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DEPARTMENT OF PSYCHOLOGY

UNIVERSITY OF SOUTHERN CALIFORNIA

BEHAVIORAL TECHNOLOGY LABORATORIES

Technical Report No. 92

# TROUBLESHOOTING COMPLEX EQUIPMENT IN THE MILITARY SERVICES: RESEARCH AND PROSPECTS

December 1979

Nicholas A. Bond and Douglas M. Towne

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Troubleshooting of complex equipments in the military remains a problem for many reasons--some technical, some administrative. At the working level, a major key to success is the technician's information base or "cognitive map" of the relations that hold among present test symptoms, normal indications, and the set of possible defective units. If this information base is reasonably complete and correct, then the technician can usually converge on the trouble in a reasonable time. Many equipments are so complex that an ordinary

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technician cannot be expected to master the information base, after only a few months of training and experience.

Psychological approaches to the troubleshooting problem attempt to improve the selection, motivation, and training of technicians. Among the aspects which have been considered are methods for enhancing the understanding of physical relations in equipment, the hierarchical analysis and practice of troubleshooting sub-skills, and the general logic of searching behavior. The aiding approach tries to "unburden" the technician by providing most of the information base in special booklets, diagrams, computer programs, and direc[illegible]t sequences. The maintainability approach concentrates on designing equipments so that they will be easy to troubleshoot--for example, key test points are made accessible, and sub-units are arranged so as to facilitate diagnosis and replacement. When psychological, aiding, and maintainability technologies are fully applied, the troubleshooting problem can be "solved", within the present state of the art, for the great majority of equipment items.

For troublesome equipments which are already in service, proceduralized aiding of troubleshooting activities is probably the best immediate solution, and many one-term military technicians might well devote most of their service to application of these aids. The aids must be specially prepared, tested, and debugged, and they must be designed from a behavioral standpoint. It should be recognized, though, that even the most effective aids will not find all troubles, and that the services will always need people with relatively deep understanding of the systems they have to maintain. To provide such people, research is needed on such topics as the visualization and memory of complex physical events, the learning of long branching sequences, individual differences in search behavior, and ways to enhance human reasoning by small computerized devices.

# SUMMARY

Troubleshooting of complex equipments in the military remains a problem for many reasons—some technical, some administrative. At the working level, a major key to success is the technician's information base or "cognitive map" of the relations that hold among present test symptoms, normal indications, and the set of possible defective units. If this information base is reasonably complete and correct, then the technician can usually converge on the trouble in a reasonable time. Many equipments are so complex that an ordinary technician cannot be expected to master the information base, after only a few months of training and experience.

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# Troubleshooting Complex Equipment in the Military Services: Research and Prospects

## SECTION I. INTRODUCTION

One of the first experiments on human troubleshooting of electronic equipment was conducted in the summer of 1953 at the Long Beach Naval Shipyard. Electronics technicians from Navy ships searched for faults inserted into radio and radar circuits. The subjects also had to troubleshoot a "simulator" representation of the same circuits. The main idea was to see if fault-locating behavior on the simulator correlated with performance on the real equipment; in fact, it did (Grings, et al. 1953).

That early work was sponsored by the Office of Naval Research because of the dramatic increase in equipment complexity that occurred after World War II. The new radars, fire control devices, missiles, analog computers, and communication sets were vastly more complex, and often more unreliable, than the equipment of the 1940's, and all the military services found themselves with a maintenance headache. While the increased capabilities which the advanced equipment afforded were highly desired, much of the time the fancy new gear was down, and often there was nobody around who knew how to fix it. As early as 1953, Carhart's Rand report was calling the Air Force maintenance situation "intolerable" (Carhart, 1953), and one could hear even stronger adjectives from operational military people who had to use the new technology, and had to live with it when it failed to operate.

