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# DATA CONDITIONING AND DISPLAY FOR APOLLO PRELAUNCH CHECKOUT

## Test Matrix Technique

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# PREFACE

This report is the sixth and last in a series dealing with the development of data conditioning and display techniques to assist Apollo/Saturn prelaunch checkout personnel in the detection, evaluation, and resolution of non-normal test conditions or situations. The first report in the series discussed the utility of critical test path display in aiding test personnel in the rapid formulation of testing strategies and the selection of appropriate test sequences. The second report described an investigation of the utility of a computer-based signal flow display technique designed to reduce time and errors in signal tracing activities. The third report covered the use of phase-plane display to detect incipient failures during servo system testing. The fourth report dealt with monitoring of rapidly changing performance data from a number of test points in order to detect patterns of fluctuation in the behavior of a single parameter or in the relationships among several parameters. The fifth report dealt with methods for transforming and displaying data from a single test parameter to permit detection of instabilities.

# ACKNOWLEDGMENTS

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# TABLE OF CONTENTS

# SUMMARY

This report describes the development and application of a technique for test data organization and display which can be used to aid system test engineers in the interpretation of test results for diagnostic purposes and in the selection and sequencing of fault isolation tests from among the set of available checkout tests.

The primary purpose of prelaunch checkout is the verification of launch readiness; therefore, current Apollo/Saturn checkout systems have emphasized the development and programming of Go/No-Go tests which establish whether or not a system is operating within acceptable tolerances. When a checkout test fails, however, additional actions are necessary in order to isolate the source of the failure and then to repair or replace the faulty element. Current Apollo/Saturn prelaunch checkout systems and programs do not provide sufficient capability in the area of fault isolation and diagnostic testing.

At present, fault isolation procedures are limited to the following activities: direct interpretation of the failure symptom and the point of the test at which the failure occurred; manual testing outside of the preplanned set of tests; and use of available programmed test routines (consisting mostly of additional "checkout-type" tests). These activities require that the system test engineer interpret test results and construct or select efficient test sequences from among the tests available to him. The system test engineer's fault isolation capability can be enhanced and made more efficient through the use of improved test data organization and display techniques.

[The Test Matrix technique, described in this report, is such an aid. It provides information on the failure sources or modes tested by each test in a checkout routine or program. This technique allows a system test engineer to follow an efficient course of action in the selection of relevant tests and the classification of components as good, failed, suspect, or untested.] It allows him to extract the maximum information obtainable with any given set of available tests and to determine when he has extracted all of the possible diagnostic information from these tests. The Test Matrix technique can be

applied manually (pencil and paper), semiautomatically (man-computer dialog), or in fully automatic fashion (under computer control). The technique is therefore not tied to any specific level of automation.

The Test Matrix concept has been discussed in detail in an earlier report(1). The present report summarizes the basic matrix operations and describes the work performed during the past year. This effort has been concerned with: development of computer software to demonstrate the concept and determine implementation requirements; evaluation of the matrix's utility in enhancing diagnostic performance; and description of potential applications of the technique.

Comparative experiments in fault diagnosis (with and without the technique) show a reduction of about 70% in diagnostic errors (false identification of failure sources) and a reduction in the number of tests required for this improved level of diagnosis.

The requirements for application of this technique in the Saturn V checkout hardware and software are also considered. The memory requirement is about 5000 words of DDP 224 Display System storage. The programming effort is estimated at approximately one man-year.

The Test Matrix technique has very wide application potential in other NASA programs as well as in military, industrial and commercial systems and equipment.

# I. INTRODUCTION

"The Apollo/Saturn checkout systems and tests have been designed to meet one primary objective, namely, the verification of vehicle and spacecraft launch readiness. The current capability of these checkout systems does not emphasize fault isolation or diagnostic testing. While it may be possible to prepare and insert specific diagnostic procedures and test programs into the systems at some later date, such expanded capability will require extensive expansion of both system hardware and software. In the meantime, it is still necessary for test engineers to identify malfunctioning components in order to repair or replace them and return the space vehicle systems to satisfactory operation. The simplest and most immediate way of improving fault isolation is the development and implementation of techniques which assist the test engineer in organizing and manipulating (1) test results, and (2) sequences of available tests. For example, if the first five tests in an automated routine are "Go" and the sixth one fails, the test engineer immediately has a certain amount of information which reduces the set of possible failure sources. His task is to interpret this information correctly and to use it in selecting and sequencing additional tests from among those available to him."(1)

This report describes a technique and how it can be applied to assist Apollo/Saturn test engineers in the planning and conduct of fault isolation procedures using existing checkout tests, procedures, and programs. "The recommended data organization and display formats are based on analysis of the requirements for fault isolation in various stages of prelaunch checkout, the information required by test engineers in identifying and isolating failure states, and the action alternatives available during such procedures."(1)

Fault isolation, as an on-line activity, involves three different kinds of decision situations on the part of the test personnel:

- Action selection from among available alternatives (e.g., do Test Segment X).
- Interpretation of test outcome (diagnosis).

- Development of new alternatives (e. g., break connection and check voltages on connector pins) when existing options are infeasible or insufficiently resolvent.

Decision aids, in order to be effective, should contribute to all three situations. Since optimum isolation procedures presently do not appear applicable because of constraints on test availability,(2) we have concentrated on the Test Matrix technique as an aid to heuristic problem solving. This report describes the research effort involved in demonstrating and evaluating the usefulness of this technique in improving on-line fault isolation. Finally, requirements for implementing the technique in accordance with Apollo/Saturn operations and schedules are identified.

## II. FAULT ISOLATION IN APOLLO/SATURN PRELAUNCH CHECKOUT

"Prelaunch checkout procedures are usually designed to establish flight readiness of all components while using a requisite number of tests. Individual checkout tests usually test groups of components, with limited overlap or redundancy between tests. Fault isolation procedures follow a No-Go indication and consist of all the activities required to evaluate the meaning of that indication and to pinpoint the source of the problem to the level of a repairable/replaceable module. Tests designed specifically for diagnostic, as opposed to checkout, purposes should exhibit greater resolvency, either by testing a smaller set of components with each test or by providing overlap in the components tested by individual tests. Since current Apollo/Saturn checkout systems do not emphasize diagnostic test capability, it becomes necessary for the system test engineers to make the best possible use of available checkout tests in carrying out fault isolation procedures. The problems involved in the use of checkout tests for diagnostic purposes depend upon where in the prelaunch checkout cycle a failure indication occurs.

In early factory testing of individual components or subsystem assemblies, checkout tests are fairly narrow in scope, and quite often the checkout test itself is sufficient to resolve the source of the failure to a repairable/replaceable module. However, as the prelaunch cycle proceeds to composite system testing and integrated system tests, this initial resolvency is usually lost; and as checkout tests become broader in scope, it becomes necessary to run additional tests in order to isolate malfunctioning components. The system test engineer's major decision function in fault isolation is, therefore, the selection of specific fault isolation actions (conduct of checkout tests, or replacement) from among an <u>available</u> set of alternatives."(1)

The set of available actions is almost always constrained by such factors as limited repertories of preplanned tests, inaccessibility of certain test points, unavailability of GSE, the inability to test certain individual assemblies and modules independently or in desired combinations, variations in initial conditions necessary for the conduct of certain tests, and certainly by the time pressures imposed during combined system tests, stacked vehicle tests, and simulated or actual countdowns. All of these factors serve to limit the number and nature of tests available. The difficulties of appropriate and efficient action selection in the face of these constraints indicate the need for some form of decision aid to assist in the organization, manipulation, and presentation of relevant information for use in selection and sequencing of tests for fault isolation purposes. Reference 3 gives criteria for the selection and sequencing of checkout tests when the time available is not enough to perform all the desired checkout tests.

In the case of fault isolation strategies, the system test engineer is primarily concerned with three categories of information: (1) the nature of the No-Go symptoms and the precise place in the test routine at which the failure indication is observed; (2) the set of possible failure sources and the possible relationships between sources and symptoms; and (3) the individual tests available to him and the relationship between tests and failure sources. These general categories can be broken down into more specific information requirements, which include the following items:

- Population of available tests and the initial conditions required for each.
- Listing of which functions or component failure modes are tested by each available test.
- Costs involved in running each test, including total test time, space system power-on time, manpower, GSE, and the range costs associated with both tests and holds.
- Limitations on the resolvency of available tests (i. e., indications of those component failure modes or functions which cannot be diagnosed to the level of a repairable/replaceable module given a set of available tests).

A previous report(2) has discussed the problems associated with the development of a perfect procedure (algorithm) for the sequencing of tests when the set of available tests is constrained. The conclusion was that such an optimizing procedure is not presently feasible and that the possibility that one can be developed within a reasonable period of time is highly unlikely. The preceding conclusion was based on the problem of scheduling equi-cost tests; the problems associated with identifying an optimum procedure are increased when the problem is expanded to include unequal and interdependent costs and changes in component failure probabilities (as a result of design modifications or fixes following previous failures).

In the absence of an overall optimum procedure, it becomes necessary to emphasize heuristic procedures and display aids to fault isolation which employ limited computer and display resources and which can approach optimality for a given set of test constraints or situations. Such techniques may involve the use of the checkout computer and the display system as an aid to the system test engineer, specifically in the functions of information retrieval and organization, data manipulation, and display. "Existing evidence(4) indicates substantial improvements in human trouble shooting performance resulting from organization of information pertaining to the relationship between symptoms and failure sources and between failure sources and tests. When the fault isolation process is structured so as to emphasize these relationships, the results show that trouble shooters can locate a malfunction in much shorter time, with fewer tests, and with still fewer irrelevant or redundant tests."(1)

These results are precisely what we expect to achieve in the Apollo/Saturn checkout system by means of the Test Matrix technique, which the system test engineer can use in formulating an efficient trouble shooting strategy. Its use will relieve the system test engineer of the necessity of carrying out those elements of data organization and manipulation which can be specified in advance. This reduces the time required for fault isolation and leaves the test engineer free to concentrate on inserting the judgmental factors which are an important element of the decision process but which cannot be handled on a completely rigid, formal, or preplanned basis.

## III. DESCRIPTION OF THE TEST MATRIX TECHNIQUE

When system test engineers use checkout tests to conduct fault isolation, they are concerned with three basic problems: (1) determining whether possible sources of a failure can be localized (to the repairable/replaceable module level) by available tests; (2) identifying which of the available tests are relevant to a given failure instance; and (3) determining the best sequence in which tests are to be run. A display showing the functional relationship between space vehicle tests and functional failure sources would be of great assistance to the system test engineers in solving these problems. The technique we have been investigating for this purpose is a test matrix display.

The Test Matrix concept consists of two elements--a set of rules (algorithm) for determining the relevance and sequencing of available tests, and a display format. The algorithm specifies the procedures used in organizing, comparing, and manipulating "test vs. component tested" data in order to arrive at a logically efficient sequence of tests. The display format permits the system test engineer to monitor the procedure, allowing him either to initiate further testing on the basis of the algorithmic solution or to select alternative test sequences based on "additional considerations" (e. g., unavailability of necessary GSE) or judgmental factors (e. g., hypotheses as to the failure source or dependent failure conditions).

The matrix algorithm, its uses, and the display format are described in subsequent paragraphs. However, before proceeding to a detailed discussion, two general comments should be noted:

- The matrix concept is not tied to any specific level level of checkout automation. While large matrices can be manipulated more efficiently by a computer, the test selection function can be allocated to the system test engineer or the checkout computer on a flexible basis. The Test Matrix technique can be applied manually (pencil and paper), semiautomatically (man-computer dialog), or in fully automatic fashion (under computer control).

- In our development of the matrix technique, we have assumed that all tests have equal and independent costs (time, GSE, manpower required, etc.). This assumption is not critical to the utility of the matrix. In actual use, test costs can be handled in two ways--known and programmable cost data can be inserted as weighting factors in selection of test sequences; less well defined test costs would be reflected by the judgment of system test engineers in the selection of tests.

## A. Definitions

The Test Matrix is a Boolean matrix in which each row represents a system component and each column represents an admissible test. Entry $t_{ij}$ is "one" if Test j tests Component i; otherwise it is zero. A test passes if all the components it tests are satisfactory; if one or more components tested are defective, the test fails. An example of a Test Matrix is shown in Figure 1. ("One" entries are shown by black squares, and "Zero" entries are indicated by blanks.) Here the test represented by Column 2, for example, tests Components D, E, H, and K. The problem is to devise optimum, or at least efficient sequences of the available tests (strategies) which will lead to identification of the failed components.

Before proceeding, we must define precisely the meaning of the terms "component" and "test" and show that ordinary tests of space vehicle components can be formalized in this way.

The term "component", as used here, means a source or mode of failure. Thus, if a device (space vehicle system, assembly, or part), regardless of the number or kind of elements it contains, can fail in n different ways (detectable by different tests), it is counted as n components, and represented by n rows in the Test Matrix. This means that the representation of a device depends on the level at which tests are being performed. Thus, for example, an amplifier which is only required to have a certain gain in order to be considered satisfactory, can be counted as one component. If, in addition, its noise level has to meet a certain standard, the amplifier must be counted as two components, since it can fail in two different ways. Similarly, a diode may have to be counted as two components if it can fail as a

|  | Test # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMPONENT OR FUNCTION | A |  |  |  | ■ |  |  |  | ■ |  | ■ | ■ | ■ | ■ |  |  |
|  | B |  |  | ■ |  | ■ |  |  |  |  |  | ■ | ■ |  | ■ |  |
|  | C |  |  |  |  | ■ | ■ | ■ |  | ■ | ■ | ■ | ■ |  |  | ■ |
|  | D |  | ■ |  |  |  | ■ | ■ |  |  |  |  |  |  | ■ | ■ |
|  | E |  | ■ |  | ■ |  | ■ | ■ | ■ | ■ | ■ |  |  | ■ | ■ |  |
|  | F |  |  |  | ■ | ■ |  |  | ■ | ■ | ■ |  | ■ | ■ | ■ | ■ |
|  | G | ■ |  |  | ■ | ■ |  |  | ■ |  |  | ■ |  | ■ |  | ■ |
|  | H | ■ | ■ | ■ |  |  | ■ | ■ |  | ■ | ■ | ■ |  |  | ■ |  |
|  | J | ■ |  |  | ■ | ■ |  |  |  |  |  |  | ■ |  | ■ | ■ |
|  | K | ■ | ■ | ■ | ■ |  |  | ■ |  |  |  | ■ |  | ■ | ■ |  |

Figure 1. Example of a Test Matrix display for use in fault isolation. (Cell entries indicate components or functions which must be satisfactory in order for a given test to pass.)

short circuit or as an open circuit. A diode quad may be characterized by the same two components if only the quad as a whole is tested. Devices that always fail together can also be considered as a single component.

A similarly narrow definition of "tests" is used. A test is a single Go/No-Go-type measurement under given conditions. Thus, if several pins of a module are examined under given conditions, each measurement on each pin constitutes a separate test.

