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DIAGNOSIS OF MALFUNCTIONS
IN COMPLEX ELECTRONIC
ASSEMBLIES

PDO 6984449, Final Report

J. A. Losure, Project Leader

Published September, 1971

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**Kansas City
Division**

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Project Leader:
J. A. Losure
Department 842

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Final Report

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ABSTRACT

A study to determine troubleshooting skills necessary to isolate the causes of malfunctions in complex electronic assemblies, to devise effective means of transmitting engineering-support information to production troubleshooting facilities, and to develop rapid and effective equipment for in-process testing of subassemblies at low levels of assembly has resulted in increased production, reduced rework, lower scrap rates, and cost savings. Troubleshooting manuals were developed to enable troubleshooting technicians to function more effectively. Special in-process testers and an on-line manufacturing troubleshooting facility were effective, and many of the findings of the assessment of required troubleshooter skills contributed to the attainment of the project objectives.

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SUMMARY

This work was conducted to define and develop methods to assure rapid, accurate, and economical isolation of faults in complex electronic assemblies being manufactured on the production line. The project work plan was divided into two phases. The objective of Phase 1 was to define and develop methods to assure an adequate skill level and to develop effective means of communicating engineering diagnostic-support information to the troubleshooter. The objectives of Phase 2 were to define the type of diagnosis and to develop diagnostic procedures for difficult troubleshooting problems.

The results of diagnostic skill studies conducted during Phase 1 work indicated the following.

- With adequate engineering support and proper equipment most diagnostic work can be performed with skills lower than engineering level. However, the technical requirements are high enough to require rigid screening of technicians.
- Familiarization and upgrading programs, rigid screening procedures, and technical supervision are required to cope with the increasing complexity of telemetry assemblies.
- Screening methods should include testing, on the job evaluation, and a nominal educational requirement to assure adequate troubleshooter skills.
- The troubleshooting classification must be compatible with other plant classifications which employ electronic technicians to assure qualified applicants for future positions in the classification.

The Phase-1 evaluation showed that the translation of engineering technical information and product function definitions to the troubleshooter level was a critical dimension in the fault finding system.

A set of prototype manuals to communicate this type of information to the troubleshooter was developed and was evaluated later on the production line. These manuals conveyed such information as theory of circuit operation and design intent, individual schematics, typical voltages and waveforms, resistance charts, integrated circuit schematics, electrical terminal designations, and a pictorial physical definition of the unit, including a cross reference arrangement that quickly locates components on the part by schematic designation. As a result of the evaluation, production manuals are now in use on some of the current programs. In-plant engineering support technicians are also using these manuals for work in telemetry

assemblies. The Design Agency is using a set of these manuals as technical aids for their technicians.

The Phase 2 work was concerned with the development of diagnostic equipment and processes that would improve failure isolation. Four general categories of testers were chosen for evaluation because they were expected to yield significant economic and quality benefits if development effort proved those concepts feasible. The four types of testers developed are listed as follows:

- In-process verifiers;
- Special diagnostic testers for electronic subassemblies;
- Diagnostic testers for evaluating components; and
- A product simulator.

Isolation of component faults and manufacturing errors by evaluating individual components on pc-board assemblies reduces the complexity of many diagnostic problems. The in-process tester can be designed to detect most of the errors. Development results indicate that these testers should be considered in the tooling definitions for future telemetry programs.

The concept of using special diagnostic testers to include special troubleshooting work loads proved to be both economical and feasible. A simulator type of tester, in which typical faults could be induced and results observed, proved useful as a training tool, but usefulness as a diagnostic tool was limited.

The recommended troubleshooting laboratory design, which included special-design and commercial equipment to verify component rejects and extend diagnostic capabilities of the inspection testers, was adopted by production.

The technique of using liquid crystals developed during the program to detect hidden short circuits on pc-board assemblies has resulted in a significant cost saving.

A electronic probe clip that contacts printed circuit board eyelets was developed. The probe is now used regularly on production and inspection testers to assure positive contact. The probe has a lock-on feature that secures it to the board under test. Commercial probes used in these applications created problems by falling free or into the unit, often causing circuit or component damage.

Routing, scheduling, and discontinuities in the diagnostic effort are factors that influence the accuracy and efficiency of the troubleshooting effort. Evaluation was conducted in this area, and computer inventory and scheduling was considered: however, these have not yet been evaluated in any factory situation.

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DISCUSSION

SCOPE AND PURPOSE

The purpose of this project was to define and develop methods to assure rapid, accurate, and economical isolation of faults in complex electronic assemblies being manufactured on the production line.

Principal areas of concern were:

- Determination of diagnostician skill level requirements, considering both adequacy and economy;
- Improvement of diagnostic procedures and process techniques;
- Determination of tester requirements for diagnostic work; and
- Determination of a suitable and effective means for communicating engineering information on product function, diagnostic techniques, and other engineering support functions to the individuals who perform the diagnostic work.

PRIOR WORK

This report is an extension and compilation of previous quarterly reports on the project and contains the essential information from those reports. A process for detecting short circuits in printed circuit boards with liquid crystals was reported individually in earlier reports.

ACTIVITY

Preliminary Considerations and Assumptions

The two fundamental considerations in any fault-isolation problem are the accuracy of diagnosis and the time required to reach a diagnostic conclusion. Troubleshooter skill level, the sophistication of analytical equipment, and the typical degree of engineering support will, in general, determine the efficiency of a given troubleshooting effort.

Operator skill tends to be inversely related to equipment sophistication and to detail in operating instructions. If one considers the extreme end of this continuum he finds, on the one end, engineers doing the troubleshooting with

open setup equipment and, on the other end, unskilled workers using computer-type analysis equipment and cookbook-type instructions.

This development approach was to first define an adequate operator skill level and to design and develop equipment, methods of communicating engineering technical information to the troubleshooter, and troubleshooting procedures that would be compatible with this skill level. The general work plan, divided into two phases, is listed below.

- Phase 1: The objectives were to define and develop methods to assure an adequate diagnostician skill level and to develop an effective means of communicating engineering diagnostic support information to the troubleshooter.
- Phase 2: The objectives were to define the type of diagnostic equipment necessary for accurate and efficient fault diagnosis and to develop diagnostic procedures for difficult troubleshooting areas.

Phase 1 Development

Defining the Operator Skill Level

The following areas were considered in a study designed to define an adequate troubleshooting level:

- Problem complexity;
- Reducing troubleshooter skill level with automatic diagnostic techniques;
- The requirements placed on the troubleshooter by possible hidden or potential field failures not detected by inspection testing;
- The skill level requirements of the troubleshooting supervisor; and
- The skill level necessary to interpret engineering support material.

Problem Complexity. The complexity of the diagnostic problems evaluated varied over a wide range. Some of the problems encountered were complex enough to require the skill of a design engineer, and required several hours of evaluation before the fault definition was complete; however, most solutions required a skill well below this level.

The more complex problems usually were associated with such things as marginal tolerance build-up in components, and spurious responses or cross-talk resulting from stray circuit capacities or radiation; however, wiring errors sometimes caused very complex effects. It is difficult to assign a quantitative value to the complexity of these technical problems, but general categories of troubleshooting problems did display various degrees of complexity.

Figure 1 categorizes over 1600 failure causes and assigns a complexity code based on the skill required to perform the troubleshooting task.

- "S" is used as a symbol for the least complex category. Failures falling in this category require a small amount of knowledge of the overall function and only a general knowledge of individual circuitry.
- "A" represents a category that requires a sound understanding of the particular overall circuit function and an average knowledge of detail circuitry and electronic fundamentals.
- "C" represents a category defined as complex, and demands detailed analysis of waveforms and general circuit operations. This type of analysis requires a thorough knowledge of theory and troubleshooting techniques.
- "E" represents those categories that require engineering skill. All problems that involve design discrepancies in assemblies or components and any diagnostic problems requiring a mathematical or technical background of an engineering nature are examples of this category. This assumes that the diagnostician had not seen the problem before.

Diagnostic Equipment Automation. The necessary skill level of the troubleshooter is dependent on the extent of the automatic analysis that can be done by the diagnostic test equipment. Although analytical and diagnostic equipment is considered in detail in Phase 2 of this report, general consideration of this subject was necessary so the operator skill level could be defined and equipment that would be compatible with that skill could be developed.

