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SUBJECT: DIAGNOSTIC PROGRAMS AND MARGINAL CHECKING IN THE WHIRLWIND I COMPUTER (Text of paper presented at the New York Convention of the Institute of Radio Engineers on March 24, 1953)

To: Stephen H. Dodd

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Date: March 26, 1953

Abstract: In the Whirlwind I computer, constructed at MIT under Office of Naval Research sponsorship and presently operated under Joint Services support, it has been found that marginal checking vastly reduces the machine failure rate. A series of test programs each of which thoroughly exercises a different section of the machine is used in the marginal checking procedure. Marginal checking cannot prevent intermittent and total failures caused by shorts and opens. These are isolated by methods combining built-in checking features, diagnostic programming, signal tracing, and operator experiance and ingenuity. These methods are greatly facilitated by a special program control which allows a periodically repeated test program to be stopped at an arbitrary point to study indicator lights and signal waveforms.

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1.0 INTRODUCTION

Through four years of experience in maintaining the Whirlwind I computer, several improvements in trouble location techniques over those originally conceived have been worked out. This experience provided knowledge of what types of failures must be dealt with, what procedures are most effective, and what special features are helpful to an operator in localizing trouble. The Whirlwind computer was constructed at MIT under sponsorship of the Office of Naval Research and is presently operated under support of the Joint Services. I will first discuss briefly the types of faults which are encountered, then will outline basic philosophies of failure diagnosis which are peculiar to the machine. Next I will describe facilities provided to aid an operator in his diagnoses, and finally will illustrate the actual procedures which are in use.

2.0 FAULTS TO BE DIAGNOSED

Faults in the computer system are classified into four categories. Three of these are well known and typical of any electronic equipment. They are (1) gradual deterioration, (2) sudden failures such as shorts or opens, and (3) intermittent or transient failures. The fourth category is peculiar to an experimental machine in which modification and expansion is being carried out. Since the central portion of the computer became operative, there has been a continuing program to expand the internal storage capacity and the terminal equipment facilities. Because of this work, it is necessary to contend with faults that are the result of maladjustment and weaknesses in newly-installed equipment. These then form the fourth category.

With the procedures which have been worked out in Whirlwind I, it has been found that the faults which can be located most easily are sudden complete failures. Gradual deterioration and defects associated with newly-installed equipment also are relatively easy to find. Intermittent failures, however, are difficult to deal with and therefore are considered the most serious.

3.0 PHILOSOPHY OF FAILURE DIAGNOSIS

It is to be expected that the trouble location methods used in a computer reflect its logical design. In Whirlwind, these trouble location methods also reflect the mechanical arrangement of the system. When the Whirlwind computer was being planned, it was felt that panels should be constructed so that all component connections would be readily accessible while the system was in operation. This would facilitate signal tracing with video probes while the system was first being checked out, and would side-step many packaging problems. With this extremely open type of construction, it has been found more practical to repair circuits in place rather than to substitute spare panels. Obviously this makes trouble location procedures more complex. Faults must be completely isolated rather than merely localized to a given panel or chassis. A strong argument in favor of such an arrangement is that the computer can be used as a powerful testing device. Bench testing, with necessarily limited facilities for signal generation and detection, sometimes may not show up all the malfunctions in a circuit.

Another mechanical design feature is reflected in the trouble location methods now employed. It is the layout of the computer's control center which consists of a flexible arrangement of panels in standard racks rather than a relatively fixed operating console. This has encouraged the installation of special machine controls and special facilities for monitoring critical signals for testing purposes. Of particular value is some equipment which can be used to change the over-all logic of the machine control. I will describe this later in my talk.

As a final point on the philosophy of failure diagnosis in Whirlwind, considerable emphasis is placed on marginal checking. By discovering deteriorating circuits before they cause trouble the number of interrupting failures can be kept low. The possibility of a deteriorating component causing intermittent failures, the type most difficult to isolate, is virtually eliminated.