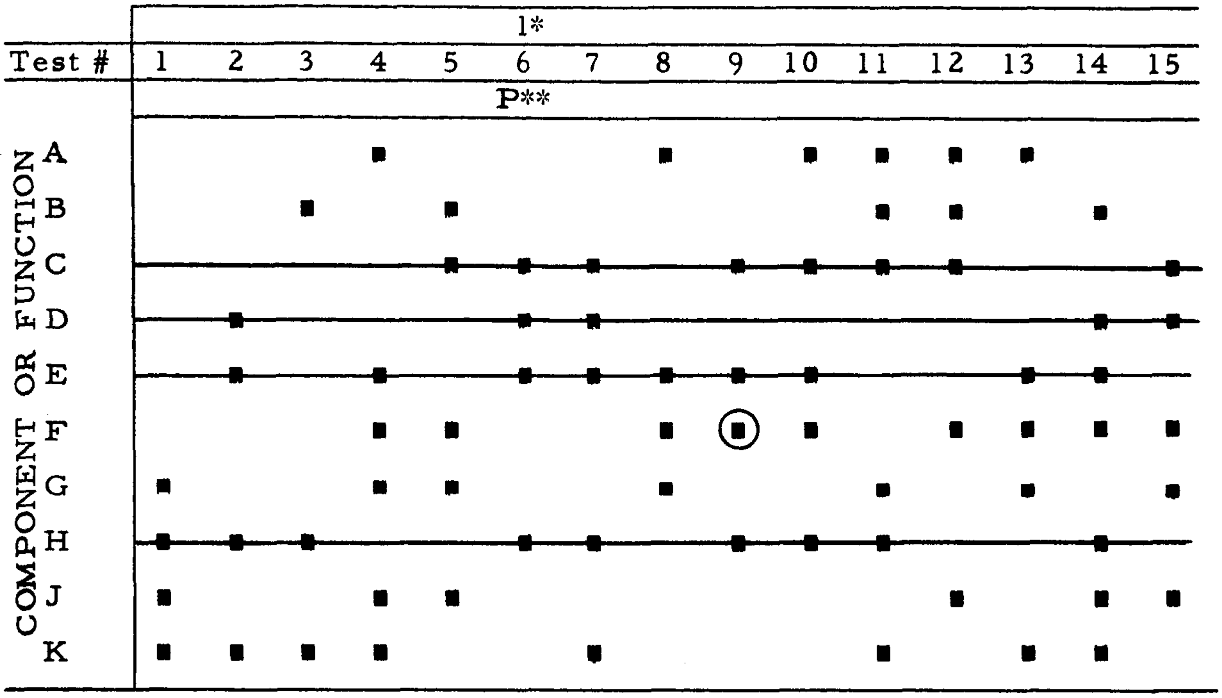
## B. Basic Test Matrix Operations

In the Test Matrix format, each row represents a failure source, and each column represents an available test. An example of a test sequence on the sample matrix display will illustrate the use of the matrix technique as a fault isolation aid. Let us assume that, given the matrix shown in Figure 1, the system test engineer chooses to perform Test 6, and it passes. This means that Components C, D, E, and H are good. There is no need to consider these components further, and thus the corresponding rows are deleted from the matrix display, as shown in Figure 2. Inspecting the reduced matrix, he finds that Test 9 is now a single-component test for F. He next elects to perform Test 9. Let us assume it fails. This means that Component F is failed. The fact that F is failed means that all tests which comprise F will necessarily fail and no purpose is served by running them. All columns which have a one in Row F are therefore deleted and the matrix now appears reduced to that shown in Figure 3. At this point, Test 7 becomes a single-component test for K. Let us assume that Test 7 also fails; repeating the deletion procedure for this component, we eliminate all remaining matrix columns (Figure 4). There are no additional tests which will yield any further information.

The matrix reducing operations used in the example are:

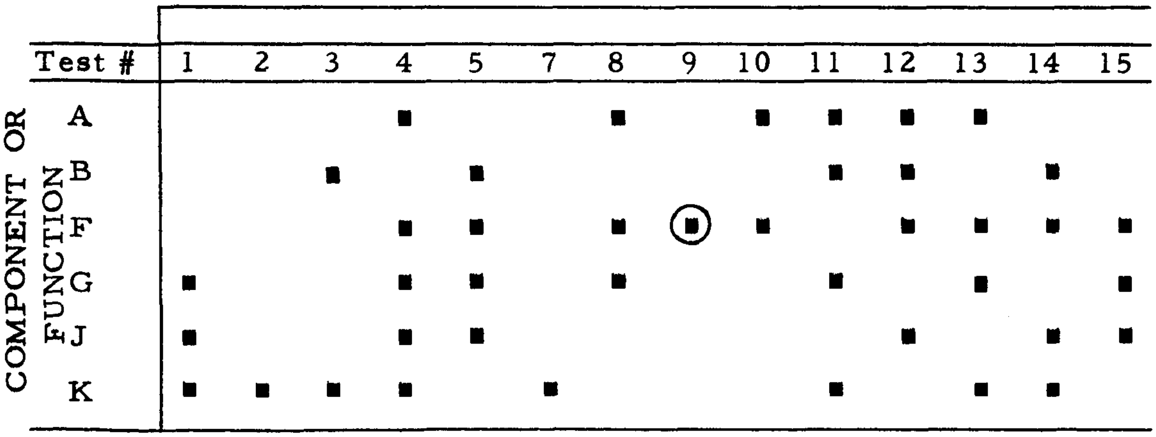
1) The deletion of rows corresponding to components tested by a passing test (good components).

2) The deletion of columns corresponding to tests dominated by a failed test (a Test A is dominated by a failed Test B if Test A includes at least all the components in the failed Test B; thus Test A must necessarily fail).



| | | | | | | | 1* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Test # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| | | | | | | | P** | | | | | | | | |
| COMPONENT OR FUNCTION | A | | | | ■ | | | | ■ | | ■ | ■ | ■ | ■ | | |
| | B | | | ■ | | ■ | | | | | | ■ | ■ | | ■ | |
| | C | | | | | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | | | ■ |
| | D | | ■ | | | | ■ | ■ | | | | | | | ■ | ■ |
| | E | | ■ | | ■ | | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | |
| | F | | | | ■ | ■ | | | ■ | ◉ | ■ | | ■ | ■ | ■ | ■ |
| | G | ■ | | | ■ | ■ | | | ■ | | | ■ | | ■ | | ■ |
| | H | ■ | ■ | ■ | | | ■ | ■ | | ■ | ■ | ■ | | | ■ | |
| | J | ■ | | | ■ | ■ | | | | | | | ■ | | ■ | ■ |
| | K | ■ | ■ | ■ | ■ | | | ■ | | | | ■ | | ■ | ■ | |

Figure 2a. Elimination of matrix rows as a result of completing Test No. 6.



| | Test # | 1 | 2 | 3 | 4 | 5 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMPONENT OR FUNCTION | A | | | | ■ | | | ■ | | ■ | ■ | ■ | ■ | | |
| | B | | | ■ | | ■ | | | | | ■ | ■ | | ■ | |
| | F | | | | ■ | ■ | | ■ | ◉ | ■ | | ■ | ■ | ■ | ■ |
| | G | ■ | | | ■ | ■ | | ■ | | | ■ | | ■ | | ■ |
| | J | ■ | | | ■ | ■ | | | | | | ■ | | ■ | ■ |
| | K | ■ | ■ | ■ | ■ | | ■ | | | | ■ | | ■ | ■ | |

Figure 2b. The reduced matrix, showing that Test No. 9 has now been reduced to a single-component test for Component F.

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[*] Order in which tests are run.

[**] Test outcome: P = Pass; F = Fail

|  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test # | 1 | 2 | 3 | ~~4~~ | ~~5~~ | 7 | ~~8~~ | 9 | ~~10~~ | 11 | ~~12~~ | ~~13~~ | ~~14~~ | ~~15~~ |
| COMPONENT OR FUNCTION |  |  |  |  |  |  |  | F |  |  |  |  |  |  |
| A |  |  |  | ■ |  |  | ■ |  | ■ | ■ | ■ | ■ |  |  |
| B |  |  | ■ |  | ■ |  |  |  |  | ■ | ■ |  | ■ |  |
| F* |  |  |  | ■ | ■ |  | ■ | ⊡ | ■ |  | ■ | ■ | ■ | ■ |
| G | ■ |  |  | ■ | ■ |  | ■ |  |  | ■ |  | ■ |  | ■ |
| J | ■ |  |  | ■ | ■ |  |  |  |  |  | ■ |  | ■ | ■ |
| K | ■ | ■ | ■ | ■ |  | ■ |  |  |  | ■ |  | ■ | ■ |  |

Figure 3a. Further reduction of the test matrix following identification of F as a failed component. All tests involving F will fail and therefore can be eliminated from further consideration.

|  |  |  |  | 3 |  |
|---|---|---|---|---|---|
| Test # | 1 | 2 | 3 | 7 | 11 |
| COMPONENT OR FUNCTION |  |  |  | F |  |
| A |  |  |  |  | ■ |
| B |  |  | ■ |  | ■ |
| G | ■ |  |  |  | ■ |
| J | ■ |  |  |  |  |
| K* | ■ | ■ | ■ | ⊡ | ■ |

Figure 3b. The reduced matrix after all tests involving F are deleted and Test No. 7 fails.

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*Failed

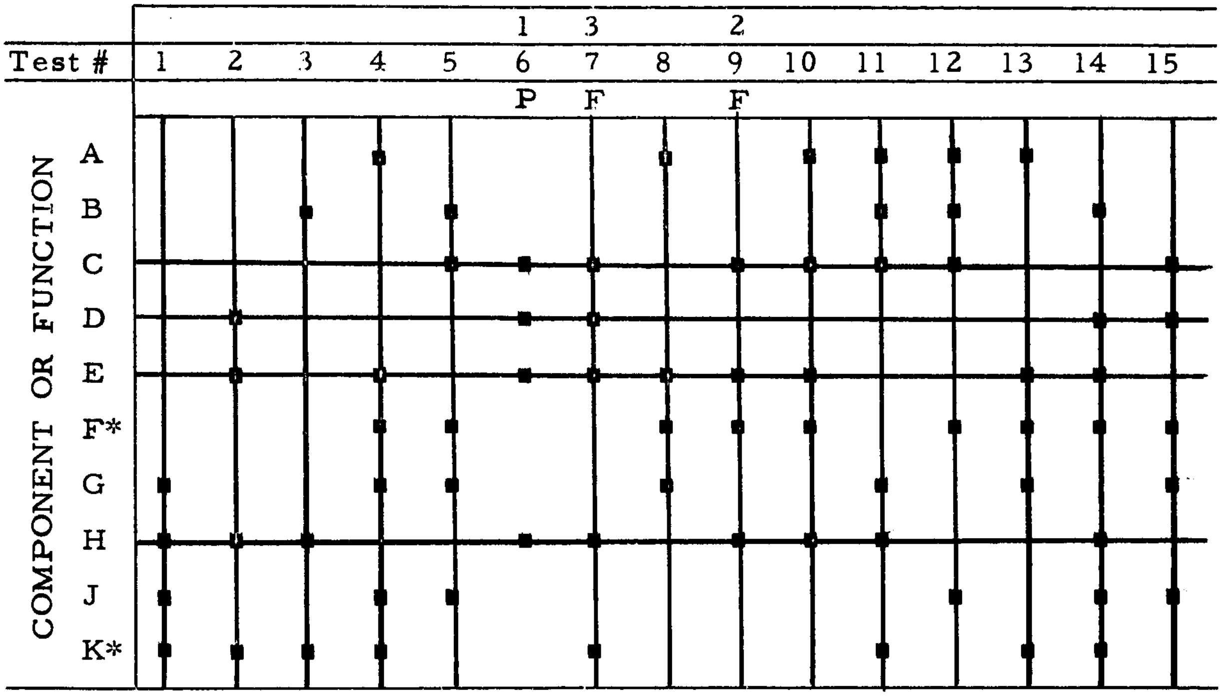

Figure 4. The original matrix, showing all columns and rows eliminated as a result of three tests. Components C, D, E, and H are good; F and K are failed; A, B, G, and J are non-resolvable given the present set of tests and their outcomes.

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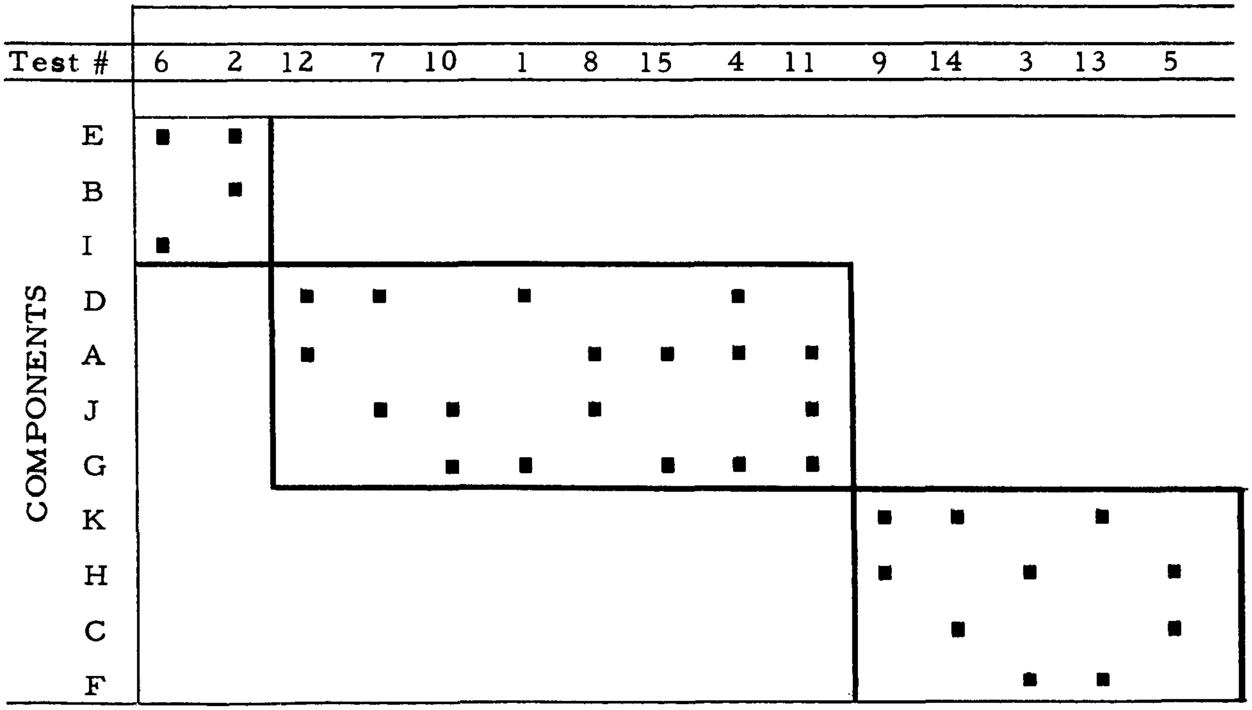
*Failed

## C. Partitioning of Test Matrices

It is sometimes possible to separate a Test Matrix into two independent submatrices. By this we mean that the components can be divided into two subsets, a and b, and the tests can similarly be divided into subsets a' and b' so that components in a are tested only by tests in a', and tests in a' test only components in a. The components in a and the tests in a' thus form a submatrix, A; and the rest of the components and tests form another submatrix, B. Matrix B has the same properties as Matrix A. The Test Matrix has thus been partitioned into two submatrices which are totally independent of each other and which together comprise all the information contained in the Test Matrix. Each one of these submatrices may, in turn, be partitionable. The partitioning process can be continued until nonpartitionable or elementary matrices are obtained. Every Test Matrix is thus composed of elementary submatrices. If a matrix is not partitionable, it is composed of a single elementary submatrix. Figure 5 shows an example of a partitioned Test Matrix.

