is very small and the molecules are in a constant state of intercollision. The gas behaves as a fluid and is known to be in a state of *viscous flow*.

As the pressure is reduced, the mean free path increases. Eventually, a point is reached at which the mean free path is equal to or greater than the dimensions of the confining chamber. Under this condition, the molecules will collide more frequently with the walls of the chamber than with each other. In this region, the gas is said to be in a state of *molecular flow*.

The division between the two regions is specified by a dimensionless parameter called the Knudsen number.[28] For a cylindrical tube, the Knudsen number is defined as the ratio of the mean free path of gas molecules to its radius R. When L_m/R is less than 0.01, the gas flow is viscous; if the ratio is larger than 1, the flow is molecular. The range between these two limits is called the *transition range*. Relationships between gas parameters are given in Table I.[29]

The gaseous medium in vacuum interruption devices is usually in the molecular-flow range. However, when high currents are interrupted, the pressure in the arc column, confined to the volume between the contacts, might be even higher than atmospheric. Calculations of the pressure of the arc column in relation to the current interrupted are shown in Fig. 4.[30] This high pressure is reduced very rapidly as the gas diffuses into the volume of the enclosure. Since the arc usually lasts no longer than half a cycle, the pressure in the enclosure will not rise above the limit that permits interruption. This limit, according to Koller,[7] is 10^{-4} torr.

This value is also mentioned in other publications.[4,8,27] The metallic vapor of the arc is condensed on the shield wall, where it pumps chemically active gases by the gettering process. This pumping activity helps to keep low pressure in the enclosure.

The dielectric strength of vacuum is greater than that of any other interrupting medium in use.[7] Breakdown voltage of vacuum compared with that of air for tungsten contacts is shown in Fig. 5.[18] This property allows the use of very short gaps between the contacts and minimizes the size of the device.

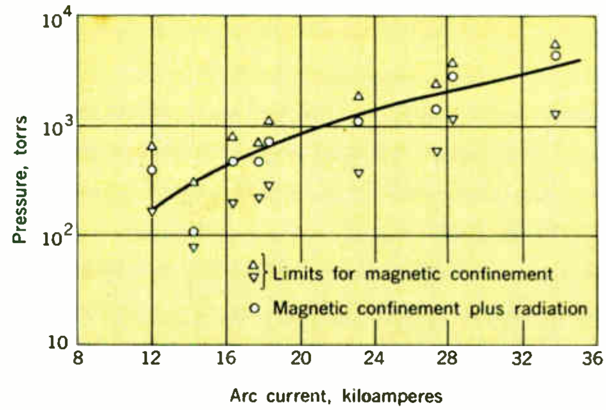
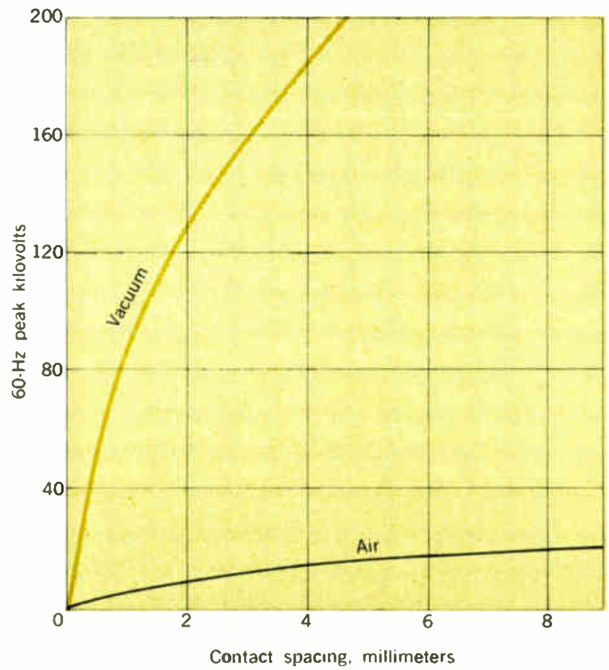


FIGURE 4. Total pressure in arc column vs. instantaneous value of arc current at peak arc voltage.

FIGURE 5. Breakdown voltage of vacuum and of air for one pair of 9.5-mm-diameter tungsten contacts.



Breakdown in high vacuum does not follow the Paschen curve[2] because the gas density is too low to develop an avalanche. The breakdown in vacuum depends entirely on the metal's surfaces. In a vacuum environment, at least one monolayer of gas exists on all metal surfaces. In order to achieve a higher value of breakdown, these residual gases must be desorbed from the contacts and other metallic surfaces of the device.

Many chemical and electrical methods are used to outgas the parts of the device. Before assembly, parts are fired in an H_2 atmosphere or vacuum at temperatures up to 800°C.[31] After a unit is constructed, it is baked in vacuum and temperatures up to 400°C for as long as 12 hours before being sealed off at pressures less than 10^{-7} torr. As it can be seen from the above, although the vacuum interrupter can operate successfully in the 10^{-4} torr range, in its development and production ultrahigh-vacuum techniques are utilized. This means that ion-gettering vacuum pumps are preferred to diffusion pumps. If the latter are to be used, the system should include a cold trap to prevent backstreaming of hydrocarbons or mercury vapors into the device. A complete description of methods used in the ultahigh-vacuum field is given by Dushman and Lafferty[28] and by Redhead *et al.*[32]

The vacuum arc

Reece[33] was the first to distinguish the vacuum arc from the low-pressure arc. He defines the vacuum arc as one that burns only on metal vapor and positive ions produced by the arcing phenomenon itself. When the arc ceases to exist, the pressure in the arc space returns to zero (in practice, below 10^{-4} torr). This definition excludes arcs between excessively hot contacts and certain mercury arcs.

In earlier works, Reece[27,34,35] found a relationship between the arcing voltage and the product of boiling point and thermal conductivity of different materials. Materials with low products also have low arcing voltages. Some values are as follows: bismuth, 8.7 volts; antimony, 9.8 volts; cadmium, 10 volts; tungsten, 26 volts; copper, 21.5 volts; silver, 17 volts; and molybdenum, 24 volts.

The *V-I* characteristics of the vacuum arc for copper contacts are shown in Fig. 6.[36] Most other materials show the same relationship. The arcing voltages for molybdenum and tungsten are above the line of copper and all other materials are below it. From Fig. 6, we can see that the graph can be divided into three parts:

1. *0–1000 A*. The arc voltage is independent of current gap length and contact shape; it is determined by the cathode material.

2. *1000–6500 A*. The arc voltage increases linearly with the current, from 20 to 40 V for copper contacts.

3. *Above 6500 A*. The arc voltage is unstable and can reach 120 V.

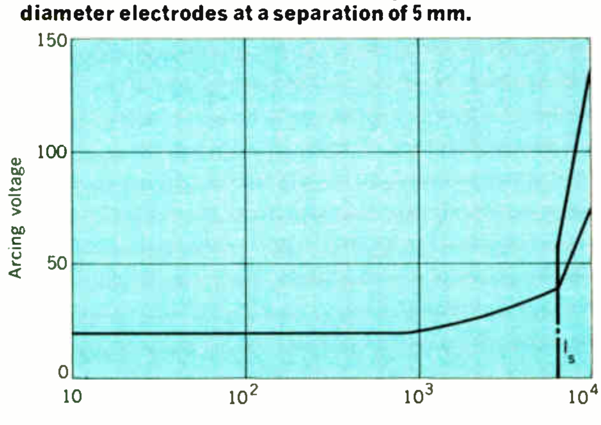
An empirical relationship between the current and the arc voltage was given by Mitchell,[37] for the current range 0–6500 A:

$$E_{arc} = 20 + GI$$

where G is a constant (see Table II), I is the current (amperes), and E_{arc} the arc voltage.

He attributed the sudden rise in arc voltage at a current of about 6500 A to a sudden lack of positive ions and termed the current at which it occurs the *starvation current*.

FIGURE 6. Arcing voltage vs. arcing current for 25-mm-diameter electrodes at a separation of 5 mm.



II. Values of G for butt copper electrodes

Electrode Separation, mm	Diameter, mm 25	45	75
5.0	2.9×10^{-3}	2.05×10^{-3}	9.5×10^{-4}
7.5	5.3×10^{-3}	3.2×10^{-3}	—
10.0	6.1×10^{-3}	4.2×10^{-3}	2.0×10^{-3}
15.0	—	—	2.8×10^{-3}

III. Cathode spot temperatures and estimated vapor pressures of vacuum arc for various metals

Metal	T_c*, K	T_c/T_b	P_c, atm	Linearity
Au	3620	1.17	5.9	excellent
Ag	2770	1.15	4.5	excellent
Cu	2570	0.905	0.4	good
W	5210	0.900	0.2	fair
Mo	4860	0.985	0.6	fair
Ta	9550	1.73	95	fair
Ti	5570	1.56	60	good
Pd	3630	1.10	3	excellent
Pt/10% Rh	4260(Pt) 4220(Rh)			good
Sn	2340	0.810	0.6	good
Mg	1210	0.875	0.25	fair

*T_c, cathode temperature; T_b, boiling temperature.

The metal vapor that supports the burning of the vacuum arc is supplied by many highly mobile cathode spots. The current density of the cathode spot is extremely high[37,38]; the highest value quoted[39] is about 10^7 A/cm². The spot moves continuously under influence of magnetic fields over the cathode surface with speeds that range from 0 to 10 m/s, and sometimes up to 50 m/s.[27] It has a tendency to follow sharp edges.[40] The spot of the copper cathode can support currents at about 100 A. If the current is increased beyond 100 A, the spot will split into two spots, which, because of the magnetic field, move apart to opposite sides of the cathode. For a current of 1000 A, for example, ten spots will exist. The velocity of the metal vapor jets ejected from the cathode was the subject of many studies.[41–44] These values of velocity differ for each material; the number quoted for copper[27] is between 10^5 and 10^6 cm/s. Using the Maxwellian portion of velocity distribution of the metal vapor, Utsumi[45] measured the temperature of the cathode spots for various materials. The results of his measurements are given in Table III.

Reece[33] proposed that the plasma associated with each cathode spot assumes a conical shape, with the apex at the cathode spot, and a semiangle of 30°. In this model, the velocity of the ions was taken as 10^6 cm/s and that of the electrons as 10^6 cm/s. The model assumes that a positive ion was introduced into the cone for every ten vapor atoms and 100 electrons. Reece concluded that some of the positive ions generated in the cathode spot would be swept along with the neutral vapor toward the anode and, because of this movement, the circuit current would be reduced to 99 percent. Davis and Miller[46] have observed higher ion velocities, which are suggested in this model: 34 eV to 60 eV.

Kimblin[47] recently showed that the ion current depends on the gap length between the contacts, on the contact diameter, and on the arc current, but is independent of the arc voltage. This investigation showed that the vapor ejected from the cathode spot was transferred to other parts of the device, 82 percent to the shield wall and the rest to the anode. The study concluded that the total ionization probability for evaporated atoms in the cathode region must exceed 55 percent.

The anode in the vacuum arc becomes much hotter than the cathode, but the energy input to it is more uniform.[33] Kimblin[48] observed the formation of anode spots at direct currents of 400–2100 A. The probability of anode spot formation increases with both arc current level and contact spacing.

Vacuum arc stability

The plasma arc existing between the contacts after separation behaves as a circuit component that allows the current to continue to flow in the circuit. This property of the arc is vitally important in interrupting electric networks—especially those with high inductive loads, since the voltage across an inductive element is proportional to the time rate of change of the current through the element. For example, if the arc between the contacts should suddenly cease to exist, the current in the circuit would be cut abruptly. This in turn would cause a high-voltage impulse that could lead to a failure of the network insulation and damage to circuit components. Such a phenomenon is referred to as *current chopping*.

In 60-Hz ac networks, the current decreases to zero approximately once every 8 ms. If the circuit is interrupted at a zero-current point, no overvoltage will result. Hence, for a successful interruption, it is necessary that the arc be stable for a half-cycle duration and particularly that it continue to exist at currents approaching zero.

The vacuum arc is a metal-vapor arc and its existence depends on metal vapor evaporated from the contacts. Copeland,[49] in his study of the stability of the mercury vapor arc, shows that when a large number of arcs are started between the same contacts under the same conditions, although the durations of the arcs will vary, an average lifetime of the arc may be calculated. Using statistical methods, Copeland found that the data fit the survival law:

$$dN = -aN\,dt$$

$$N = N_0 \exp(-at)$$

where N_0 is the total number of trials (separate arcs are treated mathematically as starting simultaneously); N is the number of arcs that exist longer than time t; a is the probability that an arc will be extinguished; dt is the time interval; and dN is the number of arc extinctions during the time interval.

Cobine and Farrall[50,51] found that arc stability depends on (1) the contact material and its vapor pressure, and (2) circuit parameters, such as voltage, current, capacitance, and inductance.

The power supply for their study was a 125-V dc generator. The gap between the contact was 5.56 mm. They analyzed their data using Copeland's methods. Their study accumulated a large amount of data for different metals and a wide range of currents, and demonstrated that metal vapor arcs also follow the survival law.

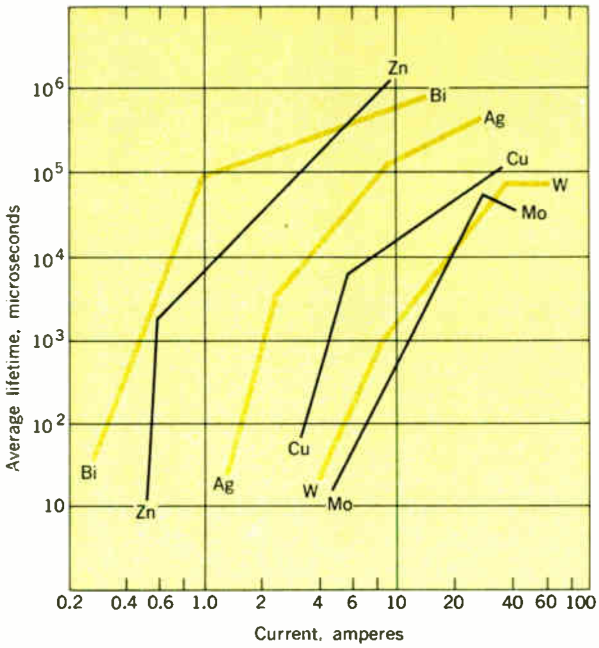


FIGURE 7. Average arc duration as a function of current for various electrode metals in vacuum.

This was also confirmed by Kesaev.[52]

The results of this study are shown in Fig. 7, in which the average lifetime of the arc is shown as a function of the arc current for different materials.[53] The data charted in Fig. 7 were determined as follows: For each value of current, 40 arcs were drawn between a set of contacts. This number, 40, will result in a relative probable error of 10.3 percent. The lifetimes of these arcs were plotted on semilog paper against dN/N. The average lifetime of the 40 arcs was found by drawing a parallel line to the ordinate at dN/N equal to 0.368 (which is the theoretical average of an exponential function). Each value of current and its average-lifetime counterpart represents a data point. The average-lifetime curve consists of two segments, each of which in its range fits the following equation: $\ln T_{avg} = A \ln I + B$, where I is the arc current, and A and B are constants.

As was mentioned before, the vacuum arc is a vapor arc and its existence depends on the vapor supply.

In low-current circuits, most of the evaporation takes place at discrete points known as the cathode spots; at higher currents the gas evaporates from cathode and anode spots.[47,54] Reece[33] maintained that in addition to these sources, gas is added to the contacts' enclosure when it is stripped from other parts of the enclosure because of high temperature and impinging metal vapor.

The absolute pressure of the contact metal vapor in equilibrium with the solid (or liquid) contact metal surface at some temperature t is known as the vapor pressure of the metal at that temperature. Figure 8 shows vapor pressures of different contact materials as a function of temperature.[51] It can be seen from observing Figs. 7 and 8 that a positive correlation exists between the vapor pressure and arc stability. The higher the vapor pressure at lower temperatures, the longer the lifetime of the arc.

Shunting the contacts with different values of capacitance demonstrates that the larger the capacitance the lower the average lifetime of the arc, as shown in Fig. 9.[50] Adding a large inductance value in series with copper-bismuth contacts results in an increase of the arc duration. Lee and Greenwood[55] concluded that the chopping level depends upon the vapor pressure and the thermal conductivity of the cathode material. A good heat conductor will cool very rapidly and its contact surface temperature will fall. This will reduce the evaporation rate and the arc will be chopped because of vapor starvation. On the other hand, a bad heat conductor will maintain its high temperature and vaporization for a longer time and the arc will be more stable. The results of this study are presented in Table IV.[55]

Lukatskaja and Formicheva[56] reported that current-chopping probability in vacuum decreases as the contact diameter increases. They explain their observation by stating that it takes the cathode spot less time to move to the outside edge on a small-diameter cathode than on a larger one. (The cathode spot dies out when it moves over the edge of the contacts.) As the result of this, the larger the diameter, the longer the time the spot exists and the higher the arc stability.

Breakdown and recovery characteristics of vacuum devices

The conducting medium (i.e., metal vapor) necessary to support the arc in vacuum interruption devices is supplied solely by the arcing phenomenon. After the arc is extinguished the rate of diffusion and condensation of the metal plasma determines the dielectric recovery characteristics of the interrupter. The ultimate voltage a vacuum gap can sustain shortly after the contacts open (and the arc extinguishes) approaches the value at which breakdown occurs under static conditions (contacts open, no arc).

Before the breakdown and recovery characteristics of vacuum devices are discussed further, mention should be made of the mechanisms proposed to describe the emission of electrons and ions from cathode spots. They are:

1. Thermionic emission.
2. Field emission.
3. Thermionic and field (T-F) emission.
4. Secondary emission resulting from positive-ion bombardment.
5. Secondary emission by photons.
6. Pinch-effect emission.[57]

Probably no one mechanism alone is responsible for all the emission of charged particles from the cathode spot.

In the thermionic-emission mechanism[28] the entire cathode surface is heated to a high temperature and the surface is then capable of emitting high currents; an example is the carbon arc. We know that in the vacuum arc, however, emission occurs only at the cathode spot and not from the entire surface of the cathode. Therefore,

IV. Current chopping and thermal conductivity

Material	Number of Tests	Average Current Chopped, amperes	Thermal Conductivity, cal/cm²/s
Sb	45	0.5	0.043
Sn	25	1.92	0.152
Cu	25	4.0	0.918
Ag	26	6.0	1.006
Ag/15% Cd	35	3.0	0.222 (Cd)
W	44	9.2	0.476

FIGURE 8. Vapor pressure as a function of temperature for various electrode metals.

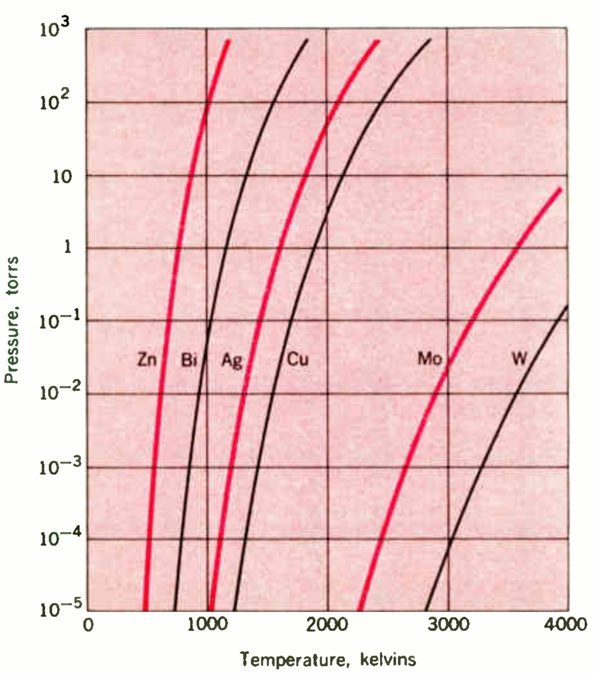
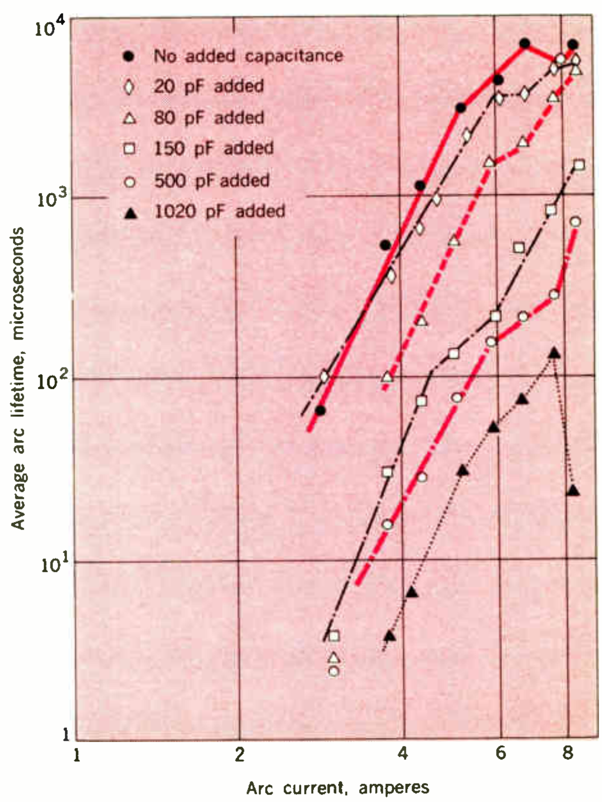


FIGURE 9. Stability of a vacuum arc between copper electrodes as it is affected by parallel capacitance.



the thermionic mechanism does not, by itself, completely describe the vacuum arc. For this reason, the vacuum arc is also known as the *cold-cathode* arc.