4.0 EQUIPMENT AIDS IN TROUBLE LOCATION

I have just described the types of faults to be diagnosed and some special characteristics of the computer which have influenced the choice of trouble location methods used. Now a brief discussion of the equipment provided to aid in trouble diagnosis will complete the background needed for an explanation of the actual checking procedures used.

4.1 Built-In Alarms

An important aid to the operator, in fact the one around which nearly all of the trouble location procedures are centered, is a system of built-in alarms. There are a total of eight different alarm indications. Any one of these will stop the computer operation when the alarm occurs. These eight alarms are evenly distributed among the four main subdivisions of the computer, the central control, the arithmetic element, the internal memory, and the input-output element. Generally speaking, they are designed to monitor the operation of critical control circuits or to show up certain cases of nonpermissible programming. One of the alarms, a transfer check, is applied more frequently than the others and covers all sections of the computer. It checks that words transferred between registers by means of the common bus system are correctly received. The check is accomplished by a special register which receives the word by two different paths, one directly from the main bus and the second from the receiving register via a second check bus.

The special identity checking facilities of the transfer check have been used for implementing an identity check order as a part of the standard order code. This order makes it possible for a programmer to arbitrarily command a check on the contents of the accumulator against a wo d stored in the memory. Such an order obviously is valuable in trouble location and diagnostic programming work.

4.2 Marginal Checking Equipment

For locating gradual deterioration, the marginal checking system is the principal tool. Marginal checking consists of variation of certain d-c supply voltages to the tubes rather than variation of heater voltages. The circuits for marginal checking are an integral part of the power distribution system and are so designed that voltage variation can take place in only a small section of the computer at a time. The whole computer is divided into about two hundred such sections. These may be chosen manually or in an automatic sequence during marginal checking procedures. Insofar as possible the sectionalization was done so that logically dependent parts of the computer are on different voltage variation circuits. This combines a powerful trouble location feature with the ability to determine whether the system performance is deteriorating.

4.3 Cyclic Program Control

Sudden failures and certain types of intermittent failures require a diagnostic approach different from that for deteriorating components. To assist in a detailed analysis of such troubles, a special computer control feature, called a cyclic program control, has been provided. Basically the cyclic program control permits a change in machine logic. It makes it possible to interpret flip-flop indicators and signal waveforms while preserving normal high-speed operation of the particular program giving the trouble. This control embodies mechanisms to stop the computer at any step in the program and then to restart it at the beginning of the program. Since the number of orders executed may be adjusted by simply varying a delay, the flow of information from one register to another can be observed visually on an oscilloscope. Furthermore, the restart is somewhat delayed following a stop so this same flow of information between registers can be observed on flip-flop indicator lights grouped at the central control location. In general, the cyclic program control permits an operator to set up complicated conditions within the computer identical or equivalent to those of normal operation and at the same time obtai an outward simplicity that makes analysis relatively easy.

4.4 Records of Intermittent Failures

For intermittent type failures, little specialized equipment is available to assist in trouble location. Two features are worthy of mention. First, a camera has been set up so that the control panels can be photographed to show all flip-flop light indications and all control switch settings at the time of an error. This makes it practical to preserve data on all such errors without seriously delaying applications work. The photograph is supplemented by a report giving other details concerning the program and method of using the computer that might be helpful in later study of the failure.

Since many intermittent failures are the result of poor connections on panels or momentary shorts within tubes, they can be precipitated by shock or vibration. A second feature which helps in localizing intermittent trouble is an arrangement for producing throughout the computer room an audible signal characteristic of the program being run. As tubes or panels are being tapped an intermittent fault is indicated by an interruption of this signal, after which the program automatically restarts.

5.0 TROUBLE LOCATION PROCEDURES

A more comprehensive picture of the built-in aids just described can be obtained from a description of the diagnostic procedures used. I will first discuss marginal checking and then will illustrate methods of locating sudden and intermittent faults.

