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Automatic Trouble Diagnosis of Complex Logic Circuits

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This paper deals with the problem of maintaining the most complex portion of an experimental electronic telephone switching system, the central control. New and more effective automatic trouble detection and diagnostic techniques were used. In order to utilize these techniques effectively, a maintenance dictionary, i.e., a table relating trouble indications with corresponding faulty plug-in package, had to be produced. The system itself was utilized to create this dictionary. Over 50,000 known faults were purposely introduced into the central control to be diagnosed by its diagnostic program. The corresponding test results were then recorded via a high speed output. Finally, these test data were sorted and printed in dictionary form by a computer.

I. INTRODUCTION

In November, 1960 Bell Laboratories started its field trial of an experimental electronic telephone switching system in the town of Morris, Illinois. This system (extensively described elsewhere)[1] was one of the first attempts to introduce electronics on a large scale into telephone switching and as such, brought us face-to-face with a new class of problems, especially in the field of maintenance of centralized telephone equipment.

The problems of maintaining an electronic telephone switching system are formidable, but as will be seen presently, the tools naturally available for this maintenance are powerful. This paper will deal with the problem of maintaining the most complex portion of the experimental electronic telephone switching system, the central control.

II. RELIABILITY AND MAINTENANCE OBJECTIVES

The character of a commercial telephone system as a whole imposes unusual maintenance objectives for its component parts. The vital role of a central office demands that it have an extremely low downtime. At the same time, since the telephone system is so widespread and cannot be concentrated in a few key locations, another objective is that it be maintainable by telephone system craftsmen.

These are extremely difficult requirements. In order to maintain a sufficiently low downtime with devices currently available, it is necessary to provide some redundancy in the equipment so that single troubles do not cause the entire system to fail. The simplest form of redundancy, and in the present state of the technology probably the least expensive, is the simple duplication of all common equipment in the system. Thus, where only one memory store is required for running the system, two are provided; where only one control unit is required for running the system, two are provided, etc.

III. DESCRIPTION OF THE MORRIS ELECTRONIC SWITCHING SYSTEM

Fig. 1 is a block diagram of the system. The customer's line comes into the office and has an appearance on the network and on the scan-

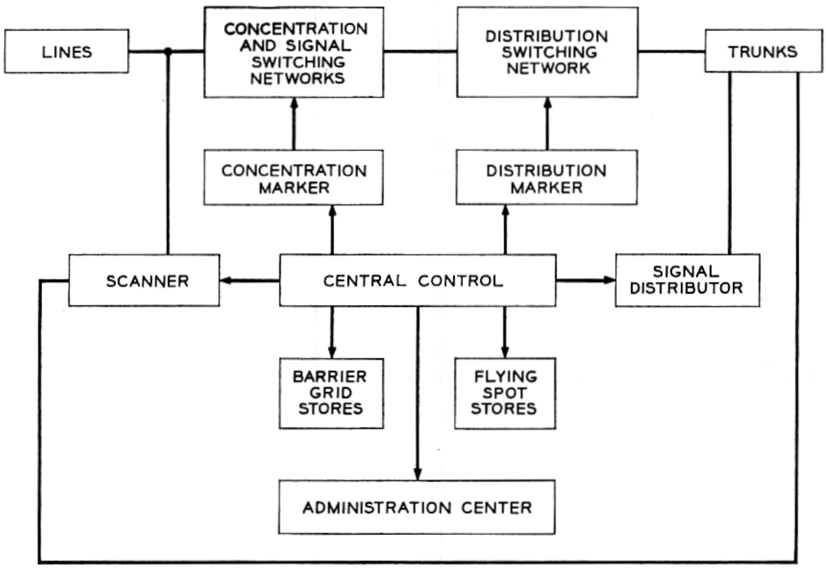


Fig. 1—General system block diagram.

ner. The appearance on the network permits him to be connected to another customer, to dial tone, or to a ringing signal. The appearance on the scanner permits the system to detect the status of his line. When a customer lifts his telephone handset off the cradle, a loop is closed to the central office, changing the voltage at a point that is detectable by the line scanner. Similarly, when dialing, this loop is opened for brief intervals; for example, if a 9 is dialed the circuit is opened nine times.

The flying spot store is used to store the program of the system and the individual translation information associated with each customer. The barrier grid store is used to store information as to the status of the lines in the office (busy, idle, or dialing) and to assemble dialing information during the time that a customer is actually dialing. The signal distributor is used to operate the test relays in the office and to signal to distant offices. It is also used to switch between working and standby units. The central control must coordinate the actions of all these units, i.e., take the output of the line scanner and the barrier grid store, act upon these outputs according to the instruction given by the flying spot store, and use these results either to set up a connection in the network or write further data in the barrier grid store; it must also request the next instruction from the flying spot store.

These facilities can be used for testing the system in a relatively sophisticated manner. Available for the purposes of setting up a call is a rather complex system for processing data. Testing is also actually a data-processing action. Thus, when a faulty unit is being tested, we get the instructions for testing from the flying spot store and we get the test results either from match circuits between units performing supposedly identical functions or from the line scanner which has test probes into various circuits. Test results are then assembled in the barrier grid store and are eventually typed out using the teletypewriter (which is also under the control of the signal distributor).

As mentioned earlier, all important and common equipment is duplicated. This leads to a two-fold advantage for testing. First, a rather sophisticated data-processing machine is always available which can automatically apply tests, and interpret and report test results. Second, an identical unit, presumably in good working order, is always available; the output of this unit may be compared with that of the circuit being tested. A match of outputs indicates a successful performance of a test, while a mismatch indicates a test failure.

The program for controlling tests is stored in the flying spot store. Storage space in this store is both expensive and limited. Therefore, it is not possible to store a program sufficiently flexible so that it can print out the identity of a defective package. Instead, the program prints out test results and these test results are then compared with test results that are anticipated by the designer and are placed in a form referred to as the "maintenance dictionary."