Partitionable test matrices tend to be sparse, or at least to have sparse regions. Partitioning separates sparse regions into denser regions and empty regions.



| | Test # | 6 | 2 | 12 | 7 | 10 | 1 | 8 | 15 | 4 | 11 | 9 | 14 | 3 | 13 | 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMPONENTS | E | ■ | ■ | | | | | | | | | | | | | |
| | B | | ■ | | | | | | | | | | | | | |
| | I | ■ | | | | | | | | | | | | | | |
| | D | | | ■ | ■ | | ■ | | | ■ | | | | | | |
| | A | | | ■ | | | | ■ | ■ | ■ | ■ | | | | | |
| | J | | | | ■ | ■ | | ■ | | | ■ | | | | | |
| | G | | | | | ■ | ■ | | ■ | ■ | ■ | | | | | |
| | K | | | | | | | | | | | ■ | ■ | | ■ | |
| | H | | | | | | | | | | | ■ | | ■ | | ■ |
| | C | | | | | | | | | | | | ■ | | | ■ |
| | F | | | | | | | | | | | | | ■ | ■ | |

Figure 5. Partitioned Test Matrix.

## IV. IMPROVEMENTS IN DIAGNOSTIC PERFORMANCE

As discussed earlier, the major criteria of diagnostic efficiency are the proper classification of components (failure sources) as good, faulty, or ambiguous, and the number of tests used to reach these conclusions. Therefore, the utility of the Test Matrix technique can best be evaluated in terms of improvements in the test engineer's ability to correctly identify the status of components and reduction in the number of tests used.

Existing research data indicate that most trouble shooters tend to perform an excessive number of tests during fault isolation. Excessive testing can occur for a number of reasons including repetition of tests already run, inability to recognize all of the components being checked by a given test, lack of awareness that certain tests are equivalent or redundant, and a tendency to emphasize certain testing patterns even when they are inappropriate to the symptoms or initial test results at hand(4). The Test Matrix format presents information on test relevance and equivalence and, therefore, should reduce the amount of excess testing. Similarly, by providing specific information on the possible failure sources pertinent to each test, the matrix should reduce errors in classifying these sources as good or faulty and help pinpoint those which are untestable or suspect.

An experimental comparison of trouble shooting with and without the use of test matrices was conducted to provide quantitative data on the improvement resulting from the use of the test matrix technique. The results were analyzed in terms of the number of tests used in excess of the minimum necessary to extract all available information from the matrix, and the number and types of errors in categorization of component status. These criteria were examined separately and also combined into an efficiency index which included the number of tests, the percentage of errors and a weighting function, based on the types of errors made. This latter efficiency criterion was included to take account of the fact that certain errors in categorizing component status are far more serious than others (e. g., calling a bad component good is more serious than calling a good component untested). The results are summarized below; a more complete discussion of the experiment design and scoring procedure is included in Appendix B.

## A. Errors in Categorizing Component Status

Across all subjects and failure cases the total number of errors in classifying components as good, faulty, or untested was reduced by 69% through use of the Test Matrix. However, this saving does not provide a complete picture of the utility of the matrix. Summing all errors, regardless of type, implicitly assumes that the various types of errors are of equal importance and weighted equally. In fault isolation this is obviously not the case since certain types of errors can be much more costly and misleading than others.

The breakdown by type of error is shown in Table 1. These data indicate that the use of a test matrix reduced the number of errors of each type and that the percentage improvement ranged from 30 to 92%. The important point to emphasize is that the highest percent reduction in errors occurred for the most serious and costly type of error, i. e., calling a faulty component good.

The smallest percentage improvement occurs for errors which involved calling an untested component faulty. A review of responses from the experiment subjects indicated that one subject accounted for one-third of such errors with the matrix. This subject was subsequently interviewed and it was established that he consistently labeled all components involved in a failed test as faulty unless they were also included in a test which had previously passed. Further training would no doubt have eliminated such systematic errors in using the matrix and resulted in higher percentage improvements through use of the matrix.

## B. Excess Tests Run

As shown in Table 1, the number of excess tests run was reduced by 12% through use of the matrix. Examination of subjects' responses indicates that further training in use of the matrix would probably reduce the number of tests run even further.

## C. Diagnostic Efficiency

The number of errors and tests are useful measures of trouble shooting performance, but when considered independently, they do not

## TABLE I

Comparison of Errors in Fault Isolation With and Without Test Matrices
(Across all subjects and failure cases)

| Type of Error | Number of Errors<br>Without Matrix | <br>With Matrix | Percent Reduction With Matrix |
|---|---|---|---|
| Faulty Component - called good | 24 | 2 | 92 |
| Faulty Component - called ambiguous | 17 | 4 | 76 |
| Ambiguous Component - called good | 57 | 8 | 86 |
| Ambiguous Component - called faulty | 27 | 19 | 30 |
| Good Component - called bad | 42 | 13 | 69 |
| Good Component - called ambiguous | 93 | 34 | 63 |
| Total Errors | 260 | 80 | 69% |
| Excess Tests Run | 315 | 278 | 12% |

give a complete picture of an individual's diagnostic efficiency. For this reason, a composite efficiency index was developed and used to evaluate each subject's performance. This composite score was based on the number of tests run, the percentage of components whose status was designated correctly, and a weighting factor for each of the several possible types of errors. A complete description of the weighting procedure and its rationale is included in Appendix B.

The efficiency scores by subject are shown in Table II. These data show that every subject had a higher efficiency when using the matrix. The range of improvement was 51 to 89%, with ten of the twelve subjects improving by more than 70%. Across all subjects, the improvement was 75%.

TABLE II

Diagnostic Efficiency Scores by Subject
(across all failure cases)

| | Efficiency Score* | | |
|---|---|---|---|
| Subject | Without Matrix | With Matrix | Percent Improvement with Matrix |
| 1 | 99.7 | 28.8 | 70 |
| 2 | 196.3 | 41.2 | 79 |
| 3 | 171.1 | 15.0 | 71 |
| 4 | 270.3 | 34.4 | 88 |
| 5 | 183.2 | 46.2 | 75 |
| 6 | 245.9 | 120.9 | 51 |
| 7 | 104.3 | 22.0 | 79 |
| 8 | 161.1 | 46.9 | 71 |
| 9 | 127.7 | 30.1 | 77 |
| 10 | 203.7 | 24.2 | 89 |
| 11 | 229.1 | 111.2 | 52 |
| 12 | 107.3 | 22.0 | 79 |
| Totals | 2099.7 | 538.7 | 75% |

*Lower scores indicate more efficient diagnosis.

In summary, use of the test matrix as an aid in fault isolation reduces both the number of tests run and the number of all types of errors. Since the effect of the matrix is most pronounced in reducing the costliest type of error, the composite efficiency index seems to be indicative of the utility of the matrix technique. The existing data on the matrix's utility are undoubtedly conservative because of the limited training given to the experiment subjects. Each subject had two or more years of experience with schematic diagrams, but only about one hour's training on the matrix. After completion of the experiment, all subjects felt that their ability to use the matrix sufficiently would improve with further exposure and practice.

# V. UTILITY FOR APOLLO/SATURN

Currently the testing procedures for Apollo/Saturn prelaunch checkout provide little in the way of automated diagnostic testing. The automatic test sequences being programmed for use at KSC are designed to verify operational readiness and to generate alarms (and holds if necessary) if a "No-Go" occurs. Because of the developmental nature of the Apollo/Saturn hardware and the lead time required for programming, the fault isolation activities following such a "No-Go" are typically still mediated by the test engineer.

At the time a "No-Go" occurs, the only test conveniently available to the test engineer will most likely be the checkout tests pertaining to the given system or vehicle stage. Checkout tests can usually be implemented with minimum cost since they do not require additional GSE, lengthy setup time or disassembly of the spacecraft or launch vehicle. Such actions may be necessary if the failure source(s) cannot be localized at least to the level of a replaceable unit with the use of checkout tests, but first the test engineer should be capable of exhausting all of the information available from checkout tests.

As discussed in previous sections, the Test Matrix provides assistance in just this area. Figure 6 depicts the fault isolation procedure typically performed by the test engineer. He selects and performs the test, obtains and analyzes the outcome in terms of its diagnostic value, determines whether there is any other meaningful tests to be run, and if so, he selects the next test. This procedure is continued until no further meaningful test is available.

As indicated in the figure, the Test Matrix technique provides important assistance in three points in the process:

1) It provides grounds in the selection of the next test to be performed.

2) It provides a format for analysis, interpretation and storage of diagnostic information and permits clear distinction to be made between failure source which can be designated as good, faulty, ambiguous, or untestable.

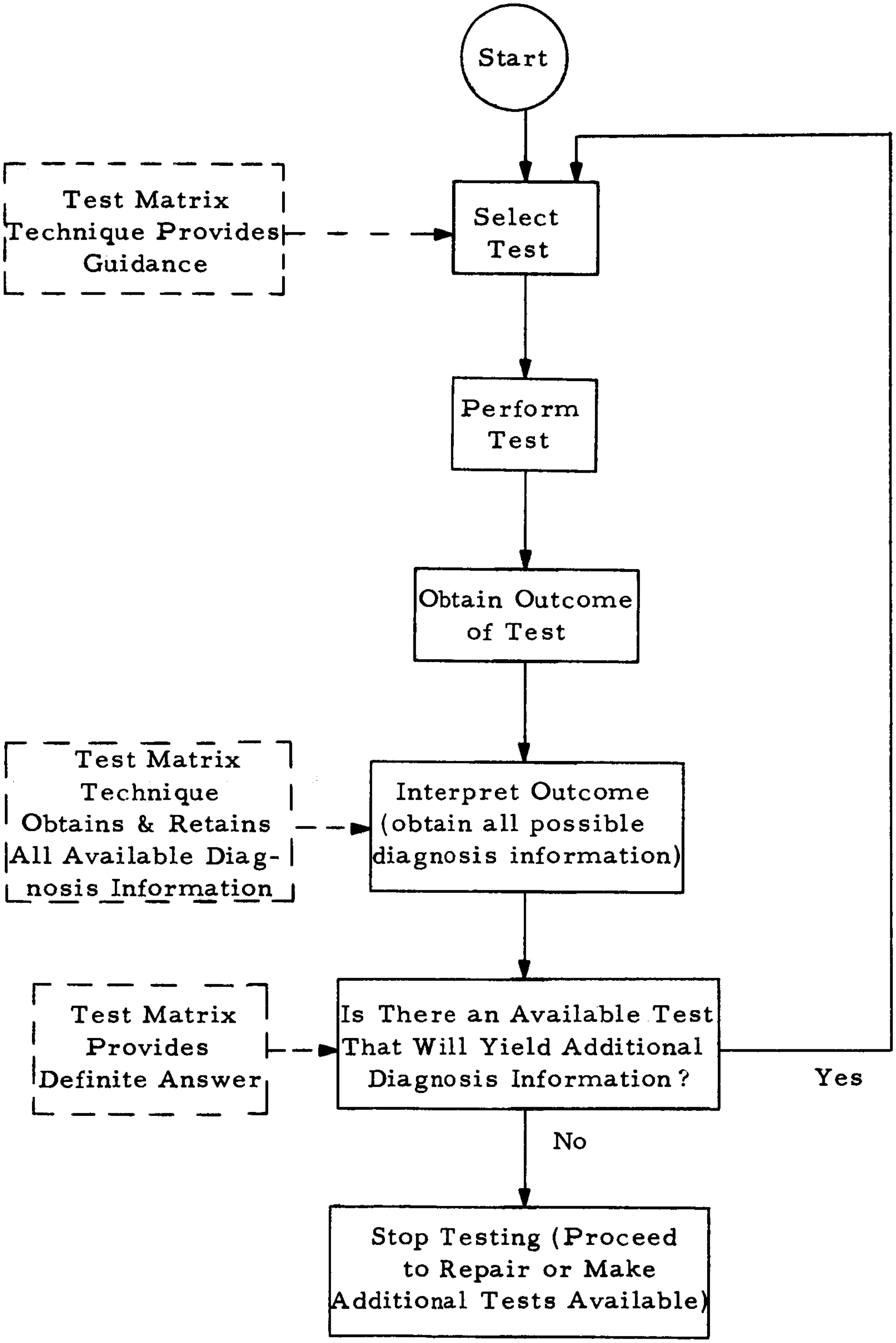


Figure 6. Generalized diagnosis procedure.

3) It determines when the end of the testing sequence is reached under the given failure conditions and with the available set of tests.

Examination of the results at that time will provide guidance as to the most efficient next step, e. g., replacement of a component known to be bad, expansion of the set of available tests, etc.

The experimental data which were collected to evaluate the utility of the Test Matrix clearly indicate its potential value to the Apollo/Saturn program. Its use reduces the number of tests used to obtain all of the information available from a given set of tests, but more important, it provides the test engineer with a clear picture of the status of each component or potential failure source. It explicitly calls out all of the failure sources which cannot be tested or resolved under a given set of conditions and pinpoints those which are clearly good or faulty. This clear definition of component status ultimately results in still further reduction in the number of tests to be run since erroneous classification of component status may often result in additional "No-Go" indications later in the checkout process. The most serious diagnostic error, of course, involves calling a faulty component good since this might result in unwarranted verifications of flight readiness. The matrix technique proved to be most powerful in reducing this latter type of error.

Detailed efforts were made to apply the Test Matrix concept to an actual spacecraft system. Trips were made to MSFC, MSC, and KSC in an attempt to obtain assistance in preparing a matrix for a sample spacecraft or vehicle system. Possible applications were discussed with NASA and Contractor personnel at each of these centers, but neither NASA nor Contractor assistance could be made available to aid us in the preparation of sample Test Matrices. The demonstration, therefore, had to be based on non-space electronic hardware.

NASA personnel at MSC, responsible for on-board checkout, have indicated a continuing interest in application of the technique to other problems, but that is outside the scope of the present contract. The Test Matrix technique was also explained and demonstrated to several NASA suppliers, all of whom express strong interest in applying it to failure diagnosis of their products, both for factory and field testing. It is therefore very likely that practical applications and demonstrations of this technique will materialize in the near future.

