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DEVELOPMENT OF FULLY PROCEDURALIZED TROUBLESHOOTING ROUTINES

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FOREWORD

This study was initiated by the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. It represents a portion of the exploratory development program conducted under Task 171004, "Techniques for Training, Aiding and Evaluating the Performance of Technical Tasks" of Project 1710, "Human Factors in the Design of Training Systems." Dr. Gordon A. Eckstrand was project scientist. Dr. Ross L. Morgan was task scientist. This research was begun in April 1966 and was completed in November 1966.

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This technical report has been reviewed and is approved.

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ABSTRACT

Several studies over the past decade have shown that proceduralized troubleshooting can produce acceptable or better performance of this complex maintenance task while permitting substantial reduction in the costly training typically associated with its accomplishment. The term "proceduralized troubleshooting" is usually applied when the decision about where in the system the technician is to check next, based on the results of previous checks, is made by a performance aid which directs his actions. This same performance aid, however, can also display expected normal readings and tolerance, test point locations, test equipment and test selection parts identification, and much other necessary and/or useful guidance. The method described follows from experiences with and subsequent to development of a fully proceduralized within stage troubleshooting performance system for purposes of experimental evaluation. It is based upon the rationale of maximizing information gain per unit test or operation cost. Examples of troubleshooting procedures developed for use in the evaluation are presented and described.

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INTRODUCTION

Corrective maintenance of Air Force electronic equipment entails high cost from many sources, and among the most severe high cost sources are those related to personnel. Long and intensive resident training preparatory to assignment to an electronic maintenance job imposes high intellectual requirements on trainees. The cost of the lengthy training courses, frequently almost a year long, is extremely high. Even after completion of resident training, on-job training of six months to one year is frequently required before a technician is thought to be fully productive. During his apprenticeship the consequences of corrective maintenance errors, in terms of equipment damage, extended down time, and unnecessary consumption of valuable spares, may add substantially to the cost and, to make the problem worse, the vast majority of first enlistment technicians fail to reenlist.

All of these severe cost-producing situations: expensive training, delayed productivity, poor productivity, and even failure to retain productive personnel (they are highly sought after in the civilian labor market) result from a job design which specifies that the technician should have the ability, given a circuit diagram, to:

1. Determine what components are suspect as possibilities for containing the malfunction given the observed symptoms.
2. Decide where in the circuitry and how, that is, with what test equipment, to check so as to eliminate suspect components as possibilities.
3. Determine normally expected readings and tolerances at any place in the circuit he may desire to check.

One might reasonably ask if it is necessary for the Air Force technician's job to be structured in such a way as to require him to solve the above kinds of problems (repeatedly) as he troubleshoots problem after problem throughout his life as a technician. It is particularly questionable when the costs incurred in training and in the inefficiency of this repetition are multiplied by thousands of Air Force technicians. It would appear to be, at least theoretically, possible to specify once the solution to each of these problems for all of the malfunctions that might possibly occur in a piece of equipment, and supply the solutions with the equipment. The job strategy embodying this approach, wherein the technician's actions are guided in troubleshooting by a performance aid rather than by his own decisions (solutions to the 3 problems mentioned above) has been called proceduralized troubleshooting.

Several studies over the past decade have shown that proceduralized troubleshooting is feasible practically as well as theoretically. A body of experimental evidence (References 1-5, 9) is accumulating which points toward several eventual conclusions: fewer errors, shorter time, smaller variances and, in some instances, lower aptitude requirements under proceduralized troubleshooting regimens as compared to conventional (decision troubleshooting) regimens. Relevant to the personnel-related cost of electronic maintenance, however, the most important (and virtually universal) finding is that proceduralized troubleshooting can reduce the training time required for even complex corrective maintenance tasks to as little as a few dozen hours.

Generally, the large savings in training time can be attributed to the elimination of functional redundancy in training and performance aids. Functions accomplished by the troubleshooting procedure and the performance aid that presents it to the technician do not have to be learned and performed by the technician. If the technician does not have to be able to decide "where to check next" because the performance aid always tells him, then he does not have to be taught to read schematics, or perform data flow analysis. If the performance aid tells him what the normal reading and tolerance at test points is then he does not have to be taught to deduce, remember, or in other ways determine them. And, likewise, if he is taught in training how to analyze an oscilloscope display to detect out of tolerance conditions, then it is not necessary to provide special instruction or templates or examples of out of tolerance waveforms in the performance aid (though it may be necessary to provide a picture of a "good" display).

The term proceduralized troubleshooting has been used to refer to a wide variety of task designs, the objective of which has been to obviate the necessity for the technician to decide, select, remember, deduce, identify, etc., any or all of a number of facts required for performance of his task. The term is usually applied when the decision about where in the system the technician is to check next--based on the results of previous checks--is made by the performance aid which directs his actions. Troubleshooting procedures can also provide other less obvious advantages. The same performance aid presentation which tells the technician where to check next can also display expected normal readings and tolerances, test point locations, test equipment and test selection, parts identifications, and additional instructions of various sorts. For example, it is possible to reduce the likelihood of error in resistance measurements by specifying a position of the meter selector switch and a scale value. Under these circumstances the technician does not have to decide where to place the switch (based on the expected reading) or convert the scale value to ohms as a function of the multiplier.

The process of developing a troubleshooting procedure requires preparation of a detailed and operational description of the specific behaviors required of the technician. This description provides an unambiguous base upon which training and performance aids can be developed jointly so as to most efficiently insure that the technician will with a high probability produce the appropriate behavior at the appropriate time. It is the typical comprehensiveness, accuracy and level of detail of this description which most differentiates it from conventional military task descriptions and which enable many of the cost savings expected to be associated with proceduralized troubleshooting.

Objections to Proceduralized Troubleshooting

The elimination of functional redundancy in training and performance aids brings with it two important requirements: accuracy and completeness of information both in training and performance aids. Requirements in both of these areas are more severe than in traditional training and performance aids because the latter contain considerable redundancy. For example, if a performance aid does not tell the technician what the expected reading at the output of a particular stage ought to be, there is some probability that he can use his training, i.e., his knowledge of the typical outputs of circuits of this type to determine the expected output. Or perhaps in some cases he could calculate from known circuit parameters the value of the output signal on dimensions of importance.* In the case of proceduralized troubleshooting, however, it is assumed that the performance aid contains the information needed at the appropriate point and that the information is correct. The technician proceeds on this assumption because it is the only way he can proceed since neither his training or his performance aid provides him with any alternative. If the information is absent or in error, the result must be failure to identify the malfunctioning component. When this happens the technician can only repeat the procedure he has just used on the assumption that it was he rather than the procedure which was in error. The problem simply cannot be solved. It is at this point that many object to proceduralized troubleshooting. The conventional type of technician, on the other hand, when faced with failure in a check sequence, may develop new check sequences or may substitute components at random in the area where the malfunction is suspected to exist and might eventually in this manner clear the trouble. However, before objections to proceduralized troubleshooting are raised, these much overlooked questions need to be answered:

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* Empirical evidence indicates that typical technicians do both of these things poorly, if at all. Reference: John D. Folley, Jr., Robert H. Woods, John P. Foley, Jr. The Design and Application of a Method for Specifying an Electronics Maintenance Entry Course. AMRL TDR In publication.

1. Do present proceduralized troubleshooting techniques yield a higher or lower proportion of correct problem solutions than present decision troubleshooting techniques?

2. What is the average solution cost under procedural and decision troubleshooting regimens?

3. Is the cost of developing troubleshooting procedures and implementing the necessary quality control on this process justified in the light of savings resulting from reduced training development and administration costs and the costs or savings implied by the answers to the first two questions?

Until recently no serious attempt has been made to answer any of these questions.

Another important objection to the use of proceduralized troubleshooting has resulted from the exposure of early examples of proceduralized troubleshooting to actual technicians under field conditions. The objection is usually stated as follows: "technicians don't like to use proceduralized troubleshooting and won't accept it".

It is undoubtedly true that some of the early attempts at proceduralized troubleshooting led to procedures which were relatively ineffective, that is, they failed fairly frequently to identify the source of malfunction. In some cases the procedures specified were more lengthy and complex than those which the technician would have used with some success if left to his own devices. In the case of troubleshooting charts (commonly classed erroneously with procedural troubleshooting), it has been said that "they provide the wrong answers to the easy problems and give no help at all on the hard ones".

It must be noted that early attempts at proceduralized troubleshooting neglected many presently employed means for job simplification and ignored the problem of integrated development of training and performance aids. In other words, much more effective procedures can be developed today than those upon which many objectors' opinions are based.

In answer to the same objection another point can be made. The most significant advantage of proceduralized troubleshooting is that it does not require expensive conventional electronics training. In spite of the fact that many highly trained, experienced technicians complain of troubleshooting by procedure as an insult to their training and intelligence, naive experimental subjects have frequently reported enjoyment of procedural troubleshooting tasks and experimenters have observed what can only be described as obvious personal involvement in the tasks.