IV. CENTRAL CONTROL MAINTENANCE

The central control is the basic control unit of a real-time, special-purpose, program-controlled data-processing machine. It controls the flow of information to the stores, markers, scanner and signal distributor. It is duplicated. There are over 8000 circuit packages (6500 transistors, 45,500 diodes) in both central controls. The two central controls normally operate in parallel, executing the same instruction and performing the same operations, even though only one of the controls, the "active" central control, is used to control such system output circuits as the markers and signal distributor. Certain key outputs of the two central controls are matched; trouble in either central control leads to a mismatch. Any mismatch initiates a special fault-check program, which is used to decide which, if any, of the central controls has the trouble. The program causes central control to make a number of decisions; if the active central control makes any incorrect decisions, it switches itself out of service. If a decision made by the active central control is correct but a mismatch occurs, it indicates a trouble in the standby central control. In case the active central control is defective to such a degree that it cannot execute the fault-check program, a time-out circuit will automatically switch this control out of service.

After the fault-checking program has been completed, a diagnostic program is started. Whenever the system finds a spare time period of one millisecond when no telephone operations are required, tests are performed on the suspected central control. The results of these tests are then typed out using the system teletypewriter. These results must then be interpreted with the aid of a maintenance dictionary.

V. THE CENTRAL CONTROL MAINTENANCE DICTIONARY PROBLEM

For most of the units of the system, a maintenance dictionary can be specified with a reasonable amount of effort by the designer of the test programs because the units are functionally comparatively simple. For example, the characteristics of different types of faults which may occur in the scanner lead to a relatively small number of simple types of patterns which can be readily examined. However, central control is much more complex both in its functions and in its circuitry. The type of symmetry which is characteristic of scanner, signal distributor, network, and even the stores is totally absent in the case of central control. Even the number of the tests which has been selected (about 900) attests to this difference of complexity. The work of preparing a dictionary by hand would have been formidable and the resulting dictionary would have been very incomplete. As a result, the automatic means described in this paper were used to produce a dictionary that was both as complete as the diagnostic tests would permit and which required only a reasonable amount of development effort.

The scheme was to introduce about 50,000 faults into central control and get the test results associated with each fault. These test results could then be sorted and finally printed as the desired dictionary.

This scheme had a number of advantages over other techniques. First of all, while considerable effort would be required to design the basic mechanism and circuits for carrying out this scheme, once this effort had been expended, the number of troubles which could be analyzed could be made very large without enormous additional expenditure of effort. Secondly, no errors of analysis could creep into the system. Thirdly, because computer analysis would be required for the final production of the dictionary anyway, it would be possible with little additional effort to create a dictionary printout format that would closely resemble the format of the test results which are normally obtained by the system. Finally, the actual process of creating the dictionary could be deferred to a relatively late date so that the dictionary would be based on the most up-to-date version of central control and the most up-to-date version of the diagnostic program.

The basic scheme for deriving the dictionary data is discussed below. First, the system must be switched to a special dictionary mode of operation, dropping all telephone work. (Since this is done in the laboratory, not in a working office, this is not at all serious.) Then, information is fed to the system concerning the identity of the package whose possible faults are to be simulated. Next, the faults are simulated. After each fault, the system diagnostic program is started; a punched paper tape output is used to record the identity of the package, the number of the fault, and a complete report of the tests that failed when that fault was simulated. Such an output record is generated for each fault that is simulated. These records are then sorted and printed in suitable form by a computer.

VI. GENERAL DESCRIPTION OF DICTIONARY PREPARATION

A number of special pieces of equipment were designed for the preparation of the dictionary. Two fault-simulation units were used to simulate essentially all the packages and their faults. A test control unit was used to sequence the faults automatically in a given package and coordinate all special recording equipment with the system.

Information identifying the package whose faults were to be simulated was stored on a regular 5-channel teletype tape and was automatically fed into the system at the proper time by a conventional 100 words per minute reader when the corresponding circuit card was to be tested.

A high-speed 1000 words per minute (100 characters per second) TELETYPE tape punch was used to record the test results. The output data for each fault consists of the package identity and its location, the fault number, and the test results.

Fig. 2 shows the functional block diagram and peripheral equipment involved in collecting the test data.

The test control unit controls the over-all operation of the fault simulation and data gathering. The "normal-test" switch on the test control unit is first operated to the test position. This requests the system to go into the dictionary mode. When the system has reached a convenient point in its program, it stops the central control clock and turns over the control to the test control unit. The system cannot start again until a signal is received from the test control unit.

When the "system-off" lamp on the test control panel is turned on, the package on which faults are to be simulated can be pulled out and replaced by the fault-simulation unit. Then the "automatic test" push-button on the test control unit is operated. This tells the system to start an automatic test.

As soon as the automatic test signal is received, the system requests the package information tape reader to read in one package identity. Since the sequence of packages to be tested is the same as that listed on the package information tape, the identity will be the package currently under test. This information is stored by the system and later affixed to the corresponding diagnostic test results.

When the package identity has been stored, the system commands the test control unit to switch in the first fault and immediately initiates a complete diagnosis. Upon completion of the diagnostic tests, the system delivers the final test results to the high-speed tape punch. The system then requests the next fault to be switched in and another round of diagnostic tests and data punching begins.