The field-emission mechanism describes the phenomenon by which electrons are emitted from cold metal surfaces that are under the influence of a high electric field. The relationship of the current density at the metal surface and the electric field at the same surface is described by the Fowler–Nordhim equation.[58]

The T-F mechanism is one in which the Fowler–Nordhim equation was modified to include the high temperatures that exist at the cathode spot. According to Farrall,[53] the T-F mechanism might provide the basis for describing the principal mechanism that occurs in cold-cathode arcs. Other emission mechanisms are adequately summarized by Hawley.[59]

Most of the physical models proposed to explain vacuum breakdown can be divided into two categories: those describing long gaps and those describing short gaps. Figure 10 shows the relationship of the average breakdown voltage V_B, as a function of gap spacing d.[58] The regions A, B, and C are related to the short gap, the transition region, and the long gap, respectively. The gap separation of most vacuum switches is of the order of 0.2 to 2 cm or higher; these lengths are represented by regions B and C. According to Chatterton,[58] the Cranberg and Slivkov theories of vacuum breakdown correlate well with experimental results in regions B and C. These models are known as the charged macroparticles mechanisms. Cranberg[60] proposed that breakdown is initiated when a charged clump of loosely adherent material is removed from one electrode surface under the influence of the electric field, traverses the gap, and strikes the opposite electrode. This causes a local rise in temperature that produces evaporation and ultimately leads to complete breakdown. In the Slivkov mechanism the clump is vaporized into a gas cloud upon striking the opposite electrode and the breakdown is initiated in this cloud.

Most experiments on breakdown are performed with highly polished electrodes. In vacuum switching devices the contacts are arced many times at high currents and as a result their surfaces become rough after a few operations. Cobine and Farrall[61] found that, after being arced, Bi-Cu contacts can withstand only 70 percent of the voltage value they could withstand before arcing. Figure 11 shows the average static breakdown voltage versus gap length for several rough-surfaced contact materials in a vacuum range of 10^{-6} torr.

Electrode geometry, such as curvature, area, and polarity (when one electrode is much larger than the other), affects the breakdown voltage.[62]

Electrodes can be conditioned to support higher voltages. The conditioning process, called *spark conditioning*, was first observed by Millikan and Sawyer in 1918.[3] The conditioning is achieved by applying high-voltage sparks to a pair of electrodes; these cause the gap to break down. After a series of breakdowns the surfaces of the electrodes are "conditioned" by the resulting discharges. The breakdown voltage increases until a plateau region is reached. Many studies appear in the literature.[62–65]

The rate of dielectric recovery of a vacuum gap in the first few microseconds after arc interruption is approximately 1 kV/μs for an arc current of 100 A, as compared with 50 V/μs in the case of an air gap.[66] Figure 12 shows the rates of recovery of different gases and of vacuum.[9] The gases are at atmospheric pressure and the current is 1600 A, with an open gap distance of 6.25 mm.

Cobine and Farrall[61] conducted a study on vacuum arc recovery strength for different contact materials. Most of the contacts were made of gas-free metal and all metal parts of the switches tested were carefully outgassed before the envelopes were sealed. The experimental method used to find the dielectric recovery rate of the vacuum gap was as follows: The positive half-cycle of 60-Hz arcing current was produced in a test switch, which was isolated from the power supply. The end of the half-cycle was observed on a cathode-ray oscilloscope and, after a

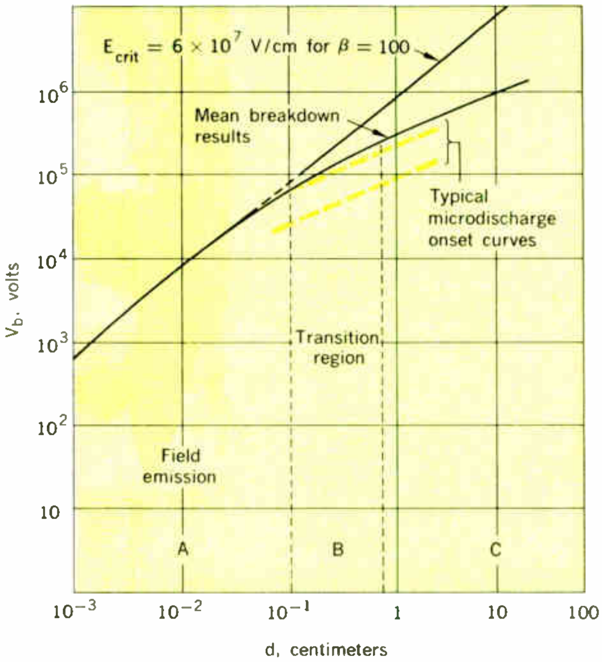
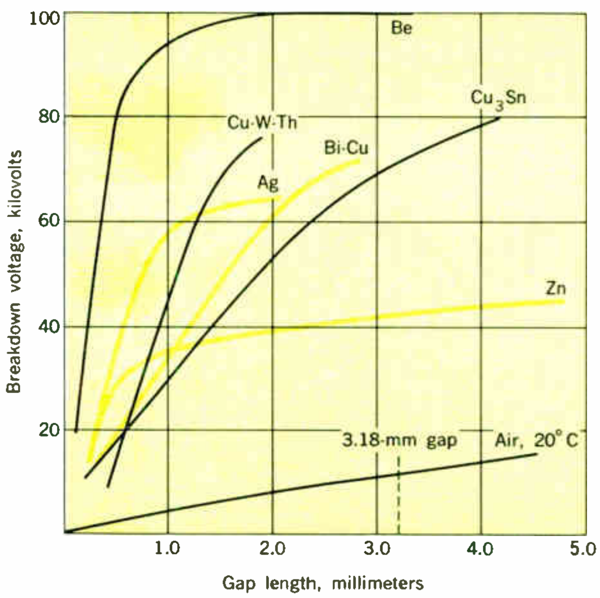


FIGURE 10. Variation of average breakdown voltage V_B vs. gap spacing d (large experimental scatter suppressed). Actual boundaries of regions A, B, and C vary greatly.

FIGURE 11. Static breakdown characteristic curves for various electrode materials in vacuum.



predetermined time delay measured from current zero, a high-voltage pulse was applied across the gap between the contacts. The time delay and the value at which breakdown occurred were recorded photographically. The peak currents used were 400 and 1600 A. The study showed that recovery for both currents was similar and that the vacuum switch recovered most of its electric strength in less than 15 μs.[61]

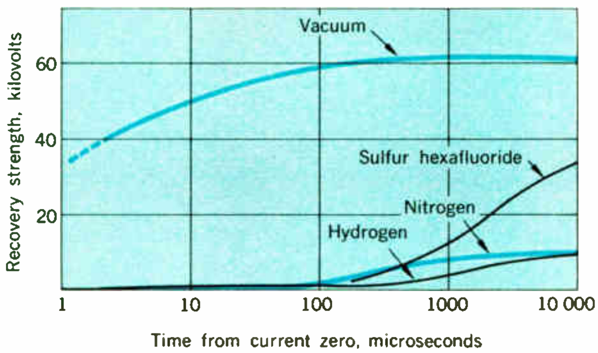


FIGURE 12. Recovery strength for vacuum and gas; 1600 amperes, 6.35-mm gap, gas pressure 1 atmosphere.

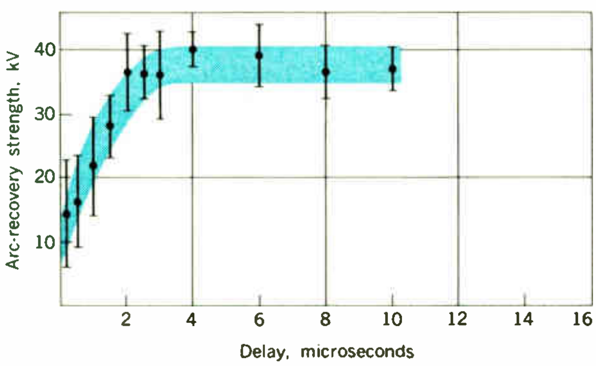
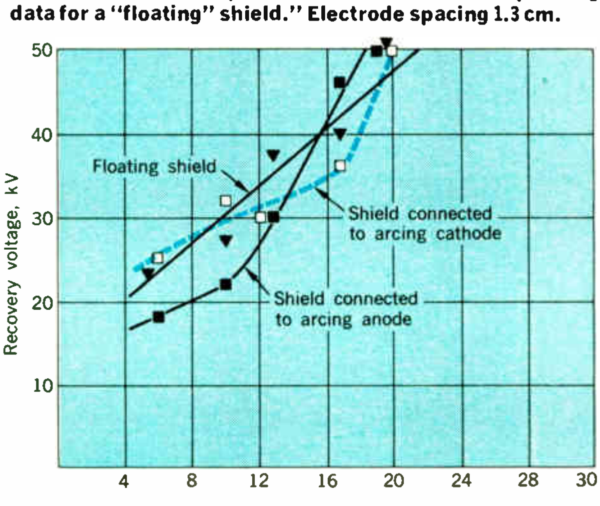


FIGURE 13. Arc-recovery-strength data for contacts in vacuum. Copper electrodes, diameter 5.08 cm, gap length 2.3 mm, arc current 250 amperes (chopped).

FIGURE 14. Comparison of the reverse-polarity recovery curves for biased vapor shields with the corresponding data for a "floating" shield." Electrode spacing 1.3 cm.



Rich and Farrall[81] measured the recovery strength of gas-free silver following the forced extinction of a 250-A arc in 0.5 μs. A negative 100-kV pulse with a 0.2-μs rise time was used with predetermined delay times to find the level of breakdown across the gap. The gap and the diameter of the contacts were varied throughout the study. Figure 13 shows the data for a 2.3-mm gap and 5.08-cm-diameter contacts.[32] The results of this study demonstrated that for a fixed gap length, recovery occurred more rapidly for large-diameter contacts. On the other hand, recovery proceeded faster with decreasing gap length. The experimental results were followed by a theoretical analysis. A reasonable correlation between the calculated and measured results supported the "vapor metal condensation" model proposed by Rich and Farrall. In studying recovery phenomenons, Kimblin[22] also used the current-zero method. Here a 50-kV step function with a rise time of 1 μs was used to probe the gap at different delay times after current zero. The vapor shield (see Fig. 1) is usually electrically isolated from the contacts, and "floats" in potential during the operation of the interrupter. However, this study showed that if the shield is connected to either contact, it affects the recovery characteristics of the interrupter. Figure 14 shows the dielectric recovery rate with a gap of 1.3 cm and 930 A when the shield is (1) floating, (2) connected to the anode, and (3) connected to the cathode.[22]

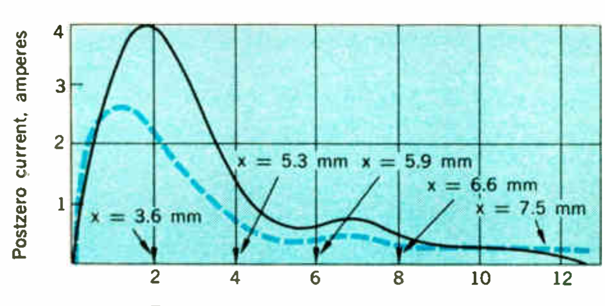
In summary, the vacuum gap possesses two advantages when compared with the air gap: higher dielectric strength and more rapid recovery capabilities.

Postzero current

After an arc is extinguished in a vacuum switch, the space inside the envelope contains a residue in which charged particles are present. When the reverse voltage is built up across the gap, these ions will move to recombine on the electrodes' surfaces; the term *electrode* here is defined as all metal parts connected electrically and having the same polarity. This transfer of charge to the electrodes causes a current to flow for a short duration in the external circuit. This phenomenon is called *postzero current*. Figure 15 shows experimental and theoretical results of a study made by Reece[67] on postzero current. The switches used in this study interrupted 1600 A, 8 kV rms, 500 Hz. The principal conclusions of Reece's study are as follows:

1. Gas ions are the main source of the ion supply to

FIGURE 15. Postzero current (due to gaseous ions only). Solid line, measured postzero current; dashed line, computed postzero current; x = computed ion-sheath thickness.



the postzero current. (Metal vapor contributes only to the volume between the contacts.)

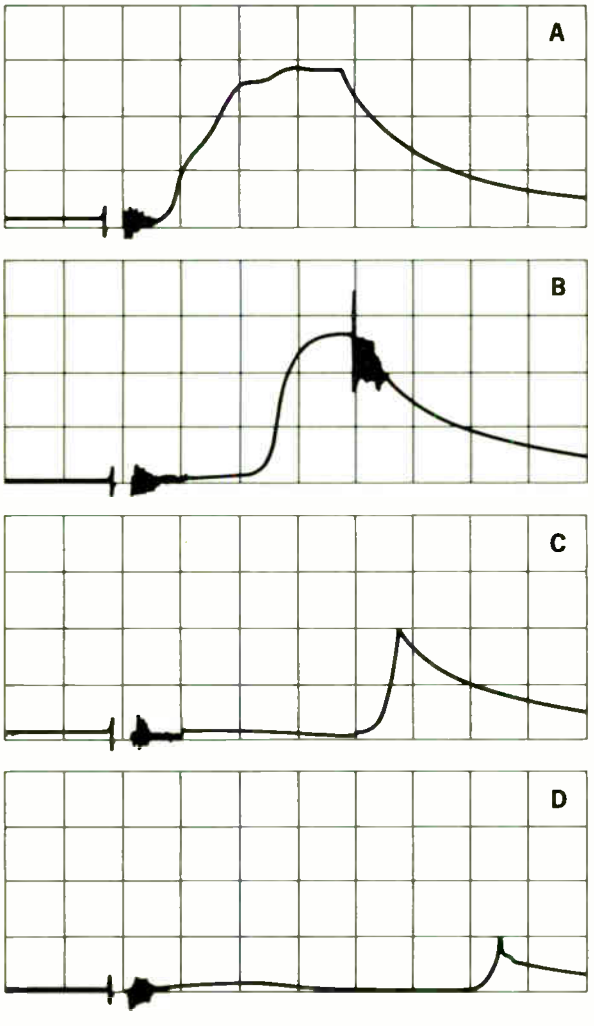
2. Most of the charge that causes the postzero current originates with ions in the space between the electrodes and the floating shield; the calculations are made on the basis of two gaps in series.

3. A space-charge sheet that becomes thicker as it sweeps through the neutral plasma while increasing its positive ion content and repelling electrons is a major contributor to the postzero current.

Hoyaux[68,69] proposed a model dealing with the postzero current that assumes that the plasma decays by ambipolar diffusion or by positive-ion free fall while the electrons obey the Tonks–Langmuir model (long mean free path model).[70] This model could successfully explain the postzero current phenomenon using the numerical values for the density of the neutral vapor existing in the gap after the main arc is extinguished. The initial values range from 10^{15} to $10^{16}/cm^3$ and, after a decay of 30 μs, are reduced to $10^{14}/cm^3$.

Farrall[71] studied the decay of residual plasma in a vacuum gap after forced extinction of a 250-A arc. At some predetermined time after the main arc was extinguished, a 6-volt battery was connected in series with a 1-ohm resistor across the gap being studied. This resulted in a current flow through the battery. The experimental results were photographed. Oscillograms taken with different delay times are given in Fig. 16.

FIGURE 16. Developments of current wave at (A) 5, (B) 10, (C) 20, and (D) 30 μs after arc extinction. Vertical scale, 100 mA/div; horizontal scale, 5 μs/div.



From observing the oscillograms we can see that a peak of short duration occurs in the leading edge of the waveform and then a long decay follows. Farrall distinguished between the leading edge of the waveform, I_p, and the start of the decay on the back edge, I_c, in his analysis. The results of this study suggested that the postzero current is principally due to ions with an initial density of $4 \times 10^{12}/cm^3$ and average velocity of 2.6×10^6 cm/s.

A complete, definitive theory of the postzero current phenomenon is yet to be established. However, our present knowledge is sufficient for many practical applications and also contributes a good basis for further theoretical investigations.

Contact materials; their erosion and welding characteristics

In order that a vacuum interrupting device be able to fulfill its functional requirements, the proper contact materials must be chosen.

The contacts should possess these qualities:

1. Mechanical strength to retain structural integrity under high voltage gradients at the surface.
2. Physical constants (boiling point, vapor pressure, etc.) that permit high interrupting capacity.
3. Low erosion rate.
4. Resistance to welding.
5. Low gas content.

Cobine and Vanderslice[54] reported that by utilizing the zone-refining process, they could produce metals that were remarkably free of gas. For example, copper was found to have an ungettered gas content of one part in 10.[9] They also studied the erosion of different materials in the vacuum gap. Most of the metals used showed a cathode weight loss of 10 to 20 mg for 10 to 110 ampere-seconds of arc. These losses were higher than those reported by Reece.[27] Mitchell[36] studied contact weight loss rate for high currents. His results are illustrated in Fig. 17.

Barkan *et al.*[72] described a class of binary alloys that exhibited excellent properties as contacts for high-power vacuum interrupters; see Table V.

In order for a binary alloy material to be included in this group, it must meet the following conditions:

1. The major constituent of the alloy must be a non-refractory metal, with a boiling point less than 3500°K.
2. The minor constituent should have the following properties:
   a. An effective freezing temperature below that of the major constituent.
   b. Substantial solubility in the major constituent in the *liquid* state and little or none in the *solid* state.[72]

If the minor-constituent film deposits around the major-constituent grains are kept thin, the alloy will possess quality 1 (mechanical strength). Because of the small solid-state solubility, these materials have a relatively high electrical conductivity for alloys. For example, 99% Cu/1% Bi alloys have an electrical conductivity that is 85 to 90 percent of that of copper.

When two clean metal surfaces are forced into contact

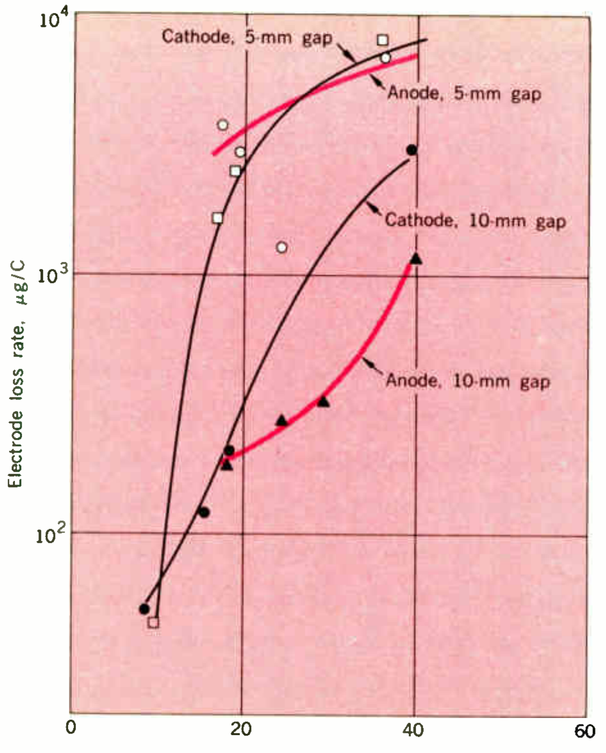


FIGURE 17. Erosion rates of 45-mm-diameter oxygen-free high-conductivity copper anodes and cathodes at 5- and 10-mm separations.

in vacuum, a high probability exists that a weld will be formed. Slade[73] studied the factors contributing to the welding of contacts in high vacuum. Four types of welds are discussed: (1) cold welding, (2) diffusion welding, (3) percussion welding, and (4) resistance welding.

In this study, Cu-Bi alloy was used (0.3% Bi). The temperature was found to increase with weld force. The rise in temperature from 84°C to 290°C is caused by increasing the current through the contacts from 50 A to 200 A.

The experimental results show that cold weld presents no problem in vacuum interruption. The rise in temperature of the contacts might produce a stronger diffusion weld; however, if the weld is exposed to the residual gas in the vacuum, the weld force is diminished. The percussion weld produced the most severe weld. However, the weld forces were low compared with the same type of weld in other mediums.