The techniques of self-check and computer-type analysis for diagnosis of electronic malfunctions, as done in large permanent radar or computer installations, are not directly applicable to troubleshooting procedures used in a manufacturing plant where the plant mission involves the manufacture of military products with a great variety of designs, relatively short production runs, state-of-the-art designs, stringent reliability requirements, and emphasis on reduced size and weight.

The size and weight restrictions prevent self-check type circuitry from being built into the unit circuitry. Circuit nodes are very close together in miniature and microminiature assemblies, making parallel fixturing pickup of all nodes necessary for troubleshooting and analysis more complex than in larger assemblies.

Fault diagnosis by computer methods was considered, but was not pursued past the preliminary planning stage for the following reasons:

- High cost of initial equipment;

SKILL REQUIREMENT CODE:

E - ENGINEERING LEVEL
 C - COMPLEX
 A - AVERAGE
 S - SIMPLE

Figure 1. Defect Categories and Complexity Ratings of Diagnostic Problems

- Additional engineering labor costs associated with compiling programs and support information;
- Lack of flexibility; and
- The inability to detect circuit abnormalities and potential engineering problems not anticipated by engineering specifications.

Since the degree of automation is limited in diagnostic problems, the optimum operator skill level must include the capability to use open setup, commercial test gear, and special-design analytical equipment.

Troubleshooting Skills Versus Engineering Support. Troubleshooting complex circuitry with which one is not familiar often requires an engineering knowledge of design intent and circuit functions; however, many technicians who are confused about some of the more-complex aspects of the circuitry are able to localize and correct many of the more simple malfunctions. Studies have shown that familiarization programs, experience in troubleshooting specific circuitry, and adequate engineering-support information will enable most technicians to troubleshoot all but the most-complex circuit malfunctions. Therefore, the engineering support which is provided is an important factor in determining the troubleshooter skills that are required.

Useful technical information must be precise and brief so it can be quickly conveyed and used. The cookbook-type instruction to the troubleshooter who must operate complex equipment and make complex diagnosis is impractical because the volume of material becomes too large if all details are included. Circuit functions, explanations, and reference parameters such as waveforms, dc voltages, frequencies, and time-delays must be quickly referenced and interpreted to be useful.

The operator must be skilled enough to quickly interpret circuit explanations and general technical data presented at a technical level which demands a sound technical background.

Supervisor Technical Skill Level Requirement. Study results indicate that the principle areas requiring technical knowledge are:

- Training personnel;
- Appraising personnel; and
- Acting as liaison to engineering and as aides in diagnostic decisions.

The training and familiarization made necessary by the transfer of personnel from program to program can be done most economically by the production supervisor, since he can plan these personnel moves to reduce training

requirements and ensure that sufficient personnel are trained for each task. This requires that he have adequate knowledge of the technical requirements of the tasks and the problems of training personnel to perform them. The technical requirements involve learning to operate specially-designed diagnostic equipment, and learning to use program-oriented troubleshooting procedures, routing procedures, and other applicable control documents.

Two areas that involve appraisal of personnel fall into the duties of the troubleshooter supervisor:

- The appraisal of individual troubleshooters doing the diagnostic work; and
- The appraisal of the capabilities of applicants for that classification.

Appraisal of the troubleshooter doing the work is necessary to determine individual performance, to aid in upgrading personnel, and to assign causes to discrepant troubleshooting results such as anonymous inspection rejections and failures that are verified and cannot be repeated.

The theoretical introduction and on-the-job evaluations of incoming applicants for the job classification may fall in the area of engineering support. Evaluating the applicant's knowledge of standard diagnostic equipment and familiarization training in this area are the technical duties of the production supervisor working on the factory floor.

The production supervisor should have sufficient technical skill to assist in the troubleshooting effort when the diagnostic problem is particularly difficult and time consuming. He should have sufficient technical knowledge of the product to recognize an engineering problem and to act as liaison between the troubleshooter and the engineering department.

Reliability Aspects of Operator Skill Level. The high reliability requirements of telemetry products demand accurate localization of production electronic failures. This, in turn, limits the minimum skill level of troubleshooting personnel. Many of the component and assembly faults observed during the study subjected associated circuitry to abnormal stress conditions. The identification of the circuitry and the judgments concerning corrective action is part of the diagnostic troubleshooting problem. Several potential engineering problems were discovered during troubleshooting, and engineering was alerted. Although some of the reports proved invalid, it was evident that highly skilled troubleshooting personnel with thorough knowledge of circuit function and design intent can be an effective safeguard against possible hidden or marginal conditions.

Definition of Troubleshooter Skill Level. The precise definition of an ideal skill level for the production troubleshooter seems somewhat elusive when such ramifications as the following are considered: the wide range of complexity found in diagnostic problems; the near-intangible factors that contribute to the definition of the troubleshooter's ability; the intricate relationship of troubleshooting skill level, translation of engineering information to the troubleshooter, and the degree of sophistication of diagnostic equipment. Review of each of these parameters indicated that limitations exist on the minimum acceptable skill level for the troubleshooter, but the job complexity review shows that, with adequate engineering support and proper equipment, most diagnostic work can be performed with less than engineering skill. However, the technical requirements are high enough to demand rigid screening of technicians. Significant economic advantages are realized by a reduction of skill level from engineer to technician.

To assure accurate and efficient diagnosis of problems with the complexities found in telemetry assemblies, the troubleshooting group must have the following capabilities:

- Technical capabilities that enable the troubleshooter to isolate 95 percent or more of assembly errors or component faults on the first diagnostic attempt, assuming a physical configuration that permits access to sufficient circuit nodes to make the analysis;
- Sufficient technical knowledge to quickly interpret technical information contained in engineering support material which is presented at a level that assumes strong technical background;
- Sufficient understanding of all circuit functions and design intent to enable the troubleshooter to recognize subtle, marginal, or abnormal parameter deviations and to evaluate stress effects on associated circuits caused by component or assembly failures; and
- Technical skill sufficient to support or correct troubleshooting decisions, to evaluate individual and group performances, to act as liaison between engineering and production on problems that involve design, to act as a buffer between the troubleshooter and other staff personnel, and to face the general responsibilities of upgrading and maintaining the technical capabilities of the group.

Troubleshooter Qualifications

Evaluating Troubleshooter Performance. Study results showed that operator performance, in many instances, did not correlate with some of the standards used to set qualifications such as technical schooling, experience, and background.

Operator performance could be judged objectively by such factors as the average time required for an individual to complete the troubleshooting task versus his accuracy, by working in the factory with an individual troubleshooter observing his techniques, and by evaluating his insight and knowledge of circuit functions. Such factors as familiarity with a particular equipment idiosyncrasy, dependence on fellow troubleshooters or engineers, and dependence on repetitive type failures made the on-the-job observation necessary.

Experience. Experience or on-the-job training is necessary to develop and become familiar with standard troubleshooting techniques and analytical equipment. The operation and the application of standard analytical equipment must be a second-nature function to the efficient troubleshooter. This includes the many features of the various types of oscilloscopes and operation and application of RF and pulse generators, spectrum analyzers, and counters. The repetitive study of similar problems and the execution of certain techniques also tends to develop habits and confidence and expedite diagnosis of certain problems. If theoretical knowledge is sufficiently strong that all the details of the process are understood, performing the task educates the operator; but if fundamentals are weak, detail functions of the circuit become vague, and limited educational benefit is realized from doing the troubleshooting by process of elimination. Operators with extensive experience and weaker technical backgrounds could troubleshoot many routine failures, but they were weak in localizing unusual or first-encountered faults.

Education. Education alone was not always an effective guide to determining the technical knowledge of a troubleshooter. The wide range of standards required by trade school, the length of time out of the school and the field, and the efforts to keep abreast of the fast-moving technology were pertinent factors that required consideration. Some operators with a minimum of trade school training had superior abilities and had acquired sound technical knowledge through extensive home study and by constantly working with engineering and technical personnel.