The foregoing is not to be interpreted as a statement that all the problems associated with proceduralized troubleshooting are solved or even necessarily solvable. Answers to some of the questions implied earlier in this report may even preclude the use of proceduralized troubleshooting in many situations. The intent here is merely to indicate that there is both rational and empirical evidence to justify serious attempts to answer these questions.

Before proceeding to suggested guidelines for developing troubleshooting procedures, it is necessary to present a few concepts required for understanding of what follows.

The Stage Concept

From the troubleshooting standpoint the value of the "Stage" concept has been that it enabled a more or less orderly and rapid selection of test points which could be used to eliminate groups of components from consideration as possible sources of malfunction. In general, two kinds of stages have been described and used for level of abstraction control in data flow performance aids for troubleshooting. A functional stage is the group of components necessary (or present) to accomplish some function such as amplification, clipping, rectification, etc. A conventional stage is a non-linear component such as a tube, transistor, etc. and its associated circuitry.

Though the above definitions are by far the most commonly used, and, for the most part, yield similar data flow configurations, they both have the disadvantage of vagueness in specification of stage limits, particularly when groups of stages are connected together as is typically the case. This vagueness tends to lead to inefficient* check sequences and equivocal checks. More importantly, however, both of the above definitions are adopted from other disciplines rather than being developed to answer the specific needs of the troubleshooter. They are of value only when they lead to the possibility of unequivocal statements about the condition of groups of components. Since it is this characteristic that determines the value of the stage concept to the troubleshooter, it is the characteristic that ought to be reflected in the definition of "Stage". This brings us to a third definition, one which we shall call the data flow stage. A data flow stage is composed of all the components lying or making connection between system inputs, outputs or points such that for each point a test can be made which, if the result of the test is good (within tolerance), unequivocally eliminates all components upstream of the point, and if the result of the check is bad, unequivocally eliminates all components downstream of the point from possibility of

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* Efficiency is defined here as elimination of the maximum number of components from consideration as malfunction possibilities with each check.

containing the malfunction. The "Stream" is the data flow stream. It implies both sequence in time (or dependency) and physical connection (wiring).

Practically speaking, it is usually impossible to identify such points as the data flow stage requires for limits without some means (switches or connection, typically) of separating points from their up or downstream connections. There is always the (admittedly scant) possibility that, for example, a grid is shorted to some other element in a vacuum tube, or that a coupling capacitor is shorted. Problems in feedback circuitry and those involving shorts across power supplies also impose the necessity for physically breaking connections in order to isolate malfunctions. Because proceduralized troubleshooting is so intolerant of equivocal checks--those which provide information only under certain assumptions the truth of which is usually not known in the particular case--it is essential that the definition of stage used draw attention to the possibility of equivocal checks so that it can be reduced or eliminated.

The data flow stage concept also focuses attention on the check or test used at each point and implies that the test should involve all dimensions of the signal which can have a deleterious effect on downstream signals. This, again, is designed to eliminate the possibility of equivocal checks.

Between-Stage vs Within-Stage Troubleshooting

The characteristic that most clearly distinguishes between-stage from within-stage is the clarity of data flow. "Between-stage, particularly if by "stage" is meant "data flow stage", implies a clear temporal or electronic sequence. Any point in the system can be clearly identified as being "upstream" or "downstream", or "before" or "after" any other point with regard to the progress of a signal through the system. This is true even of feedback loops if the option of opening the loop is permitted. Knowledge of the sequence of points or events in the system permits the application of rules of logic to generation of the troubleshooting procedures. Since the dependencies are essentially unidirectional, information obtained at one point in the system permits deductions about other points in the system.

These statements are usually not true within data flow stages. Generally, the interactions among parts within stages are too complex, and the circuits will not function if they are interrupted so that the interactions are simplified. The effect of this difference is that a different set of rules must be used in devising troubleshooting procedures for within stage than for between stage troubleshooting.

The essential difference is that between-stage troubleshooting can take advantage of functional checks of segments of the system.

Within stage must also involve an assessment of static conditions such as applied voltages, resistance, conductance, etc.

An Important Problem in the Development of Troubleshooting Procedures

Tolerances and Test Selection. One of the most difficult problems associated with development of proceduralized troubleshooting routines is the selection of tests and tolerances. For any piece of equipment there are generally two levels at which operating specifications are known; those applying to the individual components, that is, the piece-parts, (resistors, transistors, etc.) of the equipment and the overall operating specifications for the equipment such as output frequency, signal/noise ratio, etc. Between these two levels lie a myriad of test points, signals, and operating parameters the typical condition of which is not always known because it is not always necessary that they be known in order to develop the equipment in question. Since the test sequence in a proceduralized troubleshooting routine may require some of this information--the sequence will specify which--it may become necessary to discover it.

Furthermore, once it is determined that a particular piece of information, for example, the amplitude of the signal at some potential test point is required, the permissable variation in that amplitude must also be known. Though there are many possible rationales for determining the amount of permissible variation, the most common is probably implied by the following question: How much variation is required to produce a deviation from a contract design specification of sufficient magnitude to place it outside permissible limits? The process implied in order to answer this question is one of actually varying the signal at test point x and measuring the system output. Certainly this sort of procedure is outside the scope of normal equipment development activities. Because of this it is not known how efficiently the process could be mechanized or, in general how expensive the information thus obtained would be.

The same comment applies to an alternative procedure which might be employed, that of computer simulation of the equipment in question. The development of appropriate programs (there is some evidence that this effort is in progress) would permit extremely high speed variation on many dimensions, singly and together, and would even allow for corrections necessary to account for interequipment differences within the same model of equipment (these are reported by military hardware designers interviewed to be as high as several hundred percent for some test points in some equipment).

Once tolerances are specified, presently available computer techniques (Reference 8) operating on the assumption of binary test results can be employed to develop sequences which maximize information gain per unit cost. Unit cost is defined in a variety of ways, eg. time, probability of damage to equipment, spares consumption, training required, etc. It also seems within the realm of technical feasibility to develop EDP procedures wherein the range and level of confidence about particular tolerance measures could be used as a factor in selecting tests, perhaps by being counted as a cost.

The technology supporting the development of automatic test equipment long ago had to face and solve the same problem in tolerance specification. ACE has the same intolerance for equivocal checks, equivocal check results, and false positives and negatives as does a proceduralized troubleshooting routine. Mathematical tools and computer techniques for establishing tolerances and test sequences (Reference 7) have developed with the proliferation of ACE and it now remains only to adapt these techniques to the special case of the human technician. The major difference here is the speed with which tests can be performed and thus the increased demand for procedural efficiency.

SECTION II

The Method

The method described here follows from experiences with and subsequent to development of a fully proceduralized within stage troubleshooting performance system for purposes of experimental evaluation. The study is more fully described in Reference 5.

Briefly, twenty high school junior boys were used as subjects in a study of the effect of subject aptitude on performance of procedural between and within stage troubleshooting, and repair tasks on a real piece of electronic equipment, the MTS-2. Two aptitude groups (AQE electronic index 50-65 and 80-95) were used. Subjects detected malfunction symptoms in the course of checkout procedures, collected information at test points located on black boxes inside the equipment using an oscilloscope, installed and removed black boxes, isolated and repaired electronic malfunctions in circuitry inside the black boxes using a scope, volt ohmmeter, and transistor checker.

Each subject had a total of 12 hours of training and practice in operation of test equipment, the operation of the MTS-2, and in the use of troubleshooting guides, parts locations diagrams, and parts lists in connection with malfunction isolation activities. The troubleshooting guides controlled the sequence of checks performed in between and within stage isolation on the basis of results of checks having binary outcomes. Immediately after training each subject solved 13 corrective maintenance and repair problems on the MTS-2.

Results showed that:

1. Aptitude had no effect on the time required for between or within-stage isolation.

2. Aptitude had no effect on errors made in repair of defective modules.

3. A significant difference attributable to aptitude was demonstrated in the ability of subjects to correctly isolate defective modules within the system and defective components within the modules.

In the description of the method, which follows, general statements covering useful concepts and guidelines will be interspersed with descriptions of the manner in which many of them were expressed in the experimental development. The latter will be referred to as the MTS-2 Study. The Appendix contains a complete set of the performance aids used by the subjects in the MTS-2 Study for one of the several circuit modules.

Developing a troubleshooting procedure is done in three major phases:

Phase I. Establishing constraints, assumptions, and Objectives.

Phase II. Developing the sequence of operations.

Phase III. Formatting and validating the procedures.

Phase I - Establishing Constraints, Assumptions, and Objectives

Important constraints, assumptions and objectives regardless of the situation will usually fall conveniently into four categories; equipment, personnel, software, and, always, cost. The categories are not independent; each may place some constraints on any of the others. Even though establishing them finally is an iterative process, it is probably best to consider them initially in the order listed.

Equipment

a. Packaging. Of critical importance are the constraints imposed by the equipment on which the troubleshooting procedures will be used, and none has more far reaching effects than those concerned with packaging. The most serious effects of packaging on the eventual character of the troubleshooting procedure are related to the accessability of test points and to the number of components typically contained by a data flow stage.