V. Summary of contact-weld data for several alloys (closing tests)

Alloy	Peak Current Range, kA	Weld-Breaking Force, lbf
Al/4% Pb	29-30	0-400
Al/4% Sn	30	10-400
Cu/0.1% Bi	14-32	10-40
Cu/5% Te	30-40	50-170
Cu/0.5% Te	22-28	0-870
Cu/3% Tl	22-30	45-900
Cu/1% Pb	21-34	130-990
Ag/3% Bi	34	0-100
Ag/6% Pb	33-36	0-45
Ag/1% Te	29-34	0-550

Barkan *et al.*[72] studied the mechanism of antiwelding in binary alloys. They measured the force required to break the welds between 1.25-cm-diameter contacts made from different binary alloys; the results are shown in Table V. They concluded that binary alloys provide excellent antiweld properties without sacrificing adequate dielectric strength or interrupting capability.

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REFERENCES

1. Paschen, F., "Ueber die zum Funkenübergang in Luft, Wasserstoff und Kohlensäure bei verschiedenen Drucken erforderliche Potential differenz," *Ann. Physik Chem.*, vol. 37, pp. 69–96, 1889.
2. Wood, W. R., "A new form of cathode discharge and the production of X rays, together with some notes on diffraction," *Phys. Rev.*, vol. 1, 1897.
3. Millikan, R. A., and Sawyer, R. A., "Extreme ultraviolet spectra of hot sparks in high vacua," *Phys. Rev.*, vol. 12, p. 167, 1918.
4. Rittenhouse, J. W., "The role of the vacuum switch in power applications," *Elec. Eng.*, vol. 76, pp. 202–207, Mar. 1957.
5. Gaede, W. Z., *Ann. Physik*, vol. 46, p. 537, 1915.
6. Millikan, R. A., and Shackelford, B. E., "On the possibility of pulling electrons from metals by powerful electric fields," *Phys. Rev.*, vol. 15, p. 239, 1920.
7. Koller, R., "Fundamental properties of the vacuum switch," *AIEE Trans.*, vol. 65, pp. 597–604, 1946.
8. Sorensen, R. W., and Mendenhall, H. E., "Vacuum switching experiments at California Institute of Technology," *AIEE Trans.*, vol. 45, pp. 1102–1105, 1926.
9. Cobine, J. D., "Research and development leading to the high-power vacuum interrupter," *IEEE Trans. Power Apparatus and Systems*, vol. 82, pp. 201–217, Apr. 1963.
10. Lafferty, J. M., "Triggered vacuum gaps," *Proc. IEEE*, vol. 54, pp. 23–32, Jan. 1966.
11. May, M. F., "Vacuum contactors for rubber and plastic mill drives," *IEEE Trans. Industry and General Applications*, vol. IGA-4, pp. 600–608, Nov./Dec. 1968.
12. Rankin, W., and Hayward, C., "Vacuum contactor fireproofs switching," *Elec. World*, vol. 103, pp. 552–553, 1934.
13. Kling, W., "A new vacuum switch," *Gen. Elec. Rev.*, vol. 38, pp. 525–526, 1935.
14. Teare, W., "The vacuum switch and its applications," *Gen. Elec. Rev.*, vol. 41, pp. 280–281, 1938.
15. Ross, H., "New developments in vacuum relays," *Electron. Ind. Tele-Tech.*, vol. 14, pp. 58–60, 110–116, Jan. 1956.
16. "Will vacuum switches obsolete OCB's?" *Elec. West*, vol. 115, pp. 72–73, July 1955.
17. "Vacuum switch shows promise," *Elec. World*, vol. 144, p. 179, 1955.
18. Jennings, J. E., Schwager, A. C., and Ross, H. C., "Vacuum switches for power systems," *AIEE Trans. Power Apparatus and Systems*, vol. 75, pp. 462–468, June 1956.
19. Ross, H. C., "Vacuum switch properties for power switching applications," *AIEE Trans. Power Apparatus and Systems*, vol. 77, pp. 104–117, Apr. 1958.
20. Ross, H. C., "Vacuum power switches: 5 years of field application and testing," *AIEE Trans. Power Apparatus and Systems*, vol. 80, pp. 758–764, Dec. 1961.
21. Campbell, W. E., "Vacuum switch interrupts 230 kV," *Elec. World*, p. 76, June 8, 1959.
22. Kimblin, C. W., "Dielectric recovery and shield currents in vacuum-arc interrupters," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-90, pp. 1261–1270, May/June 1971.
23. Lee, T. H., "Industrial applications of vacuum insulation," *Proc. Internat'l Symp. on Discharges and Electrical Insulation in Vacuum*, pp. 195–201, 1970.
24. Brish, A. A., *et al.*, "Vacuum spark relays," *Instr. Exp. Tech.*, no. 5, pp. 644–649, Sept./Oct. 1958.

25. Rodin, A. M., and Surenyants, V. V., "A high-voltage heavy-current vacuum discharge tube VIR-100," *Instr. Exp. Tech.*, no. 6, pp. 919–922, June 1961.

26. Sokol'skii, V. V., Nastyukha, A. I., and Lobikov, E. A., "Vacuum gap with electron triggering," *Instr. Exp. Tech.*, no. 2, pp. 340–342, Mar./Apr. 1961.

27. Reece, M. P., Jr., "The vacuum switch and its application to power switching," *J. IEE (London)*, vol. 5, pp. 275–279, May 1959.

28. Dushman, S., and Lafferty, J. M., *Scientific Foundations of Vacuum Technique*, 2nd ed. New York: Wiley, 1962.

29. Lewin, G., *Fundamentals of Vacuum Science and Technology*. New York: McGraw-Hill, 1965.

30. Voshall, R. E., "Investigation of the positive column of high-current metal-vapor arcs," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-88, pp. 120–126, Feb. 1969.

31. Rich, J. A., and Farrall, G. A., "Vacuum arc recovery phenomena," *Proc. IEEE*, vol. 52, pp. 1293–1301, Nov. 1964.

32. Redhead, P. A., Hobson, J. P., and Kornelsen, E. V., *The Physical Basis of Ultrahigh Vacuum*. London: Chapman & Hall, 1968.

33. Reece, M. P., "The vacuum switch. Part I—Properties of the vacuum arc," *Proc. IEE (London)*, vol. 110, pp. 796–802, Apr. 1963.

34. Reece, M. P., "Arcs in vacuum," *Nature*, vol. 177, pp. 1089–1090, June 9, 1956.

35. Reece, M. P., "Burning voltage of arcs in high vacuum," *Nature*, vol. 181, p. 475, Feb. 15, 1968.

36. Mitchell, G. R., "The high-current vacuum arc. Part I—An experimental study," *Proc. IEE (London)*, vol. 177, pp. 2315–2326, Dec. 1970.

37. Cobine, J. D., and Burger, E. E., "Analysis of electrode phenomena in high-current arc," *Phys. Rev.*, vol. 93, p. 653, 1954; *J. Appl. Phys.*, vol. 26, pp. 895–900, 1955.

38. Von Engel, A., and Robson, A. E., "The excitation theory of arc with evaporating cathodes," *Proc. Roy. Soc. (London) Ser. A*, vol. 243, p. 217, 1957.

39. Wroe, H., "Vacuum arcs on tungsten cathodes," *Nature*, vol. 182, p. 338, 1958.

40. Germer, L. H., and Boyle, W. S., "Anode and cathode arcs," *Nature*, vol. 176, p. 1019, 1955.

41. Tanberg, R., "On the cathode of an arc drawn in vacuum," *Phys. Rev.*, vol. 35, pp. 1080–1089, 1930.

42. Kobel, E., "Pressure and high-velocity vapor jets at cathodes of a mercury vacuum arc," *Phys. Rev.*, vol. 36, p. 1636, 1930.

43. Berkey, W. E., and Mason, R. C., "Measurements on the vapor stream from the cathode of a vacuum arc," *Phys. Rev.*, vol. 38, p. 943, 1931.

44. Easton, E. C., Lucas, F. B., and Creedy, F., "High-velocity streams in the vacuum arc," *AIEE Trans.*, vol. 53, pp. 1454–1460, 1934.

45. Utsumi, T., "The temperature measurement of cathode spots in vacuum arcs," presented at the 23rd Annual Gaseous Electronics and Second Arc Symp., Hartford, Conn., Oct. 20, 1970.

46. Davis, W. D., and Miller, H. C., "Analysis of the electrode products emitted by dc arcs in a vacuum ambient," *J. Appl. Phys.*, vol. 40, pp. 2212–2221, Apr. 1969.

47. Kimblin, C. W., "Fundamental ion currents from dc vacuum arcs," *Proc. Internat'l Symp. on Discharges and Electrical Insulation in Vacuum*, pp. 125–129, 1970.

48. Kimblin, C. W., "Anode voltage drop and anode spot formation in dc vacuum arcs," *J. Appl. Phys.*, vol. 40, pp. 1744–1752, Mar. 1969.

49. Copeland, P., and Sparing, W. H., "Stability of low-pressure mercury arc as a function of current," *J. Appl. Phys.*, vol. 16, p. 302, 1945.

50. Cobine, J. D., and Farrall, G. A., "Experimental study of arc stability—I," *J. Appl. Phys.*, vol. 31, pp. 2296–2304, 1960.

51. Farrall, F. A., and Cobine, J. D., "Stability of gas and metal vapor arcs," *Bull. Am. Phys. Soc.*, vol. 5, p. 371, 1960.

52. Kesaev, I. G., "Internal instability of an arc with a mercury cathode," *Sov. Phys.—Tech. Phys.*, vol. 4, pp. 1351–1360, 1960.

53. Farrall, G. A., "Arcing phenomena at electrical contacts," *Proc. Holm Seminar on Electric Contact Phenomena*, pp. 119–144, 1969.

54. Cobine, J. D., and Vanderslice, T. A., "Electrode erosion and gas evolution of vacuum arcs," *IEEE Trans. Communication and Electronics*, vol. 66, pp. 240–246, May 1963.

55. Lee, T. H., and Greenwood, A., "Theory for the cathode mechanism in metal vapor arcs," *J. Appl. Phys.*, vol. 32, pp. 916–923, 1961.

56. Lukatskaja, I. A., and Formicheva, T. I., "The contact diameter effect on current chopping in vacuum," *Elek. Kontakty*, pp. 142–145, 1970.

57. Mitchell, G. R., "The high-current vacuum arc. Part II—Theoretical outline," *Proc. IEE (London)*, vol. 117, pp. 2327–2332, Dec. 1970.

58. Chatterton, P. A., "The present status of vacuum breakdown research," presented at the 4th Internat'l Symp. on Discharges and Electrical Insulation in Vacuum, 1970.

59. Alston, L. L., *High Voltage Technology*. New York: Oxford, 1968.

60. Cranberg, L., "The initiation of electrical breakdown in vacuum," *J. Appl. Phys.*, vol. 23, pp. 518–522, 1952.

61. Cobine, J. D., and Farrall, G. A., "Recovery characteristics of vacuum arcs," *IEEE Trans. Communication and Electronics*, vol. 82, pp. 246–253, May 1963.

62. Rabinowitz, M., "Electrical breakdown in vacuum: New experimental and theoretical observations," *Vacuum*, vol. 15, p. 59, 1965.

63. Maitland, A., "Spark conditioning of electrodes at pressures in the 10^{-5}–10^{-6} torr," *Proc. Sixth Internat'l Conf. on Ionization of Gases*, 1963.

64. Donaldson, E. E., and Rabinowitz, M., "Effects of glass contamination and electrode curvature on electrical breakdown in vacuum," *J. Appl. Phys.*, vol. 34, pp. 319–322, Feb. 1963.

65. Miller, H. C., and Farrall, G. A., "Some effects of current in electrical breakdown in vacuum," *Proc. Internat'l Symp. on Insulation of High Voltages in Vacuum*, 1966.

66. Khalifa, M. M., "Properties of vacuum as a switching ambient," *Can. J. Technol.*, vol. 34, pp. 304–315, 1956.

67. Reece, M. P., "The vacuum switch. Part II—Extinction of an ac vacuum arc," *Proc. IEE (London)*, vol. 110, pp. 803–811, Apr. 1963.

68. Hoyaux, M. F., "Some remarks concerning the phenomenon of ambipolar diffusion in gaseous discharges," *Am. J. Phys.*, vol. 35, pp. 232–242, 1967.

69. Hoyaux, M. F., "The role of ambipolar phenomena in the mechanism of the postzero current in vacuum circuit breakers," *Proc. IEEE*, vol. 55, pp. 2123–2133, Dec. 1967.

70. Tonks, L., and Langmuir, I., "A general theory of the plasma of an arc," *Phys. Rev.*, vol. 34, pp. 876–922, 1929.

71. Farrall, G. A., "Decay of residual plasma in a vacuum gap after forced extinction of a 250-A arc," *Proc. IEEE*, vol. 56, pp. 2137–2145, Dec. 1968.

72. Barkan, P., Lafferty, J. M., Lee, T. H., and Talento, J. L., "Development of contact materials for vacuum interrupters," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-90, pp. 350–359, Jan./Feb. 1971.

73. Slade, P. G., "An investigation into the factors contributing to welding of contact electrodes in high vacuum," *Proc. Holm Seminar on Electric Contact Phenomena*, pp. 89–99, 1970.

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Amos Selzer was born in Israel and received a physical education teaching certificate there in 1962. In 1963 he came to the United States and enrolled at the University of Wisconsin, where he received the B.S. degree in electrical engineering and the M.S. degree in physics and science education in 1966 and 1969 respectively. In 1967 he worked as a project assistant in the Nuclear Physics Department of the University of Wisconsin in the areas of ultrahigh vacuum and bonding of alumina ceramics to metals. In 1969 he joined the Product Research Department of Cutler-Hammer, Inc., Milwaukee, Wis., as an associate research engineer. At the present time he is working in research programs dealing with arc interruption and contact phenomenons in both high- and low-voltage applications. Mr. Selzer is a member of the American Vacuum Society.

Digital and analog signal applications of operational amplifiers

II—Sample/hold modules, peak detectors, and comparators

The networks described in this month's installment are used in a wide variety of applications, such as phase sensing, period measurement, transient- and repetitive-waveform analysis, and classification of items by amplitude

Jimmy R. Naylor **Burr-Brown Research Corporation**

There are two basic types of sample/hold circuits—inverting and noninverting—and two important parameters for these circuits—aperture time and acquisition time. Peak detectors are special forms of sample/hold modules in which the peak value of an input signal, once reached, is automatically held. The last networks discussed in this article are comparators, in which one or more summing resistors are connected to the inverting output of the operational amplifier.

Sample/hold modules[1,2]

A sample/hold module is a device that tracks an input signal and then holds the instantaneous input value upon command by a logic control signal, as illustrated in Fig. 15. Sample/hold modules are often used with measuring devices that cannot tolerate a time-varying input signal, such as some types of analog-to-digital (A/D) converters. Other applications are analog delay, phase sensing, period measurement, and measurement of short-term parameter stability.

Sample/hold fundamentals. The simplest sample/hold circuit is the switch and capacitor of Fig. 16. Two important specifications can be easily illustrated by using this basic circuit. These specifications are aperture time and acquisition time.

Aperture time is the delay (reaction time) between the time the control logic tells S_1 to open and the time this actually happens. When very long aperture time (milli-

FIGURE 15. Input and output waveforms of a typical sample/hold module circuit.

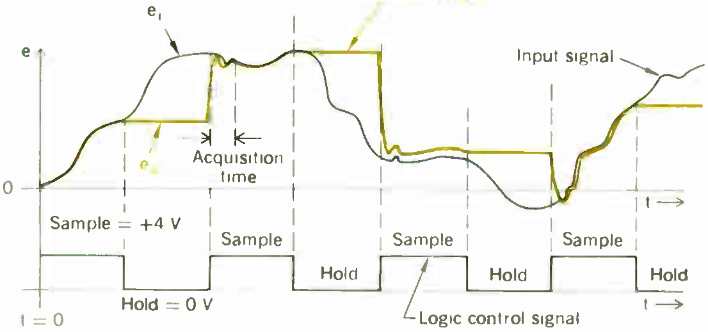
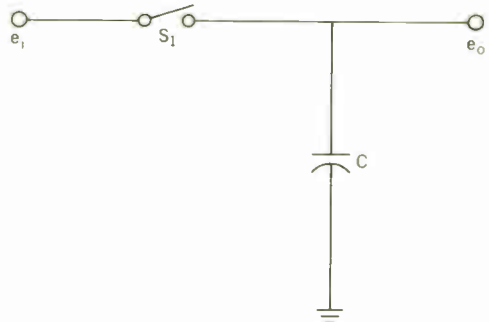


FIGURE 16. Basic sample/hold circuit.



seconds) can be tolerated, S_1 can be a relay. With FET or bipolar transistor switches, aperture times of less than 100 ns are feasible. Figure 17 illustrates the holding error caused by aperture time.

In time-varying systems the input signal to a sample/hold module changes while the module is holding a value, so the time required for the sample/hold to acquire the new value of input signal (to within a stated accuracy) when the module is switched from "hold" to "sample," is important. This is the acquisition time. The worst case occurs when the output of the sample/hold must change full scale, for example, from −10 to +10 volts or from +10 to −10 volts. If a circuit such as the one in Fig. 16 is used, acquisition time will depend upon the driving source and the available charging current $C\,de_0/dt$ (which is less than I_{max}, the maximum current available from the signal source). If e_i has a source impedance (R_S), then e_0 will change exponentially with the time constant $\tau = R_SC$. For e_o to settle to within 0.01 percent of the input will require approximately $9R_SC$ seconds. If e_i represents the output of an operational amplifier, the acquisition time will be determined by the output current capability, the slew rate, and the settling time of the operational amplifier.

Since a sample/hold module is a combination of switching circuits and analog circuits, switching spikes will occur because of the interelectrode capacitance of switches and stray capacitance. In some systems, switching spikes can be disastrous, especially in servo or display systems where the load is inductive. When a sample/hold module switches into "hold," a small amount of charge, caused by the interelectrode capacitance of the switch, is transferred from the holding capacitor. The voltage change associated with this charge offset is known as the sample-to-hold offset error. During the "hold" mode a small portion of the input signal feeds through the capacitance of the switch to the output. This feedthrough increases with increasing input frequency, but the effect can be decreased by making C larger. When a sample/hold is in the "hold" mode, leakage currents will cause output voltage to drift at a the rate of

$$\frac{\Delta E}{\Delta t} = \frac{I_{leakage}}{C} \text{ volts per second}$$

These leakage currents can be the bias current of an op amp, the "off" leakage current of a switch, or the internal leakage of the holding capacitor. If the op amp has an FET-input stage and the switch is an FET device, the leakage current (and therefore the drift) will double for every 10 K rise in temperature.

As the temperature deviates from 25°C, the input

FIGURE 17. Aperture-time error.

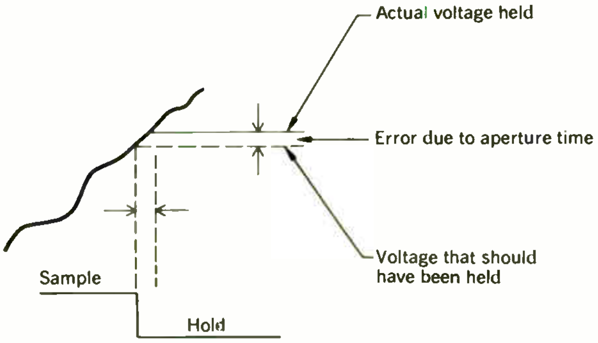
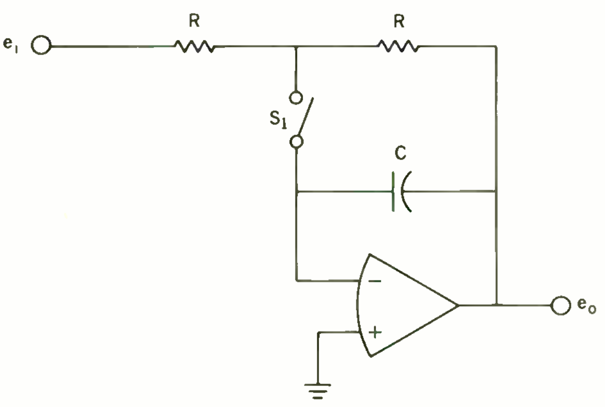


FIGURE 18. Inverting sample/hold circuit.



offset of such an amplifier will drift, causing an output offset during the "sample" mode. The gain accuracy in the "sample" mode may also change with temperature.

Sample/hold circuits. There are two types of sample/hold circuits: inverting and noninverting. The simple inverting sample/hold circuit of Fig. 18 responds to step inputs with the time constant $\tau = RC$. When e_i is a step input (this occurs, effectively, when S_1 is closed), C is charged to $e_o = -e_i$.