# VI. DATA PROCESSING IMPLICATIONS OF TEST MATRIX MANIPULATION

The program design approach is based upon a model which was designed and programmed on Dunlap's SDS 920 digital computer during the present contract. Because of the similarities (equal word lengths and operations of similar magnitude and complexity) between the SDS 920 and the DDP 224 digital computers, the model realistically reflects the implementation requirements for a comparable operational program. Of course, the laboratory model contains special purpose modules for run preparation (Generate Matrix Module) and simulation of operational data (Test Module). It also contains a Print Module for displaying matrix results on the on-line printer in lieu of a display console. Other minor adaptations must be made to apply the concept to operational use; however, the overall requirements, in terms of both memory and implementation effort are comparable.

## A. The SDS 920 Test Matrix Program

The SDS 920 Test Matrix Program model was designed modularly as illustrated in Figure 7. It consists of eight basic modules including the control activities of the executive portion of the program. Each module is discussed briefly to indicate the general function performed and the SDS 920 memory requirements. Appendix A contains detailed flow charts of the SDS 920 Test Matrix Program.

The Executive Module is responsible for branching and routing decisions within the Test Matrix Program. It must determine, for instance, whether a given test has passed or failed and set the appropriate flags and bits before branching to the appropriate processing modules. The Executive Module required 277 words of SDS 920 memory.

The Generate Matrix Module was necessary to generate the appropriate matrices for use in simulating operating conditions. It required 370 words of SDS 920 memory.

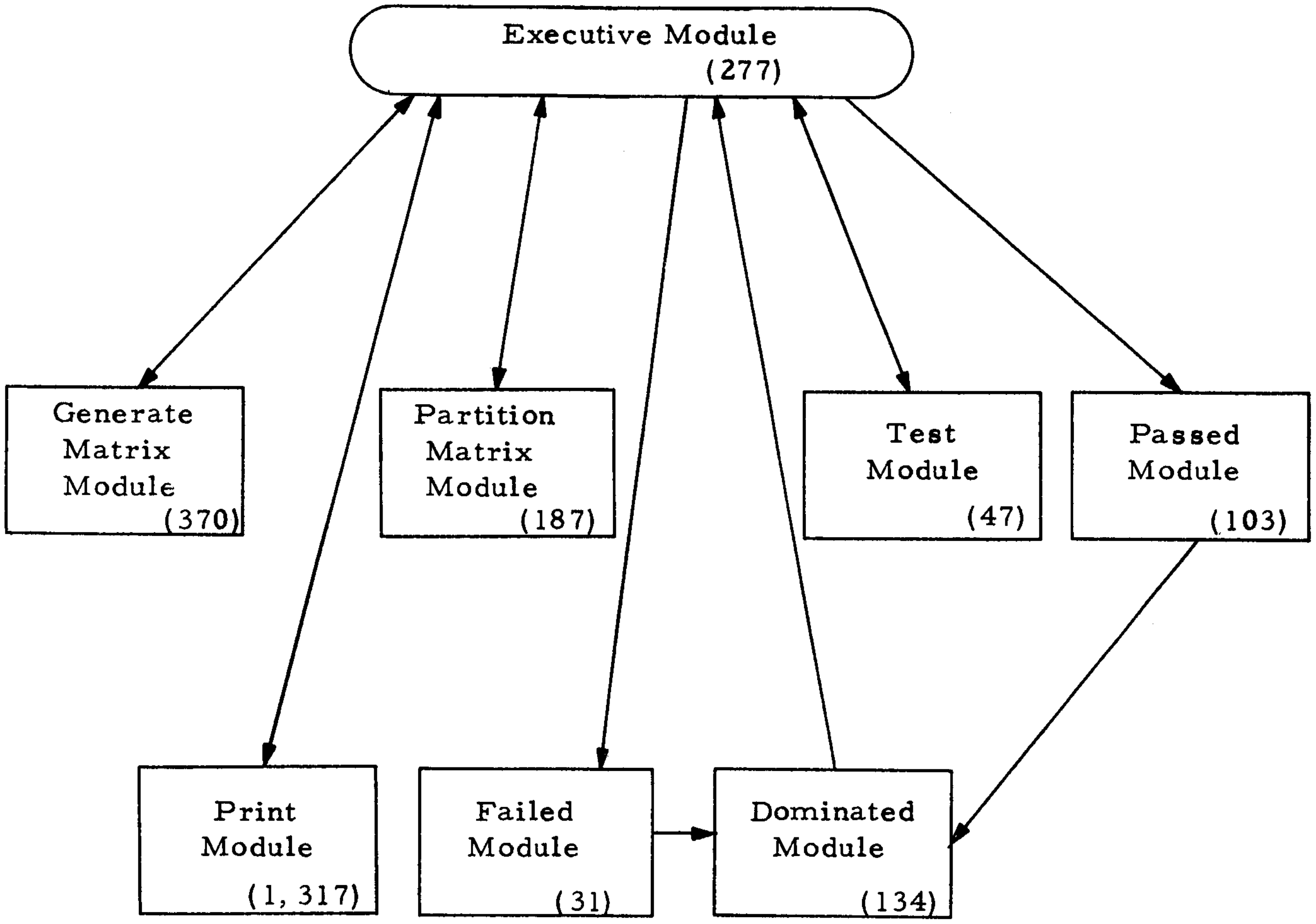


Figure 7. Modular Construction of the Test Matrix Program Model Employed with the SDS 920 Computer. (See Appendix A for detailed flowcharts of each module.)

The Partition Matrix Module groups table entries (test addresses) by tests which contain common components. This is accomplished for ease of reading and processing. The Partition Module in the model prepared for the SDS 920 contained 187 words.

The Test Module is used to simulate actual test operation in the automatic checkout test environment. Input is accepted from cards, typewriter, or from breakpoint switch settings. The SDS 920 memory requirement was 47 words.

The Passed Module is responsible for deleting component rows for all components of a test which has been successfully executed. If this deletion yields other tests which are known to pass by virtue of the fact that all of their components have now been passed by other tests, these tests are also deleted from matrix consideration and the test engineer is notified. This module required 103 words of SDS 920 memory.

The Failed Module is entered from the Executive Module after a given test has failed. It sets the proper indications about the test failure and transfers to the Dominated Module at the failed entry point. The Failed Module required 31 words of SDS 920 memory.

The Dominated Module has two entry points: one from the Passed Module and one from the Failed Module. In case of the Failed Module entry point, the Dominated Module examines the matrix for other tests containing all the components contained in the test which failed. Such tests will necessarily fail. They are thus removed from further consideration. If the entry is from the Passed Module, the Dominated Module examines all previously failed tests in the group to see if any of these (because of deletions of components of the passed test) now dominates any untested tests. The Dominated Module required 134 words of SDS 920 memory.

The Print Module displays the results on the on-line printer. This is one of the modules that will not be required for the operational Test Matrix Program; it required 1, 317 words of SDS 920 memory.

A tabulation of high-speed memory requirements for the Test Matrix Program model is shown in Table III.

## TABLE III

High-speed Memory Requirements for the
Test Matrix Program Model*

| Programmed Component | Memory Words |
|---|---|
| Matrix Storage | 3, 300 |
| Common Storage | 322 |
| Executive Module | 277 |
| Generate Matrix Module | 370 |
| Partition Matrix Module | 187 |
| Test Module | 47 |
| Passed Module | 103 |
| Dominated Module | 134 |
| Failed Module | 31 |
| Print Module | 1, 317 |
| TOTAL | 6, 088 |

*Based upon model status on 10/5/66. Subsequent changes, if any, will be minor.

Matrix storage requires 3, 300 words of SDS 920 memory for maximum storage. This storage will handle a matrix up to 240 x 300 in size for a total of 72, 000 cells. Each cell is represented by a single bit: and given the 24-bit word size of the SDS 920, 3, 000 words are required. An additional 300 words are required for control and housekeeping functions related to the Test Matrix.

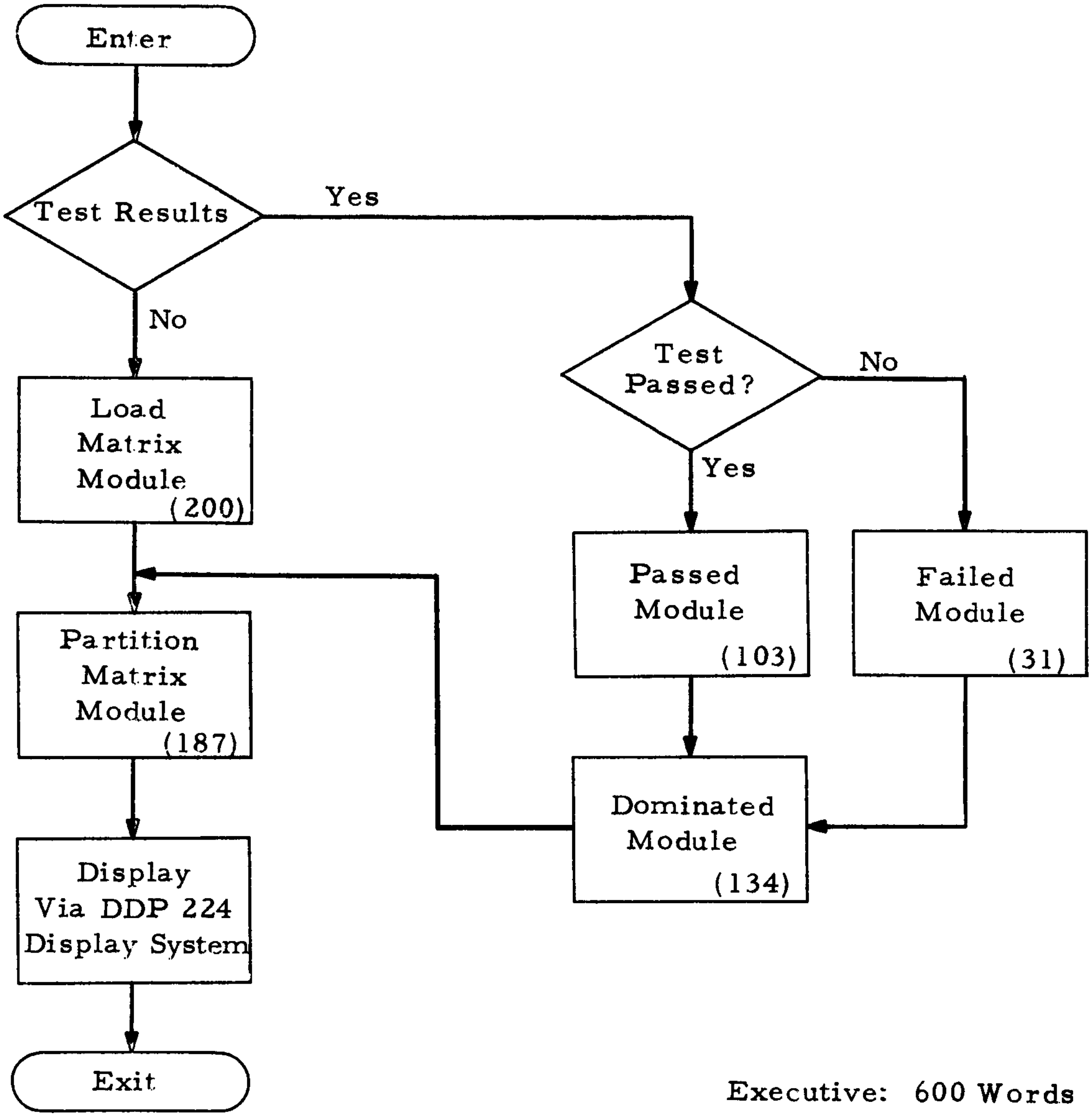
In addition to the matrix storage, 322 words are required as common storage for use by any of the modules requiring it and for intercommunication between the modules.

Execution time, even with the maximum size matrix, is insignificant and falls within limits undiscernible to the user. Using the model, the longest execution time occurred with the generation of a maximum size matrix and was approximately 2 seconds. It should be noted, however, that the operational program will not require matrix generation but will employ test matrices which correspond to systems or equipments under test.

## B. The DDP 224 Test Matrix Program Design Approach

The DDP 224 Test Matrix Program must be designed for inclusion in the Saturn V DDP 224 Display System. This requires that the program accommodate requests from the display console for initial matrix loading and from the DDP 224 Display System upon completion of automatic checkout tests. Entry upon test completion must be accompanied by information relative to the success or failure of the test involved. The operational program must also provide for a standard exit back to the DDP 224 Display System upon completion of the required matrix manipulation. The executive portion of the program must determine the appropriate processing paths and provide the exit as illustrated in Figure 8. In the illustration, all blocks which are not designated as "Modules" are a part of the Test Matrix Program Executive. The Load Matrix Module replaces the Generate Matrix Module of the SDS 920 Test Matrix Program model. The Partition Matrix Module, Passed Module, Failed Module, and Dominated Module are identical to their counterparts in the program model for the SDS 920. The display operation of the executive replaces the Print Module of the SDS 920 program.

Memory requirements for those modules which are identical to their model counterparts are shown in parentheses in the appropriate block and are estimated to be equal to the SDS 920 memory requirements. The memory required for the executive portion of the operational Test Matrix Program is estimated to be somewhat higher (from 277 to 600 words) to allow the inclusion of the set-up of display parameters for transfer to the DDP 224 Display System which will handle the actual display operations. However, it should be noted that this is in lieu of 1, 317 words for the Print Module and represents a net decrease in memory requirements of 994 words.



Executive: 600 Words
Matrix Storage: 3300 Words
Common Storage: 322 Words

Figure 8. Functional chart of operational Test Matrix Program.

Programming time for the Test Matrix Program using this design approach has been estimated and is shown in Table IV by module. Three weeks have been allocated to analysis of implications for the DDP 224 Display System and incorporation of the appropriate tables to assure compatible operation of the Test Matrix Program with the rest of the Display System.

TABLE IV

Memory/Programming Estimates for the Operational Test Matrix Program

| Module or Function | Programming* Estimate (Man-weeks) | Memory Required |
|---|---|---|
| Executive | 20 | 600 |
| Load Matrix | 8 | 200 |
| Partition Matrix | 8 | 187 |
| Passed | 5 | 103 |
| Failed | 2 | 31 |
| Dominated | 8 | 134 |
| (Matrix Storage) | - | 3, 300 |
| (Common Storage) | - | 322 |
| (Interface with DDP 224 Package) | 3 | - |
| TOTAL | 54 | 4, 877 |

*The original basis of this computation was Reference 5. However, the estimate was modified upward by approximately 25% because of the developmental characteristics and logical interactions required. The final estimate is based upon an effective program design, programming, and checkout rate of six instructions per day.

Based upon the current status of available memory in the DDP 224 Display System, the incorporation of the Test Matrix Program will require the addition of another module (4, 096 words) of high-speed memory. The logical operations and manipulations of the Test Matrix could not be stored in a refresh memory of a display console.