A data flow stage is always created by a removable unit because the circuitry is broken at the point where the unit is removed. Thus, there is no possibility for the upstream reflection of a malfunction in the removed unit. Replacement with a known good unit unequivocally either proves the removed unit good or bad (depending on the change or lack of it, in the symptom). If the replaceable units are relatively small in terms of the number of components contained within them, then the troubleshooting procedure which is necessary to identify any single component within a packaging unit as faulty can be proportionally shorter, that is, the number of steps, where a step is defined as a single test equipment or system output reading, can be smaller.

The number of steps in a procedure is of great importance to the procedure's effectiveness. This is so because of the intolerance of proceduralized troubleshooting for technician errors. If, in the course of a procedure, the technician makes even a single error he must obtain the wrong answer. Odds against making a compensating error make it statistically impossible. Other things being equal, the opportunity and hence the probability of error increases with procedure length. It therefore behooves the designer of the procedures to make the average course from the beginning of the procedure to the solution of the problem include as few steps as possible. It is frequent that unusual tests, test equipment, or techniques would be required to achieve this aim, and with these things go, of course, tne increased requirement for training, performance aids and equipment.

Packaging considerations must also be observed in so far as they affect needed tools, assembly and disassembly training and performance aids, and parts location training and performance aids. Although these considerations are not directly related to the choice and sequencing of troubleshooting procedure steps, they are necessary for the execution of those steps by technicians. And finally, packaging affects the difficulty, time, and other costs of making checks and thus should directly affect the choice and sequence of tests.

b. Signal condition information obtainable. Clearly a procedure which specifies test points which are inaccessible or test equipment which is not in the user's inventory will not perform its intended function. It is also true that some reasonably accurate specification of tolerances must be made so that technicians are able to discriminate good signals from bad signals. Though the bulk of this information is either available or can be estimated relatively effectively, some of it is virtually always absent and must be either obtained or done without depending upon the respective cost incurred in so doing. It may occasionally be better to do without it, but it is always necessary to know whether it is present or absent in order to develop procedures which will most efficiently identify the malfunction they are designed to find.

c. Relative reliability of parts. This information is useful both in determining the probable cost of a check and later in estimating the overall cost of a test sequence. The more of this information that is available, the closer the procedure designer is likely to come in minimizing these costs. Some information may be guessed at by the well-known "technician's bias" method wherein tubes and transistors are expected to fail more often than resistors which are expected to fail more often than capacitors which are expected to fail more often than coils, etc. Or the reliabilities may be calculated from known failure rates of components in particular service and under particular stresses. (Reference 11, MIL-HDBK 217) But, probably the best data is historical. Unfortunately it is most unusual when proceduralized troubleshooting can be developed on this basis either because it is being developed for a new system or because the historical data on an already existing system has never been collected.

d. Probability that equipment really contains a malfunction. In many situations where technicians are solving problems identified by persons other than themselves, the possibility exists that the equipment on which they are working contains no malfunction. If the possibility is strong, effort can be conserved if units are verified bad before they are serviced. However, this verification has costs associated with it too. Thus, the probability of a unit being good must be traded off against the cost of verifying functions on each unit received for maintenance.

e. Special test equipment permitted. It is frequently found that with the addition of a relatively inelaborate test jig or measuring device, considerable procedure simplification can be realized with consequent reduction in training and performance aid costs, as well as costs resulting from errors. It is also frequently true that the performance aid designer seldom is in a position to specify a requirement for additional equipment. When this is so it constitutes another constraint of which he must be aware in designing the procedure.

Personnel

In order to develop instructions for use by a technician in the course of troubleshooting, it is necessary to know what skills and knowledges concerning his task he possesses prior to his selection and preparation for task performance. Those which he needs and does not have must be provided for, either by training or performance aids. For example, if one of the skills required is identification of resistor values from the physical appearance of a resistor, the resistance color code might be taught the technician or he might be given one of the many resistance value calculators to serve as a performance aid. Both of these solutions have associated with them some cost and this cost can be saved where the skill concerned is already present.

However, in many situations this sort of choice is not available. It is typical in the military situation that the performance aid designer has little or no control over the content or extent of training. As a result, he is frequently in a position where he must substitute performance aids or selection as a means for insuring that technicians possess necessary skills. In the extreme situation, he has no control over either selection or training and knows little about what the technicians can actually do after selection and training since performance is seldom, if ever, evaluated in the behavioral terms the performance aid designer would most like to have used to describe the abilities of those who will use his performance aids.

Software

a. Allowability of nonresolvable sets. A nonresolvable set occurs when the troubleshooting procedure fails to detect which of two or more components in a set of components which is known to contain the malfunction actually contains it. When a nonresolvable set occurs it is generally the result of a situation in which the cost of resolving the set is higher than the cost of replacing the components in the set one by one until the malfunction is cleared. This condition is usually associated with exotic test equipment requirements, extremely time consuming tests, or great danger of reliability degradation associated with otherwise possible tests. The cost associated with nonresolvable sets are usually in terms of increased spares requirements, equipment degradation and time.

b. Allowable performance aid characteristics. Constraints in this area are generally felt most at the point where a display device for the performance aid is selected. Some examples of display devices are printed page, microfilm or microfiche readers, head phones, etc. Ideally the display device would maximally facilitate the use of the aid under the condition in which the aid would usually be used, and the facilitation would more than offset the difference between the cost of the chosen display device and the least expensive one which would do the job. Here again a limitation on the options of the performance aid designer may result from the prohibition against additional equipment.

Further constraints are likely to result from the conditions under which performance aids are used. Obviously, if the performance aid is to be used in confined spaces, it cannot be a large bulky book with easily torn pages. Other possible conditions may require the performance aid to be waterproof or washable. In some situations the performance aid may be used once and thrown away. In other situations the primary constraint on performance aid characteristics will be a minimum allowable information retrieval time. Whatever the constraints, it is best they be known early in the development of the procedure since they can have effects on the retrieval system, the display itself and on the organization and format of the information contained in the procedure, to say nothing of almost certain effects on training and possible effects on selection.

The MTS-2 Study: Results of Phase I

Equipment constraints and assumptions. In the procedures developed for the study referred to above all circuitry was mounted on erie boards and packaged in identical 3 x 4 x 5 black steel boxes (modules) with the exception of the controls mounted on the module front panel (Figure 1). It was decided at the beginning of the procedure development that no equipment modifications to further subdivide the circuitry below the level found in the modules would be necessary. After having seen the results of the study one would probably feel somewhat more equivocal on this point. It may be that some further subdividing of the circuitry within the modules would have reduced the overall procedure cost resulting from reiteration due to technician errors but perhaps not enough to offset the cost

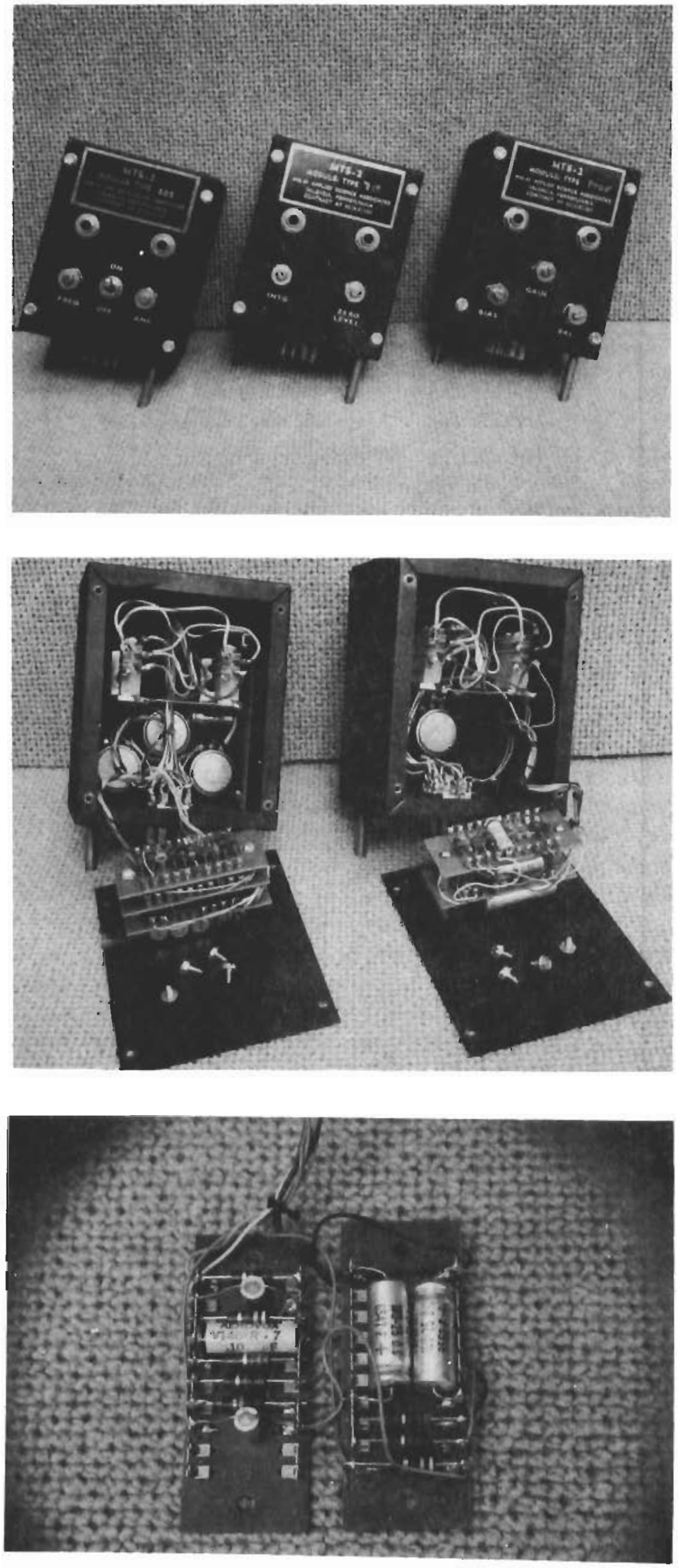


Figure 1. (upper and middle) MTS-2 circuit modules; (Lower) example circuit boards.

of modification necessary to reduce the average number of steps in the procedure. Note that by average is meant the average number of steps from step 1 to isolation of the defective component across all components in all modules, weighted by the probability of failure of these components.