During the time S_1 is open, the time-varying input signal has changed to another value, e_i'. Therefore, when S_1 is closed, e_o will proceed to the new value of input according to the equation

$$e_o = -e_i + (e_i - e_i')(1 - \epsilon^{-t/RC})$$

S_1 can be a relay, FET, or diode-bridge switch. The acquisition time of the circuit in Fig. 18 can be speeded up considerably by the use of a switch having a current gain as shown in Fig. 19. Analysis of this circuit shows that its performance is governed by the following equations:

$$i_1 - i_3 = i_2$$

$$i_1 = \frac{e_i}{R}$$

$$i_2 = \frac{-e_o}{R}$$

$$e_o = \frac{-1}{C}\int \beta i_3\, dt$$

Therefore,

$$I_3(s) = \frac{-E_o(s)Cs}{\beta}$$

For a step-function input,

$$E_i(s) = \frac{E}{s}$$

$$e_o(t) = -E[1 - \epsilon^{-t/RC\beta}]$$

Since the amplifier and the current switch can only deliver a finite current, following a step input e_o will slew at a rate

$$\frac{de_o(t)}{dt} = \frac{I}{C}$$

where I is the maximum current that the switch will deliver. (The amplifier must also be able to supply this current, plus the current i_2 and any load current to R_L.) The slew continues until the current through C drops below the maximum current that the current-gain switch will deliver. Then e_o will settle exponentially, with time constant RC/β. The current-gain switch will have nonzero voltage offset and input bias current. These effects can be compensated by summing a small current into the input of the current switch. The inverting sample/hold has the advantage that it has very low output impedance and therefore can drive loads without affecting the decay

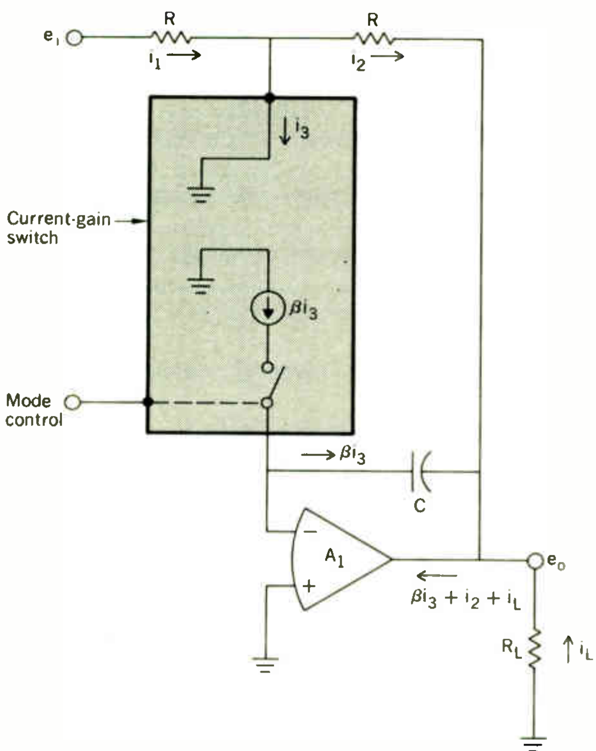
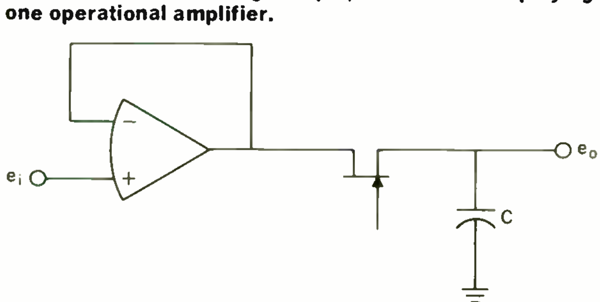


FIGURE 19. Sample/hold device with current-gain switch.

FIGURE 20. Noninverting sample/hold device employing one operational amplifier.



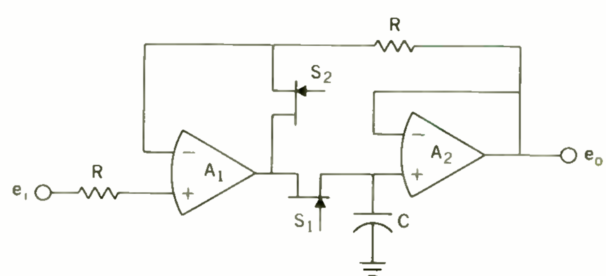
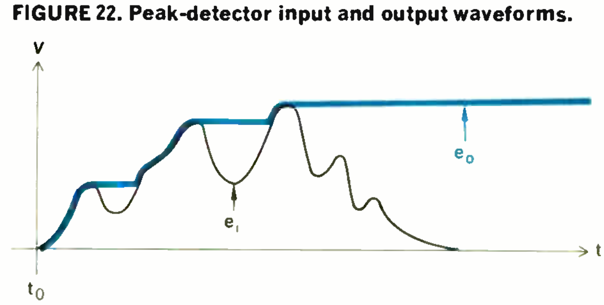


FIGURE 21. Noninverting sample/hold device employing two operational amplifiers.

FIGURE 22. Peak-detector input and output waveforms.



in the "hold" mode. The disadvantage is that the input impedance is fairly low, being equal to R.

As an example of a noninverting sample/hold device, consider the circuit shown in Fig. 20. This circuit has very high input impedance and has an acquisition time determined by the time constant $R_{on}C$, provided $C\, de_o/dt < I_{max}$, where R_{on} is the "on" resistance of the FET switch and I_{max} is the maximum current the amplifier will deliver or the I_{DSS} current of the FET (whichever is smaller). This circuit has the disadvantage that the output cannot be loaded if small decay in "hold" is required. An extension of this circuit will provide output buffering and will eliminate the $R_{on}C$ time-constant limitation. Such a circuit is shown in Fig. 21. Placing S_1 inside the feedback loop enables A_1 to deliver its maximum current through S_1 until C is fully charged. In the "hold" mode, S_1 is opened and S_2 is closed. S_2 provides feedback for A_1. This noninverting sample/hold module has the advantage that the input impedance is very high. The gain accuracy of this circuit is determined by the open-loop gain linearity and common-mode rejection of A_1. For open-loop gain and CMR in excess of 80 dB, the closed-loop gain error may be less than 0.01 percent.

Peak detector[3,4]

A peak detector is a special kind of sample/hold circuit. The input signal is tracked until the input reaches a maximum value and then the peak detector automatically holds the peak value. For a noninverting unity-gain peak detector designed to detect positive-value peaks, the output and input waveforms are expressed graphically as shown in Fig. 22.

Peak detectors can save considerable expense, especially if the only alternative is to combine an A/D converter and a digital computer to find peak values. Typical applications of peak detectors include transient-waveform analysis and repetitive-waveform analysis. Two specific applications include the output-waveform analysis of gas chromatographs and mass spectrometers.

Design considerations. The simplest peak-detector circuit is the diode and capacitor circuit shown in Fig. 23. In the "peak detect" mode, S_1 is closed and S_2 is open. Diode D_1 allows current to flow in one direction only to charge the holding capacitor C_1. When e_i becomes less than e_o (ignoring the drop across D_1), D_1 becomes reverse-biased, and C_1 holds the peak value. To reset the circuit ("reset" mode), S_1 is opened and S_2 is closed. A third mode of operation, the "hold" mode, is desirable in some applications. Both S_1 and S_2 are opened so that C_1 holds the desired peak value while ignoring other larger-value inputs. Due to the leakage current I_d of D_1 the voltage stored on C_1 will decay at a rate given by

$$\frac{\Delta e_o}{\Delta t} = \frac{I_d}{C_1} \text{ volts per second}$$

when S_1 is closed. Any shunt impedance loading C_1 causes an exponential decay with a time constant $\tau = R_L C_1$. Another useful output tells the "status" of the peak detector. The status output is a bilevel digital signal that changes state at the precise time that D_1 stops conducting.

The circuit shown in Fig. 23 has several drawbacks. For precision measurements it is difficult to compensate for the nonlinear drop across D_1, especially if the accuracy of the detector is to be independent of temperature variations and the frequency and amplitude response of the input signal. When the circuit of Fig. 23 is enclosed inside the feedback loop of an operational amplifier, the disadvantages of the basic circuit are largely eliminated. However, certain precautions must be observed when using operational amplifiers. A peak-detector circuit must be either critically damped or overdamped, because any overshoot in the step response will be held as the peak value. Eliminating overshoot can be difficult in circuits where two or more operational amplifiers are enclosed inside the same feedback loop. Also, the amplifiers must be stable when driving a capacitive load. Precautions must be taken to prevent the operational amplifiers from overloading after a peak is detected, since the feedback loop is broken when D_1 becomes reverse-biased.

Noninverting peak-detector circuits. Some of the simplest implementations of the basic peak-detector circuits used in the preceding subsection are the peak-detector circuits illustrated in Figs. 24 and 25. These are connected as unity-gain noninverting followers. First let us consider the one-amplifier circuit shown in Fig. 24. Since D_1 is inside the feedback loop, its forward voltage drop is divided by the open-loop gain of the operational amplifier, and can be expressed as an equivalent offset in series with the input of an ideal peak detector. A_1 serves two other useful purposes. The input signal source needs to supply only the input bias current of A_1. The output rise time is not determined by the time constant of the "on" resistance of D_1 times C_1, but is dependent only on the output current capability, I_{max}, of A_1. The output slew rate is given by

$$\frac{\Delta e_o}{\Delta t} = \frac{I_{max}}{C_1} \text{ volts per second}$$

FIGURE 23. Basic peak-detector circuit.

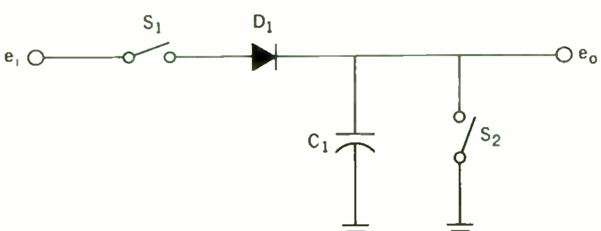
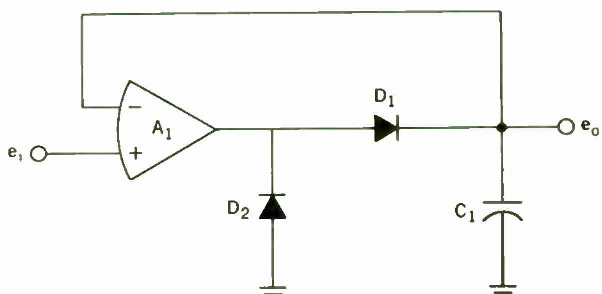


FIGURE 24. Peak-detector circuit in which one operational amplifier is employed.



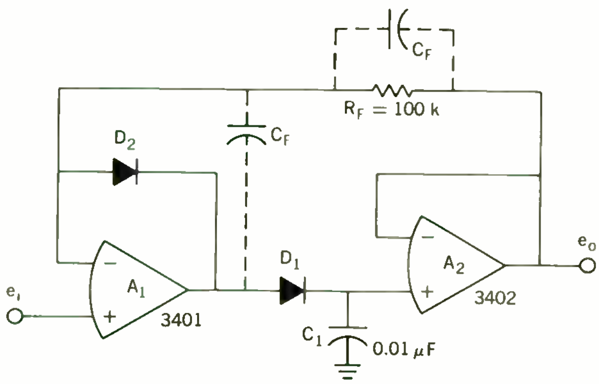


FIGURE 25. Improved peak-detector circuit, in which two operational amplifiers are employed.

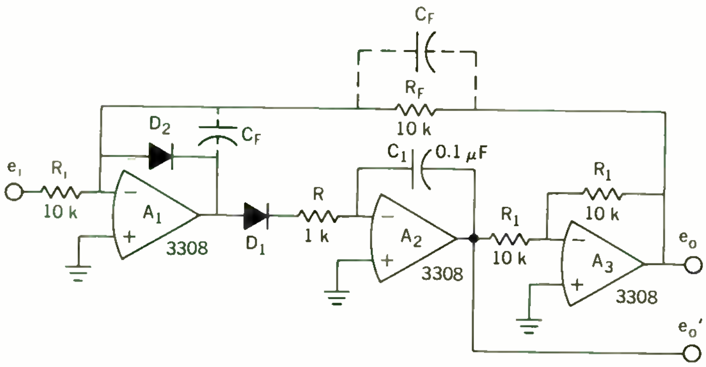


FIGURE 26. Typical three-operational-amplifier peak-detector circuit diagram.

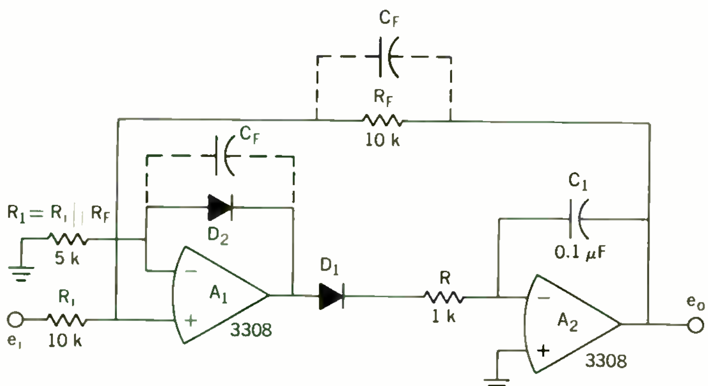
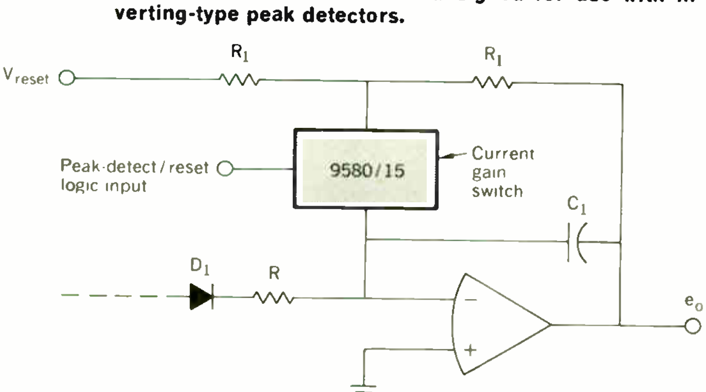


FIGURE 27. Detector circuit of Fig. 26 reduced to two operational amplifiers.

FIGURE 28. Fast-reset circuit designed for use with inverting-type peak detectors.



provided that this is not larger than the specified maximum slew rate of A_1. Diode D_2 is necessary to prevent A_1 from overloading at negative saturation voltage when E_i is less than E_o. However, D_2 must withstand A_1's short-circuit current. A_1 should be an FET-input amplifier to minimize the decay rate after detecting a peak since the input bias current of the inverting input will discharge C_1. Also, the input stage of the amplifier will not conduct when E_i is less than E_o. If the output is to be loaded, an output buffer amplifier is required to prevent the load from discharging C_1.

The two-amplifier circuit of Fig. 25 overcomes the problems of the single-amplifier circuit. A_1 never locks up and the output buffer amplifier A_2 is part of the circuit. The operation of this circuit is practically the same as the first circuit. In the two-amplifier circuit, however, A_2 operates as a unity-gain follower inside the overall feedback loop. When e_i becomes less than e_o, D_2 conducts, supplying feedback for A_1. This prevents A_1 from overloading. Capacitor C_F is required to stabilize the loop and prevent overshoot for a step input signal. In both circuits A_1 must be stable while driving the capacitive load C_1, and A_1 must have good CMR. In the improved circuit, A_1 need not be an FET-input amplifier, but A_2 should have an FET input if long holding times with small decay are required.

Inverting peak-detector circuits. Figures 26 and 27 show two inverting peak-detector circuits. Although the circuit of Fig. 26 takes three operational amplifiers, closed-loop stability is easier to obtain than in the noninverting circuits since A_2 is connected as an integrator and does not have to drive a capacitive load to ground. Diode D_1 insures that C_1 can be charged in one polarity only. When tracking the input signal, the output signal is the negative of the input; that is, $e_o = -e_i\ (R_F/R_i)$. Usually one makes $R_F = R_i$ for unity-gain operation. The input impedance to this circuit is R_i, which requires that the input signal source impedance be small. D_2 provides feedback for A_1 after a peak is detected. A_3 is connected as a unity-gain inverter to provide the proper phase relationship from input to output, and C_F stabilizes the loop. The voltage $e_o' = +e_i(R_F/R_i)$ is available at the output of A_1.

The three-operational-amplifier circuit of Fig. 26 can be reduced to the two-amplifier circuit shown in Fig. 27 without sacrificing any flexibility. The required inversion from input to output is maintained by making the "plus" input of A_1 the input summing junction. Since the summing junctions of each of the operational amplifiers in Figs. 26 and 27 are at virtual ground when in the "peak detect" mode, the CMR of the amplifiers is not important. It should be noted that both of the inverting peak-detector circuits just described provide output isolation between the holding capacitor and an output load.

Any of the positive peak-detector circuits shown can be converted to detect negative input peaks simply by reversing the direction of the diodes.

"Reset" and "hold" mode circuits. Manual switches such as those shown in Fig. 23 can be added to any of the peak-detector circuits. In the circuits of Figs. 26 and 27 S_2 is placed in parallel with C_1. For the "reset" mode S_1 is opened and S_2 is closed; for the "hold" mode both S_1 and S_2 are opened. For electronic operation, S_1 and S_2 can be JFET or MOSFET switches. If fast resetting is needed, C_1 and the "on" resistance of S_2 must be as small as practical. Another method of implementing the "hold" mode is to place a switch in series with the input signal to "gate" it off. When only the "peak detect" and "reset" modes are needed, S_1 can be eliminated if S_2 has very low impedance such as that of relay contacts. Figure 28 shows a very fast method for resetting the inverting-type peak detectors with a current-gain sample/hold switch.

This circuit has the advantage that the switch in series with D_1 is not necessary since the sample/hold switch has very low output impedance. To reset C_1 to 0 volts, V_{reset} must be zero. Capacitor C_1 can be reset to +10 volts by making V_{reset} equal to −10 volts, so input peaks can be detected over the full range of −10 to +10 volts.

Peak-to-peak detector. Figure 29(A) shows a method for measuring the peak-to-peak value of a signal that swings both positive and negative in amplitude. If only positive peak detectors are available, the circuit can be built using one extra amplifier, as illustrated in Fig. 29(B).

Comparators[2-4]

Comparators are used as analog/digital (hybrid) building blocks, since the digital output signal is simply the answer to the question, "Is the analog input signal greater than or less than the analog reference signal?" The input and reference signals can come from voltage or current sources or from a combination of the two. When operational amplifiers are used as comparators, there are usually one or more summing resistors connected to the inverting input (summing junction) of the operational amplifier. One can think of the circuit as comparing currents or voltages. In this section we shall consider several types of such comparators.

Zero-crossing detector. The simplest comparator is the zero-crossing detector, which answers the question, "Is the input signal greater than or less than zero?" A typical circuit for such a detector is shown in Fig. 30. The limit circuit shown in the figure produces one output level when i_3 is positive and a different output level when i_3 is negative.

Inasmuch as the limit circuit changes state when i_3 changes sign, the comparison point occurs when $i_3 = 0$, as shown in the following (assume the summing junction potential e_{SJ} is zero):

$$i_1 = I_2 + i_3 \tag{1}$$

$$\frac{e_1}{R} = I_2 + i_3 \tag{2}$$

When $i_3 = 0$,

$$\frac{e_1}{R} = i_1 = I_2 \quad \text{(current comparison)} \tag{3}$$

or

$$e_1 = I_2 R \quad \text{(voltage comparison)} \tag{4}$$

Equations (3) and (4) show that the comparison point occurs when the input current balances the input bias current I_2. To eliminate the error caused by I_2, a resistor equal to R can be connected from the "plus" input of the operational amplifier to ground. Similarly, a comparison-point error will occur if the voltage offset of the operational amplifier is not zero, as follows:

$$i_1 = I_2 + i_3 \tag{5}$$

$$\frac{e_1 - V_{OS}}{R} = I_2 + i_3 \tag{6}$$

When $i_3 = 0$,

$$e_1 = V_{OS} + I_2 R \tag{7}$$

The voltage offset can be adjusted to zero at a specific temperature, such as 25°C, but should be considered at other temperatures because of the unavoidable voltage drift. The error caused by the bias current is $I_2 R$. As discussed previously, this error can be eliminated by connecting a resistance of value R between the "plus" input and ground, provided the bias currents of the "plus" and "minus" inputs are equal. If they are not equal, the difference is called the differential bias current (current offset), and Eq. (7) can still be used, except that I_2 is now the differential bias current.