The same cycle of operation is repeated until the fault-simulation unit informs the test control unit that the last fault on this package has been tested, in which case the test control unit puts the fault-simulation unit in a no-fault condition and asks the system to carry out the same

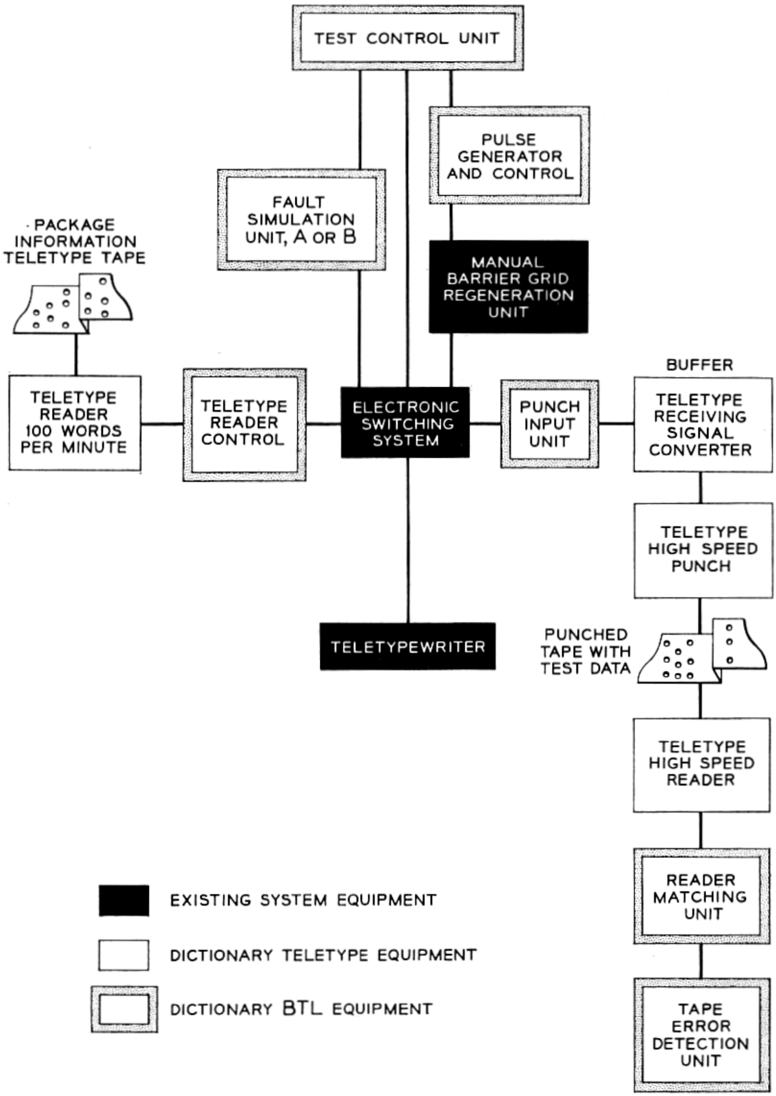


FIG. 2—Dictionary data acquisition: functional block diagram.

diagnostic routine. The test result output channel is now switched from the high-speed tape punch to the existing system teletypewriter, so that the test results will be easily readable. Normally, it is expected that there will be no test failures at the no-fault condition. Therefore, the teletypewriter will print out only the ALL TESTS PASSED message.

The main reason for making such a test is to check the correct functioning of the fault-simulation unit, i.e., that the substitution of the fault-simulation unit does not itself introduce a fault. The test also provides an auxiliary means to monitor the proper operation of the system.

When diagnosis for the no-fault condition is completed, the system performs the routine tests on all major system units; this enables the system to detect any trouble. After the system has succeeded in going through all the routine tests, it again turns itself off and lights the "end of automatic test" lamp on the test control unit panel. This completes the fault simulation for one package. The entire operation from the first fault to the last fault, then to the no-fault state, is done automatically following a single operation of the "automatic test" pushbutton.

During the time that the dictionary data was being gathered, a modified system program was used. The system did not spend a large amount of time performing unnecessary telephone work while it was actually creating the central control dictionary.

A high-speed 1000 words per minute TELETYPE reader was employed to read the tape as soon as it was punched. On the paper tape seven channels were used, six for the test data and one for the lateral parity bit generated by the system. The output of the reader was fed to a tape error detection unit which checks the parity of each character and the block length of the test records. The number of characters in the test record for each fault should be the same.

Before the data could be sorted, they were first converted from the punched paper tape to magnetic tape. A computer was then used to sort the test data. The actual dictionary was printed directly by a tape controlled printer.

In the dictionary project, work was divided into several major parts. A brief description of each part is given in the following sections.

VII. FAULT SIMULATION

The two central controls in the system are identical. Normally, one serves as the active unit and the other one as the standby or vice versa. The active unit always diagnoses the one in trouble. Therefore it is necessary to insert faults in only one of the central controls. The total number of circuit packages in which faults have to be simulated is about 4000.

About 49 different types of packages are used in central control.

All the faults simulated are of the catastrophic type. Faulty diodes are simulated as being either shorted or open, resistors as open and transistors are simulated as either permanently on or off.

Only single troubles are simulated. It would be totally impractical to simulate multiple faults. Furthermore, routine tests (at 100 millisecond and 1 second intervals) and matching between two central controls are performed often enough so that it is reasonable to assume that a single trouble will be detected and diagnosed before another fault develops.

Obviously it would be equally impractical to simulate all marginal conditions. It is hoped that a majority of the marginal conditions, if they result in trouble at all, will give the same characteristic result as a corresponding catastrophic fault. For example, if the reverse impedance of a diode is too low, a gate may behave in the same manner as if the diode were shorted.

The number of faults per package varies from 2 to 30. Over 50,000 faults were simulated in order to create the dictionary.

In the packages containing only diodes, troubles are simulated for each gate; in the other type of packages, mainly those containing transistors, only faulty output conditions are simulated. The results of the diagnostic tests are based on the output of a package rather than the individual component contained therein.

An example of fault simulation for a 2-input OR gate is given in Fig. 3. Each diode is shorted and opened by the operation of a different relay. Only an open resistor is simulated. If a shorted resistor were simulated it might cause damage to other components in the system. Furthermore, shorted resistors are relatively rare trouble conditions. The fault-simulation unit for the AND gate is similar, except that no resistor is involved.