Packaging of the circuitry made all checks essentially equal and small in cost with the exception of testing transistors outside the circuit. This cost could have been reduced by use of plug-in transistors, but in order to maintain task representativeness it was not. As it turned out the high cost of testing transistors was more than offset by the frequency with which faulty transistors were the source of malfunction.

In preparation for the MTS-2 study a questionnaire was sent to a number of technicians whose job it was to maintain equipment similar in character to that contained in the modules. The object of the questionnaire was to attempt to predict failure rates for each of the various classes of components, that is, transistors, resistors, capacitors, potentiometers, diodes, etc. The only consistent finding of this questionnaire was that about half of the malfunctions could be expected to involve faulty transistors and, therefore, this is the only failure rate assumption explicitly used in the study. It should be pointed out, however, that the method allows for a fair amount of latitude for subjective judgments on the part of the procedure designer as to component failure likelihood.

Since the MTS Study involved the insertion of malfunctions in modules to create symptoms, it was known with certainty that each module contained a malfunction and, accordingly, the procedures were designed so that verification of this fact did not take place during within-stage troubleshooting.

In the MTS-2 Study signal condition information was limited to that obtainable by a Tektronix Model 545A oscilloscope with a CA plug-in unit, and a conventional VOM. Tolerances were estimated on the basis of the tolerance of the component involved in the section of the module under test in each individual case. These tolerances were later relatively incompletely checked in order to obtain some degree of confidence in their validity. However, in the opinion of the author neither this testing nor, in fact, the study itself (since malfunctions were inserted rather than occurring naturally over time in aging electronic equipment) adequately checked the procedures.

Personnel: In the MTS Study electronically naive high school juniors were selected on the basis of the Airman Qualifying Examination (the electronic aptitude scale). No subject was selected with an aptitude below the 40th percentile. Beyond this no assumptions were made about skills or knowledges of the subjects other than that they possessed the normal verbal and manipulative abilities of naive high school sophomores.

There were literally no constraints on the allocation of skill and knowledge acquisition functions to either training or performance aids. Training, generally speaking, consisted of instruction and practice in performance of the steps required by the procedure as expressed in the performance aid system. And the performance aids consisted of instruction about where to perform which steps and what the product and tolerances of each step was to be. For example, operation of controls was directed by the procedure: reading and interpreting displays was taught. Placement of test probes was directed by the procedure: installation and removal of components by soldering was taught. Selection of parts from stock (alpha-numeric name matching) was taught: the part to be selected was directed by the procedure, etc.

Software. It was decided that in the procedures developed for the MTS-2 Study no nonresolvable sets would be permitted.

The major constraint on performance aid characteristics was the cost of the aid itself. Since previous studies had indicated that the printed page in a card file was an effective presentation device and that relatively unpracticed humans were not inferior to automatic card finders where the search field is less than 1000 or so cards, it was decided that the troubleshooting procedure would be presented on 3 x 5 cards in a card file supported by pictorial test point location diagrams.

Phase II. Developing the Sequence of Operations

The particular operations used, and the sequence in which they should be performed will depend to a great extent upon the results of Phase I.

Within those constraints, however, the procedure should be designed to maximize the information gained per unit of cost for each operation specified in the procedure.

Evaluation of Information Gain Per Unit Cost

Evaluation of information gain is a complex process which is not very precise. As with between-stage troubleshooting the maximum information is obtained when the probability of malfunction among the suspected components is halved. (Reference 10) In within-stage troubleshooting in particular, however, other factors must also be taken into account. One of these factors is the extent to which performance of a certain operation facilitates performance of a later operation. For example, disconnecting one end of a resistor from the circuit so that the resistance of a branch can be measured may also permit a measurement on the branch remaining connected to the terminal.

Making the disconnection at a point like that is preferable to making it at a point where this additional preparation for a later step does not occur.

Several kinds of costs must be considered. Generally, the most important ones are the time required by the technician to perform a given operation, the cost of making the technician capable of performing the operation, and the estimated potential effects on equipment reliability of performing the operation.

Time required to perform an operation: Usually those operations requiring shortest performance time are put at the beginning of the procedure, since this strategy will usually yield the maximum information per unit of time. This is by no means always true, however. In many cases, rather time consuming operations will occur early in the procedure either because of their large immediate information gain, their facilitation of later cheap checks, or because they must be performed before any other check.

Cost of preparing the technician: This cost factor is considered in determining what operations are economical to include in the troubleshooting procedure. For example, it may be desirable to make a certain check using an oscilloscope for a rather difficult discrimination of waveshape. But if this is the only place in which use of this item of test equipment is desirable, and if extensive training (high cost) were required to prepare the technicians to perform this check, then it should probably be excluded from the procedure. Some less expensive operation should be substituted so that the net effect is an improvement in the cost-effectiveness ratio.

Potential effects on reliability: Sometimes the best operation appears to be one in which certain components are partially or completely removed from the circuit and tested. A good example of this is tube exchanging in vacuum tube equipment. It could be argued that transistor exchanging might also be effective, since they are the active circuit elements, analogous to the tube. Transistors may be hard-wired to the circuit, however, and are sensitive to the rigors of soldering. Exchanging them may have unknown, but detrimental effects on their reliability due to overheating. Use of this type of operation should, therefore, possibly be held back as a last resort, unless the information to be gained from such an action clearly outweighs this probable cost.

Specifying the Procedure

Step 1. Visual Inspection

Almost without exception the first step should be a visual inspection. The reason for this is that this is a very cheap type of check. It is most likely to detect catastrophic failures and to miss failures caused by degradation of components. It costs so little, however, on any dimension, that this kind of check should assuredly come first.

Step 2. Fragment the Circuit

As was pointed out earlier this should be done so as to split in half (as nearly as possible) the distribution of malfunction probability among the circuit elements. That is, the circuit should be divided so that the probability that the trouble is in one fragment is about equal to the probability that it is in the other. Obviously not all splits are possible since most will result in a situation where there is no single test which will in every case tell with certainty whether the malfunction is upstream or downstream of the point at which the split is made. It is most generally found effective to attempt to find a point in the circuit which separates the circuitry into two or more data-flow stages. Then specify a power-on check of the signal at this (these) point(s) with normal inputs since this type of check is usually required to verify proper functioning.

In the MTS-Study, once the hot checks on the stage outputs were made and a group of components identified as containing the malfunction, all the transistors in that group were removed and tested. Although this step tended to be a rather laborious one, it seemed to be justified by the fact that it would solve 50% of the problems and by the fact that when it did not solve a problem it did facilitate its solution by separating the search field into a number of small and easily checked individual fragments.

To illustrate, referring to Figure 2 (upper) one of the actual circuits used in the study (an RC differentiator module), the circuit would at this point--with the transistors removed--appear as shown. (The call-out numbers shown on the schematic are used to designate test points. They correspond to test point numbers on the test point location diagram, Figure 2, (lower).)

Step 3. Identify the Fragment Which is Most Likely to Contain the Malfunction

With no failure probability data the single fragment most likely to contain the malfunction is the single fragment which contains the most components, otherwise it is the fragment which contains the most net probability of failure.*

---

*This is true, of course, only after step two has been performed.

In the case of the circuit shown in Figure 2. it is the fragment including R1002, R1004, R1003, R1005, R1006. Since R1002 and R1005 are connected only through the capacitor, a resistance measurement from one to five would not be significantly affected, However, R1003 is 270 ohms and R1006 is 10K. If we measured from one to five we could probably not detect as out-of-tolerance a shorted R1003. Clearly this fragment is too large to measure with one resistance reading since the total value of R1003 is less than the 10% tolerance of R1006, thus even though the fragment from 1 to 5 is the largest, practically speaking it is really two fragments in so far as it must be divided to be evaluated. This means then that the largest fragment is really the one between 1 and 4. This one should be tested first.