The input impedance of the zero-crossing comparator is R. The circuit has the disadvantage that noise on the input signal will cause i_3 to be "noisy"; therefore, e_o

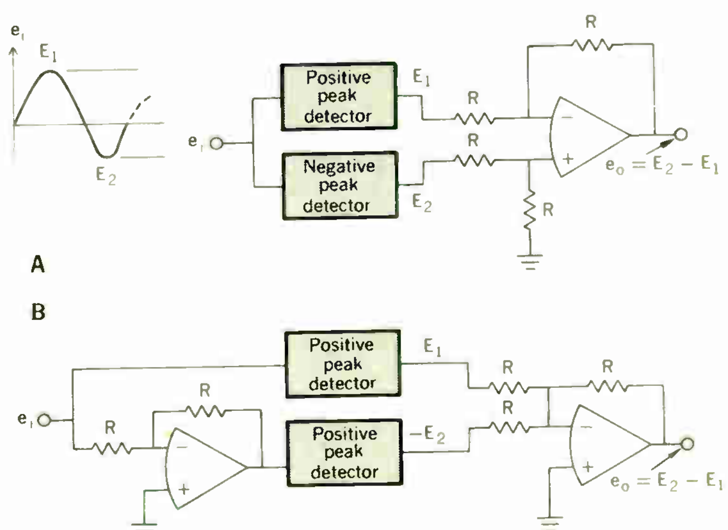
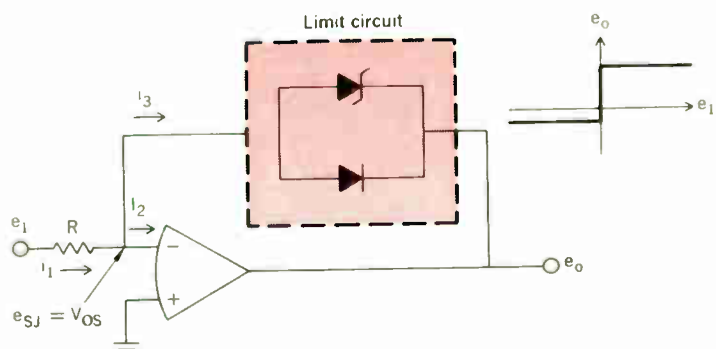


FIGURE 29. Peak-to-peak detector circuits. A—Using one positive and one negative peak detector. B—Using two positive peak detectors.

FIGURE 30. Zero-crossing comparator circuit and typical transfer curves.



will "chatter" when i_3 is changing sign. A solution to this problem will be discussed in the last subsection of this article. Many different limit circuits can be used with the comparators discussed in this section.

Level detector. To make a comparison at some level other than 0 volts, the circuit of Fig. 30 can be modified in one of the ways shown in Fig. 31. In Fig. 31(A) two summing resistors are required, but the reference voltage V_R can conveniently be the positive or negative power supply, if the supplies are well regulated. The comparison point is scaled by the ratio R_1/R_2. Voltage offset causes the following error. When $i_3 = 0$,

$$e_1 = -\frac{R_1}{R_2}V_R + \underbrace{V_{OS}\left(1 + \frac{R_1}{R_2}\right)}_{\text{(error term)}}$$

Even though R_3 is used to provide bias-current compensation, the differential bias current (offset current) will cause an error in the comparison point equal to $I_{OS}R_1$, where I_{OS} is the offset current.

In Fig. 31(B) only one summing resistor is required, but V_R must be equal to the desired comparison level. The voltage on the inverting input has two major error components, the voltage offset of the amplifier and another error voltage resulting from the finite common-mode rejection of the operational amplifier. Resistor R is needed at the noninverting input if the bias current I_2 causes a significant error. The circuit of Fig. 32 is another which may be used to make a comparison at some voltage or current level other than zero. It operates in the following manner. Assume that the limit circuit contains two 6-volt Zener diodes. When the input signal is negative and is approaching zero, the output voltage e_o will be positive since the currents i_1 and i_3 are negative. The voltage at the two inputs of the operational amplifier will be equal to

$$+\frac{6R_3}{R_3 + R_4}\ \text{volts}$$

Therefore, i_3 will not go to zero until the input voltage is also equal to this value. The limit circuit then begins changing to the opposite state (−6 volts) and the voltage on the inputs will become

$$-\frac{6R_3}{R_3 + R_4}\ \text{volts}$$

This action is regenerative because of the positive feedback to the "plus" input (inverting), and thus the switching speed increases. The switching can be speeded up even more by placing a small capacitor (10 to 100 pF) in parallel with R_4. Any noise on the input signal at the time this

FIGURE 31. Two-level detector circuits and transfer curves. A—Summing type. B—Differential type.

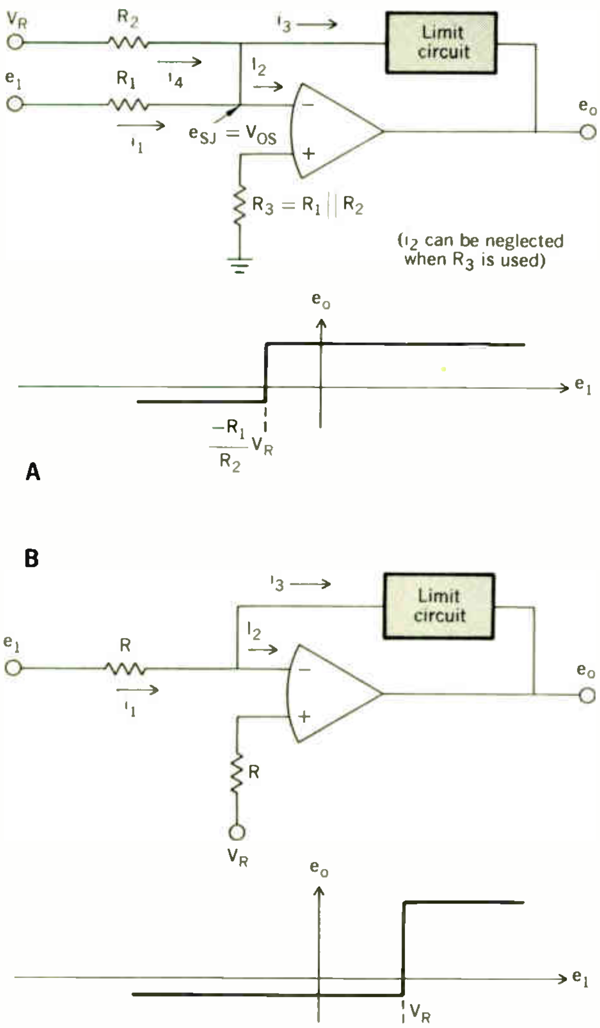
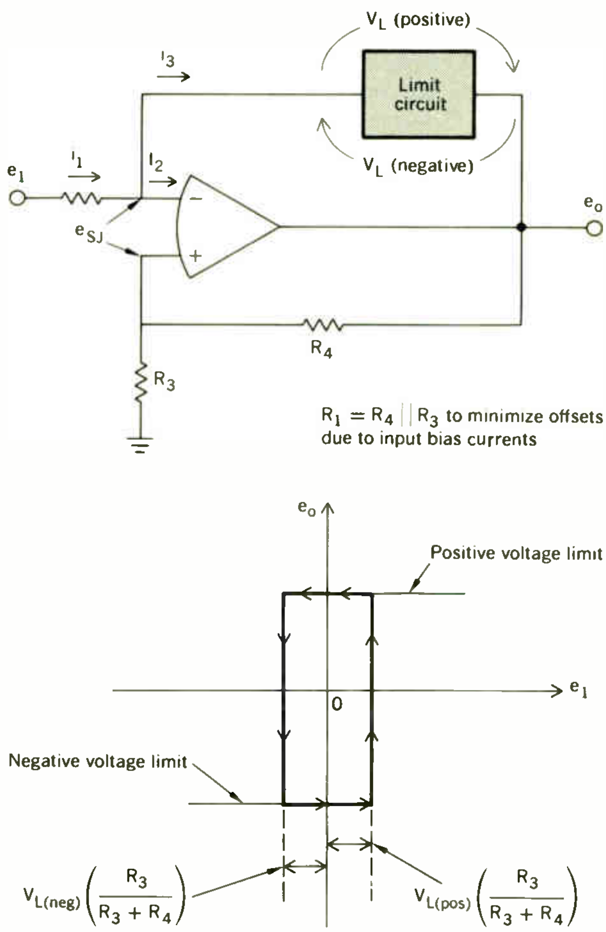


FIGURE 32. Zero-crossing detector with hysteresis.



switching occurs will not trigger the circuit to its original state unless the noise on the input exceeds a value that is equal to

$$-2\left(\frac{6R_3}{R_3 + R_4}\right) \text{ volts}$$

Now that the input signal is positive, no comparator action will occur until the input crosses zero again and becomes equal to

$$-\frac{6R_3}{R_3 + R_4} \text{ volts}$$

The transfer function for this circuit is also illustrated in Fig. 32.

The summing junction voltage e_{SJ} is given by the relation

$$e_{SJ} = \frac{e_o R_3}{R_3 + R_4}$$

but

$$e_o = e_{SJ} \pm V_L$$

Thus

$$e_{SJ} = \pm V_L \frac{R_3}{R_4} \quad \text{(hysteresis)}$$

$$e_o = \pm V_L\left(1 + \frac{R_3}{R_4}\right)$$

If hysteresis is added to the circuits of Fig. 31(A) and (B), the hysteresis can still be calculated using the foregoing equations, except that it will be centered about $-(R_1/R_2)V_R$ in Fig. 31(A) and about V_R in Fig. 31(B).

The primary disadvantage of employing hysteresis is that the comparison points do not occur at the zero reference or level. Therefore, a tradeoff must be made between the degree of noise immunity required and the error at the comparison points. Prefiltering the input signal to reduce the input noise may be helpful. In order to have symmetrical comparison points about zero, the output voltage limits must be equal in magnitude. In some applications the positive and negative limits will not be the same magnitude, and hence there will be asymmetry about the nominal comparison point.

Window comparator. The final type of comparator that we shall consider in this section is the window comparator. Figure 33 shows the circuit diagram and the transfer function for such a comparator. The center of the window is set by the negative of the input V_2 and the window width is twice the input ΔV. Thus the window can be shifted while maintaining constant window width by varying only one voltage (V_2). This feature is useful for probability studies (see Fig. 34), where the window width is swept at a constant rate across the analog input range. Similarly, the window width can be varied by a single voltage without affecting the center of the window.

The window comparator operates in the following way. When $(e_1 + V_2) < 0$, D_2 of A_1 is conducting and D_1 is reverse-biased. Therefore, the output of A_1 does not contribute to the output of A_2 since the voltage at the junction of $R/2$ and $R/4$ is zero. The limiter circuit of A_2 changes sign when the current i_d changes sign and,

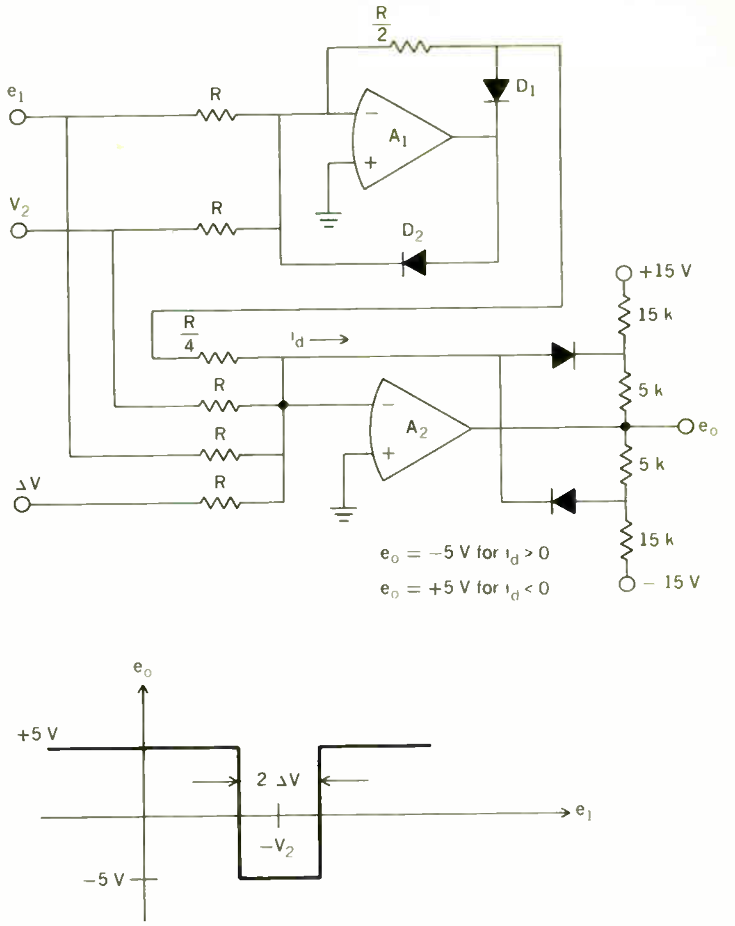
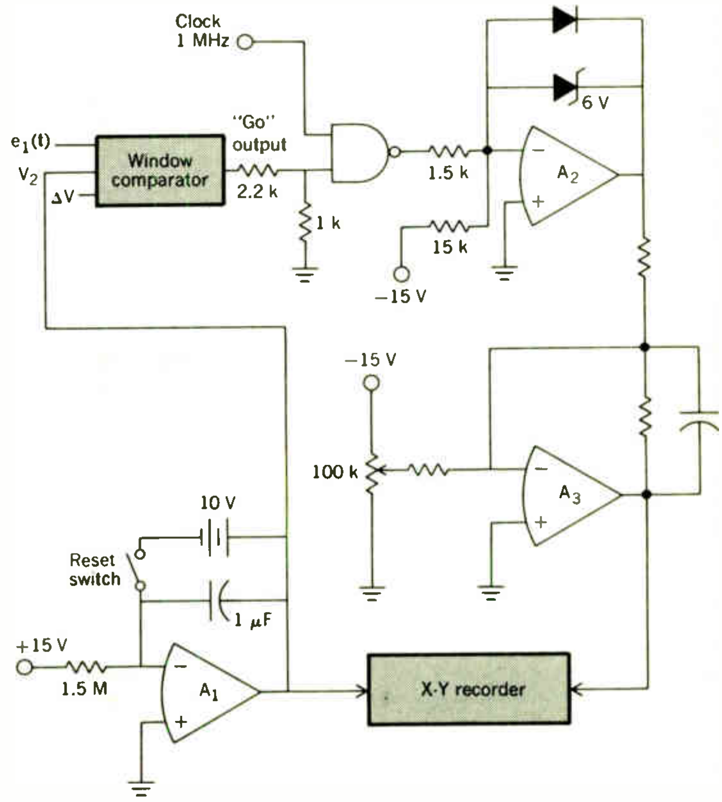


FIGURE 33. Circuit diagram and transfer function for a window comparator.

FIGURE 34. Probability density analyzer.



therefore,

$$\frac{e_1}{R} + \frac{V_2}{R} + \frac{\Delta V}{R} = i_d = 0 \qquad (8)$$

from which

$$e_1 = -V_2 - \Delta V \qquad (9)$$

Equation (9) gives the lower comparison point of the window. When $e_1 + V_2 > 0$, D_1 will be conducting so that the output of A_1 will be $-\frac{1}{2}(e_1 + V_2)$. Another comparison point will be given by the following relationship:

$$\frac{e_1}{R} + \frac{V_2}{R} + \frac{\Delta V}{R} - \frac{\frac{1}{2}(e_1 + V_2)}{R/4} = i_d = 0 \qquad (10)$$

and thus

$$e_1 = -V_2 + \Delta V \qquad (11)$$

which is the upper comparison point.

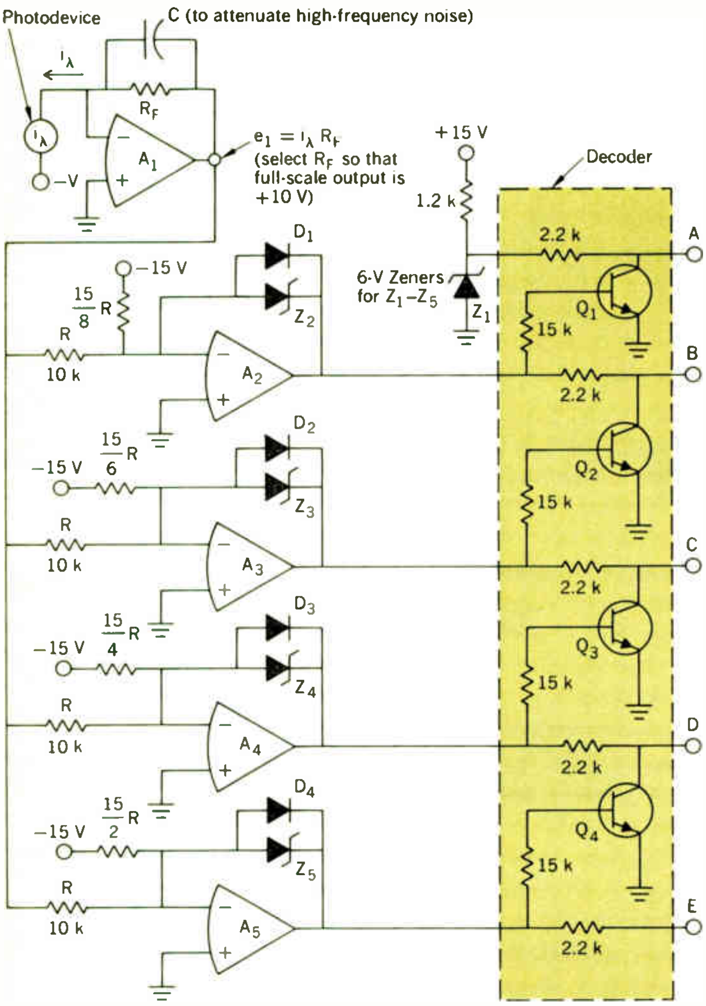
By adding the appropriate logic gates at the outputs of A_1 and A_2 a window comparator can be given three logic outputs, called the "go," "high," and "low" outputs. Whenever the input signal is inside the window, the "go" output will be at a logical 1 and the other two outputs will be at a logical 0. If the input signal drops to a value below the window, the "low" output will switch to a logical 1 and the "go" output will drop to a logical 0. When the input signal exceeds the window, the "high" output will be at a logical 1 and the other outputs at a logical 0.

The window comparator is shown in Fig. 34 as part of a probability density analyzer. The "go" output of the window comparator goes high each time the input signal is inside the window. When the clock and the "go" output are both high, the output of the first NAND goes low.

A_2 is a comparator that is employed to generate precision voltage levels for the RC averaging filter. The 100-kΩ potentiometer is adjusted to null the offset, since the "low" output of A_2 is not 0 volts. A_1 is connected as an integrator that sweeps the window center from −10 to +10 volts at a rate of 1 V/s. The window width ($2\Delta V$) and the rate the window is swept will be a function of the input being analyzed.[5]

Amplitude classifier. Often it is required to sort items into many different bins. An example of this is grading apples into different groups according to size. Figure 35 shows how a system can be implemented using operational amplifiers as comparators. Amplifier A_1 operates as a current-to-voltage converter for the light-sensitive photodiode array that is used to detect the size of the apples. Amplifiers A_2 through A_5 operate as biased comparators with a simple clamp circuit. The decoder insures that only one logic output is high at a time. This decoder can drive transistor–transistor logic or diode–transistor logic directly or an n-p-n switching transistor that can control larger currents such as the coil current of a relay. Hysteresis can be added to each of the comparators to achieve noise immunity if desired.

FIGURE 35. Five-level amplitude classifier. A—Circuit diagram. B—Table of output codes.



A

B

Inputs e_1			Op Amp Outputs					Decoder Outputs				
			Z_1	A_2	A_3	A_4	A_5	A	B	C	D	E
8	e_1	10	1	0	0	0	0	1	0	0	0	0
6	e_1	8	1	1	0	0	0	0	1	0	0	0
4	e_1	6	1	1	1	0	0	0	0	1	0	0
2	e_1	4	1	1	1	1	0	0	0	0	1	0
0	e_1	2	1	1	1	1	1	0	0	0	0	1

For operational amplifier outputs:
Logical 1 = 6 V
Logical 0 = 0.6 V

For decoder outputs:
Logical 1 = 6 V
Logical 0 = 0 V

REFERENCES

1. Close, R. N., and Thogersen, G. O., "Using an electronic analog memory," *Electron. Design*, Dec. 1955.
2. Korn, G. A., and Kron, T. M., *Electronic Analog and Hybrid Computers*. New York: McGraw-Hill, 1964.
3. *Applications Manual for Operational Amplifiers*, Philbrick/Nexus Research, 1965.
4. *Handbook and Catalog of Operational Amplifiers*, Burr-Brown Research Corp., Tucson, Ariz., 1969 (out of print).
5. Bendat, J. S., and Piersol, A. G., *Measurement and Analysis of Random Data*. New York: Wiley, 1966, pp. 247, 252.