Testing. A test oriented toward troubleshooting telemetry assemblies was developed. The test was divided into categories of dc circuitry, basic logic circuitry, pulse and transient circuitry, transistors, RF transmission lines, identification of typical circuit stages, and detail functions of individual telemetry circuits. The test complexity of each category was graduated from the elementary to the more complex for the sake of evaluating each operator. Since pulse and switching circuitry make up a large percentage of telemetry circuitry, the test was designed to evaluate this area thoroughly. A close correlation was found between test scores and operator performance. Some correlation existed between education and experience and operator performance.

Proposed Screening Methods

The truly outstanding troubleshooter approaches the unique. The exact qualities that set him apart from one with less expertise are not easy to define. Testing designed to determine knowledge of fundamental electronics and oriented toward specific job requirements, educational background, and experiences was found to correlate with performance to a usable degree. Testing proved to be the most effective of the three methods of evaluation, but all should be considered. Present bargaining-unit agreements and company procedures place the same restriction on testing.

The following method was chosen to determine adequate troubleshooter skills.

- Give a written test to determine adequate knowledge of electronic fundamentals and adequate aptitude.
- Give a 3-week on-the-job evaluation and training period under the direction and observation of a process engineer before promoting or hiring an employee into the troubleshooting category.
- Establish an educational minimum of high school graduate and a graduate of electronic trade school.

Production Improvements Resulting From Skill Level Definitions

As a result of the evaluation conducted in the development effort, production now conducts training or familiarization schools for new programs, and also maintains a training school for production troubleshooters to upgrade their overall technical ability.

Developing Troubleshooting Manuals

Preliminary Evaluation. The efficient translation of engineering information and product definition to the troubleshooter level is a critical dimension in any faultfinding system. In addition to normal unit definition, the troubleshooter needs knowledge in such areas as theory of tester and circuit functions; operating procedures; typical dc voltages; ac waveform references; general troubleshooting instructions, including failure symptoms and likely cause; and visual aids that will quickly locate components physically and identify them according to schematic designations. The design criteria for the text of the troubleshooting manual was developed by an on-the-job study, with the objective of finding the needs of production troubleshooters in the areas mentioned in the above paragraph.

A study was conducted to determine these needs, and resulting design criteria were defined as follows.

- All major subassemblies shall have separate manuals except in those cases where individual subassemblies are physically very small or where the circuitry is particularly inter-related with the next-higher assembly.
- All manuals shall contain an exposition section covering the theoretical operation of the assembly.
- All manuals shall contain individual schematics, typical voltage and current waveforms, resistance measurements, and other pertinent reference information, including caution notes if special care is required in a particular evaluation.
- All manuals shall require cross-reference arrangements so a schematic designation can be quickly translated to the actual physical location of the component.
- The troubleshooting guide shall contain a complete physical definition, showing the location of all test points, components parts, components electrical designations (such as transformer terminal numbers), anode or cathode designations of semiconductor diodes, all land and path routings on printed circuit components, part number of components, and any other essential information.
- The manual shall show electrical test specificifications and test-operation instructions.
- Analytical procedures for any unusual troubleshooting techniques or operations where the operator must be cautious to prevent damage to the unit shall be included in the troubleshooting guide.

Development of the Theory Section. The concept outlined in this section of the manual begins with the basic design considerations and general operation of a circuit of the same general type, and advances to the specific details of the particular circuit of the assembly. The text is written on the level of a skilled technician. The terminology and theory-of-operation explanations assume comprehensive knowledge of electronics. The use of equivalent circuits, partial sections of circuitry showing current flow and voltage drops, and overall circuit operations are among the techniques used in the text material.

The text does not offer a cookbook type approach, nor is it designed to teach the fundamentals of electronics. Instead, it is directed toward explaining the electronic function of the product and defining applicable parameters.

Cross Reference Between Locations of Parts and Schematic Symbols. The method developed for quickly locating a part on an electrical assembly is a convenient cross-reference from schematic symbol to physical location of the part. The components are listed by schematic symbol according to type and numerical order. For example, the resistors are all listed together in a column starting with R101, proceeding numerically to R102, R103, and so on. An index number is assigned to each component that is located on the physical pictorial drawing. The example in Table 1 and Figure 2 gives the method used for cross reference. CR421 was assigned as the index number 24 in the Location Reference column of Table 1. The number 24 locates the part on Figure 2.

Waveforms. The reference waveform includes both the normal waveforms and discrepant waveforms. Simulated faults that did not result in catastrophic failures were introduced into the unit. The junctions of a transistor were opened and shorted, a diode was reversed, capacitors were opened and shorted, and wrong-value components were sometimes introduced. Reject data was reviewed to identify the most commonly encountered component failures. These failures were built into the unit, and pertinent waveform photographs were made.

The waveforms were strategically taken to convey the proper technique to the operator. For example, if the best way to check a diode was to measure the ac drop across it, the waveform was taken with a probe on each side of the diode and the scope was adjusted to give the difference between the voltage at the scope probes or, if the best way to determine proper operation of a circuit was to view a transient phase relationship, a dual-beam scope might be specified.

Production Improvements

As a result of the study and the development of the prototype manuals, production is now using a set of production troubleshooting manuals on telemetry and other programs.

Engineering technicians are also using the production manuals for engineering technical work. The Design Agency has ordered and is using a set of the production manuals as technical aids for technicians assigned to telemetry programs.

Significant cost savings have been realized because of this improved efficiency in translating and transferring technical engineering information to the production troubleshooter and engineering technician level.

Table 1. Parts List and Figure Location Reference

Ref. Design	Part Number		Description	Figure Location Reference
	Sandia	BKC-201		
CR411	312846-00	312846-101	Diode	19
CR412	312846-00	312846-101	Diode	20
CR413	312846-00	312846-101	Diode	19
CR414	312846-00	312846-101	Diode	12
CR415	312846-00	312846-101	Diode	12
CR416	312846-00	312846-101	Diode	24
CR417	312846-00	312846-101	Diode	25
CR418	359413-00	359413-101	Diode	15
CR419	359617-00	359617-101	Diode	19
CR420	357764-00	357764-101	Diode	23
<u>CR421</u>	<u>357764-00</u>	<u>357764-101</u>	<u>Diode</u> <u>Example</u>	<u>24</u>
CR501	359413-00	359413-101	Diode	41
CR502	359843-00	359843-101	Diode	44
CR503	359967-00	359967-101	Diode	34

Figure 2. Circuit-Board Drawing for Locating Components and Test Points

Phase 2 Development

Preliminary Evaluation

Phase 2 work was concerned with the development of diagnostic equipment and processes that would improve isolation. Four general categories of testers were chosen for evaluation because they were expected to yield significant economic and quality benefits if development efforts proved the concepts feasible. The four types of testers are:

- In-process verifiers;
- Special diagnostic testers for electronic subassemblies;
- Diagnostic testers for the evaluation of components; and
- A product simulative-type tester.

The application and testing concepts associated with each of these testers are discussed in the following paragraphs.

Concept Number 1. One method of simplifying the diagnostic problems resulting from manufacturing errors and component failures is to evaluate individual components or component networks by in-process testing at selected stages of the fabrication of printed circuit board assemblies. A component failure or a manufacturing error which causes only subtle changes in output parameters can be difficult to isolate by functional-analysis methods. This is particularly true if the assembly has a large number of components or contains circuitry with complex feedback loops which make circuit parameters highly inter-related. For example, a fault in almost any stage of an oscillator-type circuit or an AGC loop can disable the overall circuit function and add to the difficulty of isolation by functional methods. The expected advantages of isolating faults at the time of assembly by checking individual components or component networks were: rapid feedback to the production line; simplification of diagnostic problems caused by assembly errors and initially-bad components; simplifying the isolation of more than one fault in an assembly; and a more thorough check of components on the board.

Concept Number 2. The second tester concept chosen for development was a special type of diagnostic tester with a design oriented toward diagnostic capabilities rather than testing.

The typical inspection tester necessarily automates operator control and influence out of the testing process. This is especially true in testers designed to test military products that require permanently stored data that is to be used for reference to determine environmental degradation. These testers are often required to meet state-of-the-art accuracy requirements which are seldom required to detect fabrication errors and faulty circuit components, since a very high percentage of these errors result in significant

deviation from the norm. The waveform and static parameters of internal circuitry have equal significance with the output circuitry condition from a diagnostic viewpoint. Troubleshooting tester design should consider accessibility to internal circuit nodes and methods for evaluating individual stages of the circuitry.