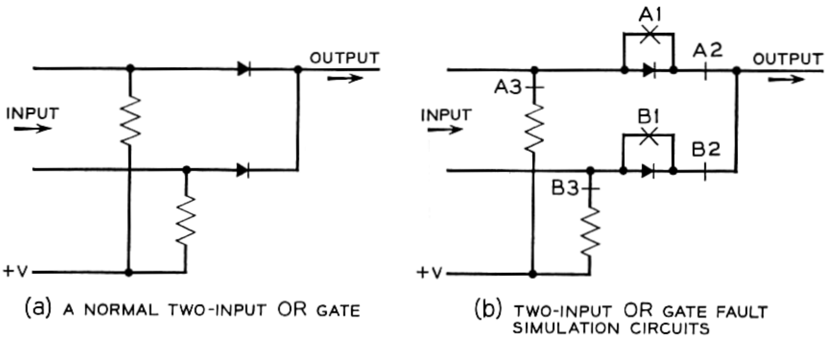
The transistor packages are simulated differently. For example, four possible faulty output conditions are simulated in a transistor flip-flop circuit.

1. Set permanently high, reset permanently low.
2. Reset permanently high, set permanently low.
3. Both high.
4. Both low.

All faults are controlled by the operation of different relays. Fig. 4 shows how this is done. The same simulation technique is used for all other types of transistor and miscellaneous circuit packages.

VIII. MODE OF OPERATION

When test data was being collected in the preparation of the dictionary, the system operated in two basic modes: normal and testing.



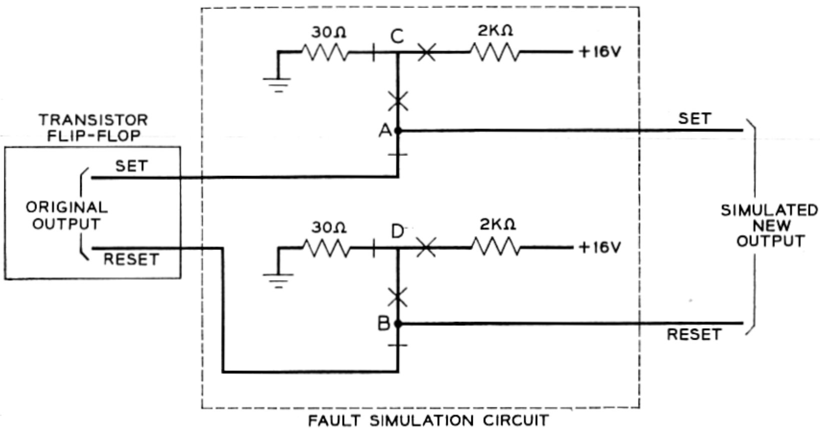
FAULT NUMBER		RELAY CONDITION	
		NONOPERATED	OPERATED
1. SHORTED DIODE	FIRST INPUT	ALL OTHERS	A1
2. OPENED DIODE		ALL OTHERS	A2
3. OPENED RESISTOR		ALL OTHERS	A3
4. SHORTED DIODE	SECOND INPUT	ALL OTHERS	B1
5. OPENED DIODE		ALL OTHERS	B2
6. OPENED RESISTOR		ALL OTHERS	B3
NO FAULT CONDITION		ALL	–

Fig. 3—Fault simulation on OR gate.

In the normal mode the dictionary test equipment is effectively disconnected from the system and the system is allowed to operate in its normal condition. If a trouble other than the one intentionally introduced is detected in the system during the course of a test, the system is placed in its normal mode so that any faults may be diagnosed and corrected.

In the test mode, the following different tests can be initiated by operation of appropriate push buttons:

1. Automatic test. This has already been described under the general description.
2. Manual test. The system can be asked to conduct diagnosis on any desired fault including the no-fault case. The results of a manual test are recorded on the system teletypewriter. Fault simulation is accomplished by means of the "fault advance" pushbutton on the test control unit. The manual test, made from time to time, is used to check the special dictionary programs and equipment. The manual test data are also used to spot-check the output data on the paper tape.



FAULTS	RELAY CONDITION	
	NONOPERATED	OPERATED
1. SET HIGH, RESET LOW	D	A,B,C
2. SET LOW, RESET HIGH	C	A,B,D
3. BOTH HIGH	–	A,B,C,D
4. BOTH LOW	C,D	A,B
NO FAULT CONDITION	A,B (C,D DON'T CARE)	

Fig. 4—Fault simulation on transistor flip-flop.

3. Skip package identity. This is a special feature provided so that a package identification block stored on the package information tape can be bypassed. When the "skip-package" button is operated, the system controls the tape reader and advances the package tape to the next block. This provision is made so that errors made during the preparation of the information tape can be corrected.

IX. SYSTEM CIRCUIT REQUIREMENTS

All communications between external equipment and the system are accomplished using the scanner and signal distributor. The scanner provides central control with an information access to lines, trunks, and test points. Signal-distributor outputs provide access from the central control to one of a large number of outputs. Very minor modifications in the system were needed to prepare the system to create the dictionary; the modifications consisted of adding a few temporary cables and connectors. The only wiring required was the jumper wiring from the external equipment to those scanner and signal-distributor points used for the dictionary project. Altogether, 12 scanner points and 23 signal distributor points were used.

X. PACKAGE INFORMATION TAPE

The package information tape records the type and location of each package to be tested. This information is read into the system via a conventional 100-speed (10 characters per second) tape reader; the identity is read once for each package to be tested. The system controls the tape reader under the command of the test control unit.

Only the pertinent codes associated with the package identity are stored. The system rejects all functional codes such as space, carriage return, etc. This package information is later attached with its associated diagnostic test results in the final output for each fault.

Eleven characters are assigned for the identification of each package. The first five specify the location, the next six indicate the type of package.