Electrical safety in industrial plants

Although the physiological effects of accidental shock range from mild sensation to electrocution, oddly enough the greatest threat to man's life comes not from higher but lower amperage values

Ralph H. Lee E. I. du Pont de Nemours & Company

Most electrical engineers and electricians are aware that the principal danger from electricity is that of electrocution, but few really understand just how minute a quantity of electric energy is required for electrocution. Actually, the current drawn by a 7½-watt 120-volt lamp, passed from hand to hand or foot, is enough to cause fatal electrocution. Just as it is current, and not voltage, that heats a wire, it is current that causes physiological damage. This article gives some indication of what this damage consists of, with specific application to the problems of industrial plants.

The different values of 60-Hz alternating current and their effects on a 68-kg (150-lb) human are listed in Table I. In short, any current of 10 mA or more may be fatal, those between 75 mA and 4 amperes are probably fatal from heart discoordination, and those above 5 amperes may be fatal from severe burns. It is a fact, however, that shocks in this last current range are statistically less dangerous than those from 75 mA to 4 amperes. In view of the wide diversity of injuries derived from contact with electric energy, it is only logical that, to prevent electric shock or electrocution, there must be minimum exposure to energized parts.

To determine the current, which is the value of interest, Ohm's law is applicable, with the human serving as the resistive element of the circuit. The E of Ohm's law is, of course, the voltage of the system itself. The R, which is the variable, is actually the controlling factor. Essentially, it is the human skin, along with such factors as area of contact, tightness of contact, dryness or wetness of skin, and cuts, abrasions, or blisters that introduces the variables. Except for the skin, human resistance is about 250 ohms per arm or leg, and 100 to 500 ohms from shoulder to shoulder or hip. The more muscular the person, the lower the resistance. Skinny arms or legs, and those made up principally of fat, have higher resistance. Bone too has a high resistance. Table II shows the range of human resistance variations. The total human circuit resistance is, of course, the sum of the two contact resistances and the internal body resistance. (Compare with Table III.)

Figure 1 provides a ready means of evaluating the physiological effect of a human resistance and a 60-Hz voltage source. Note that at about 600 volts the resistance of the skin ceases to exist; it is simply punctured by the high voltage just like capacitor insulation. For higher voltages, only the internal body resistance impedes the current flow. It is usually somewhere around 2400 volts that burning becomes the major effect; below this voltage, fibrillation and/or asphyxiation are the usual manifestations.

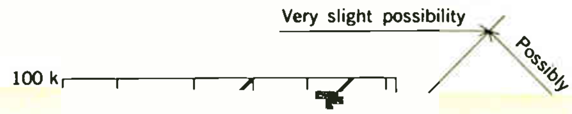
In fibrillation, the victim may not recover consciousness. On the other hand, he may be conscious, deny needing help, walk a few feet, and then collapse. Death may occur within a few minutes or, at most, hours. Detection of the fibrillation condition requires medical skill. Application of closed-chest massage—a treatment

I. Current range and effect on a 68-kg man

Current (60 Hz)	Physiological Phenomenons	Feeling or Lethal Incidence
< 1 mA	None	Imperceptible
1 mA	Perception threshold	
1–3 mA		Mild sensation
3–10 mA		Painful sensation
10 mA	Paralysis threshold of arms	Cannot release hand grip; if no grip, victim may be thrown clear (may progress to higher current and be fatal)
30 mA	Respiratory paralysis	Stoppage of breathing (frequently fatal)
75 mA	Fibrillation threshold 0.5 percent	Heart action discoordinated (probably fatal)
250 mA	Fibrillation threshold 99.5 percent (≥5-second exposure)	
4 A	Heart paralysis threshold (no fibrillation)	Heart stops for duration of current passage. For short shocks, may restart on interruption of current (usually not fatal from heart dysfunction)
≥5 A	Tissue burning	Not fatal unless vital organs are burned

the switch was opened, or by voltage checks, or both. Shorting jumpers, after a voltage check, may be applied

leading to such electrocutions is simple: during operation, the boom or cable accidently makes contact with



overhead lines, and fatalities result when persons guiding the load or touching the crane provide a current path to ground. The operator is seldom affected unless he tries to step off the crane during contact with the line. Only one state, New Jersey, has an ordinance making it the responsibility of the crane-operating authority to remain at least 3.5 meters from any overhead line.

One realistic preventive measure is to allow crane operation in an area having overhead lines only upon issuance of a "crane moving permit" by the electrical supervisor of the area, who can detail a man familiar with the area's overhead-line system to guide the crane operator clear of the line cables.

Digging into buried cable

To a lesser extent, a somewhat similar hazard arises from digging into buried insulated cables. In this instance, a digging permit clearance and checking of proposed digging locations by knowledgeable electrical personnel are the precautions customarily observed. Stakes marking the route of buried cable are also useful. Some users install wooden planks or concrete slabs above buried cables, and plastic marking sheets (about 30 to 45 cm wide) are now being manufactured that are intended to be placed about 30 cm above cable during backfilling. The prominently colored printing on these plastic sheets, even when shredded by automatic diggers, calls the attention of any excavator to the hazard below.

Portable tools, cords, and receptacles

Also high on the list of shock-fatality causes are portable tools and extension cords. These are frequently used in damp or wet locations where good earth contact exists. They also entail a full hand grasp of the tool or cord so that, in the event of insulation failure in the tool or wire, a man may not be able to release his grasp. Grounded tool frames via the third wire and prong of cords and receptacles have been an excellent means of preventing electrocution for several decades in many industrial plants that use "crowfoot"-type plugs. The recent changeover to the new UL-type plugs is being integrated into the present system, but there is always the possibility that some two-wire equipment, which will work with UL plugs, will slip by. Constant vigilance is necessary to prevent this. Regular inspection of tools and cords by tool custodians is necessary in supervising the condition of both insulation and conductors.

So-called double-insulated tools are not to be considered the equivalent of three-wire units, since both sets of insulation can be bypassed by wetness, and testing of the individual insulation systems is not practical.

For work in tanks and vessels that are entered only through manhole-like openings, only lights and tools operated at less than 35 volts were permitted until recently. With the advent of the ground-fault circuit interrupter (GFI), 120-volt lights and tools are now usable with safety.

Electric switching operations

A major cause of personnel injury at industrial plants are malfunctions that occur during the closing or opening of some types of switch or circuit breakers. Some of these are due to the inadequacy of the switch; many switches and breakers do not have sufficient capability to withstand possible fault currents, especially with supply systems increasing in fault capacity. In particular, when a switch is to be closed after work has been performed on its load circuit, there is a possibility of switch failure. Such failure frequently initiates a phase-to-phase or ground fault, which either burns through the cover or blasts open the cover or door of the switch, injuring or burning the man who operated the switch.

Failure of a fuse with insufficient fault-interrupting capability upon switch closure can likewise initiate a fault within the enclosure with similar results.

In general, a well-defined method of closing switches and circuit breakers can go far toward eliminating personnel hazards involving this operation. Steps in this procedure include:

1. Wear gauntlet-type gloves.
2. Wear safety glasses, preferably with side shields.
3. Stand to one side of the switch, not directly in front of it, facing the wall or structure on which the switch is mounted, and as close to it as possible (hug the wall).
4. Use the hand nearest the switch to operate the handle; i.e., if standing to the right side of the switch, operate the handle with the left hand.
5. As the switch is operated, turn the face the opposite way. (If at the left of the switch, look to the left, etc.)
6. Keep other personnel away from the front of the switch, and at least 1.2 meters to either side.
7. Selection of the side to stand at will depend on the proximity of the handle to one side or the other, or on ease of operation of the handle, or on the side of the enclosure more remote from line terminals. The hinges are as likely to rupture from the internal pressure as the latch is to burst.
8. Firm and smart operation is desirable, never indecisive "teasing" of the switch.

Using this systematic method, if an electrical explosion does occur, the exposure to injury is reduced to a minimum.

In switching open units with a hook stick, although it is not possible to stand to one side, all of the other provisions are still applicable.

Electrical testing

Electrical testing is a difficult subject to encompass since it covers such a wide variation of circumstances. In addition, much testing involves energized circuits, with bypassing of shutters, barriers, interlocks, etc. Fortunately, most of the intricate and hazardous testing is done by, or under the direction of, experienced or highly trained personnel who can visualize the risks and employ suitable protective measures.

High-potential testing. Install barriers (or ropes) to keep all except test personnel away from equipment, wiring, and test sets. Ground all components except the actual circuit under test.

After each test, ground the circuit that had been energized to drain off the absorption current. A number of IEEE Standards, existing or in preparation, specify that the circuits should remain grounded for four times the duration of test potential application.

Primary-distribution-voltage testing. Make all connections (while hot) using the proper "hook stick" for the purpose. Lineman's gloves are used, of course. Where potential transformers are involved, a suitable fuse or limiting device at the hook-stick end of any connecting wires should be used; the potential transformer could develop a short circuit, or the wire break or burn off, thus initiating an arc. Such a series arc can easily transfer to a nearby bus and become a major power arc.

For switchgear connections used in phasing, etc., a framework of insulating members fitted onto a circuit-breaker carriage is recommended, with mounting contacts that can be extended by the carriage mechanism to touch the hot terminals. Such a contacting device is infinitely safer than attempting to use two individual stick-supported prods by hand to contact the rack-in terminals.

Low-voltage testing (120 to 600 volts). The use of soft, thin, dry, leather gloves, or metermen's gloves, and safety glasses is recommended. Conventional solenoid-type voltage testers are suitable, but frequently expose an excessive length of metal at the end of the prod holder. Covering these with small-diameter surgical rubber tubing slightly longer than the exposed length is useful here. The side of the prod cannot then impinge on another conductor while the point is on the one being tested.

Multimeters are being used more and more by electricians. Some of these employ meter protection to keep the meter movement intact in case the switch was left in the wrong position for a test. This type of design is almost obligatory; the unprotected kind has too high a mortality rate for industrial use.

All too frequently, the frame of equipment being tested at other than its permanent location has its ground return path disconnected. The attachment of a ground lead in such cases should precede connection of any circuit conductors.

Grounding of equipment and enclosures. It is a rarity in modern plants to find equipment frames and enclosures that are not grounded. The danger, however, lies in the physical and electrical adequacy of the grounding conductor. Occasionally, ground conductors are left off, for example when a motor is changed, and sometimes the conductors are broken or corroded off. More often than not, however, the ground-conductor routing travels a path remote from the power-supply conductor, so that in the event of a ground fault a relatively high voltage drop is developed through the impedance of the ground conductor. Flexible and liquid-tight conduits also have relatively high impedances, and incur quite high voltage drops when fault current flows. Such conduits are really long, small-diameter coils of flat wire, with high inductance.

Conduits and heavy trays have been found to be excellent ground-fault returns. The important and often-overlooked points of consideration are first to provide a path for fault current from the equipment frame to these good return conductors, which then must be adequately connected to the grounded terminal of the power source.

Planning

Instances of highly involved hazardous work are bound to occur that cannot be covered by generalized procedures such as we have outlined here. In such instances, it is desirable to develop in advance a detailed procedure, or preplan, to perform each step of the work safely. Such preplans are most useful if they are written out, in complete detail, with all involved crafts agreeing on each step of the procedure. An organization with one experienced individual serving as safety officer for regulating the procedure and performance of work will go far toward eliminating inherent hazards.

Safety morale

With all of the possible physical means available for working and operating safely, good results still will not be attained unless both workers and their supervisors believe in safety and work at it all the time. Some men may assume the philosophy that "the other guys need safety, but not me; I'm good enough that I don't make mistakes." Such attitudes have to be overcome by a continuous reminder that the safe way is the only way; posters, meetings, and safety instructions along with specific technical instruction on each job are a few of the means that should be employed.

All too frequently it is the top supervision who have to be convinced that safety must be part of each job, even though it may not be particularly expedient. This is a difficult problem to overcome, but if safety doesn't start at the top, it can never precipitate to the bottom. Just as product quality reflects management policy, so too do accident rates reflect management's outlook toward personnel safety. Hence, with safety, it is obligatory to start at the top. It pays!

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REFERENCES

1. Kouwenhoven, W. B., and Milnor, W. R., "Field treatment of electric shock cases—I," *AIEE Trans. Power Apparatus and Systems*, vol. 76, pp. 82–84, Apr. 1957; discussion, pp. 84–87.
2. Dalziel, C. F., "Effects of electric shock on man," *IRE Trans. Medical Electronics*, vol. PGME-5, pp. 44–62, July 1956; also reprinted as USAEC Safety Bulletin 7.
3. Dalziel, C. F., and Lee, W. R., "Reevaluation of lethal electric currents," *IEEE Trans. Industry and General Applications*, vol. IGA-4, pp. 467–476, Sept./Oct. 1968; discussion, pp. 676–677, Nov./Dec. 1968.

Reprints of this article (No. X71-064) are available to readers. Please use the order form on page 9, which gives information and prices.

Ralph H. Lee (F), senior design consultant to the Engineering and Design Departments of E. I. du Pont de Nemours & Co., Wilmington, Del., received the B.Sc. degree in electrical engineering from the University of Alberta, Edmonton, Canada, in 1934. From 1934 to 1937, he worked at a gas utility company; and, from 1937 to 1942, he served with the National Geophysical Company, where he was involved with seismic oil exploration. Joining Du Pont in 1942, his activities there have included the design and start-up of nuclear reactor control systems, military explosive and commercial chemical and textile manufacturing installations, developing improved performance of motor installations, motor control, solid-state inverter motor drives, industrial distribution system coordination, and switchgear and grounding systems. Mr. Lee is a member of the National Electrical Safety Code Grounding Committee and the UL Ad Hoc Committee on Fire Protection of Tray Cables, and is a registered Professional Engineer in the state of Delaware.

IEEE Reports for 1970

Introduction

J. H. Mulligan, Jr. ***President IEEE 1971***

It has become a tradition in the relatively short interval of time since the founding of the IEEE to print in SPECTRUM about midyear the reports of the Treasurer and the Secretary for the preceding calendar year, which is also the Institute fiscal year. Accordingly, the reports of Treasurer R. W. Sears and Secretary R. H. Tanner are given on the following pages.

Under the leadership of President John V. N. Granger, many Institute activities achieved new highs of performance in 1970. In introducing the reports for 1969, President Granger expressed the view that 1970 would be a year of consolidation for the Institute. In reviewing the reports, we find that consolidation of several activities that had begun in previous years was indeed achieved, but not to be overlooked are the several innovative activities that were conceived and implemented during 1970. You will find ample details in the report of the Secretary.

President Granger also noted a year ago the apt quotation of Martin Meyerson concerning the definition of a profession—to wit, "A profession is not only the trustee for a body of learning, it is a commitment to service." It is on this note that I would like to conclude this introduction. Although a detailed study of the Secretary's report will convey to the analytical observer a good picture of membership involvement in helping one another and generally serving the profession, one can hardly assess accurately the total amount of volunteer effort that made possible the tangible accomplishments in 1970. Members of our Institute in substantial numbers have displayed the self-sacrificing commitment to service to which Meyerson refers. As one who has had the opportunity to see at first hand the efforts contributed by many, I should like to express the appreciation of the Institute to all those who have given so much.

Report of the Secretary—1970

Robert H. Tanner *Secretary IEEE*

To the Board of Directors
The Institute of Electrical and Electronics Engineers, Inc.

Gentlemen:

The Report of the Secretary for the year 1970 is presented herewith.

The membership voted favorably on amendments to the Constitution, as recommended by the Board of Directors. The purposes served by the amendments were (1) to recognize explicitly the office of Division Delegate–Director; (2) to permit the offices of Secretary and Treasurer to be combined; (3) to advance the date of the annual Assembly to permit all new Directors equal opportunity to make preparation before assuming office; (4) to specify in the Bylaws the requirements for submitting nominations by petition, with such rights extended for elective offices in all organizational units of the Institute; (5) to make changes recommended by legal counsel to conform to recently enacted New York State laws; and (6) to specify the transnational character of the Institute.

The membership reached an all-time high of 169 059, an increase of 1.6 percent during the year. Membership in the United States increased 1.3 percent; membership in Canada also increased 1.3 percent; there was a 7.3 percent membership increase in Regions 8, 9, and 10. A record number of new members were elected during the year: 13 540 Students, 4049 in other grades, for a total of 17 589. (See Table I.)

Group membership increased 1.8 percent during the year. Some 48 percent of the Student members and 56 percent of the membership in other grades participated in the Group program. Three of the Groups became Societies of the IEEE effective January 1, 1971: Computer, Control Systems, and Power Engineering. (See Table II.)

Five new Sections, two Subsections, and 17 Student Branches were established in 1970.

Adverse economic conditions and rapidly rising costs in all phases of IEEE operations led to many economy measures, including curtailment in Headquarters staff personnel, termination of the IEEE STUDENT JOURNAL, and the closing of the Information Services Department. Organizationally, the Headquarters management appears to have achieved a realistic program of operations to cope with the economic situation.

Respectfully submitted,
Robert H. Tanner
Secretary

Publications and Information Services

During 1970 the Editorial Department processed 3436 papers and 1439 correspondence items for printing in IEEE publications, excluding the translated journals, for a total output of 31 319 editorial pages. Of these, 24 653 pages were published in regular journals of the Institute, a slight increase over the previous year's output of 24 075 pages.

The Executive Committee approved the creation of an IEEE Press to publish collections of reprints on timely subjects and to engage in such other publication activities as may later seem appropriate.

The practice of offering IEEE publications in microfiche form as well as in regular printed editions, which was begun experimentally with three *Transactions* in 1969, was successfully extended to all IEEE journals in 1970.

Four more publications adopted voluntary page charges during the year, bringing to 16 the total number of IEEE journals that follow this procedure. The page charge was raised from $50 per page to $60 per page to reflect mounting publication costs.

The Institute was greatly saddened by the death of Edward C. Day, whose 22 years of dedicated service included many years as secretary of the Technical Program Committee and more recently as manager of production for the forthcoming *IEEE Dictionary*.

IEEE Spectrum. An important event in the SPECTRUM year was the appointment of a new Editor, David De-Witt of International Business Machines. He succeeded J. J. G. McCue, who stepped down after 2½ years of dedicated service to the profession in this capacity.

The Executive Committee authorized offering national societies in other countries a reciprocal arrangement whereby their members can subscribe to SPECTRUM at $7 per year plus handling cost, starting with the IEE (London) and the VDE (Germany).

The improved format, the new departments, and the broadened editorial coverage—all changes introduced in 1969—were continued and consolidated in 1970. It was decided to publish occasional special reports on areas of special applications interest to readers. The first of these, a staff-written survey of minicomputers, was published in the August issue, and the preparation of several more of these reports for 1971 publication is under way.

A total of 78 articles and 96 letters were published during the year. Eight of the articles were written by members of the editorial staff. The total pages published numbered 1666, of which 1183 were devoted to technical and other editorial material and 483 to advertising and related matter.

Group Transactions and Journals. The majority of the pages published in IEEE journals appeared in the technical publications of the Groups. During the year 184 issues constituting 21 157 pages were published. This output represents a continuing increase over the 20 266 and 19 847 pages published in 1969 and 1968 respectively.

A total of 2325 papers and 972 technical letters appeared in the *Transactions* and *Journals* in 1970.

Most publications followed normal production schedules, having recovered from perturbations introduced the previous two years by strikes at printers used by the Institute. This progress was made possible, in part, by acquiring the services of three additional composition and printing sources, two of which are outside of the United States.

Rising costs placed added emphasis on exploring alternative production methods. The IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS initiated an experiment in the use of high-quality typewriter composition as an economical substitute for conventional typesetting. Also, a special committee was formed to look into the increased speed, flexibility, and economies that might be realized by using the latest electronic and optical printing techniques. The Aerospace and Electronic Systems Group made plans to conduct its own experiments in publishing techniques in 1971.

Proceedings of the IEEE. Five successful special issues, each devoted to a single area of major interest, were published during the year. The subjects covered were computers in industrial process control (January), air-traffic control (March), detection theory and applications (May), cable television (July), and optical communications (October).

The program of inviting technical leaders to write tutorial-review papers in their areas of special technical competence was continued. Ten of these papers, on subjects ranging from sensory aids for the blind to nonlinear filtering, were published during the year.

Total pages published in 1970 numbered 2128, of which 2037 were editorial pages and 91 contained paid advertising and related material. The number of papers published was 134, and 100 of these appeared in special issues. The technical letters section contained 462 pages devoted to the publication of 368 letters.

IEEE Student Journal. Five issues of the STUDENT JOURNAL, each organized around a theme of special importance to students, were published in 1970. The subjects treated were opportunities in bioengineering, the engineering technician, careers in consumer electronics, computers, and employment expectations. Five guest editorials and 48 signed articles appeared in the 276 pages of STUDENT JOURNAL during the year.