The present method of determining the necessary test equipment for incoming schedules is based on the summation of inspection time, troubleshooting time, and tester down-time estimates. These are derived from projected reject rate, task rates and time studies, and schedule information. In those cases where the troubleshooting time estimates indicates the need for an additional tester, a troubleshooting tester should be considered an alternative to buying another inspection tester because economic benefits can be realized by the reduction in initial cost of equipment and more efficient troubleshooting. Additional benefits can be realized where particular diagnostic problems are affecting schedules or interrupting normal product flow.

Concept Number 3. This tester concept included portable equipment that would supplement the inspection testers. The concept includes diagnostic equipment to evaluate components, special-design testers that adapt to the inspection tester to extend its diagnostic capabilities, special probes, simulated loads, and other similar types.

Concept Number 4. A type of tester that simulates product circuitry was selected for development. This concept assumed the following features.

- The tester circuitry simulates the circuitry in an electronic subassembly so faults can be self-imposed into the circuitry and the results of the faults can be observed.
- The tester is to serve as a training unit and a diagnostic aid.
- The tester provides overload protection against accidental shorts, and extreme-value substitution will not damage the tester.

Development of Tester Concept Number 1.

Feasibility Studies. Before starting the tester design efforts, the following areas were evaluated to set design criteria and to outline a detail development plan:

- The various types of circuitry that the tester must test;
- A universal tester versus small individual testers;
- Selection of a typical piece of circuitry to use in the experiment; and
- Outlining the plan to prove the concept feasible.

Types of Circuitry. One of the early evaluations was directed toward determining if there existed a packaging technique and a particular circuit type that could be considered representative of the present and future telemetry build. In one telemetry assembly, 80 to 90 percent of the electrical circuit components were mounted on some type of printed circuit board. Some of these boards had over 90 percent of their components integrated into sealed packs, whereas others employed only discrete components. Over 90 percent of the circuitry was switching or pulse circuitry, and a majority of these circuits were logic switches of some type.

The technical problems associated with verifying that integrated circuit components meet their component requirements are indeed different from those used to verify that a discrete resistor or capacitor meets requirements. The integrated circuit has many components that are not accessible from the outside of the sealed package, making a functional check of the individual package necessary to verify the electronic validity of the component. Discrete components may be more precisely evaluated by measuring parameters such as resistance and capacitance. This is true only when parallel-circuit guarding can be accomplished.

The typical fabrication errors were found to be very similar. Some of the more common errors were shorts between adjacent component leads, mislocated or interchanged components, misoriented components, improper wiring, missing components, solder-splatter and wire-clipping shorts, and open welds or solder joints.

Functional evaluations of integrated circuit logic, in general, are more easily accomplished than evaluation of linear circuitry, since only one low-voltage B supply is necessary, and excitation voltage amplitudes are often standardized.

Universal Tester Versus Individual Testers. Feasibility studies were extended to evaluating the choice between a large automatic universal type of tester that could be adapted to a large number of assemblies versus a series of small, relatively inexpensive testers designed to test specific circuitry. The main advantage of the universal type of tester is the economic gain resulting from long term program-to-program usage. These gains can be realized only if product configuration is standardized to the point that the features required to make the tester universal remain simple enough to make the tester economically feasible. The small tester is more flexible in application, and can be located in the production line, so the assembler can evaluate each assembly immediately after build. This results in rapid feedback to the production line. A group of smaller, specialized testers may also require less initial cost than the universal type of tester because expensive computer or tape-type controls can be eliminated when design is optimized toward testing specific circuitry.

Maintenance and down-time problems are reduced by this tester simplification, and they are more-easily localized to smaller sections of the build line. The individual tester concept allows the tester design to be oriented toward a type of error peculiar to the assembly being tested. The percent of rejections caused by manufacturing errors compared to the percent of rejects caused by component failures, the nature of the fabrication errors, and the severity of stress that the error imparts to the circuitry are factors that can determine which errors are most advantageous to isolate.

The feasibility of the concept could be more economically evaluated by a small tester; however, in large-scale production operation, the large computer or tape-controlled tester might be more economical.

Selection of a Typical Unit for Evaluation. The product piece selected for evaluation is representative of a typical type of printed circuit board assembly. The circuit board selected has 19 integrated circuits and 51 discrete components. The individual circuit stages are logic circuits and are representative of current trends in telemetry circuitry. The criteria used to justify this typification were the ratio of discrete components to integrated circuits, the total components per assembly, and the type of circuitry (Figure 3).

Definition of Concept. The feasibility of the following testing plan was evaluated. The details of the plan are listed below.

- The testing plan was to use a group of small, economical, printed circuit board testers integrated into the production line, which would evaluate individual components or component network at the time of assembly.
- The evaluation would be done only on the more-complex assemblies.
- Testing would be done at two stages in fabrication: one test would be performed after the discrete passive components, the other after the active circuits had been assembled to the board.
- The tester would be a go/no-go type of tester, and would be simple enough to enable the production assembler to operate it.

Plan for Checking Feasibility. The development plan was to choose a typical printed circuit board with both integrated and discrete components and a representative circuit type, and to develop a verification tester that would evaluate the components and their installation by the production assembler as an in-line process. The tester was to be evaluated as a diagnostic tester also. The actual tester concept included two types of detectors; one to evaluate discrete components prior to the installation of the active components, and one to evaluate each stage functionally and check active components.

Figure 3. Sealed Packs Used in a Typical Product Subassembly Compared to Discrete Components Used

However, since both detectors must be developed and proven feasible, and since switching, fixturing, and general testers could be evaluated separately, the following development plan was chosen as the most economical approach.

- A complete tester would be developed to include a functional type of detector that would make functional checks of individual stages of circuitry.
- A separate detector would be developed and evaluated for checking individual passive components.
- The tester would be evaluated under actual production line conditions to evaluate such areas as speed of testing, fixturing, operating simplicity, attitudes of the assembly workers concerning the tester, and the general effectiveness of tester performance.
- Recommendations for production equipment would be made on the basis of the combined effectiveness of the two detector types.

Fixture Design and Development. The two most important dimensions in the fixture design were:

- Speed required to mount the printed circuit board; and
- The reliability of electrical contact.

Since this type of tester is to be operated by unskilled operators, false indications needed particularly to be avoided. A study of spring-type fixtures showed that failures were often caused by:

- Uneven holding pressures resulting in circuit board tilt;
- Isolation at the point of contact due to oxide films, flux or other foreign material, or irregular solder surfaces; and
- Spring contact failures because of faulty contact and bent contacts.

The fixture is shown in Figure 4. Installation of the board to the fixture requires approximately 15 seconds. The spring contact design has a cupped head with a lip around the periphery of the cup, allowing better probability of contact than a pointed configuration, and the cup mates well with the normal contour of a solder joint. This mounting arrangement provides clamps that pick up tooling holes approximately 120 degrees apart and clamp the printed circuit assembly down against standoff posts. The platform plane containing the spring contacts is raised into the board by pushing a lever forward. The lever is mechanically linked to an eccentric cam. Rotation of the cam by the forward motion of the lever applies an upward force to a rod riding on the cam. The rod, in turn, lifts the platform containing the

spring contacts into the unit under test. The mounting dimensions and mating connections are completely independent of operator adjustments. Factors such as tilt and distortion from irregular pressures are automatically controlled. A schematic diagram of the tester is shown in Figure 5.

Detector Design. The two detectors in the tester were designed for the following capabilities:

- To check logic gates by running them through a truth table or by simulating actual operation in the circuit, depending on the stage of fabrication being tested;
- To check the pulse widths of monostable and other types of multivibrator circuits; and
- To check resistors, diodes, inductors, and capacitors by testing the individual components with no power applied to the board.

Functional Detector Operation. The circuitry on the printed wiring board consists of logic gates, one-shots, flip-flops, and various other typical logic switches. The schematic sketch below is representative of the type of circuitry on the board.