5.1 Marginal Checking

Checking for low operating margins is a daily preventive maintenance procedure. For the complete routine, several different programs are used each designed to thoroughly exercise a different portion of the computer. The principal followed is that when one portion has passed a test satisfactorily it may then safely be used in checking another part of the computer. For example, a test is first made of the central control using a minimum of storage, arithmetic element, and input-output facilities. Next is a thorough test of the arithmetic element, followed by tests of storage, and finally of the input-output element. The programs for these tests are designed with as many check orders as possible so that no more than a few orders can be executed after any error before the computer is stopped by an alarm.

Typical operating procedure for testing a section of the computer is as follows. The marginal checking equipment is set for an automatic mode in which it selects voltage variation lines in sequence and applies a voltage excursion to each. The magnitude of the voltage excursion is preset for each line and therefore may differ from one line to the next. The preset values are those that give excursions 10 percent less than the maxima the circuits can tolerate without failing. With such settings an automatic marginal checking sequence will cause no failures until the margin on a circuit has dropped by more than 10 percent. If deterioration of some component causes the margin for a line to drop more than 10 percent, during automatic marginal checking an alarm will occur which stops the equipment and permits manual determination of the new failure point. The excursion is then reset to 10 percent below this new value and the new excursion is entered on a record sheet for this line. In this manner, the only data which need be recorded during the routine checking are those on the few lines which have deteriorated appreciably. Unless there has been an abnormally large drop in margin, no corrective action is taken during the marginal checking period. Instead, a weekly maintenance period is scheduled during which circuits whose margins are approaching a dangerously low value are investigated and repaired.

As was pointed out at the beginning of my talk, one type of fault that must be dealt with in the Whirlwind machine is maladjustment or other weaknesses in the system resulting from installation of new equipment. Abnormally large changes in margins detected during a routine checking period is one way in which such weaknesses are made apparent. For example, one installation required that an existing control pulse be also fed into the new equipment. In order to do this the physical arrangement of video cables carrying this signal was changed although their logical function was not. After this installation several low margins were found which were the result of an unforeseen change in pulse timing caused by the change in pulse routing.

The marginal checking facilities are also valuable in trouble location work not related to the routine preventive maintenance, especially in evaluating the performance of new circuits or ones that have been repaired. In a typical case an electronic switch utilizing eight flip-flops of a new design was installed after passing exhaustive bench tests. In the computer system, it was found that the flip-flops showed low margins and several failures of the switch were reported within a week. Improved flip-flop circuits which gave wide margins were then substituted. These have operated about six months without failure.

5.2 Sudden Failures

For sudden or intermittent failures a somewhat different approach is needed. In the case of a sudden failure within the system, it is necessary to isolate and repair the circuit in order to get the system back into operation. Fortunately the procedure for doing this is relatively straightforward so little time is lost on the average. A program is inserted which shows the failure. This can be the one that was in use at the time the failure occurred or a simplified one designed on the spot which produces the same failure. With the cyclic program control, it is possible to quickly determine on which step the alarm occurs. This control periodically restarts the program and then stops it after an arbitrary number of orders have been executed. Usually an analysis of flip-flop indicator light patterns for a few steps preceding the alarm will show where information is failing to transfer properly. Then simple signal tracing in the suspected circuits using the test oscilloscope and remote video probes will pinpoint the difficulty.

5.3 Intermittent Failures

The most troublesome failures in Whirlwind, as, I suspect, in any computer, are intermittent failures. Usually the amount of data available is highly inadequate for localising the difficulty so one is forced to use cut and try procedures. The search for an intermittent starts with a study of all available reports on recent transient failures; report forms filled out by users, photographs of the indicators and controls taken following unexplainable errors, and any observations made by engineers and technicians while working on the system. From such information, a technician familiar with the machine logic, in general, can estimate what area of the computer produced the failure. He then inserts a program and tests the suspected components or panels by lightly tapping them to see if any errors are introduced. A momentary short between a control grid and another element in a gate tube is an example of an intermittent failure which can be located quite regularly. It generally will cause an output pulse from the tube even when no input pulse is supplied. If such a failure were suspected, the program inserted would be one which supplied no input signals to the tube but which checked for presence of output pulses from it.