In summary, the hardware/memory/programming implications of incorporating the Test Matrix Program into the DDP 224 Display System are estimated as follows:

- Hardware: One additional module (4, 096 words)
- Memory Utilized: 4, 877 words
- Programming Effort: 54 man-weeks

# VII. APPLICATIONS OF THE TEST MATRIX TECHNIQUE

## A. Types of Systems and Environments

This procedure is completely general, and therefore, applies to a wide variety of diagnosis situations. The Test Matrix concept therefore appears to have very broad applicability: it can be used on electrical, electronic, mechanical, hydraulic, and chemical systems, as well as on electromechanical and other hybrid systems. It can be used in any environment where the equipment itself can function: on the ground, in flight, and in space, as well as at sea and under water. It can be implemented manually by pencil and paper or similar devices, semi-automatically with the assistance of mechanical devices or by man-computer interaction, or fully automatically.

In-flight and in-space checkout and diagnostic testing is another area of possible immediate application for the Test Matrix technique. This application can take several forms:

1) On-board diagnostic testing by the astronaut, via manual, semi-automatic, or fully automatic means. This application is currently being discussed with NASA personnel in connection with the Apollo Applications Program on-board checkout system.

2) Remote testing. The Test Matrix processor--human or mechanical--is on the ground and requests the performance of a selected test. The astronaut performs the test and transmits its outcome to the ground. This is done until sufficient information for diagnosis is available to the test engineer on the ground. He then gives repair instructions to the astronaut. This application is not restricted to space-ground links; it is equally applicable to space-to-space links. It can also be used between equipment location and equipment manufacturer. This is essentially troubleshooting by phone: the person in charge of the matrix processor and the operator of the equipment to be diagnosed exchange test instructions and results until diagnosis is made, in the same manner as the astronaut and ground operator.

This application can be implemented at present, by means of the matrix processing program available on our computer. All that is necessary is the construction of the Test Matrix for the desired equipment or system. The program, the computer, a telephone line, and possibly a space communication link allow implementation of remote fault diagnosis anywhere on earth or in space. All the elements mentioned are available today, with the exception of the long-range space links, which will be available as the corresponding space missions are flown.

3) Remote unmanned testing and repair. The technique can also profitably be applied on remote links which are unmanned at one or both ends, such as remote locations and unmanned space vehicles. Telemetry links can transmit test instructions and outcomes, and either the testing or the analysis, or both, can be done automatically. Subsequent remote repair based on more accurate diagnosis is also a possibility. Further development of this application will necessarily come only after the manned link application is explored in greater detail.

## B. Stages of Checkout or Diagnostic Testing

Test Matrix checkout and fault diagnosis techiques will find application at many different stages of the life of systems and equipments. The first would be checkout testing at the manufacturing level, including diagnostic testing of those equipments and systems which failed the checkout tests. Such applications are currently being discussed with a number of NASA equipment suppliers, and they all have shown great interest in the technique.

The next stage would be field testing by the user, again both for checkout and diagnostic purposes. For small, relatively simple systems field and service manuals can include test matrices for specific equipments, together with a brief explanation of their use. The consequent simplification of troubleshooting procedures will enable some repairs to be made in the field which previously could only be made at the factory; some that required a manufacturer's field representative can now be made by the user himself with the aid of the new technique. The Test Matrix represents a convenient form of transmitting "canned" knowledge of diagnosis from the equipment, system and test designers to the test engineer, who will necessarily be less familiar with the detailed workings of the equipment. One possibility is to provide the matrix with a transparent plastic overlay. In this way, the same copy of the matrix can be used repeatedly with a grease pencil or crayon which can be wiped off. This application is also being discussed with NASA suppliers.

For larger systems which require automatic processing of test matrices, these can be supplied in machine-readable form (punched cards, tape, etc.) for processing in the field. Matrix processing programs or subroutines, applicable to all matrices, may be available from user organizations and libraries, either in machine language for specific computers, or in some more common language acceptable to different types of computers, similar to Fortran. Automatic test sequences, which must now be programmed separately for each piece of equipment and generally cover only a small number of alternatives, will cover very large numbers of alternatives without individual programming; all that must be supplied with each equipment is its Test Matrix. This application is not actively under discussion at present. It deserves serious consideration after some of the simpler applications are implemented and evaluated in the field. The computer program for the processing of test matrices, developed by Dunlap and Associates, Inc., under this contract can be used as a starting point for the full development of this application.

Two other areas of application of the Test Matrix technique can be envisioned:

- Extension of self-diagnosis capabilities of computers and other digital devices. Many computers are provided with so-called diagnostic programs, which check individual functions. Application of test matrices can extend this capability by allowing more detailed diagnosis with fewer tests, and with less programming effort, since again a standard test matrix program can be used.

- Extension of the capabilities of automatic testing and checkout equipment. Most of these equipments presently perform tests in fixed sequences and provide little diagnostic information if tests fail. Here again, the number of tests required for both checkout and diagnosis can be reduced, the level of diagnosis can be refined with the use of test matrices, and the programming of these devices can be simplified. Automatic testing equipment is currently used both at the manufacturing level and in the field; the technique can be applied equally well to both types of use. With the application of Test Matrices to automatic testing equipment, the development of full-fledged diagnostic computers becomes a possibility.

## C. Application of Test Matrices to Test Planning

The analysis of the Test Matrix of a particular system will often reveal some inadequacies in the tests provided; in some cases it will show the existence of redundant or otherwise superfluous tests. The Test Matrix may thus influence the design of tests for a given system, if the inadequacies and redundancies are remedied. These changes may in turn eventually affect the design of new systems as more becomes known about the checkout and fault diagnosis process and its philosophy.

Experience with the Test Matrix of a particular system may lead to changes in the matrix itself: addition and deletion of components and tests, for example. Repeated use of a particular matrix may show that certain tests are performed almost every time. These may then become part of a good diagnostic strategy: they may be run first, without reference to the matrix itself. Thus, it can be seen that, although optimum diagnostic strategies are either impossible or impractical (see Ref. 2), "good" strategies can be devised with the matrix alone or by repeated diagnosis experience with a particular system and its Test Matrix.

## VIII. CONCLUSIONS AND RECOMMENDATIONS

### A. Conclusions

Judging from all the available evidence, the Test Matrix technique has great potential as a useful tool in many fault diagnosis and trouble-shooting situations. It is especially useful in those situations, such as prelaunch checkout, where it is either impossible or undesirable to examine the various failure sources (components) individually.

In NASA operations, the technique can be applied to both ground and spaceborne equipment at various levels. It will probably find most direct and immediate application in prelaunch and on-board checkout and fault diagnosis. As its use is extended and benefits due to its use are realized, it will progressively affect test planning, test design, and evenually even equipment design. It provides a basis for incorporating checkout and fault diagnosis facilities into the system from the very beginning.

The technique can be applied to many different classes of systems and equipments: electric, electronic, electromechanical, hydraulic, etc. Both analog and digital systems can benefit from the application of the technique; however, application is simpler and more direct for digital systems.

The Test Matrix technique can be used at various levels of automation: it can be used in a strictly manual environment as a pencil-and-paper technique; it can be used in a semi-automatic mode which provides the test engineer with various degrees of assistance in carrying out the purely mechanical operations of matrix manipulation; and it can be used in completely automatic fashion, where the whole diagnostic procedure and failure analysis is carried out by computer.

### B. Recommendations

#### 1. Recommendations for Implementation

In view of the apparent potential of the Test Matrix technique, it is recommended that it be implemented on selected NASA systems on a pilot basis, in order to determine the amount of improvement in fault diagnosis and checkout that can be obtained. Such a preliminary implementation will also help determine the amount of effort required to incorporate the Test Matrix technique into a specific system. It is recommended that these initial applications be selected so as to represent a variety of environments: different types and sizes of systems, various degrees of automation, sizes of matrices, etc. The experience acquired in this way can then be used to extend the technique to other systems. Figures for before-and-after improvements will also be obtained in this fashion.

## 2. Recommendations for Further Study

There are many aspects of the Test Matrix technqiue which merit further investigation. Additional knowledge of these will yield further improvements in fault diagnosis, and will simplify the installation of the technique in new systems. The following are the most important areas of future research on this topic:

- Optimum test selection criteria (fault diagnosis strategies). Given a Test Matrix, and the outcome of some tests, which is the best test to run next. Fault diagnosis strategies in general should be developed. In addition, strategies applicable to specific test matrices can be found. General methods for these strategies should also be developed.

- Computer application of Test Matrix technique. Some experience has been obtained in this area in the course of the contract. Computerization of those features of the technique not yet included in the present program should also be investigated.

- Semi-automatic modes of fault diagnosis with the technique. The possibility of building simple devices which will facilitate the diagnosis process without the aid of a full automatic computer should be studied. These could be mechanical or electrical devices.

- Construction of Test Matrices. At present the construction of a Test Matrix for a specific system or piece of equipment is somewhat time consuming. Techniques for simplifying this process should be investigated.

- Optimum sizes of Test Matrices. The size of the Test Matrix in terms of number of failure sources and tests will vary as a function of type of equipment or system, complexity, degree of detailed diagnosis desired, and degree of automaticity in the application of the technique. Test Matrix sizes resulting under various conditions should be investigated. Typical, optimal, and maximum matrix sizes for each processing method should also be determined.

- Extension of the Test Matrix technique. In practical situations not all tests obey the rules of logic assumed for the Test Matrix technique until now. Means for incorporating such "anomalous" tests into the framework of the technique should be investigated.

- Generalization of the technique. Until now only deterministic relationships between failures and test outcomes have been considered (a test fails if and only if a component in it has failed). It is possible to define probabilistic or "noisy" fault-test relationships, which would yield test matrices containing numbers other than 0 or 1. The possibility of developing methods of fault diagnosis for this case should also be investigated.

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# APPENDIX A

## Flow Diagrams of Test Matrix Computer Program

EXECUTIVE SUBROUTINE

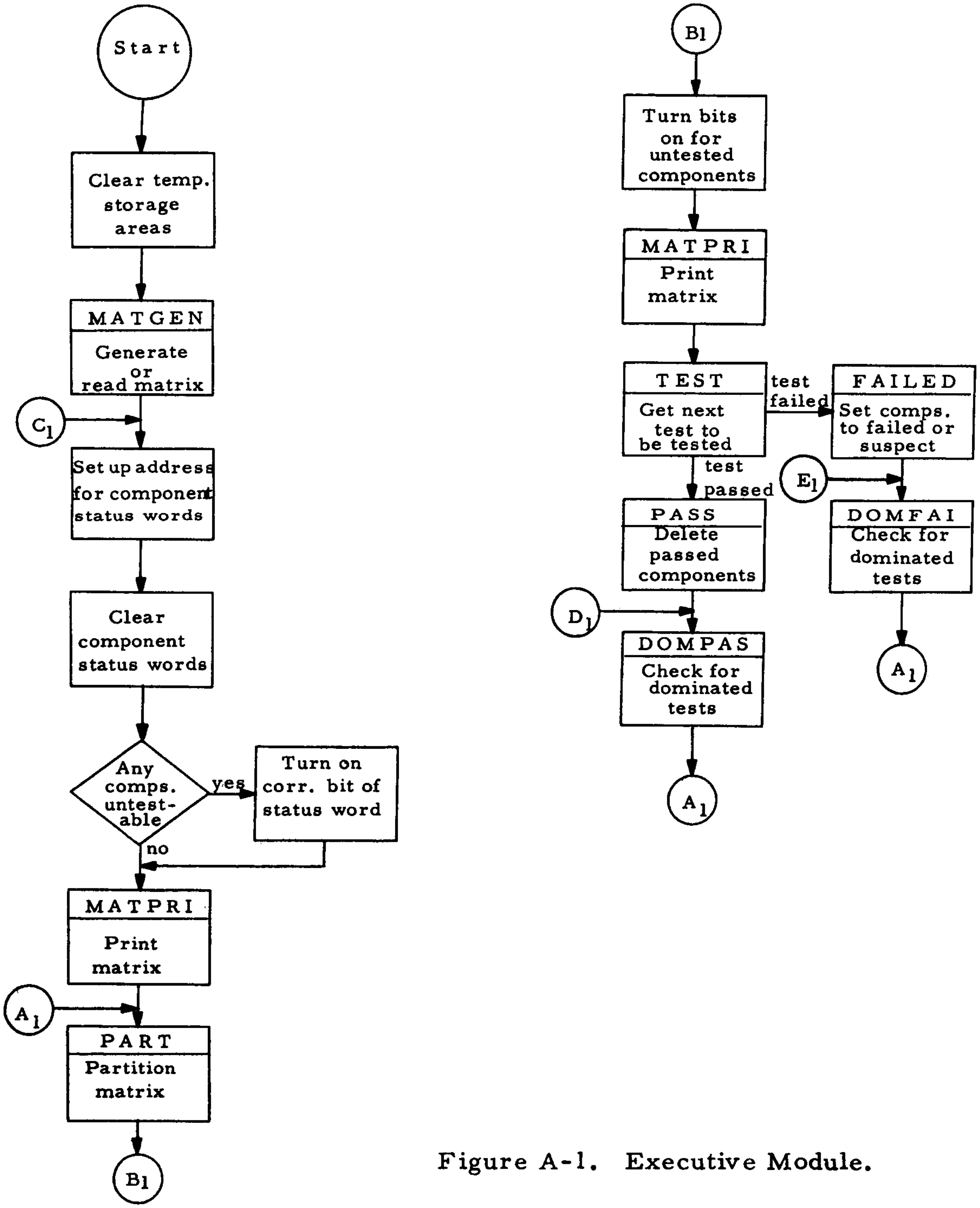


Figure A-1. Executive Module.