Step 4. Specify the Test Sequence

If the overall test from 1 to 4 is bad, it can be for one of two reasons, and they must be separated. First the cause may be a low resistance capacitor between 1 and 4 and second, the cause may be a bad resistor in the string of resistors between 1 and 4. Note that the possibility of a shorted capacitor exists only if the reading from 1 to 4 is too low. Note also that the setting of R1004 must be considered in making the resistance measurement from 1 to 4. All of the test possibilities associated with the string (1 to 4) may be stated, in the following manner:

First, set R1004 for maximum resistance. If the instruction were to set it to minimum resistance, it would effectively be removed from the circuit, thus concealing a potential source of malfunction. Read the resistance between 1 and 4. If it is good, i.e., in tolerance, read the resistance between 4 and 5. If the reading between 1 and 4 is above the stated tolerance, read between 1 and 3. If the reading between 1 and 4 is below stated tolerance, unsolder one end of the capacitor and read again between 1 and 4. If this last reading is now good, replace the capacitor. If it is bad, read the resistance between 1 and 3, and so forth. The decision tree is diagrammed in Figure 3.

The principle for checking the remainder of the circuitry is the same. Eliminate by resistance checks, all of the fragments, one by one, until a bad one is found then subdivide that fragment until a single faulty component is identified.

A situation not covered in the above example is a fragment containing a diode and the very similar situation wherein two fragments are connected to each other by a diode. The fragment or fragments can be tested including or excluding the diode as necessary to control fragment size by proper selection of the polarity of the ohmeter.

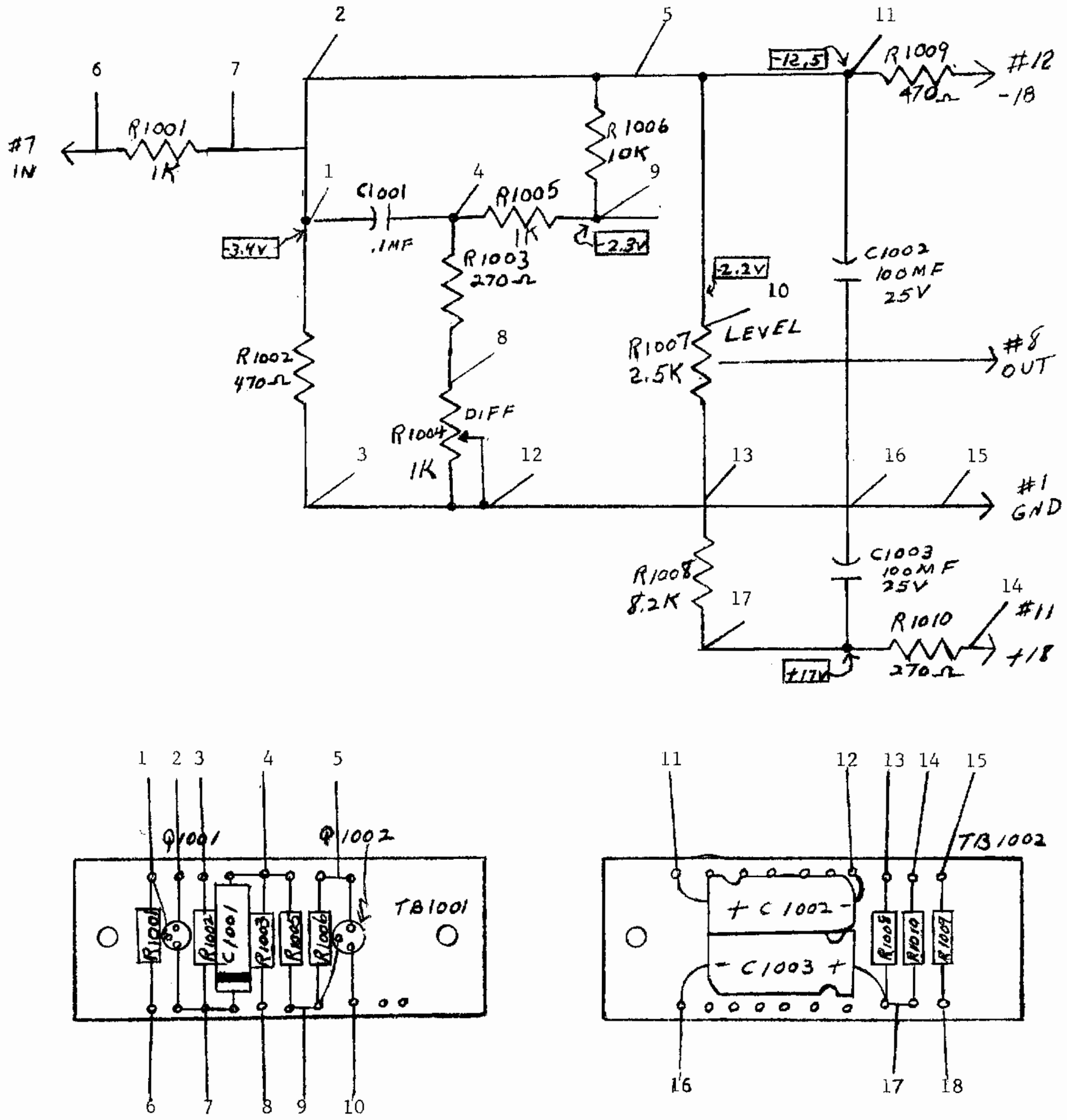


Figure 2. Example schematic (upper).
Example parts location diagram (lower).

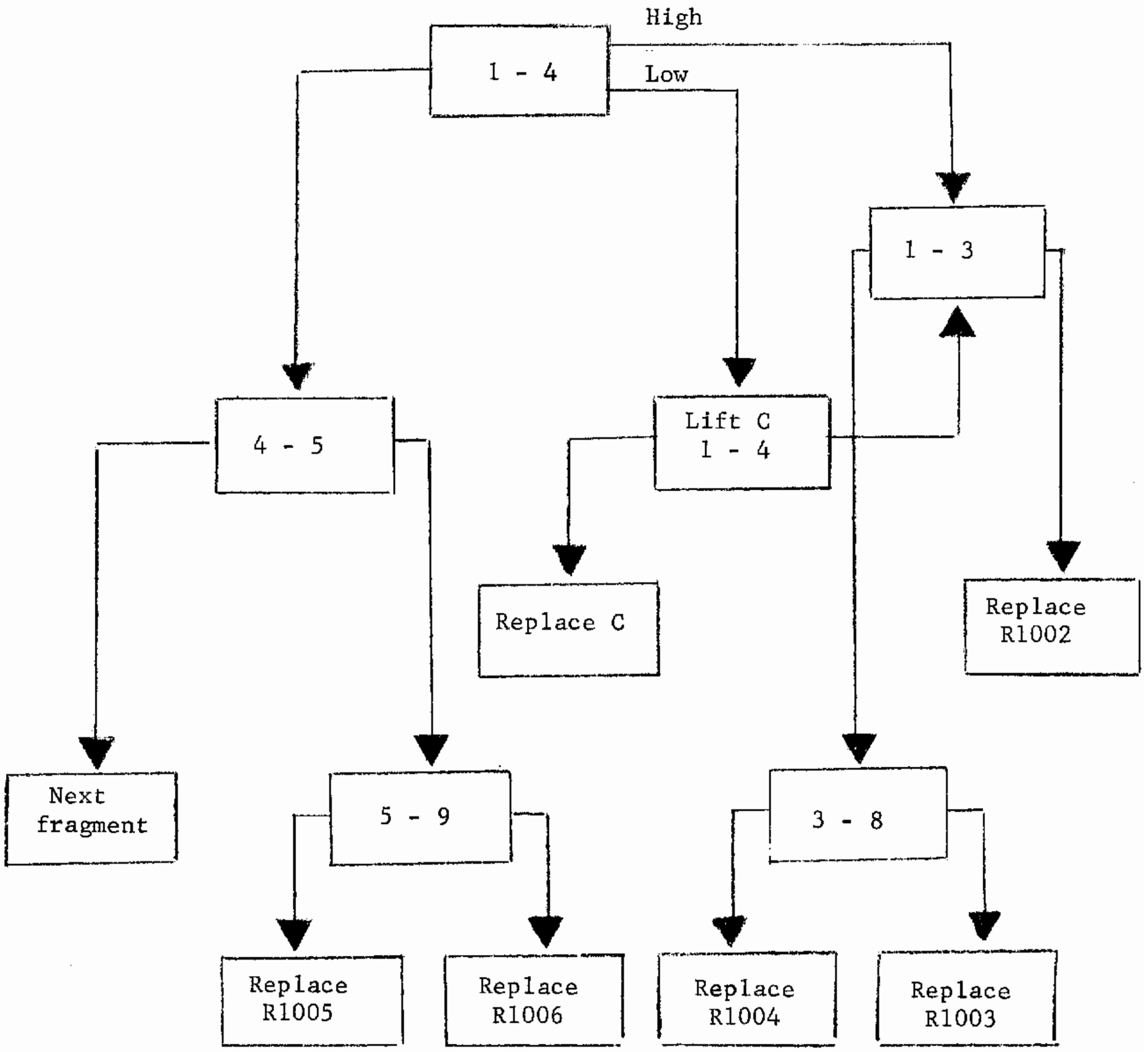
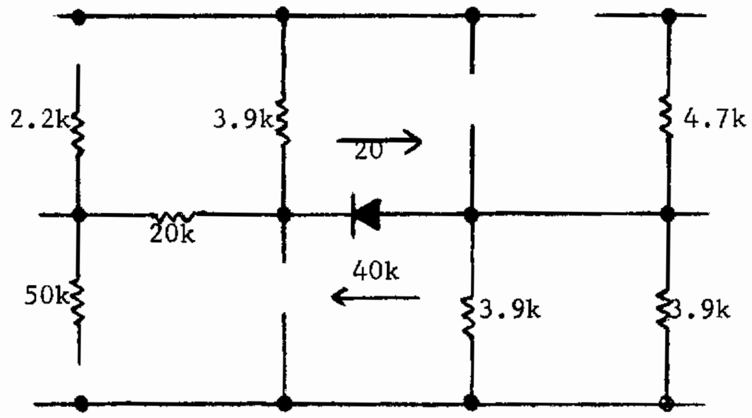


Figure 3. Example Troubleshooting Decision Tree. Good alternatives to the left; bad alternatives to the right.