In carrying out cut and try procedures for locating intermittents, the cyclic program control and marginal checking facilities may also prove useful. There was a recent instance where the computer showed symptoms of an intermittent failure which was later tracked down by means of special diagnostic programs and the use of the cyclic program control. After the trouble was located, it was obvious that marginal checking would also have pointed out the defect. In this instance, the symptoms indicated that a register occasionally was not being cleared at the proper time. A special program designed to emphasise this failure was inserted. It uncovered the fact that the clearing operation was correct but the register was receiving a spurious read-in shortly after the clear pulse. This was traced to an improperly terminated delay line which was reflecting a delayed pulse with sufficient amplitude to cause the occasional read-in. However, the faulty delay-line condition had existed for some time. It was discovered that the routine action of replacing the buffer amplifier that fed the delay line was the direct cause of the intermittent trouble. It gave a somewhat higher output so the unwanted reflection occasionally exceeded the permissible limit for noise in that circuit. If marginal checking had been performed on this amplifier, the line would have shown a very low margin so the defect could also have been readily found by that means.

6.0 SUMMARY

As a brief review of my remarks, I will show some slides which illustrate the more significant points that have been covered.

(SLIDE 1)

In the first slide are listed the types of failures which have shown up in operation and maintenance of the Whirlwind I computer: gradual deterioration, sudden failures, intermittent failures, and weaknesses due to new equipment installation. The intermittent type are most troublesome since the other types can be dealt with in a routine and straightforward manner.

(SLIDE 2)

The second slide is a view of a part of the computer showing the open type of construction used. This suggests why it is practical and desirable to repair circuits in place rather than to replace panels. Remote video probes can be placed on any point in a circuit for viewing waveforms on a central test oscilloscope. As I have pointed out this has had an influence on the trouble location procedures that have been developed.

(SLIDE 3)

The next slide shows the computer control center. The flexibility provided by this relay-rack type of installation permitted frequent alteration of the control facilities while trouble location techniques were being worked out. Grouped in this area are the marginal checking controls, flip-flop indicators, alarm lights, switches for controlling the computer operation and inserting or altering its program, a computer output display scope, test oscilloscopes with pushbutton selection of many critical waveforms or signals from remote video probes, and a master intercom station for communication with other computer working areas.

(SLIDE 4)

In maintenance procedures, major use is made of the marginal checking facilities built into the Whirlwind computer. It is used daily in routine examinations of the system for deteriorating circuits. These daily tests provide records of gradual deterioration so most component replacement can be done during scheduled maintenance periods. This slide shows a typical record of deterioration on one line. The dated entries are new voltage excursions set in after the program failed with the previous excursion. In December 1952 the negative margin dropped to the danger point of 12 volts. Two tubes were replaced and the original margin was restored. The marginal checking equipment is also invaluable in evaluating the performance of newly installed equipment as well as in isolating intermittent failures that inadvertently may result when installation or repair work is done.

(SLIDE 5)

Sudden failures are analyzed by utilizing the cyclic program control and observing results on indicator lights and on the test oscilloscope. Intermittent failures requires careful study of all available symptoms and a shrewd estimate by an experienced operator of where to look for the trouble. This slide is a typical photograph of the operating console taken after an alarm. It shows indicator light patterns and switch settings which can be analyzed when tracking down failures. In both of these cases the computer program used is highly significant but little success has been achieved in developing one that is universally useful. Instead it has been found that relatively simple order sequences uniquely designed for the problem at hand and modified as test results require are a more powerful tool.