The package information was first tabulated at random manually from an apparatus designation chart. IBM cards, one for each package, were prepared from the tabulated list, and were manually checked. After the cards were sorted according to the predetermined order in which the packages were to be tested, a printed list was prepared. This list was used as the master package test schedule during data gathering. The punched cards were then converted into a fully perforated, 5-channel paper tape in TELETYPE code. From this tape, a final printed, chadless tape was prepared. A printed tape was used so that the operator would be able to read it. Thus, a check could be made before a package identity was read into the system. A printed tape so obtained would go through a final check.

XI. SYSTEM PROGRAM MODIFICATIONS

Modification of existing programs, mainly the central control diagnostic programs, and the flow charting and coding of a number of new program segments were required. About 1000 new program words were added as a result of the changes and additions made. Modifications were necessary in order to have the system operate in different modes and perform different tasks.

During the period of dictionary preparation, the system had two additional teletypewriter communication channels: one input channel from the conventional 100-speed tape reader, for reading the package information into the system, and one output channel to the high-speed tape punch for test data recording. In addition, the existing teletypewriter output was retained for conveying auxiliary information to the test team.

Most of the new program segments were for data handling, coordination of different test modes, control and reading of the package information tape, recording of test data on the high-speed punch, etc.

XII. PUNCHED PAPER TAPE TO MAGNETIC TAPE CONVERSION

The sorting of the test data was done on an IBM-704 computer. The test data recorded on paper tape in binary code had to be converted into magnetic tape, compatible with the 704. Conversion was made on an IBM-9200 machine. Information was processed at the rate of 500 characters per second.

The magnetic tape recording was an identical image of the paper tape. The code conversion was somewhat different from conventional conversions. In the 7-channel paper tape, the test data utilizes all 64 combinations of the first 6 channels, and the 7th channel is used for an odd parity bit for each character.

XIII. DATA RECORDING AND PROCESSING

13.1 *Data Recording*

Over 900 central control diagnostic tests are grouped into eight phases. Each phase diagnoses faults of certain parts of the central control.

During the normal diagnostic operations, the test results are recorded at the end of each phase. The printout consists of two parts. The first part is the system component identification, i.e., whether it is central control 0 or central control 1, together with the phase number (A, B, $\cdots$ or H). The second part is the test results. Only the numbers of those tests that fail are printed out. Each has a 3-digit octal number. The test results, therefore, are variable in length, depending on how many tests have failed.

For dictionary preparation, a binary coding system was adopted for recording test data. Every test in the diagnostic program was represented by one bit on the paper tape. This was also true for the magnetic tape, whose recording was identical to the paper tape except with higher longitudinal density: 200 versus 10 characters per inch. A "1" or "hole" means that the corresponding diagnostic test has failed and a "0" or "no hole" indicates that the test passed. Each character consists of 7 bits, 6 for registering six different test results, and 1 for parity. The basic advantage of using this binary coding system is that it makes the sorting process easier. The number of characters in the test record for each fault is the same regardless of the number of test failures.

13.2 *Data Processing*

The data processing for the dictionary was done by an IBM-704 computer and the actual printing of the dictionary by a high-speed tape-controlled printer.

The 704 program is quite complex and involved. It can be divided into three major parts: phase sorting, test sorting, and data printing. The entire program is about 2500 words.

In the central control dictionary, all diagnostic test results were arranged in an orderly manner so that, given a certain sequence of test failures, the maintenance man could easily look for the same sequence in the dictionary. Associated with each sequence, one or several package identities and locations are listed. When several appear, failure of any one of them could result in such a test failure sequence.

13.2.1 *Phase Sorting*

All test records were sorted first according to their phase information. The test record for each fault contains three parts:

1. The package identification and fault number.
2. The individual test results.
3. Phase information, which is represented by 8 bits, one for each phase. If all tests have passed in a phase, the corresponding bit will be 0; if one or more tests have failed, the bit will be 1.

The purpose of this phase sorting is to arrange all records according to the alphabetical order given by the phase information. For example, consider a record α with phase information 00101100 and a record β 11000100. The 8 bits represent phases A, B, C, D, E, F, G, H. Omitting all zeros (that is, those phases which do not have any test failures), phase information for record α becomes CEF and record β ABF. After the phase sorting, record β will be placed in front of record α, that is, ABF in front of CEF, as are the words in a regular dictionary. Sorting by phase involves only part 3 of the test record.

13.2.2 *Test Sorting*

After the test records were sorted by phase information, they were subsorted in accordance with test failures. This was necessary because, with 255 possible phase combinations and over 50,000 different records, many records have the same phase combinations. The test sort takes all the records with identical phase information and further arranges them in a numerical order according to the binary test results which are given in part 2 of each test record. The actual test results consist of 916 bits without counting the added dummy bits. Dummy bits were added to make up a complete 704 machine word (36 bits) required by the computer. Each bit corresponds to a particular test. A "1" or "hole" means that the test which the bit represents has failed.

As an example, assume three records, α, β, and γ, having identical phase information and, for simplicity, only 6 diagnostic tests. The test failure information on these records is the following: $\alpha = 0\ 0\ 1\ 0\ 1\ 1$, $\beta = 1\ 1\ 0\ 0\ 1\ 0$, and $\gamma = 0\ 1\ 0\ 0\ 0\ 0$. The leftmost bit corresponds to test No. 1. Therefore, tests No. 3, 5, and 6 have failed in record α; 1, 2, and 5 in β; and 2 in γ. After test sorting, the three records will be arranged in this order:

Record	Binary Test Data	Translated Test Result	Analogous Alphabetic Sequence
β	1 1 0 0 1 0	1, 2, 5	ABE
γ	0 1 0 0 0 0	2	B
α	0 0 1 0 1 1	3, 5, 6	CEF

It can be seen that the binary test data is so arranged that the analogous alphabetic sequence is in true alphabetic order.