## MATGEN SUBROUTINE

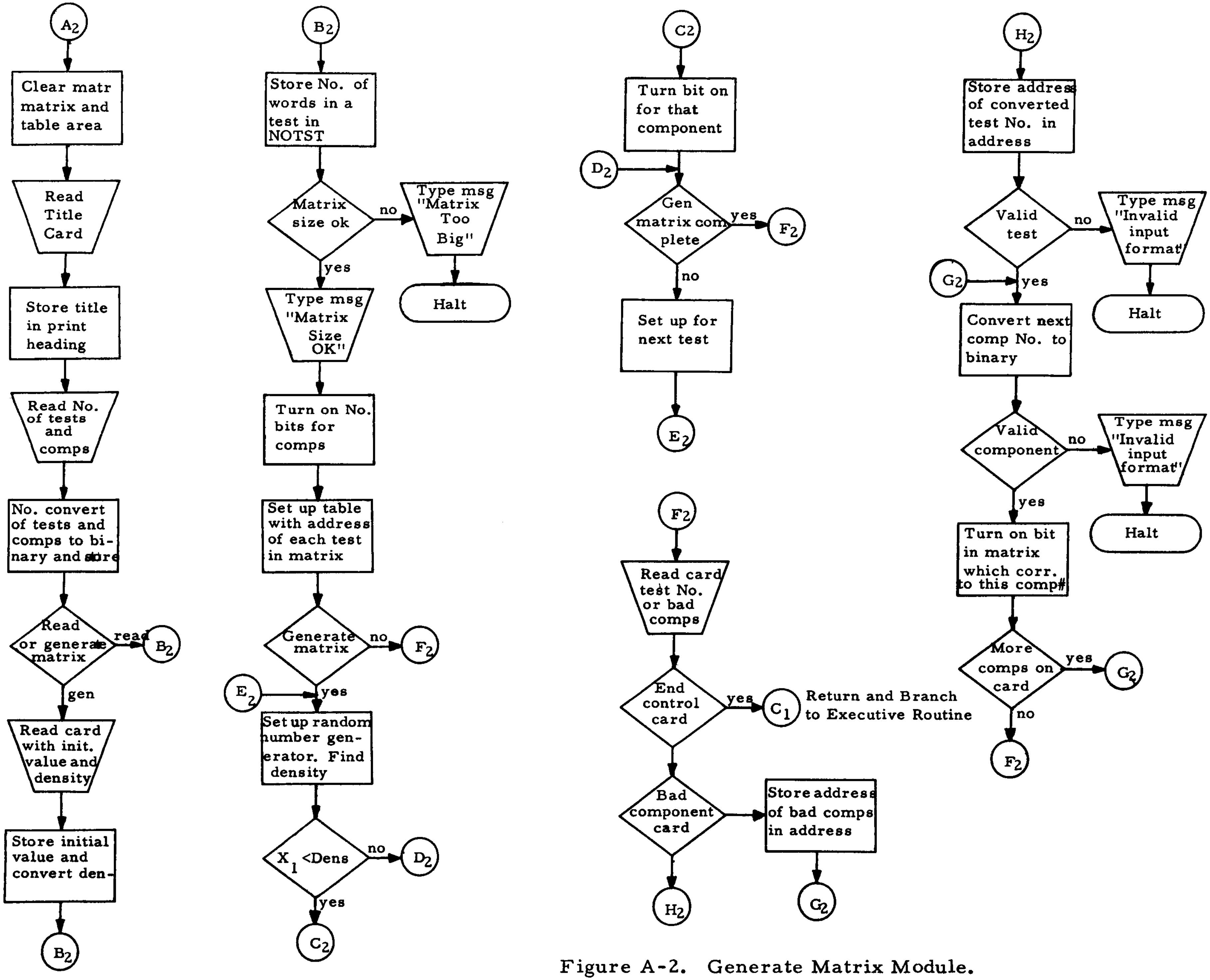


Figure A-2. Generate Matrix Module.

PART SUBROUTINE

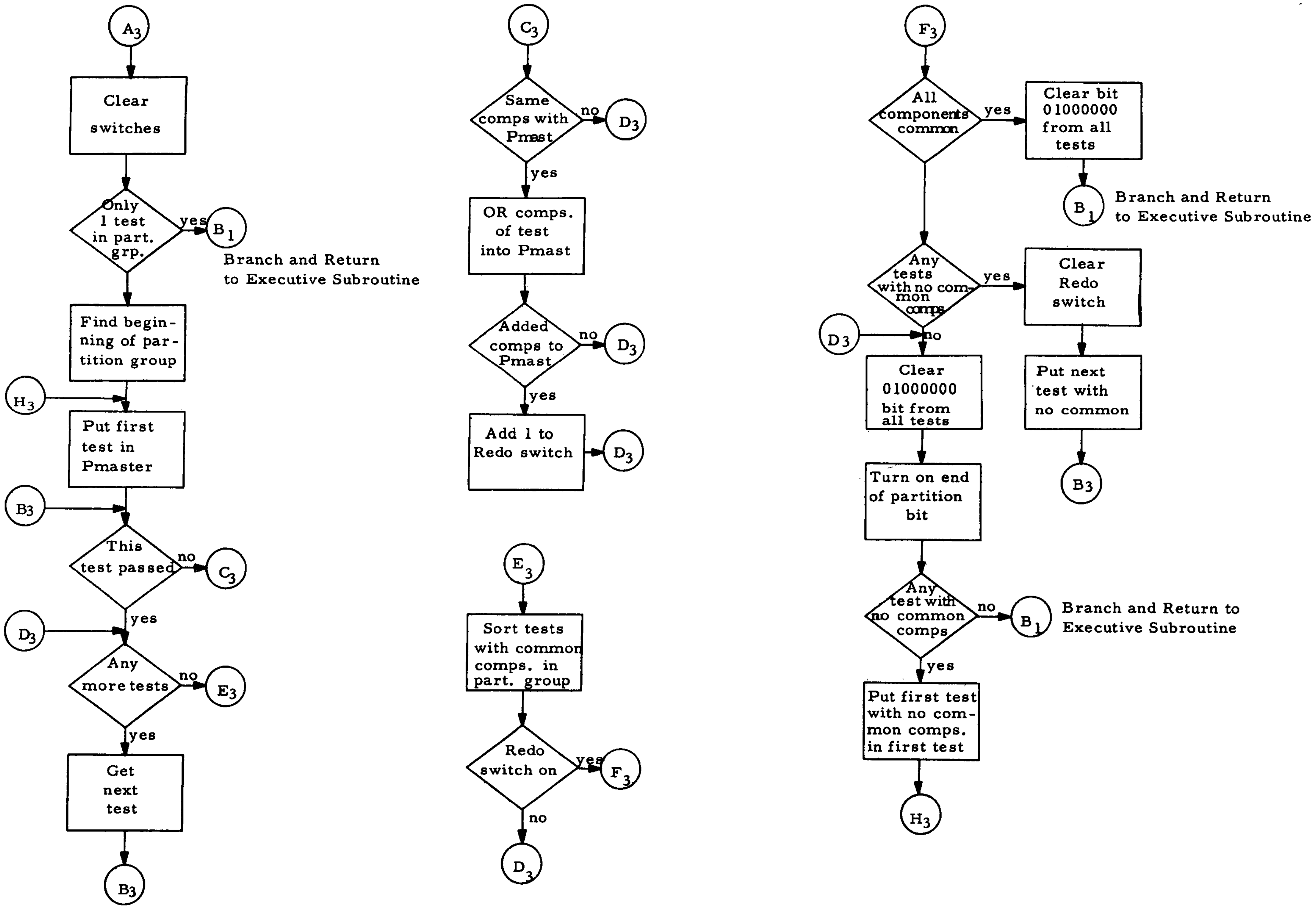


Figure A-3. Partition Matrix Module.

MATPRI SUBROUTINE

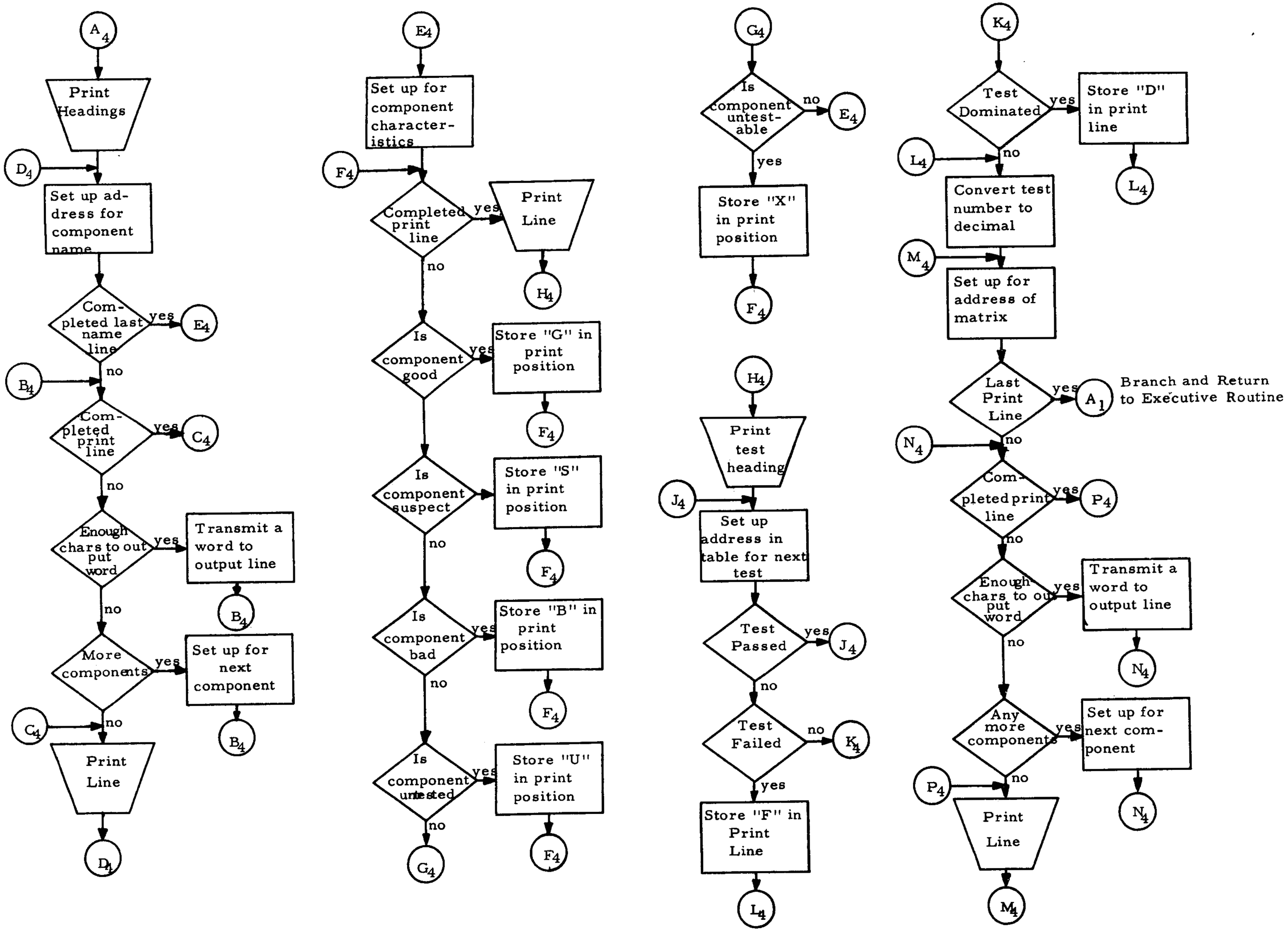
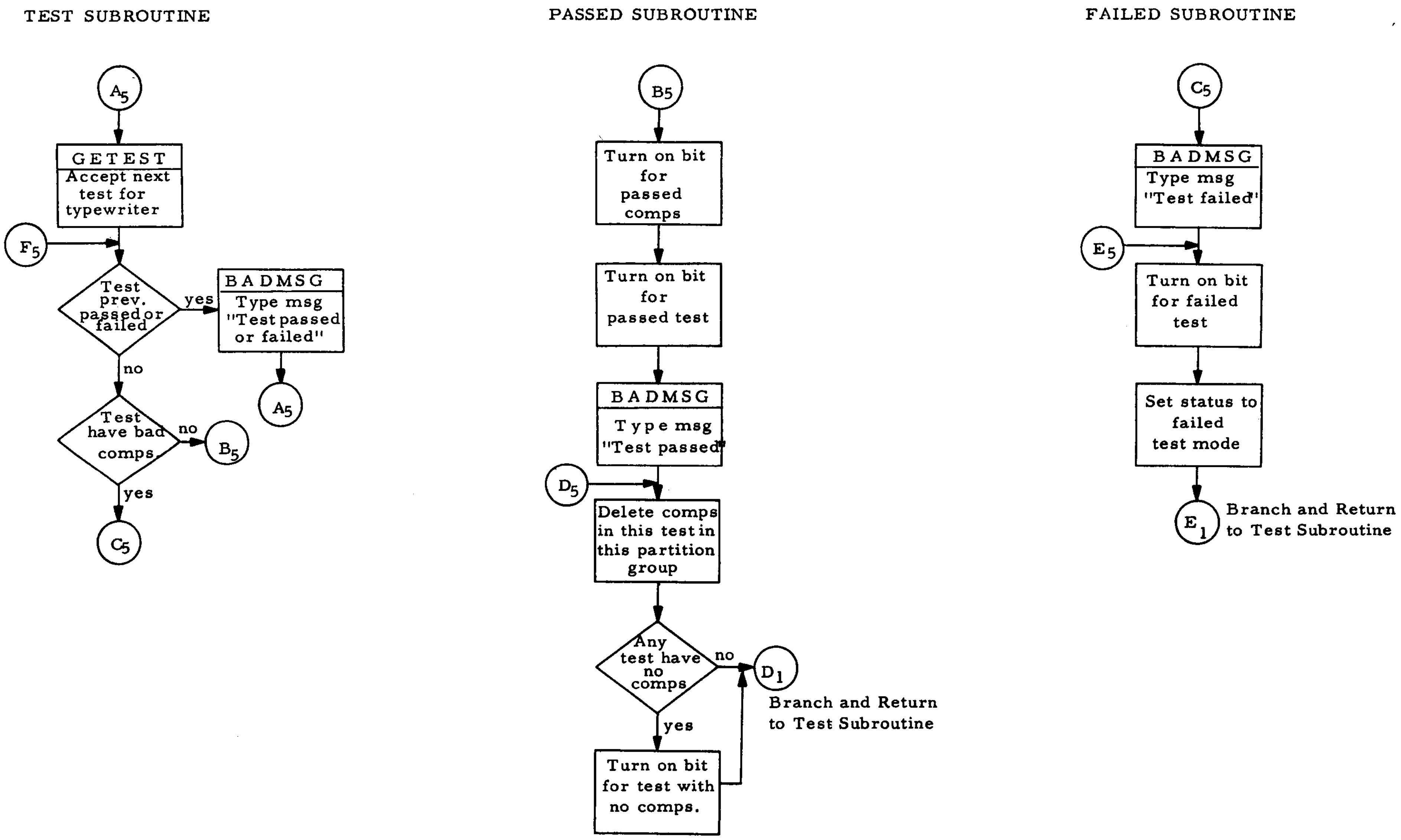