(SLIDE 6)

An adequate measure of the effectiveness of trouble location procedures in Whirlwind is difficult where new installation is continually being carried out. On this slide, however, are listed some data that I feel have significance. Of the time scheduled for useful computation during the past year about 90 percent was usable. This figure is based on reports submitted by groups using the computer rather than on statements of personnel maintaining it. During that period there has been an average of about 100 man hours of installation work per week done on a weekly basis. Twenty four hours per week of preventive maintenance is listed. About half of this is routine daily checking while the remainder is test periods following installation work. The average length of the periods when the computer has been forced out of operation during scheduled computation work is of the order of 20 minutes.

Although this record may be a tolerable one at present, continued effort is being expended to better it. Most needed is a more powerful attack on the problem of intermittent failures.

SIGNED N. L. Daggett

E. S. Rich

NLD:ESR/cp

List of Slides

Slide No.	File No.	Dwg. No.	Photograph No.
1	SN-511	A-54193	F-1838
2	SC-281	A-54623	F-901
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4	SN-510	A-54195	F-1837
5	S-509	A-54624	---
6	SN-512	A-54194	F-1839

TYPES OF FAULTS

DETERIORATION

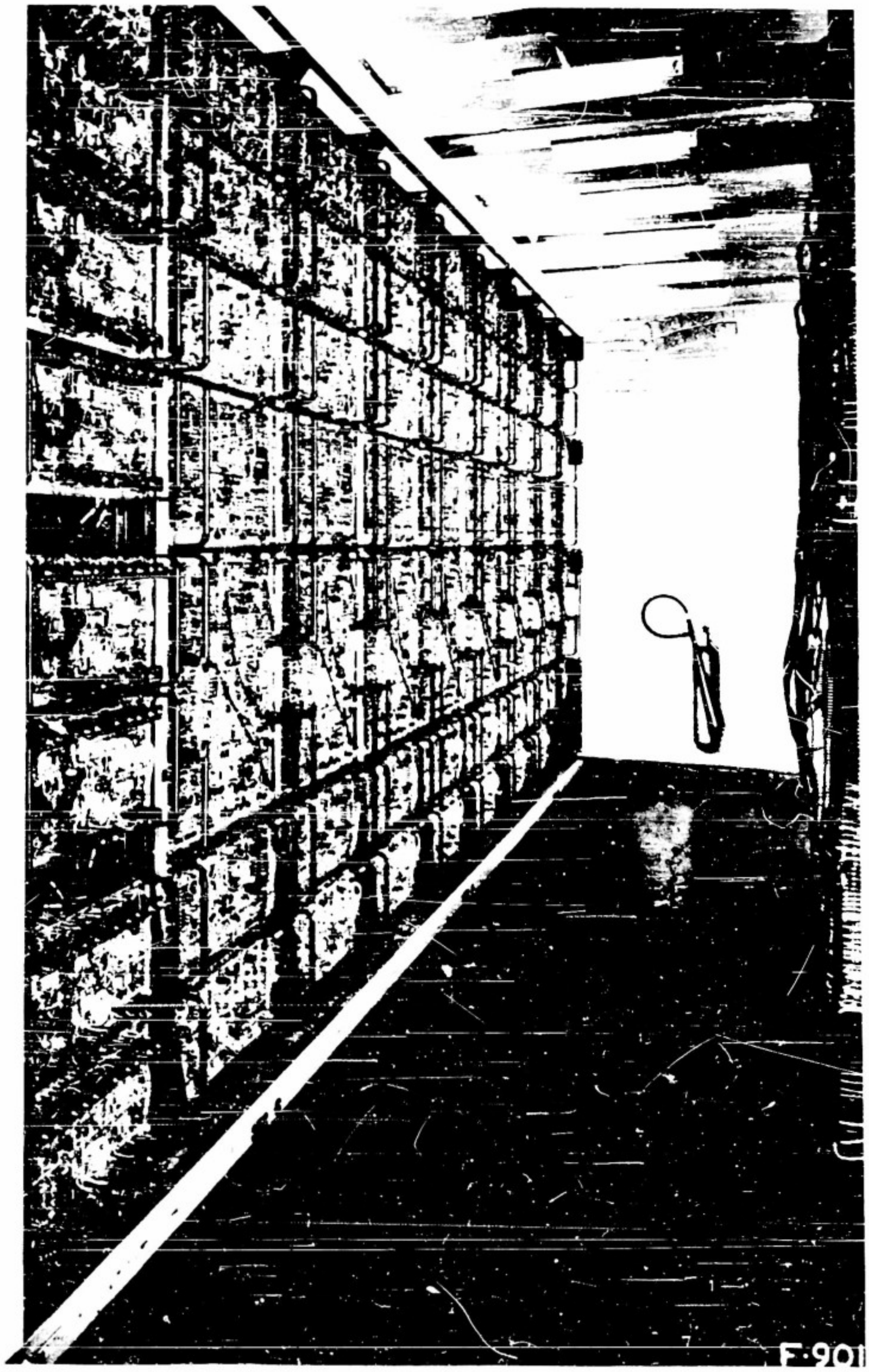
SUDDEN FAILURES

INTERMITTENT FAILURES

MALADJUSTMENT IN NEW EQUIPMENT

SLIDE 1

A-54193
SN-511
F-1838



SLIDE 2 TYPICAL COMPUTER RACKS

A-54623

A-54622

F-1593

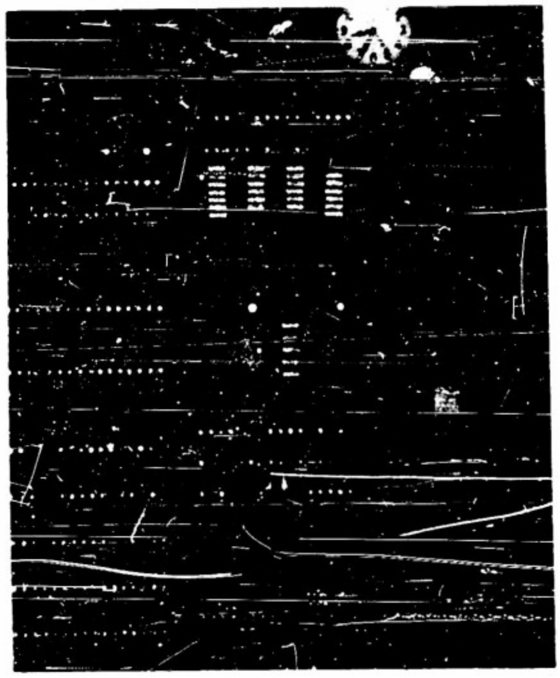
COMPUTER CONTROL ROOM

MARGINAL CHECKING RECORD

LINE 268	DANGER POINT 12 VOLTS		PROGRAM T-2012
DATE	EXCURSIONS		REMARKS
31 AUG 51	−31	+40	
8 JAN 52	−31	+36	
2 APR 52	−30	+40	
24 SEP 52	−20	+40	
18 DEC 52	[−12]	+40	
3 JAN 53	−30	+40	TWO TUBES REPLACED

SLIDE 4

A-54195
SN-510
F-1837



SLIDE 5

INDICATOR LIGHT PATTERN
FOLLOWING AN ALARM

A-54624

MAINTENANCE EFFECTIVENESS

SCHEDULED TIME USEABLE	90 PERCENT
INSTALLATION TIME	100 MAN HRS/WEEK
PREVENTIVE MAINTENANCE TIME	24 HRS/WEEK
AVERAGE UNSCHEDULED DOWN TIME	20 MINUTES

SLIDE 6

A-54194
SN-512
F-1839

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