Late in the year the IEEE Board of Directors regretfully concluded that a separate student publication could no longer be justified, and publication of the STUDENT JOURNAL was terminated with the November 1970 issue. The major factors leading to this decision were rapidly rising costs in all phases of IEEE operations and the fact that over 50 percent of the Student members had been electing to receive SPECTRUM instead. All Student members will now receive SPECTRUM, which will include editorial material of particular interest to them.

Translated journals. The IEEE program of publishing translated journals with the aid of grants from the National Science Foundation yielded 2508 English pages during the year, of which 2216 pages were translated from Japanese and 292 from Ukrainian. This program was terminated when the translation of the 1969 issues of the source publications was completed. The 1970 issues will be continued by a commercial publisher.

Advertising. Adverse economic conditions in the electrical/electronics industry had serious effects on advertising throughout the industry in general, and within IEEE publications in particular. On an industry-wide basis, 3000 fewer pages of advertising were run in 1970 as compared with 1969, a drop of nearly 28 percent.

IEEE SPECTRUM carried 362 pages of advertising in 1970 as compared with 458 pages in 1969. SPECTRUM'S losses were mainly in recruitment advertising, an area that it has dominated for several years. However, SPECTRUM nonetheless succeeded in increasing its share of the market slightly in product advertising, a trend that bodes well for the future.

The PROCEEDINGS OF THE IEEE carried 57 pages of advertising in 1970 as compared with 86 pages in 1969. It is expected that in the future, PROCEEDINGS advertising will be restricted primarily to its covers.

Regional and Section publications. Two Regional publications, inaugurated in 1967, continued publication in 1970. Four issues of IEEE ELECTROLATINA were published and distributed to members in Region 9 (Latin America). This technical magazine contains articles and other appropriate material in Spanish and Portuguese. The IEEE REGION 8 NEWSLETTER, serving members in Europe and adjoining areas, was issued four times during the year.

A major activity of many Sections is the publication of a monthly Bulletin for the announcement of local activities. Seventy IEEE Sections are now issuing monthly publications.

Electrical Engineering. This IEEE management newsletter, averaging six to eight pages plus inserts per issue, notes completed and impending changes in the structure, Bylaws, policies, and operations of the Institute, and evolution of its organization units. Its mission is to encourage an exchange of information among boards, committees, Divisions, Societies, Groups, conferences, Regions, Councils, Sections, Subsections, Chapters, and Branches. Its bimonthly distribution includes about 4000 officers of these units and the Headquarters staff. Its usefulness is increased by insertion of documents, forms, and offerings of operating aids.

Technical activities

Technical Activities Board. The year 1970 was the first year of operations with a Divisional structure for the Technical Activities Board. The Divisional Directors served, essentially, through appointment, as has been the case in the past for TAB OpCom members-at-large; three of the Divisional Directors were serving concurrent terms as IEEE Directors-at-large. Two of the Divisions (3 and 4) completed nominations and elections. Plans were initiated for two additional Divisions to hold elections in 1971; in this connection it was deemed desirable to switch the numerical designations for two Divisions (2 and 5) in order to conform to the even-year, odd-year election pattern that applies to the IEEE Regions.

The appearance of Technical Divisions was accompanied later in 1970 by the transition of three Groups to become the first IEEE Societies: Computer, Control Systems, and Power Engineering. At the year's end the impact of these organizational changes was not yet fully understood and TAB became involved in a dialogue on the roles and missions of the Divisions, and Divisional Directors, Groups, and Societies.

Two Groups—Man-Machine Systems and Systems Science and Cybernetics—merged as of January 1. The merged Group—Systems, Man, and Cybernetics—will continue to support the activities of the two former Groups. Other Groups have also entered into serious reviews of merger possibilities. The *Ad Hoc* Committee on Manufacturing Technology was converted into an Organizing Committee. Petitions for the formation of Manufacturing Technology Group have been circulated, with a good response, and it is planned for this new Group to become operational in 1971.

Several joint meetings were held by the Regional Activities Board and TAB OpCom, to facilitate joint efforts to improve IEEE activities and programs. Attention is being given to mutual problems related to Student members, and Branches and Chapters; also, TAB assistance is being mustered to help the Sections with arrangements for technical speakers. A joint RAB/TAB Technical Meetings Committee has been established to help with this important phase of IEEE's technical activities.

A reorganization of the IEEE Standards Committee, and all related programs and procedures, which was planned in 1969, has been put into effect. The Technical Committees of the IEEE Groups and Societies are an important part of the entire program and are now being given an opportunity to fulfill their potential roles with appropriate recognition. The procedures for publishing IEEE Standards are revised to include publication in the appropriate IEEE *Transactions* or *Journals*. All appropriate IEEE standards are being sent to the American National Standards Institute for consideration as ANSI standards. Procedures for IEEE participation in ANSI affairs have been streamlined, with emphasis on genuine technical representation responsible to the appropriate Technical Committees.

The TAB Finance Committee made further progress in clarifying the relationships between IEEE finances and the budgets of the individual Groups and Societies. The computer programming for handling the annual budgets has been simplified and a similar program is being developed for financial statements. A program was also developed to give detailed information on all double memberships between the Groups and Societies. A workshop was held during WESCON to assist treasurers and other officers in their responsibilities for budgeting and administration.

The TAB Publications Committee has continued to work closely with the IEEE Publications Board and Headquarters staff in facilitating the prompt publication of the periodicals.

Joint Technical Advisory Council. The JTAC, sponsored by IEEE and the Electronic Industries Association, held six regular meetings during 1970. The Council held a briefing session in November 1970 for the Federal Communications Commission and the Director of Telecommunications Policy to discuss the many factors that influence progress in the field of spectrum engineering/utilization. The Council has had four committees active in various areas relating to the radio art.

JTAC Committee 63.1—Electromagnetic Compatibility. Committee 63.1 has been concerned with following through on efforts made by government and private concerns regarding adoption of the recommendations made in the JTAC report "Spectrum Engineering—The Key to Progress."

The committee prepared a comprehensive list of activities that have been intiated, scheduled/planned, and needed by the JTAC, the FCC, and the OTP on each of the many recommendations made in the Report. Committee 63.1 will monitor action in this area and is being retained on a standby basis to be able to take on a study at short notice.

JTAC Committee 65.1—Future Needs and Uses of the Spectrum. Activity on Committee 65.1 subsequent to the publication of its report "Future Needs and Uses of the Spectrum," included as part of the Proceedings of the Hearings before the Subcommittee on Activities of Regulatory Agencies of the House Select Committee on Small Business, has been curtailed. This has been mainly due to the inability to obtain a meaningful evaluation of the needs and uses of the spectrum without full knowledge of government needs. This committee was disbanded in the course of 1970 but the area is being monitored by its chairman.

I. IEEE Membership by Region, Grade, Percentage; as of December 31, 1970

Region	H	F	SM	M	A	Total Grades Other Than Student	Student	Total Membership	Percentage
1	2	937	5 821	25 713	3 831	36 304	5 057	41 361	24
2		531	4 565	16 959	1 882	23 937	3 129	27 066	16
3		282	2 320	9 058	836	12 496	2 264	14 760	9
4		232	2 553	10 955	1 483	15 223	3 456	18 679	11
5	1	176	2 009	8 628	839	11 653	3 175	14 828	9
6		527	4 589	21 281	2 015	28 412	3 620	32 032	19
7		65	796	4 631	1 067	6 559	1 926	8 485	5
8		158	884	2 903	475	4 420	1 131	5 551	3
9		12	212	1 459	268	1 951	548	2 499	2
10	1	29	432	1 968	367	2 797	313	3 110	2
U.S. possessions and military overseas		2	48	498	75	623	65	688	
	4	2 951	24 229	104 053	13 138	144 375	24 684	169 059	100

JTAC Committee 66.2—Testing Sharing of TV Channels by LMRS. The JTAC established this committee to assist the FCC in tests being conducted by the Commission on the feasibility of the Land Mobile Radio Service sharing television channels. Subsequent to the Commission's acceptance of the final report of the committee, JTAC disbanded Committee 66.2.

JTAC Committee 67.1—Spectrum Utilization Aspects in the Use of Space Techniques. Established to study spectrum-utilization aspects of space techniques, Committee 67.1 submitted its report, "Radio Spectrum Utilization in Space," to JTAC. H. Edward Weppler, JTAC chairman, was selected as a delegate to the Special Joint CCIR Meeting in February to prepare for the World Administrative Radio Conference—Space Telecommunications.

Educational activities

Dr. John G. Truxal, chairman of the Educational Activities Board, called five meetings during the year at which reports were submitted by the following standing committees: Accreditation, Pre-College Guidance, and Student Activities. In the area of continuing education, a number of new projects were initiated.

Accreditation. The Accreditation Committee continually reviews and evaluates the status of the profession and electrical engineering education and develops broad minimum acceptable criterions for use by IEEE inspectors who have been selected by ECPD to visit a given institution and review its electrical engineering curriculum. An *ad hoc* committee for engineering technology was established during 1970 to perform a similar function in that area. Among other actions, guidelines for IEEE/ECPD Visitors were developed and published, indoctrination workshops were conducted for Visitors, and it was recommended to ECPD that procedures be established to accredit the masters-degree programs.

Precollege guidance. The Pre-College Guidance Committee, under the chairmanship of Dr. Lindon E. Saline, held three meetings during the year at which it evaluated existing programs in the guidance field and considered future roles and activities. Among its recommendations were that IEEE participate in the International Science and Engineering Fair, that IEEE Sections and Groups take greater part in guidance activities, and that IEEE not establish a high school membership grade.

Continuing education. The EAB as a whole reviews, evaluates, and conducts the IEEE continuing education programs. Current ongoing programs include:

1. *Resources handbook.* Information on slide tape lectures, films, film sources, video tapes, study guides, etc.

2. *Slide tape lectures.* Recorded and packaged unedited material presented at various major meetings as program material for Sections and Branches.

3. *Seminars.* One- and two-day seminars presented periodically.

4. *Cassette colloquia.* Technical information recorded at conferences, conventions, and seminars, and not available in any other format. Five titles are currently offered. An expansion of the program will be undertaken during 1971.

5. *Soundings.* Cassette report service on the latest developments and state-of-the-art topics in the electrical/electronics field; available to members on an annual subscription basis or as individual cassettes.

6. *DATE service.* Telephone information service providing members with brief basic information and bibliographies as introductions to areas of engineering with which they may not be familiar. The service is being tested in the metropolitan New York area with a library of 21 titles. Expansion of the service is contemplated for 1971.

7. *Self-study courses.* Two self-study courses are being offered in Regions 1–9. Both are introductory in approach; one covers financial management and the other electronic data processing. Under development is a self-contained self-study course consisting of text, visual material, and audio cassette.

Future programs under consideration by EAB include study guides covering all major electrical engineering disciplines, development of a unified program of credit, development of a newsletter on educational affairs, and cooperation with universities in the development of retraining programs for unemployed engineers.

Student activities. Two meetings of the Student Activities Committee were held in 1970, with Dr. Richard B. Russ acting as chairman. As coordinator of the IEEE student program, the committee recommended (1) restructuring the Student member grade to eliminate the Student Associate category and to have only one grade of Student Branch; (2) redefining the term "school of recognized standing" to include community colleges, junior colleges, and technical institutes; and (3) defining the role and scope of the Student Activities Committee to strengthen and delineate its responsibilities. In other actions, the committee concurred in the EAB recommendation that coordination of student activities come under the responsibilities of the Regional Activities Board and confirmed continuing sponsorship of Branch and Regional Prize Paper Contests, the annual Vincent Bendix Award, and various Group awards.

IEEE Student and Student Associate Branches showed an increase of 17 new Branches for a total of 359, as follows:

Region	Student Branches	Associate Branches	Total Branches
1	51	20	71
2	37	7	44
3	34	4	38
4	34	8	42
5	32	6	38
6	40	7	47
	228	52	280
7	20	12	32
8	19	1	20
		Section	2
9	21	3	24
10	1	0	1
	289	68	359

Board and standing committee activities

Admission and Advancement Committee. During the year a record number of applications for new members were processed, 13 540 Student members and 4049 in other grades, a total of 17 589. The Admission and Advancement Committee met 12 times in 1970, when actions were taken as follows:

	Senior Member	Member
Admissions approved	240	466
Admissions rejected	58	57
Transfers approved	391	60
Transfers rejected	42	9
	731	592

Awards Board. The Awards Board met three times in 1970 and all meetings were held at IEEE Headquarters in New York.

As well as recommending to the Board of Directors for approval candidates for the Medal of Honor, four Major Annual, eight Field, two Prize Paper, and two Scholarship Awards, the Awards Board submitted recommendations for four external awards: the National Medal of Science, the Niels Bohr International Gold Medal, the Kelvin Gold Medal, and the Alfred Noble Prize. The Awards Board also approved recommendations for appointments to three Intersociety Boards of Awards to replace those IEEE Representatives whose terms expired during the year.

With regard to presentation of IEEE awards, the Medal of Honor and Major Annual and Prize Paper Awards were presented during the International Convention. Presentations of the Field Awards took place during the following meetings: Winter Power Meeting, New York; International Solid-State Circuits Conference, Philadelphia; International Conference on Communications, San Francisco; International Symposium on Information Theory, Noordwijk, The Netherlands; Western Electronic Show and Convention, Los Angeles; International Electron Devices Meeting, Washington, D.C.; Northeast Electronics Research and Engineering Meeting, Boston; and National Electronics Conference, Chicago.

Other actions and recommendations of the Awards Board during 1970 included the discontinuation of the Institute Student Prize, and the approval of the establishment of one Group Award and two Group Committee Awards. In addition, the Awards Board approved the recommendation for a substantial increase in the stipend for the Charles LeGeyt Fortescue Fellowship from $3000 to $4000.

Several years ago the Awards Board recommended that the Edison Medal Deed of Gift be modified to permit the awarding of this medal to persons residing outside the U.S., its dependencies, and Canada. After much negotiation and necessary legal action, authorization was finally given to the IEEE for the granting of the Edison Medal to residents of any country where the IEEE has members.

For the past two years the Awards Board has been conducting an extensive review of the IEEE awards structure. This study, undertaken in accordance with the Institute Bylaws, was completed by the Awards Board in 1970 and the Board of Directors took action on the recommendations submitted.

Fellow Committee. The committee met twice in 1970. The first meeting was devoted to review and adoption of the scoring procedures to be used in evaluating the Fellow grade nominations, and agreement on new procedures to facilitate the heavy workload involved in the scoring process, including a new scoring card to be used by the judges.

The computer facilities at the University of California (Berkeley) were used to develop detailed scoring analyses, which were reviewed by the committee at its second meeting, when final selection was made of those candidates being recommended for elevation to Fellow grade as of January 1, 1971. The Board of Directors considered the report of the Fellow Committee and conferred the grade of Fellow on 123 members.

In the fall of 1969 the Board of Directors appointed an *ad hoc* committee to examine the Fellow recognition in the broad context of IEEE's recognition activities, and the mechanisms employed in the conduct of the Fellow recognition function. The recommendations of the *ad hoc* committee will be submitted for consideration by the Board of Directors in 1971.

Finance Committee. The Finance Committee held six meetings during 1970 and primarily concerned itself with reviewing investment results, comparing actual results of operations with budget, determining where expenses could be reduced, and preparing the 1972 budget.

The committee accepted the Audit Report of Price Waterhouse for December 31, 1969, and recommended that it be published in SPECTRUM.

The Investment Committee Charter was prepared by the Finance Committee and forwarded to the Executive Committee for approval. On the Investment Committee's recommendation, half of the Equity Fund was transferred to bonds. The investment of surplus cash of the Cowan Fund in AT&T 8¾ percent debentures was approved by the Finance Committee.

At all meetings, the results of operations to that date were compared with the "seasonalized" budget to show variations as they were occurring. This enabled the preparation of a forecast for the complete year to highlight expected variations and to pinpoint areas that were out of control and needed attention. Reductions in several departments were voted in midyear to partially absorb the expected lower income.

The first draft budget for the fiscal year 1971 was reviewed five months before the beginning of that year on both a departmental and functional basis. This allowed sufficient time to make adjustments needed to balance the budget.

The Finance Committee was enlarged to include all of the members of the Executive Committee.

History Committee. A formal meeting of this committee was held in March at the International Convention, but most of the committee work was carried on by correspondence. The preparation of a history of the formation of the IEEE from the merger of the American Institute of Electrical Engineers and the Institute of Radio Engineers is an ongoing project of Nelson Hibshman, retired IEEE Executive Consultant, under the auspices of the History Committee. Preliminary steps were taken for assembling a limited collection of archival documents having special relevance to the Institute. An attractive locked display case, purchased with funds made available by the Life Member Fund Committee, was installed in the New York offices to house this collection.

Internal Communications Committee. The ICC held four meetings during 1970. The committee operated as an advisory group and reviewed internal communication

II. IEEE Group Membership, December 31, 1970; three-year comparison

Group No.	Group Name	Students	Members	1970 Total	1969 Total	1968 Total
1	Audio and Electroacoustics	887	4 412	5 299	5 075	4 572
2	Broadcasting	271	1 916	2 187	2 090	2 009
3	Antennas and Propagation	688	4 338	5 026	5 203	4 937
4	Circuit Theory	2 315	7 962	10 277	10 167	8 868
5	Nuclear Science	306	2 169	2 475	2 510	2 453
6	Vehicular Technology	227	2 278	2 505	2 359	2 192
7	Reliability	79	2 525	2 604	2 638	2 486
8	Broadcast and Television Receivers	299	2 230	2 529	2 430	2 299
9	Instrumentation and Measurements	457	4 280	4 737	4 848	4 732
10	Aerospace and Electronics Systems	764	7 681	8 445	9 092	9 150
12	Information Theory	1 063	4 800	5 863	5 209	4 558
13	Industrial Electronics and Control Instrumentation	337	3 190	3 527	3 473	3 293
14	Engineering Management	613	6 203	6 816	6 725	6 293
15	Electron Devices	2 141	7 447	9 588	9 959	9 175
16	Computer	3 318	14 313	17 631	16 862	14 982
17	Microwave Theory and Techniques	900	5 887	6 787	6 920	6 370
18	Engineering in Medicine and Biology	1 209	4 452	5 661	5 206	4 614
19	Communication Technology	1 273	8 569	9 842	9 631	8 972
20	Sonics and Ultrasonics	110	1 275	1 385	1 357	1 246
21	Parts, Materials and Packaging	41	1 962	2 003	2 108	2 176
23	Automatic Control	1 622	5 933	7 555	7 425	6 769
25	Education	190	1 984	2 174	1 966	1 880
26	Engineering Writing and Speech	221	1 944	2 165	2 202	2 103
27	Electromagnetic Compatibility	43	1 787	1 830	1 877	1 719
28	Systems, Man and Cybernetics	1 088	4 409	5 497	1 463	1 225
29	Geoscience Electronics	226	1 531	1 757	1 707	1 571
31	Power	1 170	13 809	14 979	13 873	12 897
32	Electrical Insulation	48	1 281	1 329	1 246	1 139
33	Magnetics	161	2 155	2 316	2 134	2 019
34	Industry and General Applications	308	5 486	5 794	5 287	4 713
35	Systems Science and Cybernetics	...	...	...	4 762	3 987
		22 375	138 208	160 583	157 804	145 399

problems, recommending ways to improve the interface between the Institute and the member.

As a result of the establishment of RAB, the Long Range Planning Committee, the *Ad Hoc* Public Relations Advisory Committee (PRAC), and certain *ad hoc* committees of TAB, ICC's duties under Bylaw 311.5 have been superseded. The committee was disbanded as of December 31, 1970, subsequent to submitting a report to the Executive Committee recommending areas in which the several programs it generated during its lifetime should be monitored.

Intersociety Relations Committee. During 1970 the ISRC reviewed IEEE's participation in 35 organizations throughout the world as reported by 99 volunteer representatives. A comprehensive grouping of digested reports from the IEEE representatives was sent to the Executive Committee for review.

As an example of the type of activity continually under review by the committee, IEEE's involvement with the newly created World Federation of Engineering Organizations (WFEO) was clarified and the committee recommended continued support and active participation by IEEE.

The committee studied the implications of the ECPD Constitutional changes relating to admissions and reaffirmed its long-held position that voting membership in ECPD should rest with societies with primary curricular responsibility. The Executive Committee has so suggested to ECPD. ISRC also reviewed EC PD's guidance activities and agreed with the EAB that close monitoring over the short term is required to determine the degree to which IEEE would be willing to continue its present policy of reliance on ECPD for profession-wide coordination of local guidance activities, as against joining with other societies in developing a new program.

The ISRC reviewed the subject of IEEE representation and support in connection with national engineering societies in Regions 8–10 and decided that individual members or a unit of IEEE in another country could join national societies if they wish in order to participate in joint conferences or other activities of mutual benefit in specific technical areas, but that IEEE should not become involved as a society. Any support in connection with such interaction should come through the normal Section or Group budgets but, if there should be special circumstances requiring additional support from IEEE, such situations should be considered on a case-by-case basis.