In the case shown below, if the proper polarity is observed the front resistance of the diode may be checked at the same time the resistors between 1 and 5 are checked and the back resistance of the diode, when the resistors between 3 and 7 are checked (this can be done after the 1-5 check by a 5-7 check).



Occasionally it is necessary to physically break a connection in order to create a testable fragment--suppose, for example, the capacitor C1001 in Figure 2 was replaced by 1K resistor. It would then be necessary to break the resistor loop. Several possibilities offer themselves, but in this case it makes little difference where the loop is broken. However, in every case it is important to insure that the selection of the point at which a component is lifted in order to divide a fragment does not create the necessity for another lift which would not have been necessary had a different point been selected. The most common pitfall is including a low value resistor in a string of high value resistors or vice versa.

Another case not covered by the discussion so far is that of the open capacitor. The circuitry in the MTS-2 contains relatively few capacitors other than power supply filter and decoupling capacitors. Failures in capacitors used in these two capacities would have been detected at the between module troubleshooting level and thus were of no concern at the within module troubleshooting level. Of the few remaining capacitors used in coupling, waveshaping, and frequency determining applications, those smaller than .05mfd. were left to be replaced only after all other failure possibilities had been exhausted. This sort of failure is thus the most expensive in terms of the number of checks required to solve the problem. The great expense seems to be justified because of the small number and of low probability of failure of capacitors in this service, and thus the very low expected contribution to average cost per malfunction from this source. Capacitors .05mfd. and larger are assumed good if when measuring across them the ohmeter needle rises from infinity briefly and falls back.

Step 5. Refine and Check the Procedure for Efficiency

Once the test and test sequence have been specified at this point it is profitable to refine and check the procedure by examining the logic (and in the case of the MTS-2 Study, probe placement) for efficiency. By the efficiency of the logic is meant the components with the greatest likelihood of failure should be checked first and thus should have associated with them the smallest number of checks. If we count the number of fragments, then rank order them by the likelihood of their containing a malfunction, (on a parts count or any other suitable basis) giving the first rank to the fragment most likely to fail then the decision tree diagram should follow in order 1 through N down the left side with branches to the right for checks inside fragments. Other things being equal, the fragmenting should be done to produce the smallest number of these left-side checks. The number of right-side checks (those inside fragments) is also of interest, however, and it may be useful in order to obtain an overall picture of check likelihood to make a tally, as below, of the number of checks required in the case of each component's failure. If the information is available it can then be checked against actual failure ratio. Even if it is not, alternative test schemes may be compared in this manner under a single assumption of component reliabilities.

Component	1	2	3	4	5	6	7	8	9	N	
Checks	7	6	3	2	4	4	3	5	2	$\bar{X}$	4.0
P.	.001	.001	.05	.02	.04	.03	.01	.02	.01	Σp	1.0

Such a tally is also of value in predicting the distribution of check times and errors since the time required for most checks is the same and error likelihood can be expected to increase almost linearly with sequence length.

It was of some small value in the MTS-2 Study to assure, where possible, that probe placement change in check sequences within fragments are made at the rate of one test point per check: as in Figure 3, for example, where the sequence is 1-4, 4-5, 5-7. This should reduce both time and errors in probe placement.

It is of value also before continuing to the next step to assure that the procedures are complete. This is most effectively done in two operations. First, look down the left side of the tree to assure that there is a check on each fragment, then, count the number of placement operations (at the end of check strings) in the total tree.

The number should be equal to the total number of components (R, C, D) plus the number of diodes and capacitors--this, because diodes and capacitors can be replaced for 2 reasons which are usually identified separately (in the case of the diode, bad front or back resistance; and in the case of the capacitor; open or short) while resistance measures are simply in-tolerance or out-of-tolerance. Transistors or tubes are considered separately in Step 2.

Step 6. Determine Normal Readings and Tolerances

Once the test sequences have been checked for efficiency and completeness it is necessary to make the measurements specified by the test sequences. One might argue that the expected readings and tolerances could as well be calculated and this is theoretically true. In practice, however, actually making the measurements serves as an additional check on the accuracy of the steps which have gone before and provides an opportunity to refine the logic still more by further subdivision of fragments, or more rarely, by recombination of fragments. It also provides an opportunity to vary the values of individual components in fragments in an effort to determine what realistic tolerances are. This can easily be done with a potentiometer provided with a pair of clips which permit connecting the variable resistor across the component in question or in series with the meter and the component.

The above not withstanding, the setting of tolerances involves a certain amount of guessing. Ordinarily the more components there are in a fragment the looser the tolerance in terms of the total fragment, eg. 10% times the number of components in the fragment might yield a tolerance as high as 80%. This is probably too much. However, reducing the tolerance on the fragment to 20% would in this example imply something less than 5% per component.

Though it would seem to be inconsistent a tolerance of approximately 20% was used for fragments and approximately 10% for components in the MTS-2 Study. The figures are approximate because no interpolation between scale divisions on the meter was permitted. Readings were made to the nearest scale division.

Phase III - Formatting and Validating the Procedure

Place the test sequences, readings, and tolerances into the format in which they will be used by the troubleshooter. Though many of the decisions bearing on this matter will have been made in Phase I, it may have been found necessary in the meantime to modify them. In any case some of the formatting can be done along with Steps 5 and 6. Appendix I contains the complete set of materials for one of the circuits used in the study: the troubleshooters did not, of course, have schematics of "theory of operation". Those two items are provided along with the test sequences so that those familiar with electronic circuitry can follow the test logic on the schematics.

Complete validation of the procedures would require that each component in each circuit be failed in a variety of ways under a variety of conditions of degradation of related components and the procedures used to identify the malfunction. Though this seems a great task, in fact, it is less so than might be imagined.

On the average a malfunction, in the MTS-2 Study, required less than 6 checks and most were simple resistance checks. Nonetheless, the above activity would have required more time than was available, therefore, the procedures were checked only against the 25 malfunctions to be used in the study. They correctly identified the malfunction without exception. It should be noted that the malfunctions to be used were selected by a different individual from the one who developed the procedures, after the procedures were developed, and with no knowledge of the details of procedures other than the general method by which they were developed.

Some Untapped Possibilities

The use of output deficiency analysis. Output deficiency analysis (ODA) has been described as the ability possessed by some experienced technicians to combine with knowledge of where in the system certain functions are performed and knowledge about what kinds of components perform those functions, certain characteristics, either present, absent, or changed, about an out of tolerance output or signal inside the equipment to considerably narrow the search field containing the malfunctioning component. Another sort of ODA occasionally mentioned describes the ability of the technician to learn in the manner of paired-associates learning symptom signatures for particular malfunctioning components or groups of components. At the present time proceduralized troubleshooting has not attempted to incorporate either of these two kinds of output deficiency analysis into the test routines. There are several reasons for this. First, the information on malfunction signatures is generally not available and must be generated. Second, ODA implies experience (symptom-cause history) with the equipment and there is generally nobody with experience at hand when initial troubleshooting procedures are developed. Third, incorporating this sort of information into the procedures would necessarily require branch points having more than two alternatives, thus making the procedures considerably more complicated. And, finally, ODA has something of the status of folklore in that it has not been systemtically investigated, and, in fact, the literature contains some support for an argument that this ability is not highly developed if present at all in the average technician. Yet, probably the most important reason that it has not been done is simply that it has not been done.

In a slightly different vein, relevant to ODA, recent work at the Air Force Aero Propulsion Laboratory (Reference 12) has resulted in development of a method for computer generation of expected malfunction signatures based on circuit transfer functions. Though the method has not been tested in a "real world" situation it shows considerable promise of making a significant contribution to proceduralized troubleshooting possibilities. Where the method can be applied (a primary consideration at this point) there would be substantially reduced need for within circuit testing.