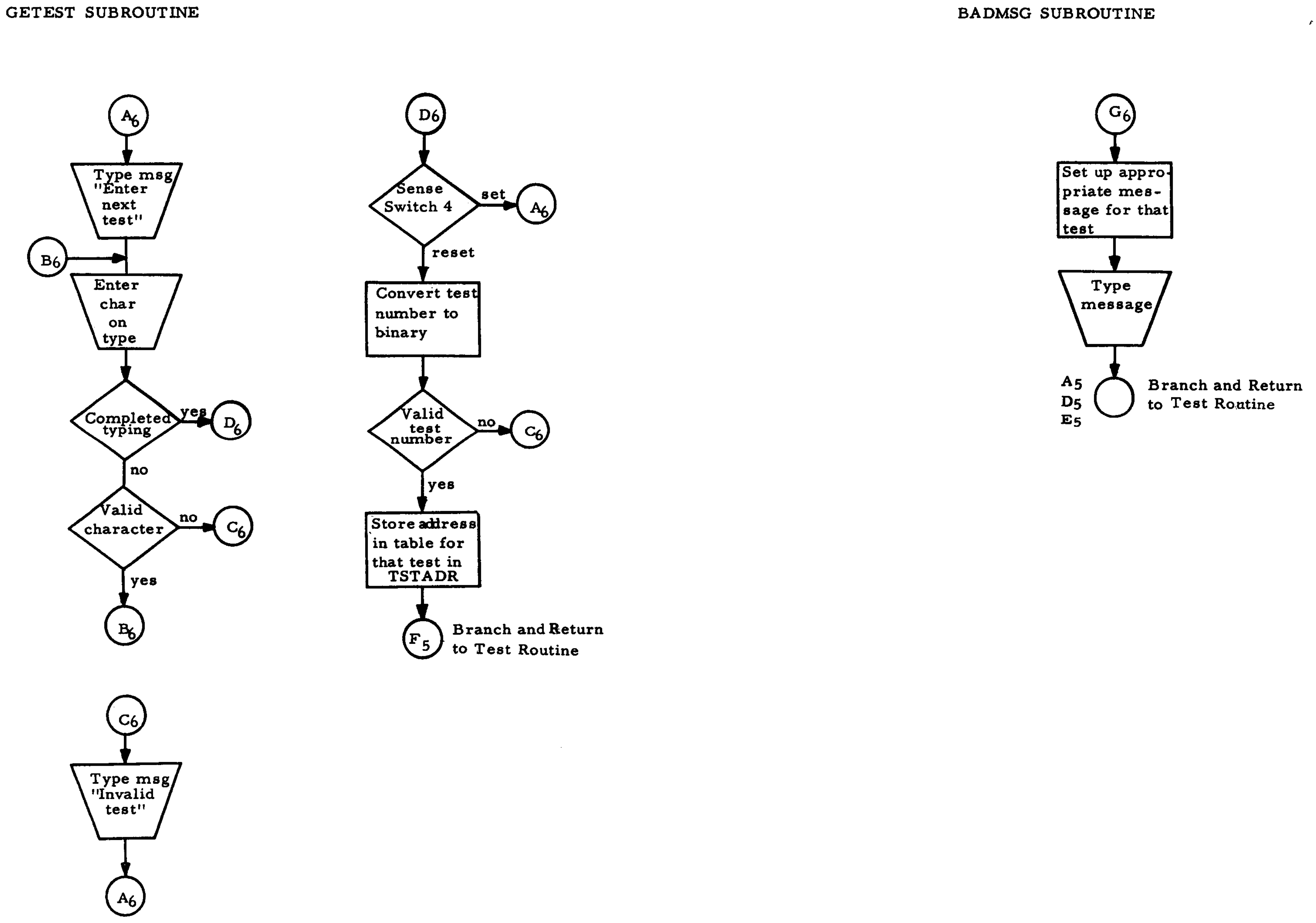
Figure A-4. Print Module.


TEST SUBROUTINE

PASSED SUBROUTINE

FAILED SUBROUTINE

Figure A-5. Test, Passed and Failed Modules.


GETEST SUBROUTINE

BADMSG SUBROUTINE

Figure A-6. Typewriter Input-Output Modules.

DOMPAS AND DOMFAI SUBROUTINE

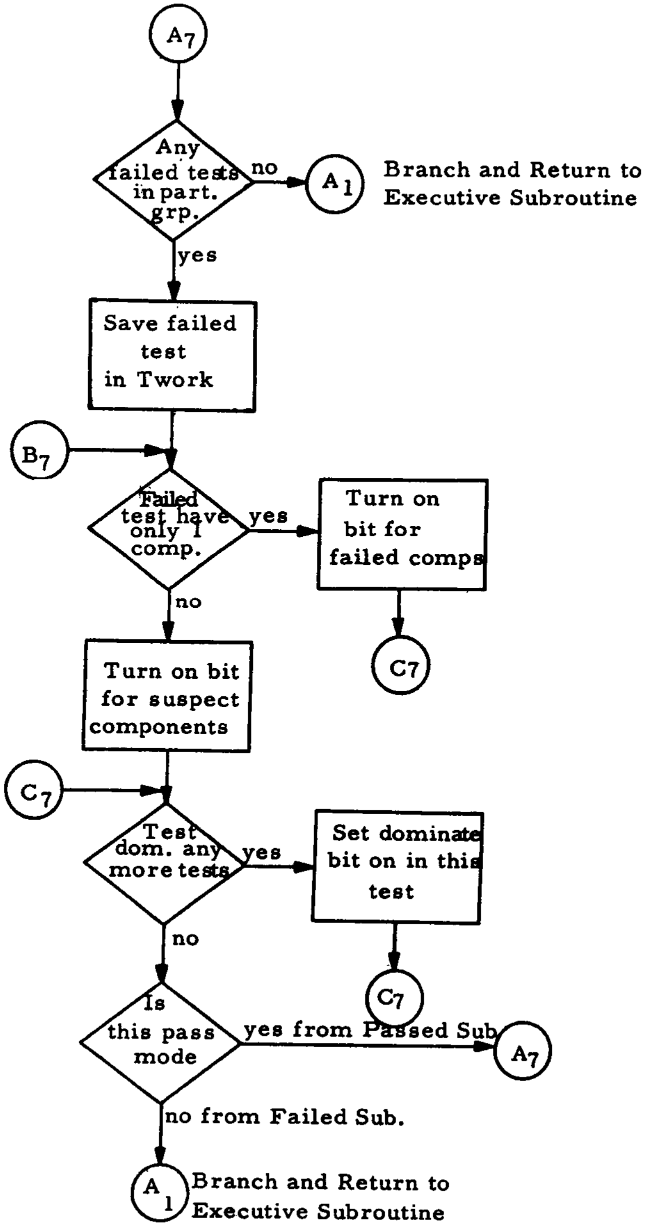


Figure A-7. Dominated Module.

# APPENDIX B

## Experimental Investigation of Fault Isolation Using the Test Matrix

## Introduction

This experiment was undertaken to evaluate the utility of the Test Matrix technique. It was designed to yield information about the effect of the technique on the number of tests used, the number and types of errors made and the efficiency of fault isolation procedures. Each subject served as his own control and was run under two conditions: (1) using a circuit diagram and a listing of possible failures and available tests; and (2) using these materials plus a Test Matrix.

## Experimental Materials

The equipment used for this experiment was a relatively simple five-tube superheterodyne receiver originally designed for the U. S. Navy. A total of 17 test points and 22 possible failures were indicated on the schematic diagram for this receiver. A copy of this schematic with the possible failure sources and available test points indicated, is reproduced in Figure B-1.

The corresponding test matrix was constructed following a careful analysis of the equipment and of all the effects of the occurrence of each failure considered. Three types of measurement could be obtained at each test point; therefore 17 x 3 = 51 separate tests were available. However, some of these tests turned out to be identical in terms of the failure sources considered, and they were consolidated into 36 different tests (this identification of equivalent tests is one of the advantages of the Test Matrix technique). The resulting matrix consisted of 792 elements. It is depicted in Figure B-2.

For the "without matrix" condition each subject was provided with a copy of the schematic, a listing of the test points, and a brief description of each of the possible trouble sources. For the "with matrix" condition, each subject was presented with the same set of materials plus a copy of the Test Matrix. Subjects were allowed to make notes on the schematic and matrix; a clean copy of all materials was provided to each trial.

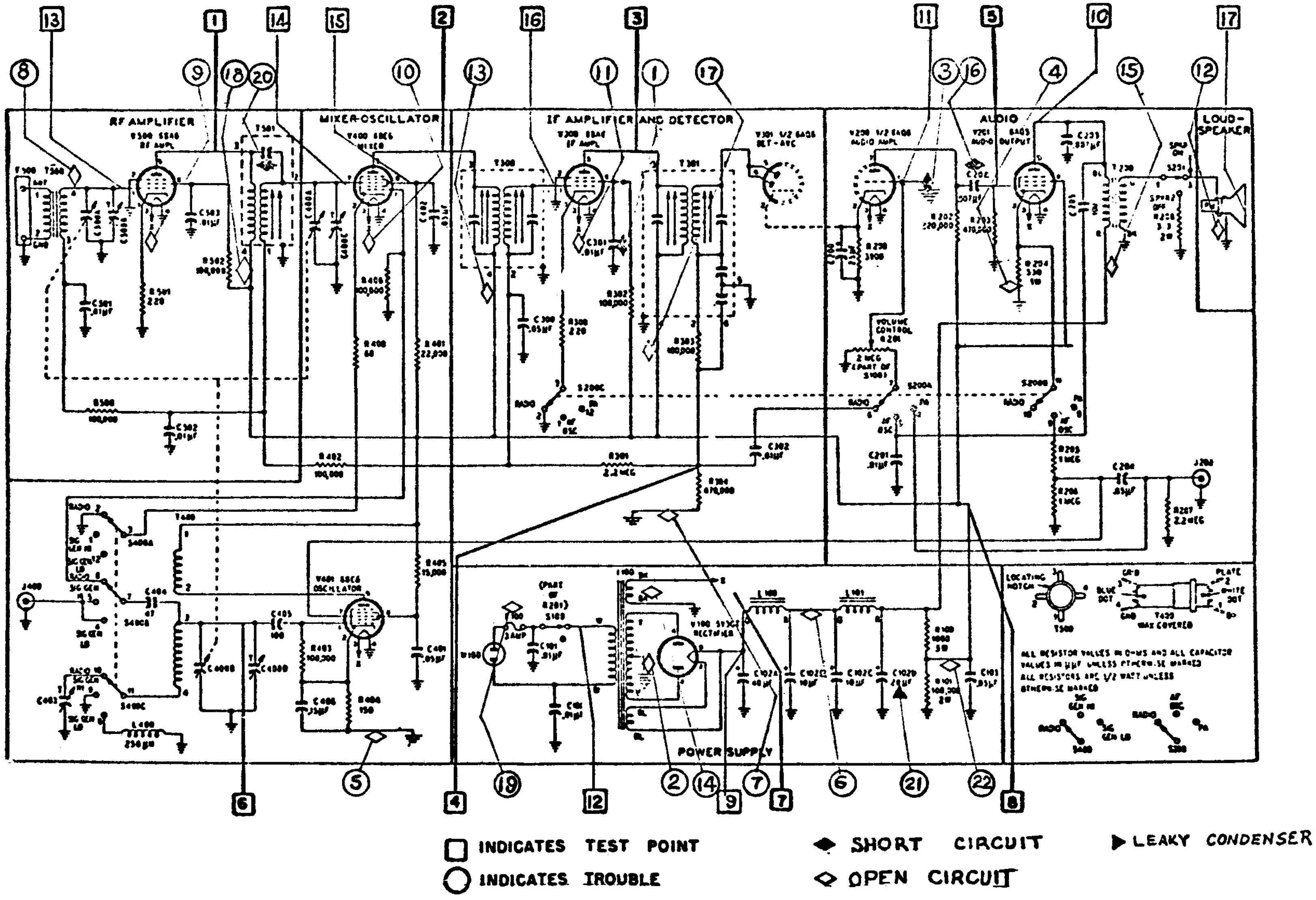


Figure B-1. Schematic of Equipment Used in Test Matrix Experiment.

| Test Point | 1 | | | 2 | | | 3 | | | 4 | | 5 | | 6 | | 7 | 8 | | 9 | 10 | | | 11 | | | 12 | 13 | | | 14 | | | 15 | 16 | | 17 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Instrument | S | D | V | S | D | V | S | D | V | SD | V | D | V | S | DV | all | SV | D | all | S | D | V | S | D | V | all | S | D | V | S | D | V | S | D | V | – | |
| Equivalence | | | | 16S | | | | | | 5S | | | | | 15DV | | | | | | | | | | | | | | | | | | | | | | |
| Test No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | |
| Test Result | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | F | |
| **Failure Sources** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | | | | | | | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | | | | | | | ■ | 11 |
| 2 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | 34 |
| 3 | | | | | | | | | | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | | | | | | | ■ | 9 |
| 4 | | | | | | | | | | | | | | | | | | | | ■ | | ■ | | | | | | | | | | | | | | ■ | 3 |
| 5 | | | | ■ | | | ■ | | ■ | ■ | ■ | | ■ | ■ | ■ | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | | | | ■ | | ■ | ■ | 16 |
| 6 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | 33 |
| 7 | ■ | | | ■ | | | ■ | | | ■ | | | | | | | | | | ■ | | | ■ | | | | ■ | | | ■ | | | ■ | | | ■ | 10 |
| 8 | ■ | | ■ | ■ | | ■ | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | ■ | | ■ | ■ | | ■ | | | ■ | ■ | 26 |
| 9 | ■ | | ■ | ■ | | ■ | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | ■ | | ■ | | ■ | | | ■ | ■ | 19 |
| 10 | | | | ■ | | ■ | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | | ■ | | | | ■ | ■ | 15 |
| 11 | | | | | | | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | | | | | ■ | | ■ | 12 |
| 12 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | 1 |
| 13 | | | | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | | | | | | ■ | ■ | 15 |
| 14 | ■ | | ■ | ■ | | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | | ■ | ■ | ■ | ■ | | | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | 26 |
| 15 | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | | ■ | 4 |
| 16 | | | | | | | | | | ■ | ■ | ■ | ■ | | | | | | | ■ | | ■ | | | | | | | | | | | | | | ■ | 7 |
| 17 | | | | | | | ■ | ■ | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | | | | | ■ | | ■ | 13 |
| 18 | ■ | ■ | ■ | ■ | | ■ | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | ■ | | ■ | | | ■ | ■ | 19 |
| 19 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | 36 |
| 20 | | | | ■ | | ■ | ■ | | ■ | ■ | ■ | | ■ | | | | | | | ■ | | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | | | ■ | ■ | 17 |
| 21 | ■ | | | ■ | | | ■ | | | ■ | ■ | | | ■ | | | ■ | | | ■ | | | ■ | | ■ | | ■ | | | ■ | | | ■ | | | ■ | 14 |
| 22 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | ■ | | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | 32 |
| Dot Count | 10 | 5 | 8 | 14 | 5 | 11 | 17 | 5 | 15 | 19 | 18 | 6 | 17 | 7 | 6 | 2 | 5 | 4 | 2 | 21 | 4 | 19 | 18 | 16 | 17 | 1 | 7 | 6 | 5 | 11 | 7 | 9 | 8 | 7 | 12 | 22 | |

S: scope D: DC voltmeter V: VTVM

Figure B-2. Test Matrix for Equipment of Figure B-1.

## Subjects

A total of 12 engineering technicians were used as the experimental subjects. These subjects were selected from a group of 18 on the basis of previous trouble shooting experience and scores on a pretest designed to insure their understanding of the equipment. Each subject was given a one-hour lecture on the equipment and a 1-1/2 hour lecture and demonstration on the use of the Test Matrix. None of the subjects had previously been exposed to the Test Matrix technique.

## Experimental Design

Of the 22 possible component failures shown in Figure B-1, eight single-component and two double-component failures were selected, using a table of random numbers. These 10 failures (labeled A - K) were divided into two groups as shown in Table B-1.