13.2.3 *Dictionary Printing*

The printing of the actual dictionary was done by an IBM high-speed tape-controlled printer. When all the records were properly sorted by phase and test information, they were converted and printed in a dictionary form.

The test data collected for the dictionary was in binary form. This was converted to the form used by the system in typing out test results. Whenever a bit is "1", the location of that bit in the test recording indicates the phase and test number of this test failure. This is converted into a 3-digit octal number. The test data format in a dictionary, therefore, looks exactly like the system teletypewriter printout in a normal diagnosis. Identical test data produced by different faults is entered only once in the dictionary, but all the faults are listed. Fig. 5 shows a sample sheet of the dictionary.

XIV. EQUIPMENT EMPLOYED

14.1 *TELETYPE Equipment*

14.1.1 *Highspeed Tape Punch and Receiving Signal Converter*

A 1000 words per minute (100 characters per second), tape punch was used to record test data from the system. It was equipped for punch-

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VØLUME 3                         PHASE DE                         PAGE 936
****************************************************************************

        PHASE D PARTIAL
    010 044 046
        PHASE E
    036 037 040 041 042
    043 044 070 077

         CC-010 J-F52615-12
    ***********************

        PHASE D PARTIAL
    010 055
        PHASE E
    077

         CC-023 J-F52616-14
    ***********************

        PHASE D PARTIAL
    010 055
        PHASE E
    077 115

         CC-024 L-F52601-3
         CC-025 Y-F52618-29
    ***********************

        PHASE D PARTIAL
    010 055 056
        PHASE E
    070 077 115

         CC-025 L-F52600-4
    ***********************

        PHASE D PARTIAL
    010 056
        PHASE E
    070

         CC-023 J-F52616-10
    ***********************

        PHASE D PARTIAL
    010 056
        PHASE E
                  (CØNTINUED)
```

```
    070 115

         CC-024 L-F52601-5
    ***********************

        PHASE D PARTIAL
    010 056
        PHASE E
    115

         CC-024AA-F52615-8
    ***********************

        PHASE D PARTIAL
    010 057
        PHASE E
    026

         CC-012 L-F52600-3
         CC-011 L-F52601-3
    ***********************

        PHASE D PARTIAL
    010 057 060
        PHASE E
    026

         CC-012 L-F52600-4
    ***********************

        PHASE D PARTIAL
    010 073
        PHASE E
    010 032 034 070 077

         CC-313 E-F52616-15
         CC-309AD-F52630-5
                         7
    ***********************

        PHASE D PARTIAL
    011 012 013 014 015
    016 017 043 044 045
    046 073
        PHASE E
                  (CØNTINUED)
```

```
    010 030 032 033 034
    035 036 037 040 041
    042 043 044 077

         CC-010 N-F52617-2
    ***********************

        PHASE D PARTIAL
    011 012 013 015 016   }
    017 043 044 045 046   }
    073                   }
        PHASE E           }
    010 012 013 014 016   }
    027 030 031 032 033   }  Test Results
    034 035 036 037 040   }
    041 042 043 044 070   }
    071 072 073 074 075   }
    076 077 10C 101 102   }
    103 104 105           }

         CC-210 P-F52628-20
    ***********************

        PHASE D PARTIAL
    011 012 016 017 043
    044 045 046 073           Package Identity
        PHASE E               — central control
    012 013 017 027 030
    031 032 033 034 035       — location of
    036 037 040 041 042          package
    043 044 070 071 072       — type of package
    073 074 075 076 077
    100 101 102 103 104       — type of fault
    105

         CC-210 P-F52628-18
    ***********************

        PHASE D PARTIAL
    011 013 015 017 043
    045 073
        PHASE E
    011 013 015 017 027
    031 032 033 034 035
    036 037 040 041 042
                  (CØNTINUED)

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VØLUME 3                         PHASE DE                         PAGE 936
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ing eight channels, although only seven channels were used. The high-speed tape punch is a rotating device which can be operated only at a particular point in the cycle. The receiver signal converter acts as a buffer between the system and the punch. This equipment has coded input circuits, consisting of two wires each, so arranged that information appearing on these leads will be punched on the tape at the proper point in the punch operating cycle. Since the punch can accept information only at a certain point in a cycle, a buffer store is included in the receiving signal converter, where the coded signal is stored until the punch is ready to accept it.

14.1.2 *High-Speed Tape Reader*

The reader operates at a speed of 1071.4 words per minute (107.14 characters per second). It is a parallel output device, equipped for eight-channel operation. The reader was used in conjunction with the tape error-detection unit to check the output paper tape.

14.1.3 *Transmitter Distributor*

A transmitter distributor was used to read the package information tape. This unit operates at 100 words per minute (10 characters per second) and is equipped with a set of five parallel code-reading contacts. These contacts were used to feed the code signals to the system.

14.2 *Equipment Built*

14.2.1 *Test Control Unit (Fig. 6)*

The test control unit was the master control for the dictionary tests. This unit coordinated the operation of the system and all peripheral dictionary equipment. Since the operating time of any type of logic employed in this unit was insignificant compared to the total time consumed in changing the packages, recording the test data, loading, and unloading paper tapes for the punch, etc., relay logic was used. The circuits were so designed that any improper operation of pushbuttons and control levers did not cause erroneous data to be recorded.