Future research in the area of ODA might well direct its attention toward solving some of the problems implied earlier in the discussion by attempting to answer the following questions:

1. What is the effect of multiple choice branch points in proceduralized troubleshooting instructions on the procedure development process, on task performance, on procedural efficiency?*

2. Can such a skill as ODA be identified in the field and (a) can it be taught; (b) can it be incorporated into proceduralized troubleshooting instructions?

Computer generated troubleshooting trees. Reference 8 describes a method for computer generation of troubleshooting decision trees under a set of assumptions most appropriate to between stage or between black box troubleshooting. Though the method described has yet to be applied to an actual hardware system by technicians using the methods' materials to solve real troubleshooting problems, it has shown considerable promise "on paper". The procedures produced in connection with the present study could serve as a nucleus around which computer generated troubleshooting trees under assumptions appropriate to within stage or within black box troubleshooting might be developed. Before this is done, however, some considerable amount of work remains to be done on increasing the applicability of this method to circuitry using many different packing techniques and a broader range of component types.

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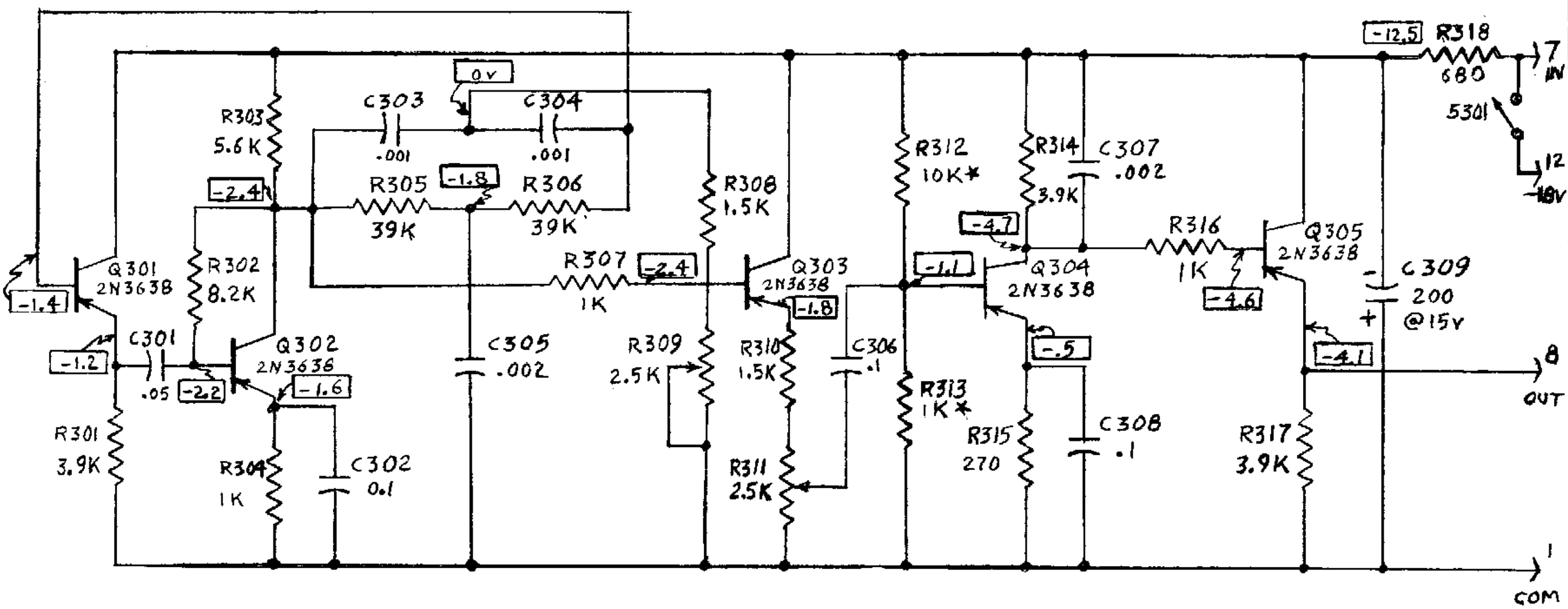
[*] Average information gain per procedural operation divided by total cost of all operations times average probability of an operation's being performed, across all possible malfunctions.

APPENDIX

Example Schematics, Theory of Operation

Test Point Location Diagram and Troubleshooting Procedure (Module 300)

With the exceptions noted, these materials are those actually used in the study described in Reference 5. The schematic and theory of operation are self-explanatory. Though they were not provided for use by subjects in the study they are presented here to facilitate the reader's understanding of the test sequences. The troubleshooting instructions were presented to the subjects on 3 x 5 cards numbered in the upper left hand corner. The test points shown on cards were located through the use of a test point location diagram page 46. Most of the instructions are self-explanatory with the exception of those requiring a resistance check. An example is card 305 on page 33. The instruction is: "Set the meter selector switch on the VOM to the 1K position and place the probes of the meter on points 8 and 9 respectively. A reading between 5 and 6 on the resistance scale is considered in tolerance." Note that there is no necessity to convert the reading to ohms or to consider the multiplier since the position of the meter selector switch fixes the predetermined scale factor. In a case where polarity of the voltage applied by the meter is important, for example, in checking the resistance of a diode, the test point on which the red lead is to be placed is circled. An example is card 316 on page 37. The page numbers shown on some of the cards (card 321) were, of course, not found on the cards used by the experimental subjects. They are presented here for the reader's convenience in locating cards referred to in the text.



Notes: 1. Resistors in ohms unless otherwise noted

2. Reference Dwgs:
   a. Parts Layout - Dwg. No. A601AS61002M
   b. Parts List - Dwg. No. A601AS61003M
   c. Waveforms - Dwg. No. A601AS61004M

3. Voltage measurements by 20KΩ/V meter with respect to ground, R309 @ min. (max. Freq.) & R311 set for 6V p-to-p, pin 8 to com and ext. 2.2KΩ load.

*Selected Value for proper output

Supply Req.	- 18V @ 8 ma.
Freq. Range:	10 to 13 KC
Output Load:	1 KΩ Max.

VARIABLE FREQUENCY, VARIABLE AMPLITUDE
SINUSODIAL OSCILLATOR MODULE No. 300

SCHEMATIC DIAGRAM

12/18/65 RAM/ A601AS61001M

VARIABLE FREQUENCY - VARIABLE AMPLITUDE SINUSOIDAL OSCILLATOR

MODULE 300

Module 300 is composed of a twin T feedback sinusoidal oscillator followed by a three stage amplifier to isolate and amplify the oscillator output.

Q302 with its associated circuit forms the oscillator stage with Q301 serving as an emitter follower in the feedback circuit to prevent loading of the oscillator. Q303, Q304, and Q305 form a three stage inverting amplifier.

When power is applied to Pin No. 7 or when S301 is turned on the current distrubance at the base of Q202 will be amplified and appear at its collector. R305, R306, R308, R309, C303, C304, and C305 form a twin T feedback network. This network has a very narrow frequency pass band and thus permits feedback of one frequency only.

The feedback signal is fed to the base of Q301 which acts as an emitter follower to prevent loading of the twin T network by the oscillator input. R309 provides an adjustment of the frequency by varying the center frequency of the twin T network. The feedback signal appearing at the base of Q301 is developed across the emitter load resistor R301 and then coupled through C301 to the base of the oscillator transistor Q302. Since this signal is in phase at the oscillator frequency, it will reinforce the amplifier, sustaining the oscillations.

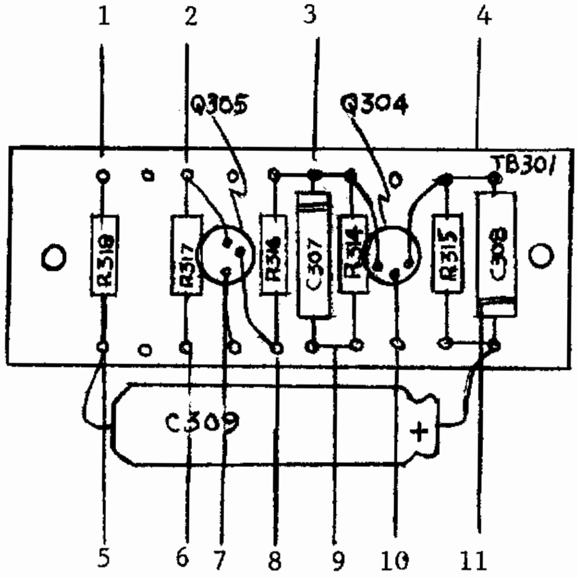
The collector signal of Q302 also feeds through R307 to the base of Q303. Q303 is also an emitter follower to reduce loading effects on the oscillator. The signal is developed across the emitter resistors R310 and R311. R311 provides a variable amplitude control. The selected amplitude is fed from the arm of R311 through C306 to the base of Q304.

Q304 is biased in the linear range of its operation by the voltage divider action of R310 and R313. R313 is selected for maximum amplitude with minimum distortion. Q304 also obtains a part of its bias from the small negative voltage developed across R315. C308 acts as a filter to prevent degenerative feedback at the oscillator's frequency. The signal appearing at the base of Q304 is amplified and developed across the collector load resistor R314. C307 acts as a noise filter to remove high frequency components from the waveform.