TABLE B-1

Assignment of Failures to Groups

| Group | Single-Component Failures Unique to Group | Single-Component Failures Common to Groups | Double-Component Failures |
|---|---|---|---|
| $\alpha$ | A, B, C | D, E | J |
| $\beta$ | F, G, H | D, E | K |

The subjects were randomly divided into two equal groups. The first group was presented with the alpha failures in the "with matrix" condition and with the beta failures in the "without matrix" condition. The other half of the test subjects were assigned the reverse conditions. As shown in Table B-1, two of the failure cases, D and E, were included in both the alpha and beta groups to allow evaluation of the differences between the matrix and non-matrix approaches without introducing variance effects due to subjects or failure cases.

An attempt was made to determine whether a priori knowledge that only a single failure was present in any trial had any effect on trouble shooting strategy or efficiency. Each subject was presented with one trial on which he was told that only a single failure was present; this trial was randomly selected for each subject. On all other trials he was told only that at least one failure had occurred. Each subject was presented with a total of six trials under each of the two conditions ("with matrix" and "without matrix"). The order in which subjects were exposed to the two conditions was counterbalanced to eliminate practice effects and the sequence of trials within each condition was randomized for each subject for the same reason. Two days elapsed between conditions for each subject. The overall experiment plan is shown in Table B-2.

## Methodology

At the start of each experimental trial, each subject was given the materials for the appropriate experiment condition and asked to determine the status of all the 22 possible failure sources as best he could, given the available tests and to do this using a minimum number of tests. Subjects were told they could select DC, AC, or Oscilloscope readings at each of the indicated test points. The subjects were instructed to select a given measurement and test point, one at a time, and to inform the experimenter of their choice. The test outcome (pass or fail) was then provided by the experimenter. Subjects were instructed to report those components that they had classified as good or faulty following each test, and then to proceed to the next test until they felt that the status of all components had been adequately designated or until no more information could be obtained by further testing.

For each of the trials, the following information was recorded by the experimenter:

1. Identity of the test subject and the experimenter.
2. The experimental condition (with or without matrix) and failure case.
3. Date and time the experiment was begun.

## TABLE B-2

### Experimental Plan

| Experiment Condition | Group of Failure Cases | Day | Test Subject | Order of Presentation 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|---|---|
| Non-Matrix | α | 1 | 1 | C | B | E | D | J | (A) |
| | | | 2 | B | E | C | D | (A) | J |
| | | | 3 | J | A | D | B | (C) | E |
| | | 3 | 4 | A | J | C | E | (B) | D |
| | | | 5 | D | C | A | E | (B) | J |
| | | | 6 | E | J | B | A | D | (C) |
| Matrix | β | 3 | 1 | F | E | H | (G) | K | D |
| | | | 2 | E | H | F | (G) | D | K |
| | | | 3 | K | D | G | E | (F) | H |
| | | 1 | 4 | D | K | F | (H) | E | G |
| | | | 5 | G | F | D | (H) | E | K |
| | | | 6 | H | K | E | D | G | (F) |
| Matrix | α | 2 | 7 | C | B | E | D | J | (A) |
| | | | 8 | B | E | C | D | (A) | J |
| | | | 9 | J | A | D | B | (C) | E |
| | | 4 | 10 | A | J | C | E | (B) | D |
| | | | 11 | D | C | A | E | (B) | J |
| | | | 12 | E | J | B | A | D | (C) |
| Non-Matrix | β | 4 | 7 | F | E | H | (G) | K | D |
| | | | 8 | E | H | F | (G) | D | K |
| | | | 9 | K | D | G | E | (F) | H |
| | | 2 | 10 | D | K | F | (H) | E | G |
| | | | 11 | G | F | D | (H) | E | K |
| | | | 12 | H | K | E | D | G | (F) |

Note: () indicate that subject was informed that he was being presented with a single failure case.

4. The elapsed time for each trial.

5. The tests called for by the subject and the sequence in which they were requested.

6. The total number of tests called for.

7. The status of each component, as designated by the test subject (good, faulty, ambiguous).

8. At which point in the testing sequence he designated a component's status.

9. Any changes in status designation and when they were made (the last designation was used in scoring).

10. Any notes the experimenter made during the evaluation.

## Data Analysis

Three types of analysis were performed on the data gathered. The data were first studied factor by factor without any attempt to weight and combine them. For example, the number of faulty components diagnosed as "good" was compared for the matrix approach vs. the non-matrix approach. The number of faulty components diagnosed as "ambiguous" was compared for the matrix and non-matrix approach. Secondly, overall comparisons were made combining the factors into a single figure of merit, the diagnostic efficiency. Thirdly, the data were checked for evidence of improvement with time which could result from practice effects or collusion among test subjects between testing sessions. No consistent trends for these two causes were found. This is attributed to a variety of factors, including: the intentional lack of feedback on test results (inhibited learning); the absence of failure case identification to the subjects; and the competition between subjects to earn the bonus paid for better than median test scores.

The diagnostic efficiency function used was:

$$E = n_t C_t + \frac{1}{\eta} n_{ij} \quad C_{ij} \quad - n_o C_t$$

where,

$$\eta = \frac{\sum_k n_{kk}}{\sum_k n_{kk} + \sum_{ij} n_{ij}}$$

$$\left.\begin{array}{l} i = g,\ a,\ f \\ j = g,\ a,\ f \\ k = g,\ a,\ f \\ i \neq j \end{array}\right\} \quad \text{i.e., good, ambiguous by virtue of any possible tests, or faulty.}$$

$n_{ij}$ is the number of components designated "j" which are truly "i".

$n_{kk}$ is the number of "k" components that are correctly designated.

$n_t$ is the number of tests performed.

$n_o$ is the minimum number of tests required to identify the status of as many components as possible.

$C_{ij}$ is the cost of incorrectly designating a component as "j" which is truly "i".

$\left[n_{ij}\right]$ is the matrix of the number of diagnostic errors.

diagnosed component status
reported by subject

$$\begin{array}{cc} & \begin{array}{ccc} g & a & f \end{array} \\ \text{true component status} \begin{array}{c} g \\ a \\ f \end{array} & \left[\begin{array}{ccc} - & n_{ga} & n_{gf} \\ n_{ag} & - & n_{af} \\ n_{fg} & n_{fa} & - \end{array}\right] \end{array}$$

$\left[C_{ij}\right]$ is the matrix of assigned costs or weights for each mistaken diagnosis.

diagnosed component statuses

$$\begin{array}{ccc} & & \begin{array}{ccc} g & a & f \end{array} \\ \text{true component status} & \begin{array}{c} g \\ a \\ f \end{array} & \left[\begin{array}{ccc} - & C_{ga} & C_{gf} \\ C_{ag} & - & C_{af} \\ C_{fg} & C_{fa} & - \end{array}\right] \end{array}$$

$\left[C_{ij}\right]$ is the matrix $\left[C_{ji}\right]$

$C_t$ is the cost of each test performed

the value of $C_{ij}$ is set to

$$C_t \left[\begin{array}{ccc} - & 1 & 3 \\ 2 & - & 2 \\ 40 & 1 & - \end{array}\right]$$

and setting $C_t$ to 1,

$$C_{ij} = \left[\begin{array}{ccc} - & 1 & 3 \\ 2 & - & 2 \\ 40 & 1 & - \end{array}\right]$$

The values in the $C_{ij}$ matrix are somewhat arbitrary. We have said that $C_{ga} = C_{fa} = C_t = 1$. That is, if a component is incorrectly designated as unknown, we can correctly determine its status after making typically one more test. We have further said that $C_{ag} = 2\ C_{ga} = 2$. That is, if a component is truly ambiguous but is designated as good, we are probably correct but will never find out through further tests. Arbitrarily, we set the cost of such an error at twice $C_{ga}$. We set $C_{af} = 2\ C_t = 2$. That is if a component is truly "ambiguous" but we call it "faulty" it will be replaced unnecessarily at a cost of two tests. We set $C_{gf} > C_{gf} = 3$. That is, if the component is truly "good" and we call it "faulty" it is worse than if it were "ambiguous" (insofar as any testing could show) and hence possibly faulty. Lastly, we set $C_{fg} \gg C_{ag}$. That is, if a component is truly "faulty" but designated "good" the costs incurred are far greater than if the component is "ambiguous". If we say that 5% of the components are faulty then the risk involved when an ambiguous component is designated as "good" would be approximately 5% of the risk when a faulty component is designated "good". Which is to say that

$$C_{ag} \cong .05\, C_{fg}$$

or

$$C_{fg} \cong 2/.05 = 40$$

As an example of a calculation of E, the diagnostic efficiency, when test subject 5 was asked to diagnose failure case A with non-matrix methods he performed 10 tests before he felt he could gain no further information with additional tests. Actually, only six tests were required to extract all the information possible under the conditions of case A. Also, the subject diagnosed three of the 22 components incorrectly. A faulty component was designated "good", an ambiguous component was designated "good" and an ambiguous component was designated "faulty".*

Thus for this subject

$$n_{fg}=1,\ n_{ag}=1,\ n_{gg}+n_{aa}+n_{ff}=22-3 = 19,\ n_t=9,\ n_o=6,\ C_t=1$$

$$\eta = 19/22 = .865$$

$$E = 10(1) + \frac{1}{.865}\left(1(40)+1(2)+1(2)\right) - 6(1) = 55$$

A diagnostic efficiency score was derived for each of the 144 evaluations (12 subjects x 6 trials x 2 conditions). An analysis of variance was made and factors of interest were compared.

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*The ambiguous components could not properly be designated good or faulty because the components which definitely were faulty would mask the test results of ambiguous components, regardless of their condition.

## Test Results

The matrix technique was significantly superior to the non-matrix analysis of errors. In the aggregate the non-matrix cost scores were 2099.7 and the matrix cost scores were 538.7. That is, the non-matrix approach resulted in 3.9 times the excess costs of the matrix method. Independently of the function used in scoring, we find that 12 times as many subjects called bad components good using the non-matrix method as compared to the matrix method. Though the cost significance of this may vary in different circumstances, it is typically the most serious of errors. In all other categories of error, the matrix approach was far less costly than the non-matrix method. The matrix approach also required fewer excess tests to get the better results. The raw data comparisons between the schematic and matrix approaches are summarized in Table B-3. It is significant to note that regardless of the weighting function that might be selected, the matrix method would score best since it gave better results in all categories.

TABLE B-3

Comparison of Matrix and Schematic Approaches, Independent of Cost Factors

| | S | M | Ratio |
|---|---|---|---|
| $n_{bg}$ | 24 | 2 | 12.0 |
| $n_{bu}$ | 17 | 4 | 4.2 |
| $n_{ug}$ | 57 | 8 | 7.1 |
| $n_{ub}$ | 27 | 19 | 1.4 |
| $n_{gb}$ | 42 | 13 | 3.2 |
| $n_{gu}$ | 93 | 34 | 2.9 |
| | 260 | 80 | 3.2 |
| excess tests | 315 | 278 | 1.1 |

To remove the effects of variances caused by differences in failure cases, a separate study was made of failure cases D and E. It will be recalled that D and E were presented to all subjects in both the matrix and non-matrix conditions. For both D and E each group of three men tested at one time using the same technique did better with the matrix than without it. This was true regardless of whether the subjects used the matrix or the non-matrix approach first. For failure D the difference was greater when the non-matrix method was used first; for failure E the difference was greater when the matrix method was used first. The results are summarized in Table B-4.

### TABLE B-4

### Comparison of Cost of Schematic and Matrix Approaches for Failure Cases D and E

| | Subjects | Case D | | Case E | |
|---|---|---|---|---|---|
| Schematic approach first | S(1, 2, 3) | 130.0 | | 18.0 | |
| | S(10, 11, 12) | | 112.1 | | 63.6 |
| | M(1, 2, 3) | -14.2 | | -13.0 | |
| | M(10, 11, 12) | | -62.6 | | -13.0 |
| | total (1, 2, 3) | 115.8 | | | |
| | total (10, 11, 12) | | 49.5 | | |
| | total (1, 2, 3, 10, 11, 12) | | +165.3 | | +55.6 |
| Matrix approach first | S(4, 5, 6) | 29.0 | | 30.4 | |
| | S(7, 8, 9) | | 22.9 | | 74.0 |
| | M(4, 5, 6) | -24.8 | | -10.1 | |
| | M(7, 8, 9) | | -8.0 | | -21.5 |
| | total (4, 5, 6) | 4.2 | | 20.3 | |
| | total (7, 8, 9) | | 14.9 | | 52.5 |
| | total (4, 5, 6, 7, 8, 9) | | +19.1 | | +72.8 |
| overall total | | | 184.4 | | 128.4 |

Note: Schematic was more costly for all groups of subjects.

Breaking the raw data down further and comparing each of the twelve subjects scores for cases D and E, in 20 out of the 24 cases the matrix was superior to the non-matrix approach, in 3 out of 24 cases the reverse was true, and in one case both approaches gave the same results. Table B-5 shows the difference in scores for each subject using the schematic and matrix approaches. We conclude that the matrix approach is statistically significantly better at the .999 level of confidence.

TABLE B-5

Comparison of Scores for All Subjects
for Cases D and E

| Subject | Difference | |
|---|---|---|
| | D | E |
| 1 | 15.5 | 3.0 |
| 2 | 46.7 | 0 |
| 3 | 53.7 | 2.1 |
| 4 | 6.9 | 13.0 |
| 5 | 1.2 | 6.0 |
| 6 | 3.9 | 1.3 |
| 7 | 5.5 | 5.4 |
| 8 | 8.9 | 48.7 |
| 9 | .5 | -2.0 |
| 10 | 68.8 | -2.0 |
| 11 | -26.4 | 48.2 |
| 12 | 7.1 | 51.8 |

Comparing the data gathered for Cases D and E for learning during the test we conclude that there was no learning during the tests, and the sequences of tests were not therefore of any significance. Table B-6 summarizes the score results for all subjects for these cases.

## TABLE B-6

### Lack of Improvement in Solving Cases D and E

| | Case D | Case E |
|---|---|---|
| Schematic Approach Improvements | 100.3 | -22.7 (i.e., negative learning) |
| Matrix Approach Improvements | -44.0 (negative learning) | |
| Overall Improvements | 56.3 | -17.1 (negative learning) |

Considering all failure cases, no learning trend (decreased cost with sequence number) was observed. The result is shown in Table B-7.

## TABLE B-7

### Scores as a Function of Sequence of Presentation

| | Total of All Scores Earned | |
|---|---|---|
| Sequence Number | Schematic Approach | Matrix Approach |
| 1st | 335.5 | 119.5 |
| 2nd | 338.5 | 101.8 |
| 3rd | 367.3 | 70.0 |
| 4th | 381.0 | 54.3 |
| 5th | 381.6 | 55.1 |
| 6th | 232.9 | 138.2 |

Knowledge that a case dealt with a single component failure did not seem to improve score results; subjects tended to jump to (the wrong) conclusions in what they felt were easy cases. Observations made outside of the context of the experiment indicate that improvements would occur in this case, when the analyst is more skilled in the matrix methodology.

## Conclusions

In conclusion, the data gathered tend to demonstrate the superiority of the matrix approach even when the test subjects were given only a very few hours of instruction in the matrix method. The need for true cost factors was made obvious for the construction of a realistic scoring mechanism.