The test control unit performs the following major functions:

1. Controls the system clock: when the system clock stops, it will not start again until a command is received from this unit.
2. Governs the reading of the package information tape.
3. Communicates with the system and provides instructions for per-

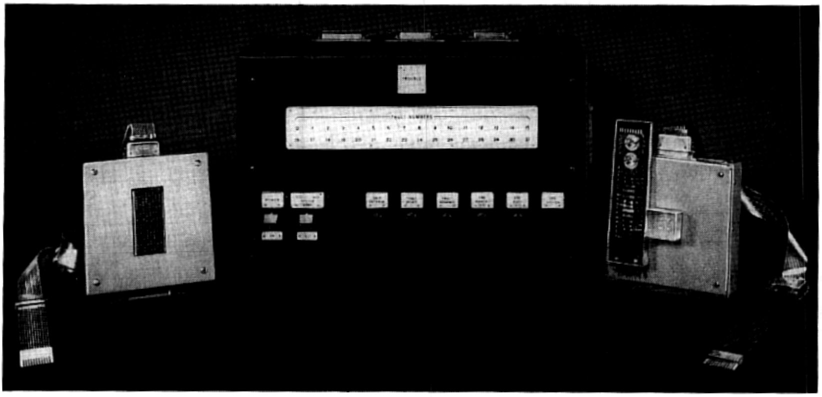

Fig. 6—Left: fault-simulation unit for gate packages. Center: test control unit. Right: fault-simulation unit for transistor packages, with flip-flop package plugged in.

forming an automatic or manual test or a package identification skipping operation.

4. Instructs the fault-simulation unit as to when a particular fault by itself or as a part of a series of faults should be simulated. The simulation and sequencing of faults during an automatic test are accomplished automatically.
5. Allows manual insertion of any desired faults with the aid of the fault reset button, fault advance button, and fault number indicator.
6. Provides visual indications for the following: (a) mode of operation: (test or normal), (b) which fault is being tested, (c) occurrence of an unsimulated trouble in the system, (d) completion of either an automatic or manual test or the skipping operation, (e) the off state of the system.

14.2.2 *Fault-Simulation Unit*

A total of 49 different types of packages are employed in the central control units. A study of the type and number of faults to be introduced in all the circuit packages used revealed a logical division between gate packages and other types of packages, such as flip-flops, amplifiers, etc. Two fault-simulation units were designed which simulated essentially all the circuit cards in the central control.

The fault-simulation units were wired to create the required circuit packages with the necessary fault-simulation features by means of a plugboard arrangement. The plugboard consisted of a 150-pin connector. The socket portion of this connector was wired to various components provided in the fault-simulation unit. For each circuit package, a separate plug was used which contained the necessary jumper wires to simulate the corresponding package.

To minimize the stray capacitance, the fault-simulation units were laid out to be as compact as possible. Each unit was about 7″ x 7″ x 4″, as shown in Fig. 6. Microminiature relays were used inside the units to switch the various faults. During testing, they were placed in close proximity to the package socket. The AND and OR gate fault-simulation unit consisted of 30 relays plus the components necessary to simulate any one of the 16 types of gate package.

The second fault-simulation unit was used for transistor and miscellaneous packages. Most of the faulty conditions for these packages were simulated on the output terminals; therefore, only a few types of circuit cards needed to be wired up from components provided in the unit itself. In the majority of cases, a good package was plugged into a socket supplied on the fault-simulation unit, and the conditions on the output terminals were controlled by relays inside the unit. As in the first unit, plugboard connectors were provided for each simulated type of circuit packages.

The sequencing of faults was controlled by the test control unit. A signal from the fault-simulation unit was sent to the test control unit when all the faults were completed for a package.

14.2.3 *Tape Error Detection Unit*

The tape error detection unit was designed for checking the punched paper tape. The code signals were fed into this unit in parallel by the high-speed tape reader. Two types of tape errors were detected by this unit: parity of each character, and predetermined block length of test data. The output tape was checked as soon as it was punched.

XV. DETAILED PLANNING OF TEST PROCEDURES

In order to take up a minimum amount of system time to create the dictionary, careful plans were made. The plans included the detailed test procedures, manpower requirements, job descriptions for the operators, and the equipment operation instructions involved in the acquisition of test data. Suggested procedures were also given in case of trouble during the dictionary test. All conceivable major and minor troubles were analyzed. The effort spent in planning was worthwhile.

XVI. EXPERIENCE WITH MORRIS CENTRAL CONTROL MAINTENANCE

The following points summarize our experiences:

1. Certain troubles were not detected by the diagnostic program. These can be attributed to one of the following:
   (a) The particular component in which the trouble was simulated was not actually used by the system.
   (b) There was some redundancy in the circuits, creating the possibility of troubles that could not be detected.
   (c) The diagnostic program was not exhaustive. Circuits in certain areas have not been covered. Additional tests could have been added to the present diagnosis, but it was felt that such an effort was not justified for the Morris System.
   (d) Due to the design of the Morris central control, there were limitations which made it impossible to detect certain troubles. For example, a shorted clock diode on an AND gate usually resulted in no test failures. The low impedance of the clock supply prevented the clock pulse from being clamped. However, the margins were decreased and occasionally a test failed when this type of trouble was introduced. An open clock diode on an AND gate at the input to a flip-flop which had no feedback around it usually resulted also in no test failures. The flip-flop merely changed state, without waiting for the clock pulse which normally initiated the change. However, some flip-flops could be operated falsely by the noise on the gate leads which could occur before the clock pulse arrived.
2. Some troubles resulted in inconsistent test results. Most of these were due to circuit design. For example, certain troubles introduced caused complementary functions to be performed simultaneously, such as writing a "0" and a "1" in a memory spot. These troubles produced race conditions in the central control logic, resulting in inconsistent test results.
3. Some troubles introduced in the standby central control affected the operation of the active system. This indicated that better isolation was required between the two central controls.
4. Many test results were extremely difficult to analyze. Since there are some 900 tests made on each fault, even sketchy analysis is time consuming. It is very difficult to explain why certain tests fail with respect to trouble introduced and to predict all the tests that should fail. For these reasons, the dictionary is extremely useful. Even now, if a set of test failure results is not found in the dictionary, analysis presents grave problems.