The detector examines the input and output pulses of each stage for proper amplitude and pulse width, and indicates the failures. For example: assume that the production operation places the printed circuit board on the tester, switches a rotating selector to position-1, and gets an accept indication; but when the test switch is advanced to position-2, a rejection is indicated. The operator is referred to a visual aid which is a pictorial view of the unit where components C1, R1, and P1 are clearly identified. The assembler

verifies correct fabrication by use of the aid and a general visual inspection of these components and their connections. If the defects are component failures, the assembler notes that C1, R1, or P1 are defective and gives the unit to the troubleshooter who makes the final component fault isolation.

A photograph and a schematic drawing of the tester are shown in Figures 4 and 5. The schematic shows a dual comparator which has adjustable limits to detect correct logic-0 and logic-1 pulse amplitude levels. The following gates accept either a negative or a positive pulse if these levels are met. The pulse is shaped and applied to a counter which monitors 50 consecutive pulses. If a sample of 50 pulses meets amplitude requirements, a pulse-width detector examines the width of the incoming pulse. The resolution of the pulse width detector is approximately 70 nanoseconds. Indicator lamps are activated for both accept and reject conditions.

Passive-Component Detector. This detector consists of a comparator type of circuit. The original design considered three standards for comparison:

- Simulated components and networks;
- A printed circuit board that had passed all inspection requirements; and
- Adjustable or programmable voltage limits.

The final tester circuitry used both of the first two types of standards. Some modification was necessary if programmed voltage standards were to be used. The simulated component or network standards were chosen for the sake of simplicity and for the reason of economy. The same concept feasibility would apply also to automatic or programmed comparator methods, and modification required to adapt to this technique would be minimal.

The detector places the component under test in series with the standard and compares the total voltage across the standard with the voltage across the component or network under test. The voltage across the standard is one-half of the total voltage when components have the same value as the standard. The voltage across the component under test is amplified by a factor of two, inverted, and compared to the total voltage by a differential comparator. The comparator is opened up with a strobe pulse and can be strobed up at any time after the application of the driving function. The driving function can be selected for the most ideal circuit response. This extends the diagnostic capabilities of the detector by allowing some network checks, as shown in the following sketch.

A block diagram and an electrical schematic of the passive-component detector are shown in Figures 6 and 7.

Functional-Detector Evaluation. The functional detector was evaluated separately from the passive-component detector to determine the effectiveness of this portion of the tester on general production types of problems.

A review of defects occurring in a production run of 809 units was made, and component failures and fabrication errors were isolated. In cases where the errors could represent marginal conditions, these errors were built into a unit and then subjected to the verifier for test. The verifier isolated 100 percent of these faults. Table 2 lists the results of this evaluation.

Text continues on page 42.

Figure 4. The Electronic Verifier Tester

Figure 5. Verifier Tester Schematic Diagram

Figure 6. Passive-Component Detector Block Diagram

Figure 7. Passive-Component Detector Schematic Diagram

Table 2. Product Defects Detected During First Evaluation

Sample Number	Failure Modes	KCD 413 No.
1501	A216 Pins 2 through 7 not welded	35881
1583	R211 Broken	32585
1436	FM Shorted A212 Pin 11 to 12	
1801	R216 wrong	33797
1149	Q202, Q203 wrong and reversed	31288
1157	R209 and R214 reversed	31334
1507	Replace Q203	32584
1687	C204 missing	33778
1722	A203 upside down	33782
1746	C204 missing	35071
1766	A203 is 1846 S/B 1847	33776
1114	C204 missing	31333
1456	Replace Q301 and A203	32847
1710	C204 missing	34287
1540	A217 reversed	33205
1703	A217 Pins 8 through 14 not welded	33763
1481	C217 incorrect valve	32815
1520	C219 incorrect valve	32395
1356	A219 leads not welded	32205
1763	A217 upside down	33779
Total units tested 809		
Total inspection rejects 20		
Percent rejected $\frac{20}{809} = 2.47$		
Number of defects detected by verifier 30		
Percent error isolation 100		
Only component failures and manufacturing errors were considered		

In the second evaluation, a group of 40 production units was randomly tested and rejects were investigated. The units were visually and electrically inspected. Inspection personnel were not aware that special conditions existed. Seven of the first 14 units failed because of a missing wire. Two failed because of out-of-tolerance capacitors, and one failure was not detected. The undetected failure was not immediately rejected during the inspection tests. That component was a reversed tantalum capacitor failure which was aggravated by stress. Table 3 summarizes these results.

Table 3. Product Defects Detected During the Second Evaluation

Number of Faults	Nature of Faults	Inspection Tester		Verifier	
		Detected	Undetected	Detected	Undetected
7	Missing Wire	0	7	7	0
2	Out-of-Tolerance Capacitor	0	2	2	0
1*	Misoriented	1	0	0	1
<p>* This capacitor was a tantalum capacitor that was reversed. Neither the verifier nor the inspection tester rejected this unit until after continuous stress aggravated the unit.</p> <p>Total Units Evaluated 40</p> <p>Total Existing Faults 10</p> <p>Rejects (percent) 25</p>					

The appropriate production operator was alerted to the missing wire oversight. Investigation reflected that the next three levels of inspection testing did not check for the presence of this connection. Corrective rework and reassembly time at the higher level was estimated at 2 hours. Reflow time was estimated at 72 hours. This included retesting and visual inspection time.

The two capacitors had capacities reading slightly out of specification, but did not cause any output parameters to be out of tolerance. They did cause one parameter to shift significantly away from normal distribution.

The tantalum capacitor that was reversed was not rejected by either tester until the voltage had been applied for several minutes. Verifier test time was shorter than inspection test time, causing the fault to go undetected.

The tester could detect pulse width differences within 70 nanoseconds throughout a range of 500 nanoseconds to over 10 milliseconds by adjusting the pulse width detector. The logic-1 levels could be verified to within ± 10 millivolts.

Passive-Component Detector Evaluation. This circuitry was mostly open setup, and was evaluated to determine the accuracy of measurement and the percentage of passive components that could not be evaluated because of parallel circuitry or inaccessible circuit nodes. The following results were obtained.

- Over 96 percent of the components could be evaluated by two-stage testing.
- The accuracy was within ± 5 percent for inductors and capacitors, and ± 1 percent for resistors over ranges of 10 ohms to 10 megohms, 5 pF to 10 uF, and 100 uH to 10 H.

Production-Line Tester Evaluation. The Verification Tester was evaluated on the production line, with the following results.

- The assemblers working with the tester maintained a good attitude toward operating the tester and the results assured them that they had fabricated the assembly correctly.
- The bargaining unit agreed that the production assembler should operate the tester, but only to isolate fabrication errors. Final rejection of a bad component was to be treated as work falling in the troubleshooter classification.

Cost of a Typical Tester. The tester design was oriented toward operating simplicity, low cost, and small size. Development cost for material, build, and design was estimated at approximately \$6,000. Inspection tester costs for the assembly were eight to ten times the verifier cost because of the inspection requirements for measurement accuracies of output parameters. The development cost was higher than the cost of a similar production tester because of the extra cost of experimentation required in development. The cost of sophistication and automation should be justified by the economic gains they yield from reducing the task rate.

Production Results. The verifier was converted to a production tool and is now in use. The down time is somewhat higher than desirable because development parts were not as heavy-duty as production designed tester components normally are. The faultfinding capabilities are close to design goals.

Development of Tester Concept Number 2

This concept deals with the development of a tester with the design oriented toward troubleshooting rather than testing. The best application of this tester occurs when the troubleshooting work load requires so much time of the inspection tester that additional test equipment is required to ensure that schedules will be met, and when adequate troubleshooting features not found on the inspection tester are badly needed because of circuitry peculiarities or special diagnostic problems.

From data taken during earlier studies conducted on troubleshooting problems in the factory, it was determined that a telemetry power supply assembly had diagnostic and testing problems that would be compatible with evaluation of this concept.

The power supply package had three circuit boards stacked vertically. The electrical circuit was a chopper-type power supply that chopped the output of a 28-volt battery to a 10 kHz square wave, then transformed and rectified the square wave to the desired B-supply voltages.