The committee reviewed the subject of engineering registration within Regions 1–6 and the trend toward state laws tending to be more restrictive as to who may call himself an engineer and practice engineering. It was decided that IEEE should develop a channel of information to keep its membership advised on registration requirements and developments throughout the United States and in other countries. It was suggested that there should be at least a yearly report on the situation published in SPECTRUM and notification to the membership of any special developments that might be of immediate interest to them during the interim.

The ISRC Subcommittee on Scientific and Cultural Exchanges continued its efforts to enlarge the scope of the exchanges to include additional Eastern European countries. There was very positive response from Romania and Hungary and the latter sent one representative to the 1970 IEEE International Convention.

As a result of negotiations started at the IEEE Convention, a number of U.S. companies involved in solid-state technology had considered sending a five-man subgroup with the regular IEEE delegation to the 1970 Popov Society Congress for an in-depth look at solid-state installations in the U.S.S.R. However, it was decided that it would be more feasible for this group to plan its activities separately since the work involved would most likely postpone any exchange to a much later date. Negotiations are still under way for an exchange to take place in 1971. If this exchange can be agreed upon, it could provide a model for future IEEE exchanges, which might be organized as subdelegations of the Popov exchange but emphasizing a specific area of technology. As an effort in this direction, the chairman of the subcommittee wrote a memo to all the Group chairmen to describe the IEEE/Popov exchange and request their assistance in expanding into special areas of technology.

The 1970 IEEE delegation to the Popov Society Congress visited Kiev for the first time and had very rewarding visits to installations in Leningrad, Novosibirsk, and Moscow as well. The program continues to expand both in numbers of participants and quality of installations visited.

Life Member Fund Committee. One formal meeting of this committee was held in 1970 at which $3000 was appropriated toward student registration fees at the International Convention, on a one-time experimental basis only. As a result of this experiment, the Institute received approximately 1600 new student applications during 1970 over 1969.

The Board of Directors appointed an *ad hoc* Committee on Professional Concerns of Young Engineers to seek ways in which the IEEE can more vigorously serve the young professional, and the LMFC appropriated $6000 to compensate members of this committee for their travel expenses to attend authorized meetings during 1970.

The new *Historic American Engineering Record* is a government–professional program that will undertake the broad-scale identification and recording of significant examples of engineering history. The work will be carried out in cooperation with interested public and private groups on a donated-fund basis. The LMFC voted to provide the seed money if the History Committee should express interest in IEEE's participation.

Following the committee's recommendation, the Board of Directors approved a Bylaw that broadens the scope of the Life Member Fund Charter to include the interests of older members, whether or not they qualify as Life Members.

A newsletter was developed and mailed to all Life Members, thanking them for their generous contributions to the Fund and outlining the worthy projects that the Fund has made possible. It is hoped that a similar newsletter will be prepared each year.

Long Range Planning Committee. This committee held four meetings during 1970, one of which was held with the Executive Committee. During all meetings, attention was focused on the economic problems and the socio–technical interface.

Regarding the economic betterment of the engineer, the committee felt that the Institute can best serve its individual members through its continuing educational programs, through its publications, and through prognosis, by charting the future of the profession. It urged support of portable pensions for the long-range well-being of the Institute. It recommended special *ad hoc* task forces to study areas related to environment.

The Public Relations Advisory Committee, at the joint Long Range Planning/Executive Committee meeting, recommended that the Institute concern itself with (1) obtaining public and member support for IEEE activities; (2) obtaining public support for science and engineering in general, and for electrical and electronics engineering in particular; and (3) developing a social consciousness among its members so that they practice their profession in a way that deserves public support.

The RAB was asked by LRPC to report on what action might be taken by Sections to assist the educationally disadvantaged. The importance of keeping IEEE's perspective transnational was stressed and non-U.S. Directors were asked to recommend specific things the Institute should be doing for non-U.S. members.

Membership and Transfers Committee. The committee held three meetings during 1970. "Area Representatives" were designated and assigned to particular Sections with which they maintained communication in the matter of membership and transfer activities. "Regional Representatives" also were designated to assist Regional Directors in supporting effective M&T programs at the Section level.

At its first meeting, the committee set a membership goal that called for each Section to realize a 10 percent net increase in membership during the calendar year. Forty Sections achieved this goal, and plans are under way to give them appropriate recognition.

Because a large percentage of IEEE members fail to renew their membership each year, a concentrated effort was made in 1970, with the cooperation of the Regional Directors, to reclaim these members through personal follow-up at the Section level. The subsequent substantial reduction in the number of members in dues arrears can be traced to this direct communication, which only the Section can provide, and thus a formal program will be initiated in 1971 to encourage greater involvement by the Sections in this area.

Statistics prepared in 1970 show that the major input to the general IEEE membership comes from Students transferring to higher grades. It was determined that the Institute needs a concentrated program to get graduating Students interested in continuing their IEEE membership, and that this activity should have priority at all levels of the Institute.

Upon recommendation by the committee, the IEEE Bylaws were amended to permit members in any grade to continue IEEE membership at reduced rates for a specified period while in military service.

Some Sections maintain the names of non-IEEE members on mailing lists to receive announcements of Section meetings and activities. Although it is good practice to add the names of prospective members to Section mailing lists for a limited time, the committee felt these should be dropped if the individuals cannot be persuaded to join the IEEE. Following the committee's recommendation, the Executive Committee adopted a Statement of Policy in this regard.

The committee made recommendations to be incorporated in a new brochure for newly elected members and in the current brochure for prospective members when it is reprinted.

During the year members of the IEEE staff operated Member Services Desks at 20 conferences sponsored or cosponsored by IEEE. Some 575 applications for membership and 656 for enrollment in Groups and Societies were received, and 3011 inquiries were handled verbally or by letter.

It was apparent to the M & T committee that the success of any of its programs requires active participation by the organizational units of the Institute—Regions, Groups and Societies, Group Chapters, and Student Branches. The composition of the 1971 committee is being changed to include a chairman, a vice chairman, a representative from the Student Activities Committee, and one representative from each Region and Division. The objective is to combine efforts in these areas to implement an effective and continuing membership and transfers program.

Nominations and Appointments Committee. This committee serves for the term April 1 to March 31. Six meetings were held to discharge the following responsibilities: report to the Board of Directors, recommending candidates for President and Vice President for election by the voting members as well as candidates to serve as chairmen and members of the various boards and committees reporting to the Board of Directors; report to the annual Assembly, recommending candidates for election by that body for Vice President—Publication Activities, Vice President—Technical Activities, Secretary, Treasurer, Director of Region 10, chairman of Awards Board, chairman of Educational Activities Board, and vice chairman, Technical Activities Board; report to the Executive Committee, with recommended candidates to serve on the Admission and Advancement, History, and Membership and Transfers Committees.

Regional Activities Board. The Regional Activities Board held four regular and one special meeting during 1970. In addition, it participated in two dinner meetings with the Technical Division Directors and arranged a Regional Directors Orientation Session in November attended by the Regional Directors-Elect.

The objective of the Board as stated at the outset of the year was to formulate plans and take actions that would result in better communication with the members; to determine and try to meet the needs expressed by the members and to encourage the Sections to be more active in serving these needs. To this end a number of subcommittees were appointed, each charged with the responsibility of developing plans to be put into action during 1970 in addition to working on projects that would continue through the following years. The emphasis, however, was on immediate action. The Regional Directors were charged with the responsibility of being Regional executives who develop in the Sections a businesslike attitude by setting goals, allocating funds, and establishing performance accountability.

The RAB chairman attended Regional Committee meetings in each of Regions 1 through 8 as well as many Section meetings all over the United States. The Regional Directors developed various means for stimulating additional Section activities; e.g., Region 2 held three Regional Committee meetings, two of which were combined with Section Workshops; Region 4 established a Regional Operating Committee to provide a means for taking care of Regional problems and to make possible more visits to Sections, Subsections, and Branches; Region 7 used the Council structure; Region 8 focussed the activities of the Sections on EUROCON 71. Region 3, which operated as a laboratory of the RAB Policy and Planning Committee of which the Region 3 Director is a member, used the Area Chairman concept. Six Area Chairmen were appointed by and reported to the Regional Director. Each chairman was assigned approximately six Sections to work closely with during the year. Region 3 also established six Regional Subcommittees whose members worked with and supported the Area Chairmen. This effort resulted in establishing a new format for Regional Committee meetings with workshops that proved to be highly productive.

The RAB Policy and Planning Committee, which met nine times during the year, developed and tested in Region 3 training material for Section officers and committees. The projects covered: slide presentations; a Section Management Guide that included job descriptions, monthly operating schedules, and suggested measures of performance for each officer and committee member; and the development of a brochure inviting members to become more active in IEEE affairs, which was mailed to Region 3 members. The results were presented to the Regional Activities Board and the tools made available for use by other Regional Directors.

The RAB Member Services Committee, comprised of two members from each Region, held two meetings during the year. Most of their efforts were concentrated on workshops. A total of 11 Section workshops were held in Regions 1–7, seven of which were arranged by the MSC. In addition, the MSC participated in workshops for Student Branch Chairmen and Student Counselors and in the RAB Orientation Session.

The RAB Finance Committee. A small RAB development budget was approved early in the year, providing limited support for some of the foregoing activities. For 1971 RAB has obtained funds for Regional Workshops, RAB committee operations, and RAB development funds, as well as additional staff support in the form of a staff director for the new Member Services Department. The Regional Activities budget retains the present rebate formula for Sections. The RAB Finance Committee has proposed a new concept of Section and Region financing and a new rebate structure is currently being developed with the object of motivating Sections to be more active in meeting the needs of their members.

The Student Activities Committee was transferred from the jurisdiction of the Educational Activities Board to the Regional Activities Board effective January 1, 1971. A major effort will be made to establish better communication and increased activities between the Sections and Student Branches.

Tellers Committee. The Tellers Committee met once in 1970 for the purpose of supervising the count of votes on the ballot returns from the voting members in the annual IEEE election. This year members were asked to vote on amendments to the IEEE Constitution, and the ballot mailed to Group members in Technical Divisions 3 and 4 called for additional voting for a Divisional Director to represent them on the IEEE Board of Directors.

In accordance with IEEE Bylaws revised in 1970, the ballot included space in which the voter could write the name of any person he desired to elect for any of the offices appearing on the ballot.

IEEE Group Insurance program

The Insurance Program approved by the Institute for its members showed another increase in participation during 1970. The total number of certificates in force for the policy year ending in 1970 was 35 791, a gain of about 7.4 percent.

Experience with the plan continued to be very favorable. Members insured during the policy year ending September 1, 1970, will receive a dividend credit equal to 60 percent of the amount paid for coverage during that policy year.

Headquarters staff activities

As of December 31, 1970, there were 271 permanent employees on the IEEE staff.

Personnel changes during the year included the following: William J. Hilty became director of the newly created Convention Services Department; J. Howard Schumacher, Jr., previously in Technical Services, was named Manager of Convention Services; Joseph M. Doblmeier became Manager of Exposition Services; Sava I. Sherr was named Manager of Standards Operations, with headquarters in Newark, N.J.

Announcement was made of the death of Edward C. Day, manager of the Dictionary Project.

Report of the Treasurer—1970

Raymond W. Sears *Treasurer IEEE*

The financial activities of IEEE for the year ending December 31, 1970, are given in the accompanying audited statements on a consolidated basis, including the financial operations of Groups and Societies in the same form as was initiated last year. The financial and services support to Sections and Regions are included in the General Account, but all of their financial activities are not included on a consolidated basis. The IEEE General Account, financial results of Groups and Society operations, and Investment Fund operations are shown individually with the appropriate elimination of inter-account transactions between these accounts.

The IEEE was fashionably in line with most institutions and businesses and had a financially stressful year. Many income items fell below our expectations and budget. Advertising income was down by a net of $115-000; the International Convention was down by a net of $90 000; Education, Information, and Reimbursed Services income was down by a total of some $200 000. In addition, escalating costs of printing and other supplies resulting from the general inflation of our economy caused us some difficulty. Membership dues income, which amounts to about 43 percent of the total, was counter to the trend and above budget by $25 000. A potentially large 1970 deficit was held to a minimum during the year, and we prepared ourselves for a critical situation in 1971 by a series of belt-tightening exercises. These resulted in staff reductions totaling 12 percent, the elimination of the Information Services Department, the freezing of merit salary increases, a critical review of services in the Administrative Department, and the abandonment of all services not considered absolutely essential.

The afore-mentioned actions held our deficit in the General Account to $79 132 (one percent) for 1970 compared with a loss of $106 501 for the previous year. Financial operations of Groups and Societies resulted in a surplus of $194 737 for a combined operating surplus of $115 605. This should be viewed as an indication of the good overall financial condition of the Institute, particularly since the gross activities of Groups and Societies received a cash support of $725 451 from the General Account. It should be noted, however, that the excellent financial record of the Groups and Societies was due, mainly, to a $150 000 surplus of the Computer Society obtained principally from its proceeds of AFIPS. The balance of the Groups and Societies varied over a range from substantial deficits to moderate surpluses.

Early in 1970, the membership of the Investment Advisory Committee was augmented and the performance of our equity investments came under close scrutiny. In March, the Executive Committee, on the recommendation of the Investment Advisory Committee, divided the equity account into equal parts, putting one half of these funds into high-yield bonds. This move resulted in an increased interest yield from investments and decreased further potential capital losses by bridging the precipitous security-market dip in 1970. Although we had a realized capital loss of $413 888 during 1970, there have been substantial capital gains in the early part of 1971.

In summary, our operations experienced an overall successful year whereas our investments sustained a substantial capital loss in the general market decline. The total assets of the Institute decreased by $227 927 during 1970 and we will need to find new sources of revenue in the years ahead to replace the declining sources of income in order to maintain essential services and to initiate forward-looking activities.

Auditors' report

Price Waterhouse & Co.

60 Broad Street
New York 10004
March 5, 1971

To the Board of Directors of
The Institute of Electrical and Electronics Engineers (Incorporated)

In our opinion, the accompanying financial statements present fairly the financial position of The Institute of Electrical and Electronics Engineers (Incorporated) at December 31, 1970 and the results of its operations for the year, in conformity with generally accepted accounting principles applied on a basis consistent with that of the preceding year. Our examination of these statements was made in accordance with generally accepted auditing standards and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

Price Waterhouse & Co.

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (INCORPORATED)

STATEMENT OF INCOME AND EXPENSES AND OPERATING FUND BALANCE

DECEMBER 31, 1970

(Note 1)

	General Account	Groups	Investments	Total
Operating income:				
Membership, entrance fees, and dues	$3,303,279	$ 744,519		$4,047,798
Advertising	614,904			614,904
Periodicals subscriptions, publications, and sales items	830,288	1,421,800		2,252,088
Information services and products	226,114			226,114
Conventions and conferences	1,205,208	554,413		1,759,621
Investment income	108,437	61,213	$248,387	418,037
Miscellaneous other	355,903	23,651		379,554
Total	6,644,133	2,805,596	248,387	9,698,116
Operating expenses:				
Headquarters services to members	1,128,952	427,848		1,556,800
Support of Regions, Sections, and Branches	603,156			603,156
Periodicals, publications, and sales items	2,123,696	2,423,790		4,547,486
Information services and products	521,872			521,872
Conventions and conferences	870,057	388,102		1,258,159
Unallocated general administration	972,642	39,009	13,031	1,024,682
Total	6,220,375	3,278,749	13,031	9,512,155
Excess of operating income over (under) operating expenses	423,758	(473,153)	235,356	185,961
Loss on sale of securities			(413,888)	(413,888)
Excess of income over (under) expenses for the year (Note 2)	423,758	(473,153)	(178,532)	(227,927)
Add (subtract)—Intrafund transfers:				
Investment income to General Account	165,000		(165,000)	
Support of Groups from General Account	(667,890)	667,890		
	(79,132)	194,737	(343,532)	(227,927)
Fund balance, beginning of year	3,110,356	922,640	379,976	4,412,972
Fund balance, end of year	$3,031,224	$1,117,377	$ 36,444	$4,185,045

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (INCORPORATED)

STATEMENT OF FINANCIAL POSITION

DECEMBER 31, 1970

(Note 1)

Operating Fund

Current assets:		
Cash including $1,300,171 in savings accounts and time deposits	$1,670,606	
Marketable securities, at cost, approximate market value $4,875,000 (Note 3)	4,695,449	
Other investments, at cost, approximate market value $1,280,000	1,261,900	
Notes and accounts receivable, less allowance for doubtful accounts of $35,924	604,588	
Prepaid expenses, inventory, etc.	353,650	
Total current assets		$8,586,193
Fixed assets:		
Office equipment and leasehold improvements, at cost, less accumulated depreciation and amortization of $567,641		330,179
Total assets		8,916,372
Less—Current liabilities:		
Accounts and accrued expenses payable	910,852	
Deposits by Sections and other custody accounts (Note 3)	146,262	
		1,057,114
Deferred income:		
Groups	829,124	
Dues	1,988,639	
Subscriptions	444,555	
Convention	411,895	
		3,674,213
Total current liabilities		4,731,327
Operating Fund balance (accompanying statement)		4,185,045

Property Fund

Advance to United Engineering Trustees, Inc. (Note 4)		265,000

Restricted Funds

Cash	46,272	
Accrued interest receivable	11,527	
Marketable securities, at cost, approximate market value $287,000	277,840	
	335,639	
Less—Accounts payable	3,401	
Restricted Fund balance (accompanying statement)		332,238
Total all funds		$4,782,283

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (INCORPORATED)

STATEMENT OF CHANGES IN RESTRICTED FUNDS FOR THE YEAR ENDED DECEMBER 31, 1970

Restricted Fund	Fund balance January 1, 1970	Receipts from contributions and marketable securities, net	Disbursements for awards and related costs	Fund balance December 31, 1970
Life Member Fund	$ 89,550	$ 7,480	$19,746	$ 77,284
International Electrical Congress—St. Louis Library Fund	6,917	213	200	6,930
Edison Medal Fund	17,728	1,725	782	18,671
Edison Endowment Fund	7,986	263	263	7,986
Lamme Medal Fund	9,317	432	404	9,345
Mailloux Fund	1,057	43	69	1,031
Volta Memorial Fund	12,150	525	1,800	10,875
Kettering Award Fund	2,838	201		3,039
Browder J. Thompson Memorial Prize Award Fund	5,409	140	568	4,981
Harry Diamond Memorial Prize Award Fund	1,061	46	61	1,046
Vladimir K. Zworykin Television Award Fund	3,088	(23)	506	2,559
W. R. G. Baker Award Fund	10,244	674	2,150	8,768
William J. Morlock Award Fund	5,363	241		5,604
W. W. McDowell Award Fund	9,146	391	797	8,740
William D. George Memorial Fund	727	24	100	651
Frank A. Cowan Award Fund	153,993	8,542		162,535
IEEE Region 9 Award in Electric Power Engineering Fund	2,155	38		2,193
Total	$338,729	$20,955	$27,446	$332,238

NOTES TO FINANCIAL STATEMENTS—DECEMBER 31, 1970

NOTE 1—THE INSTITUTE: The Institute is a scientific and educational organization organized for the advancement of the theory and practice of electrical and electronics engineering and related arts and sciences primarily through Sections and Groups. Sections are unincorporated geographical subdivisions of IEEE. The books and records of the Sections are maintained by the treasurer of each Section and are not included in the accompanying financial statements. Groups are unincorporated units within IEEE formed to serve the specialized professional interests of members and to coordinate these with the local activities of the Sections and the broader activities of the Institute. The Groups promote the technical interests of its members through symposia, conferences, and various publications. The Groups receive income and incur related expenses from these activities and such monies are handled by the Institute and accounted for as a separate fund.

NOTE 2—ADVERTISING: No provision for federal income taxes on advertising income earned by the Institute has been made because, in the opinion of management, the Institute had no net advertising income after allocation of direct and indirect expenses.

NOTE 3—MARKETABLE SECURITIES: Marketable securities include $81,119 deposited by certain Sections of the Institute. Such funds with pro rata share of income and unrealized gains or losses can be withdrawn by the Sections concerned at the end of any fiscal year or quarter.

NOTE 4—COMMITMENTS: In accordance with a Founder's Agreement between the Institute and the United Engineering Trustees, Inc., the Institute has agreed to maintain permanently its principal offices in the United Engineering Center, which currently involves an annual payment of approximately $195,000. The $265,000 advanced to United Engineering Trustees, Inc., is repayable only out of available reserve funds on dissolution of United Engineering Trustees, Inc., and carries interest at an annual rate of 4 percent.

NOTE 5—PENSION PLAN: The Institute has a voluntary noncontributory pension plan covering substantially all of its employees. Pension cost for the year was $79,241, which included amortization of past service cost over 20 years. The Institute's policy is to fund pension costs accrued. Unfunded past service cost at December 31, 1970, is approximately $66,000.