5. The fault-simulation units introduced sufficient capacitance in the circuit to cause marginal operation in some of the circuits. By testing most transistor packages in a fixed state (that is, a flip-flop permanently set, etc.), and by reducing the value of diode gate resistors, it was possible to obtain meaningful data on all but seven packages in central control. These seven persisted, in spite of all efforts, in failing tests when the simulated package was plugged in and no actual faults introduced.
6. It appeared evident that a central control dictionary cannot be written from an analysis of the circuit with respect to the diagnostic tests. The complexity of the central control made it difficult to predict how the central control will perform with any given fault.
7. Even if a dictionary were not produced, extensive trouble insertion or trouble simulation was necessary to debug and measure the effectiveness of the diagnostic program.

XVII. SOME INTERESTING STATISTICS

The central control maintenance program has about 7200 program words, 6000 of which are for diagnosis. Over 50,000 faults were simulated. About 250 hours of actual system machine time were used explicitly for data gathering. The total data (about 60 million bits) occupied 93 reels of 1,000 foot, 7-channel paper tape. These in turn were converted by an IBM-9200 machine into four reels of magnetic tape. The conversion time was about 12 hours. Out of 51,671 records, about 35 were destroyed and 25 rendered doubtful because of machine errors.

The sorting program for the IBM-704 computer is about 2,500 words long, and was written by one man in about eight months. The total sorting time on the IBM-704 computer was 34 hours.

The time spent in designing the diagnostic program and producing the dictionary was about 12 man-years, of which two man-years was for designing the diagnostic program and two man-years was for debugging and modifying it.

The dictionary consists of 1,290 pages (11″ x $14\frac{7}{8}$″), bound into four volumes.

XVIII. DICTIONARY RESULTS

There are 10,315 different test patterns, 73 per cent of which list only one possible package failure, 13 per cent two possible package failures. Therefore, for a large number of catastrophic troubles (86 per cent), the dictionary will be able to pinpoint the fault to within two packages.

Our experience indicates that a man with a few minutes of training will be able to consult the dictionary and determine the faulty package, usually within two to three minutes, sometimes as long as five to ten minutes, and this appears adequate. Our preliminary evaluation of the dictionary indicates that it will be able to locate about 75 per cent of the troubles.

XIX. CONCLUSIONS

The feasibility of producing a central control dictionary by the system itself has been proven, and a dictionary has been produced. Considerable experience has been gained with the maintenance of a large electronic logic circuit. As a result, a number of improvements can be made. A great deal has also been learned regarding the limitations of diagnosis due to the central control circuit design. These limitations cause inconsistent test results or no test failures. With the improvements which can be made in the diagnosis and the circuit design, it appears feasible to have a central control dictionary which will be able to locate 90 per cent or more of all the probable troubles.

Using the dictionary techniques, the average repair time may be kept very low, and the maintenance was made much easier. Success in this area of work has contributed greatly to meeting the initial maintenance and reliability objectives.[2]

Considering that this was an initial attempt to solve a very complex and difficult problem, the results have been gratifying. Considerable headway has been made in automatic diagnostic techniques. However, we must develop these techniques further if we are to cope successfully with the problems of maintaining the even more complex electronic telephone switching system now being developed.

XX. ACKNOWLEDGMENTS

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APPENDIX

Description of the Central Control Diagnostic Program

A complete understanding of the central control diagnostic program demands an intimate knowledge of the central control. This appendix will therefore only illustrate the types of tests used and the methods for observing test results.

For clarity, it is desirable to define a simplified repertoire of instructions. A, B, C, D, AA, AB refer to symbolic designations for flip-flops, flip-flop groups, or storage locations.

SM	Sample match circuits for a mismatch condition during the process of executing the next instruction.
G A, B	Gate the contents of flip-flop group A to flip-flop group B, via bus.
ST1 AA	Set up transfer register 1 (T1) to quantity AA.
R0, AB R1, AB	Transfer to the address stored in transfer register 1 if the reading at AB is 0 or 1 respectively.
RFF0, C RFF1, C	Transfer to the address stored in transfer register 1 if FFC is 0 or 1 respectively.
WFF C, D	Write the contents of flip-flop C into memory at address D.
W0, AB W1, AB	Write 0 or 1 respectively into memory of address AB.

Match circuits are provided to compare the outputs of the instructions to the stores (transfer or advance to next instruction for the flying spot store, read or write 0 or write 1 to the barrier grid store) and to match the busses of the two central controls.

In the following examples, each program step is listed, followed by a symbolic modifier and by comments. In studying these programs it is important to remember that the two central controls are working in synchronism, and that the working central control is addressing and writing into the stores.

First, to check the ability to make decisions, the following program was applied:

W0 AB (AB is any convenient address.)
SM
R1 AB

If a mismatch is detected on the R1 instruction, the standby central control has falsely transferred on a reading. The program

W1 AB (AB is any convenient address.)
SM
R1 AB

will check the ability of the standby central control to transfer on a reading.

In order to check the ability to write correctly, register R was first set up, to all 1's. Register R has the property that its individual flip-flops may be written into memory using the WFF instruction, or may be read using the RFF0 and RFF1 instructions.

The program:

ST1	All ones	
G	T1, R	
SM		
WFF	C, D	Any flip-flop C, of register R, to any convenient address D.

In order to check the flip-flop groups of central control, the following program was used:

ST1	All zeroes	
G	T1, A	(A is the flip-flop group being tested.)
SM		
G	A, R.	

As previously mentioned, individual flip-flops of register R may be examined. If a mismatch has occurred, the proper flip-flop may be isolated by repeated use of the two instructions SM, RFFO, followed by a check to see if the flying spot store order-match circuit indicated a mismatch on the RFFO instruction (the instruction which followed SM was sampled for a mismatch); by checking all the flip-flops in R, the flip-flops of A which were not capable of being set were detected. R and T1 were previously checked to make certain that all their flip-flops could be set and reset.

The above programs are typical. Common subroutines were used to record the results of tests in the barrier grid store and to control the typing out of these results with the teletypewriter.

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