The power supply was selected as a vehicle for evaluations for the following reasons.

- The troubleshooting work load was so heavy that additional test equipment was needed.
- Several diagnostic problems were encountered in troubleshooting the power supply.

When marginal over-current conditions existed, no functional check could be made on the unit, since input power must be applied at full amplitude and with a fast ramp to simulate field conditions. The oscillator would sometimes operate at lower voltage conditions and lighter than normal loads without drawing out-of-limit current when various types of defects occurred in the oscillator. The troubleshooters used a 28-volt supply and a 9-volt battery to start the unit when troubleshooting the oscillator under these conditions. The disadvantage of this approach was that no fixture was used to assure correct connections and to expedite hookup. No automatic-timing circuits were available to alert the operator to run-time limits and no over-voltage or over-current protection was being used.

The failure of a driving transistor sometimes burned a resistor which delaminated a printed circuit board, causing the entire assembly to be scrapped. When troubleshooting units which are known to have a gross defect and when full supply conditions need not be applied to display the defect the reduction of input power can be a beneficial precaution.

Most of the oscillator section of the power supply was contained on one printed circuit board. If problems existed in this section, isolation of the individual components in the final power supply configuration was difficult because of the inaccessibility of circuit nodes and the frequent necessity of breaking the electrical circuit. No tester was available to evaluate the individual printed circuit board assembly. Neither functional evaluations nor verification after rework was possible if the oscillator printed circuit board assembly was rejected as a unit.

The circuit nodes that were most often examined to make diagnostic judgments required the connection of probes to component leads which were near other components and often difficult to get to, creating a condition conducive to accidental shorting of the circuit node under test to adjacent circuitry by the probes being used for evaluation.

Tester Development. A set of specifications and preliminary sketches were developed to define a tester that would be more economical and have better diagnostic capabilities than an inspection tester. The tester design criteria are outlined below.

- The tester shall excite and load the oscillator printed circuit board assembly, the final power supply assembly, and the next-higher assembly.
- The tester shall bring out all accessible test nodes to jacks on the front panel and identify the nodes by schematic symbols compatible with those of the troubleshooting manual. The reduction of necessary probe connections reduces the likelihood of accidental short by evaluation probes.
- The tester shall allow any dc load to be removed or applied separately, but only when the power is removed from the unit. The removal and application of a load during operations generates undesirable transient conditions.
- The tester shall lock out over-voltage and over-current conditions.
- All applied voltage shall be continuous and adjustable from 0 to a maximum operating range.
- The tester shall interrupt troubleshooting operation after a specified operating time at specific current levels by disabling the power to the unit.

- The tester shall be designed to adapt to open setup diagnostic equipment such as scopes, counters, and voltmeters.

The additional circuit reactances that would result from bringing out the many circuit nodes to the front panel and the additional circuitry necessary to switch the loads individually to various values and to furnish the additional loading, excitation, and fixture connections for three levels of assembly were recognized as critical parameters. Development work included definitions of wire dress and fabrication techniques and evaluation of the feasibility of such an approach.

Development circuitry simulation in the switching circuits showed the parameters to be very critical. Cross-talk between conductors and additional wire length caused severe differences in unit waveform parameters and, in some cases, the unit developed spurious oscillating conditions in various nodes. This effect was minimized to an acceptable level by strategic choice of wire routing and by shielding critical circuits. Point-to-point wiring was required with no bundling of critical circuit wires.

Results. As a result of the study, a production tester was built according to the guide lines of the developed design criteria.

The tester extended the troubleshooting capabilities of production lines, and the initial cost was 10 to 15 thousand dollars less than the cost of an inspection tester. The capability of evaluating the individual circuit board increased the accuracy of diagnosis in the oscillator circuit and allowed electrical verification of these circuit boards after rework and prior to reassembly. The probability of accidental short circuits caused by probing was also reduced by bringing testpoints on the printed circuit board out to the panel.

This tester concept proved to be a feasible and economical method of extending the capacity and range of diagnostic test equipment when the inspection testing and troubleshooting overload inspection equipment was overloaded and when particularly difficult diagnostic problems occurred. Figures 8 and 9 show photographs of this tester.

Figure 8. Special On-Line Troubleshooting Tester

Figure 9. Troubleshooting Tester Fixtures and Test Terminals

Development of Tester Concept Number 3

Defining the Areas of Need. The third tester concept deals with the feasibility of extending the diagnostic capability of the inspection tester by a supplementary type of diagnostic tester. A review of the testers being used on a telemetry program currently in production proved a need for this type of extension in the following areas.

- There were several levels of assembly that had no electrical inspection requirements; consequently, no tester was available to evaluate units at those assembly levels. Therefore, extension of tester capabilities was necessary to load and excite these units and test them at intermediate assembly levels. Testing at intermediate assembly levels permits manufacturing errors, intermittent failures, and defective components to be detected before they are made less accessible by higher levels of assembly, thereby reducing rework. It also minimizes loss of intermittent failures that might be undetected at higher levels of assembly because of changes in operating environment or tester limitations. When test points are inaccessible, it is desirable to disassemble only to the point where access is possible. Intermediate level testing aids that purpose.
- Tester diagnostic capabilities were not always adequate to accomplish diagnosis at the failure level.

Troubleshooting at Intermediate Assembly Levels. The extension of tester equipment capabilities to test the intermediate level of assembly, where no electrical tester was available for testing or troubleshooting, involved three principle areas: additional loads, B-supply voltages, and, sometimes, excitation or signal stimuli. Any assembly level higher than the power supply level needs only to have the input dc voltage that simulates the batteries as its input power source.

Analysis revealed that the master circuitry that triggers a large part of the logic circuitry would furnish most of the excitation necessary for testing at the intermediate levels of this particular product.

The development concept definition was to design and build a generator that would furnish parallel output pulses to excite the logic assembly. The generator was to be portable so it could be used on any of the applicable, higher-level testers, to have open setup loads that would simulate the various subassembly loads, and to furnish dummy RF loads for the transmitter to allow the transmitter to be operated on the lower-level testers that had no terminating transmitter port connection.

The tester concepts and the preliminary design were developed and recommended for production application and, as a result, Production built a generator of special design to be used as auxiliary equipment to extend the excitation capabilities of the inspection testers. That generator is shown in Figure 10.

Figure 10. Special Product Simulator and Logic Generator

Additional Diagnostic Equipment. The extension of the diagnostic capabilities of both final and subassembly testers was considered in a detailed review as to specific need in each category of troubleshooting problems. Many of the diagnostic testers needed were available commercially, and required no special design. The only portable equipment being used on the line were conventional multitesters. The multitesters used a 30-volt battery in the high-resistance range-select position, which delivered a power output high enough to damage semiconductors in the product.

The following categories were defined as special needs in portable analysis equipment.

- When transient or switching discrepancies occur, a multichannel visicorder is needed to record current and voltage parameters during the turn-on transient.
- A dual-beam scope equipped with current and voltage probes and dual-channel preamplifiers is very useful when making time or phase comparisons of pulse conditions.
- Digital multitestors have the advantage of quick readout, accurate interpretation of the readout, and relatively high input impedance.
- A small portable counter that would count frequency, display time delay between pulses, and give the ratio between two frequencies or repetition rates was often needed.
- A logic generator that would furnish a compatible logic output was often needed to allow signal injection techniques to be employed.
- Portable power supplies were often necessary to eliminate dc supply lines as possible contributors to cross-talk and spurious problems.
- High-sensitivity clip-on current probes, along with associate amplifiers and current milliammeters, were sometimes needed in transistor circuit analysis.

In this phase of the study, diagnostic equipment for evaluating components was considered. The equipment used was to aid in diagnosis and to verify that a component was bad at the time of rejection, confirm the assembly rejections, and furnish fast feedback on the line.

A frequent need existed for analytical equipment that will evaluate the following:

- Semiconductors such as tunnel diodes, rectifier diodes, zener diodes, transistors, and other discrete devices;
- Components such as capacitors, inductors, and resistors; and
- Parameters such as voltage, current, frequency, and ratio between repetition rates or frequencies.

Integrated and hybrid circuits were sometimes questioned, but they were welded to the mother boards and could not easily be evaluated without removal from the board.