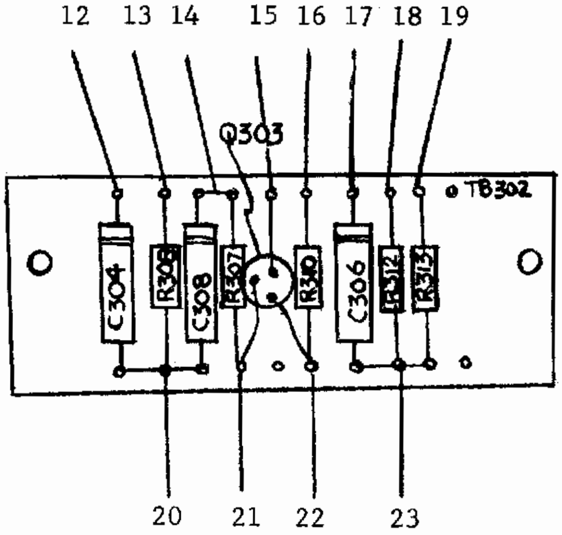
The signal developed at the collector of Q304 is fed through R316 to the base of Q305. Q305 acts as an output emitter follower to isolate the amplifier from the external circuit. The signal is developed across the emitter load resistors R317 and fed to Pin No. 8.

R318 and C309 form a decoupling network to prevent signal variations from being fed between modules through the supplies.

Ⓒ


1
2
3
4
Q305
Q304
TB301
R318
R317
R316
C307
R314
R315
C308
C309
+
5
6
7
8
9
10
11

Ⓑ


12
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17
18
19
Q303
TB302
C304
R308
C308
R307
R310
C306
R312
R313
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21
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23

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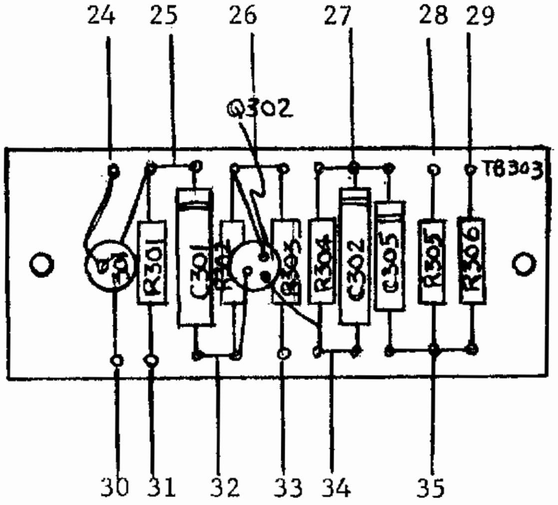
24
25
26
27
28
29
Q302
TB303
301
R301
C301
R302
R303
R304
C302
C305
R305
R306
30
31
32
33
34
35

301

When module is properly installed on the test jig carefully inspect each component, wire, and connection for visible signs of damage.

If none is found go to 302.

If a wire or connection is broken repair it and ask E to inspect your work.

If a component is damaged remove it and turn it in for a good one from stock. Install the good one and ask E to inspect your work.

302

Scope probe at 17

Scope Controls

Volts/CM 0.1

Time/CM 0.1 M Sec.

Good 303 Bad 324

(page 39)

303

One at a time pull and check Q 304 and 305 until a bad one is found.

If a bad one is found replace the transistors removed thus far except the bad one. Replace the bad one with a good one from stock and ask E to inspect your work.

If all transistors check good do not reinstall them on the board. Go to 324.

(page 39)

304

VOM: 1 k

18
19

Read: After 10 sec. reading will gradually increase to 12.5 to 14. If reading does not gradually increase replace C309.

Good 305 Bad 319

(page 38)

305

VOM: 1 k

8
9

Read: 5 to 6

Good 306 Bad 313

(page 36)

306

VOM: 10

4
11

Read: 22.5 to 27

Good 307 Bad 310

(page 34) (page 35)

307

VOM: 1 k

2
6

Read: 4.0 - 5.0

Good 308 Bad 309

308

Replace C 306 and replace it with a good one from stock 17-23. The end of C 306 with the black stripe should be connected toward 17. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

309

Remove R 317 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

310

Lift C 308 4

VOM: x 10

4

11

Read: 22.5 to 22.7

Good <u>311</u> Bad <u>312</u>

311

Remove C 308 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

312

Remove R 315 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

313

VOM: 1 k

8
3

Read: 0.9 to 1.1

Good <u>315</u> Bad <u>314</u>

314

Remove R 316 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

315

VOM: 1 k

3
9

Read: 4 to 5

Good <u>Call E</u> Bad <u>316</u>

(Page 37)

316

Lift C 307 3

VOM: 1 k

3
9

Read: 4 to 5

Good 317 Bad 318

317

Remove C 307 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

318

Remove R 314 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

319

Lift C 306 (17)

VOM: 100 k

⑫
13

Read: .8 to 1.0

Good 320 Bad 321

320

Remove C 306 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

321

VOM: 1 k

18
㉓

Read: After 10 sec., reading will gradually increase to 11.8 to 13.2.

Good 322 (page 39) Bad 323 (page 39)

322

Remove R 313 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

323

Remove R 312 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

324

One at a time pull and check Q 301-3 until a bad one is found.

Replace the transistors removed thus far except the bad one. Replace the bad one and terminate. Install the good one and ask E to inspect your work.

If all transistors check good do not reinstall them on the board. Go to 325.

(page 40)

325

VOM: 1 k

27
22

Read: 3.6 to 4.4

Good <u>329</u> Bad <u>326</u>

(page 41)

326

VOM: 1 k

27
16

Read: 2.2 to 2.8

Good <u>327</u> Bad <u>328</u>

(page 41)

327

Remove R 310 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

328

Call experimenter

Unscheduled malfunctioning in R 311

329

VOM: 1 k

27
20

Read: 3.5 to 4.5

Good <u>333</u> Bad <u>330</u>

330

VOM: 1 k

27
13

Read: 1.1 to 1.3

Good <u>330</u> Bad <u>331</u>

331

Call experimenter

Unscheduled malfunctioning in R 311

332

Remove R 308 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

333

VOM: 100 k

15
24

Read: 0.8 to 0.9

Good 340 (page 44)

Bad 335 (page 43)

335

VOM: 1 k

15
26

Read: 5.6 to 6.4

Good 337 Bad 336

336

Remove R 303 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

337

Lift C 301 25

VOM: 100 k

15
24

Read: 0.74 to 0.90

Good 339 (page 44) Bad 338 (page 44)

338

Remove R 302 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

339

Remove C 301 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

340

VOM: 100 k

28
29

Read: .72 to .85

Good <u>348</u>	Bad <u>341</u>
(page 47)	(page 45)

341

Lift R 305 from 35

VOM: 100 k

20
29

Read: 0.9 to 1.1

Good 342 Bad 343

342

VOM: 1 k

20
28

Read: After 10 sec. reading gradually increases to 19.8 to 24.2.

Good 345 (page 46) Bad 344 (page 46)

343

Remove C 304 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

344

Remove C 303 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

345

VOM: 1 k

28
35

Read: 35-44

Good 347 Bad 346

(page 47)

346

Remove R 306 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

347

Remove R 305 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

348

VOM: 1 k

27
4

Read: .27 to .33

Good <u>350</u> Bad <u>349</u>

(page 48)

349

Remove R 304 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

350

VOM: 1 k

25
27

Read: 4.0 to 5.0

Good 352 Bad 351

351

Remove R 301 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

352

VOM: 100 k

Lift C 302 from 27
and check as specified below:

Read: Red lead to free end, black to 34.
Rise in meter then fall to infinity.

Good 354 Bad 353

(page 49) (page 49)

353

Remove C 302 and replace it with a good one from stock. Replace all the transistors which were removed from the board and solder down the ends of components which were lifted. When you are finished ask the experimenter to check your work.

354

VOM: 100 k

Lift C 301 from 25 and check
as specified below:

Read: Read lead to free end. Black to 32.
Rise in meter, then fall to infinity.

Good: 355 Bad 356

(page 50)

355

Lift R 307

From 21
Check Free end to 14

VOM: 1 k

Read: .9 to 1.1

Good E Bad Replace

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13. ABSTRACT

Several studies over the past decade have shown that proceduralized troubleshooting can produce acceptable or better performance of this complex maintenance task while permitting substantial reduction in the costly training typically associated with its accomplishment. The term "proceduralized troubleshooting" is usually applied when the decision about where in the system the technician is to check next, based on the results of previous checks, is made by a performance aid which directs his actions. This same performance aid, however, can also display expected normal readings and tolerance, test point locations, test equipment and test selection parts identification, and much other necessary and/or useful guidance. The method described follows from experiences with and subsequent to development of a fully proceduralized within stage troubleshooting performance system for purposes of experimental evaluation. It is based upon the rationale of maximizing information gain per unit test or operation cost. Examples of troubleshooting procedures developed for use in the evaluation are presented and described.

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