Inspection reports and on-the-job observations revealed that probes used on scopes, voltmeters, and other diagnostic instruments were sometimes large enough to cause accidental short circuits during probing.

Developing a Laboratory. From data collected from the study, a system was defined to increase the diagnostic capability of the troubleshooter and to allow component verification, with the exception of integrated and hybrid components. The concept proposes a troubleshooting laboratory conveniently located so that the operators, by use of special carts, could transport portable equipment from the lab to the production line or bring the units to the laboratory.

The list of recommended laboratory equipment included those diagnostic testers previously outlined in Phase 2 and those listed below:

- A curve tracer for semiconductor evaluation;
- A portable transistor checker;
- A logic generator, Figure 10;
- Any specially designed diagnostic equipment falling in the various categories of this report;
- ANRLC bridge;
- Two digital multichckers with minimum 10 megohm input resistances and minimal reactances;
- A dual-beam oscilloscope;
- A small, portable frequency-counter/time-interval meter;
- Accessories such as special hookup devices, clip leads, and probes; and
- An ohmeter with open-circuit voltage and short-circuit current limited to assure no damage to semiconductor functions.

Equipment that would analyze integrated circuits and hybrid circuits was not recommended. Although open-setup test methods are economically feasible, welded or sealed construction in many assemblies prevents ready access for conventional test probes. When such assemblies are opened for testing, they normally cannot be reused. In addition, evaluation of such a unit is more complex than evaluation of individual components. For example, a capacitor can be evaluated by simply lifting one end of the capacitor, but a sealed hybrid pack containing many components may require specially-designed equipment. When troubleshooting this type of circuitry, emphasis must be kept on diagnosis with the pack on the board.

Results. A production troubleshooting laboratory was set up in the telemetry assembly area, using the recommendations and data from the process evaluation. The laboratory was largely made of pool equipment, although it was necessary to buy some commercial equipment. Figure 11 shows the completed laboratory.

Figure 11. The On-Line Troubleshooting Laboratory

Verification that a component is defective by checking its individual characteristics reduces troubleshooting errors, and is often a necessary part of the diagnosis. In the instances of sealed integrated or hybrid packs, component mounting techniques, complexity of verification equipment, and the inter-relationship between circuits became factors that must be evaluated to determine the practicality and the feasibility of verifying these components on a particular unit or program.

Development of Tester Concept Number 4

An electronic simulator to simulate a product part with various types of faults was developed and evaluated. The tester was built with the intent of evaluating the concept for feasibility and application. A telemetry modulator assembly was chosen for this evaluation, because the circuitry was not so extensive as to make the tester expensive, but it was complex enough to be representative. The tester was designed to be used as a training device, where the nature and degree of change in output parameters could be observed for a particular change in a component value. The tester was to be

used with its respective troubleshooting manual to study the electronic function of the unit and for diagnostic work. For example, the duplication of a waveform deviation observed in a faulty unit by imposing a fault into the simulator might either strengthen or weaken a troubleshooting judgment.

The tester was designed and built with a schematic overlayed on the front of the panel. Each component has an associated control near it so the control is an obvious adjustment for that component. The control is also labeled. A reference point is shown on each control so that the circuit components can be returned to normal value without considering other nomenclature on the panel (Figure 12). High-limit crowbar circuits (protected against catastrophic high-current conditions) and lamps indicate the presence of overload.

Figure 12. The Special Product-Defect Simulator

Diodes can be reversed, opened, or leaky and capacitors and inductors are variable on each side of tolerance and, in some cases, can be continuously variable through extreme values. Open and shorted conditions that are very obvious are not simulated, such as filter capacitor shorts and open B+ lines. The more subtle and marginal effects were chosen for display. The tester is to be used also as a reference unit when operated in the normal mode so the operator can refer to the circuit for reference waveforms.

Comparisons of waveforms in the normal condition to those of several production units proved that some differences that were significant enough to obscure some of the more subtle changes in components did exist. The causes of these differences were found to be extra wire length, additional switch capacity, and changes in components. These changes were necessary to improve the circuitry for long-term, continuous operation and intermittent overload conditions, and to furnish the switching necessary to place faults into the simulator.

The tester was evaluated as a troubleshooting device under factory operating conditions, but did not meet production troubleshooting requirements. Several failures occurred in which the output waveforms were degraded. This effect was apparently caused by distributed inductive and capacitive reactances introduced by the component switches, lead dress, and some of the components themselves. Stray reactances might be reduced by careful planning and layout; however, the improvements that could be obtained did not appear sufficient.

In spite of the shortcomings of the simulator as an in-process production tester, it proved to be very useful as a training device. Since many types of failures can be easily simulated, it is well adapted for use as a training aid.

Waveform photographs incorporated into the troubleshooting guides proved to be the most effective and economical means of displaying this type of information. The simulator proved to be useful for diagnosis if the circuit being simulated did not require high-frequency response.

This approach works well for a training unit, since all circuit nodes are easily accessible and the schematic layout is conducive to association of the physical component with the schematic symbol.

Special Probe Development

Two types of problems existed with probes. One problem involved accidental shorts caused by probes during diagnostic investigation, and the other occurred when it was necessary to make connection with circuit board eyelets to test the product or make electrical setup adjustments. The commercial probes that were used for this often fell off the unit during testing or did not make reliable contact. Several types of commercial probes were evaluated, but none was found adequate. No particular type was found that was applicable to all problems. Several types of probes were purchased and evaluations were made in actual production work. No particular type was found that completely eliminated the problem. Guaranteeing that the proper probe was used for each application also became a problem.

A probe that assured positive connection to the circuit board eyelet was designed and built. Figure 13 shows a sketch of the special probe. After evaluation of this probe, it was adopted for production and inspection testers used on the program. These probes are now used for contacting eyelet test points on a great variety of printed wiring boards.

Figure 13. The Special PC-Board Test Probe

The improvements in probes and a requirement to turn unit power off during installation of hook-on type probes reduced probing accidents significantly.

Special Troubleshooting Procedures

Preliminary Work. The results of a study of troubleshooting methods used in the factory showed that one type of electrical fault could not be isolated by conventional troubleshooting methods. When short circuits occurred inside or under a flatpack and on a line common to many packs, such as a B-supply line to ground, the short could not be isolated because the only isolation between the sealed packs was the low resistance of the printed circuit board paths.

The short isolation technique was developed on a printed circuit board assembly which had failed a production electrical test because of a short circuit on the 28-volt supply line. The 28-volt path passed adjacent to ground paths underneath six separate hybrid circuits and also entered these hybrid circuits to become part of the internal circuitry. There were many possible locations for the short. The only isolation between these possible locations was the resistance of the copper circuit paths between these points. The obvious choice seemed to be current detection, since workable current can be passed through low resistance circuits with negligible power dissipation.

The method chosen for isolating the short circuit was to apply a low voltage to the 28-volt line and try to identify the paths carrying current; then, by strategically moving the current application points and observing those paths that carried current, to plot a physical location of the short circuit. Voltage and resistance measurements were not considered desirable because of the obvious difficulties encountered in measuring voltage drops or resistance in short lengths of copper circuit paths. Noncontacting current probes are commercially available, but design changes would be required to adapt such probes to printed circuit board paths. Since no totally-adequate probe was readily available and redesigning a probe would be time consuming and expensive, alternate methods of detection were investigated.

X-ray techniques were considered, but were not chosen as a primary technique principally because of analysis time and possible additional equipment needs. Thermal indicators and liquid crystal techniques were then considered. Because speculation about the location of the short could be replaced with exact knowledge of the location of the short, several hybrid components worth about \$250 each were saved.

Short-Circuit Detection With Liquid Crystals. By using the liquid-crystal technique, hidden short-circuit faults (inside flatpacks, hybrid circuits, and under large components) may be isolated by identifying current-carrying circuit paths with a liquid-crystal temperature indicator. The liquid crystals are mixed to display color through a temperature range of approximately 3°C. Below and above this range, the crystals are transparent. The mixture is adjusted so the lower end of the 3°C range is at ambient room temperature. The color at the lower end of the range is red and at the higher end it is blue.

Blue indicates that the land which carries the current has a temperature about 1.5 to 3°C above room ambient. Green is the mid-color of the spectrum, and indicates a partial temperature rise. Figure 14 is a partial sketch of a printed circuit board subassembly that failed electrical testing on the production line. Preliminary troubleshooting showed the 28-volt line to be shorted to ground. The short circuit had a resistance of less than 100 milliohms, and its location was within or underneath one of the hybrid packs. The short was so near the circuit path resistance level that it could not be isolated by conventional voltage or resistance measurements without breaking the electrical circuit. The sealed hybrid circuit components are welded to the mother board, making it impossible to remove the components without degrading the pack. The circuits cost approximately \$250 each, making identity of the faulty pack highly desirable. On the pc board tested (Figure 14), a current source limited to 800 mA was applied between the 28-volt input terminal and the ground input terminal. Temperature checks with liquid crystals proved the top of pack-B to be at a higher temperature than the other packs. With the current source applied between land-1 and ground, land-2 and the circuit path from land-1 to land-2 gave a blue crystal indication. Land-5 and the associated circuit paths remained cool. Application of the current source to the 28-volt input land and taping the circuit path from land-5 to the 28-volt input indicated that this path was carrying current, thus verifying a short to ground between lands-2 and -5.

After the short circuit has been located, the circuit pack can be removed and the cause of the short can be corrected. In some instances, where metal flakes under the circuit are causing the short, sufficient flexibility in the terminal leads may allow removal of the short. Care must be taken not to overstress leads.

The following items of test equipment are needed:

- A dc power supply (0 to 6A, 0 to 20V) and meters to monitor terminal voltage and current;
- A limiting resistor (1 ohm, 5 W);
- A roll of Mylar tape (3 inches wide, 1/5 mill thick, dark tint); and
- A kit of liquid crystals (Vari-Light Model 101).

Mix R and L components 50/50. Add one drop of broadner for each 20 drops of R and L component mixture. The predominate color of the crystal mixture at 72°F ambient temperature is red. If the temperature condition is such that this mixture does not yield a predominate red, adjust by adding more R component. The section of the pc board to be tested is covered with a strip

Figure 14. A Typical Product Board That Shorted Under Flatpack B

of Mylar tape and the liquid crystal mixture is brushed onto the surface of the tape. The liquid crystals should be applied evenly. As soon as the crystals turn red, indicating that the lower range of the mixture is at ambient temperature, testing may begin. Body or hand heat imparted to an insulator such as a Formica table top will affect the color of the liquid crystals. The unit under test was isolated from the table by a folded tissue, and careful handling prevented any serious trouble from extraneous heat sources. Care must be taken not to contaminate the R or L components to prevent a change in the mixing ratio required to obtain color at a given temperature. Separate eyedroppers were used for each mixture and individual eyedroppers were used for each bottle.

Routing and Flow-Time Effects. Another type of failure that sometimes could not be isolated occurred when an electrical rejection could not be repeated or was lost in evaluation. The isolation between operator error, test equipment, and the production unit cannot always be made from data from one-time reject information. If the fault can be found by troubleshooting at the time of failure, there is a better chance for isolation; but if the unit is removed from the tester by inspection and sent to troubleshooting, an inspection error or equipment failure may be lost. In such cases, a technical plan which severely tests those circuits associated with the purported failure is normally outlined and, if no failure is found during this investigation, the unit is submitted to the complete inspection testing again in accordance with a defined anonymous-failure procedure in the electrical specifications.

One definition of a successful troubleshooting attempt might require that the requested rework correct the discrepant parameter and bring it within specifications and normal distribution limits, but a more rigid definition requires that the rejected part be found defective when removed from the assembly and tested separately. In the more-complex higher-level assemblies, a small percentage of rejected units failed to meet the last requirement, but apparently met the requirements of the first definition. Such incompatibilities can be caused by one or more of the following.

- Operators can make errors in verifying the purported failure.
- In cases where critical circuits limit the degree of margin in design, the worst-case design condition cannot be applied, and when many components are involved, unique tolerance buildups may cause marginal conditions between two particular subassemblies or between testers at different levels of testing.
- An intermittent condition can exist where the failure is very critical to environmental parameters such as temperature, humidity, or electrical or physical stresses.

- The fault may be lost during handling or disassembly as a result of removing an interconnection fault, removing a piece of foreign material, or relieving a pinched-wire condition.

Since faults falling in the last two categories must be isolated to assure high reliability requirements, strict accountability procedures are required by specifications to provide a logical explanation for each failure, a limit on the time required for completing the verification of the original failure, and to identify the associated lower assembly and component faults causing the failure. Violations of this requirement cause delays in factory output because of the time required for engineering disposition and the special handling required to clear the failure.

Some of the areas affecting the capabilities of the factory to meet the time limit requirement on completing a diagnostic attempt are listed below:

- Failure to identify units in the pipe-line according to date rejected;
- Lack of a suitable method for expedient daily inventory of units in the rework and troubleshooting pipe line; and
- Failure to identify the status of all assemblies associated with the same rejection.

An inventory of units by date of rejection, calculation of the percentage of successful diagnoses by each operator, and the daily status of units in rework with troubleshooting, verification, and stamp removal notations would provide very beneficial information for the troubleshooting foreman to aid in planning priorities and keeping informed of employee performance. An out-line plan to computerize this approach was prepared and submitted to programming for a feasibility study. The plan included installation of a remote computer substation in the production area so that KCD413 production test data can be routed directly to the central computer system. This plan should become feasible when the present computer facilities expansion is completed.

When disassembly of the product is necessary to allow diagnostic effort to continue, routing methods can cause discontinuities in the diagnostic effort. The rejected unit may not return to the troubleshooting stations for several shifts after the request for disassembly, and there is no assurance that the unit will be returned to the same shift or to the operator that started the diagnostic attempt.

Ideal diagnostic procedure would require:

- That the unit be diagnosed at the time of failure before removal from the tester; and
- That the diagnostician be allowed to remove stamps and proceed with a planned and careful disassembly of the unit when it is necessary to assure fault isolation.

This approach has the disadvantages of:

- Operator error in removing stamps;
- Less efficient disassembly; and
- Less skillful disassembly, unless disassembly is done by a skilled assembler under the supervision of the diagnostician.

The possibility of inspection stamps being in the form of a seal that would be broken automatically by disassembly was evaluated, and no universal type of stamp that would conform to the many different unit configurations was found. Further study would be required to prove this concept feasible. The reliability gains from rigid controls that ensure that no oversight is made in stamp removal and that disassembly is performed by personnel trained for that work must be weighed against the effects that discontinuities have upon diagnostic results. However, the detailed study required to establish new product stamping specifications was beyond the intended scope of this project.

ACCOMPLISHMENTS

A faultfinding system congruent with the project objectives was developed. The system employs highly-trained technicians who are supported by engineering troubleshooting information, a technical manual of instructions, and both specially-designed and commercially-available diagnostic equipment to fill every troubleshooting need. Training programs and grading systems were established along the guidelines stipulated by the development order. Production troubleshooting guides designed from the prototype manuals developed during this program are now in scheduled production use and have proved effective in transferring and translating technical information and troubleshooting instructions to the production operators. Both Bendix and Design Agency engineering-support technicians use these manuals as technical aids.

Isolation of fabrication errors and component failures with the in-process testers proved feasible. The development tester used to study the basic concepts was converted to regular production use, and has simplified some diagnostic problems significantly.

- In many instances, special testers designed particularly for troubleshooting can provide significant economic and diagnostic advantages over inspection-type testers designed to test products.
- The average complexity of diagnostic problems on telemetry and similar types of assemblies is sufficiently high to require special types of diagnostic features which are not always included in inspection testers. Much of this equipment is common to all programs, but special design equipment may be required for specific products.

FUTURE WORK

Since this work achieved the stipulated objectives and most of the test facilities, troubleshooting manuals, and training programs described have been successfully integrated into present production programs, no further work on this project is planned. However, contingent upon a favorable outcome of a feasibility study by the Computer Programming Section, work on another process development order may be necessary to implement the proposed centralized-computer manufacturing test data reporting plan soon after completion of computer-facilities expansion program which is now well advanced.