More than a quarter-century later, the troubleshooting problem is still with us. Ships, aircraft, missiles, and control centers are still plagued with unfindable troubles and marginally performing equipment. Many expensive items never perform up to design expectations, or are unavailable at crucial moments. Maintenance still requires a lot of people and a lot of money, with nearly 60 percent of total life-cycle equipment costs attributable to personnel expenses (Blanchard, 1979; Shriver, 1975). Maintenance difficulties are not confined to sophisticated electronic systems, either. Consider this astounding quote from Secretary of Defense Schlesinger, after the Mayaguez incident of 1975:

> "...The thirty-one year old carrier Hancock...operating without one of its four shafts...never reached the scene. The helicopter carrier Okinawa,...with part of its boiler plant off the line...also never arrived at the scene. The escort vessel Holt, the first ship at the scene, had power-supply problems, and consequently its main battery was down the night before the engagement."

All of these difficulties occurred in a combat area following a major war, when the Navy had days of warning. Evidently, things are still "intolerable" in military maintenance.

This report was undertaken in the belief that now is a good time to take stock of the troubleshooting behavior problem in the military. The whole field is changing and particularly so in the electronics domain. For one thing, we are in an era of sharply improved hardware reliability. After many years of promises and disappointments, hardware is finally meeting its claims. These days, a new mini-computer with dozens of terminals may run for days or weeks without a main frame failure. This is true "ultra-reliability." Already, integrated-circuit components are manufactured to be "fault-tolerant," so that if something fails the system keeps running as before. In a certain sense, the failure never happened because the user never knows it. But as Rouse (1978) points out, relatively rare breakdowns mean that a maintenance technician will not get much practice in troubleshooting. Another big change is the micro-circuit technology, which makes it feasible to localize a fault only down to a board, can, or chip unit. At the same time, cheaper and larger computer memories make it possible for system designers to employ very long operating and fault-locating programs in a small unit, and this means that a technician often has to be something of a programmer. So we can see that technicians will have to become more oriented to logic and software and will be less frequently concerned with the old soldering, wiring, and parts-replacement skills. We are probably at a crossroads, too, in the aiding and training of troubleshooters. Handy and comprehensive "briefcase" troubleshooting guides are already here (Rigney & Towne, 1977). A portable test unit as big as a TV set can store a whole book of system information on a single floppy disk (De Paul, 1979), and all of the data can be interrogated instantly. Not long from now, such a compact guide will tell the military technician which check to make next, will evaluate the results of all checks made, and will furnish a hard-copy printout of every troubleshooting step. And these aiding functions may, on occasion, be instantly transmitted from a remote ship or field site to an analysis center, for further analysis and advice. This kind of detailed aiding can be so effective that much training might well be directed at teaching the aid, rather than teaching the usual circuit, hydraulic, or electro-mechanical theory. There will be arguments over such aiding and training, but it is clearly on the military horizon for the 1980's. Another prediction is easy to make: more systems will be digital. As one writer asks, "Is everything going digital? Whatever happened to 6SN7 tubes, low-distortion amplifiers, and feedback circuits?" (Gasperini, 1976).

If indeed we are already in an era of ultra-reliable but more complex digital equipment, in which technicians will be aided in their work by extremely "smart" test sets, then there are many interesting questions. What can we expect of our troubleshooters? Exactly what will their intellectual requirements and difficulties be? How much efficiency can we anticipate? What administrative and planning considerations should be most crucial regarding the military technician force of the next couple of decades? How should we train and "transition" all of the people required? What contributions can be made by disciplines such as the psychology of reasoning?

This report was written primarily for the military research community, which is a network of technical commands, laboratories, contracting bureaus, industrial contractors, and academic institutes. As a secondary audience, there are numerous training, support, and operational personnel who run the technical schools, who have to face troubleshooting problems in the field, or who prepare technical manuals and automatic test equipment. Such people are often engaged in the delivery of a specific system, course, document or procedure.

We also hope that some military manpower planners will consider some of the issues raised here. There are rather few manpower people and they are not particularly visible, but they are the ones who decide how many Data Systems Techs we will have in 1986, and their decisions can affect long-range military prospects. There is no need to plan for an expensive new ECM installation on a ship if the prime equipments will not be available for use. With so many big changes in the hardware, software, and aiding capabilities, manpower projections will be more difficult and more critical, and they should be based on what we know about the key behaviors that will be needed.

## Outline of the Report

Section II examines the logic of diagnosis, and also reviews material from academic psychology regarding human-search performance. The next chapter takes up aiding and training issues, many of which are being pursued right now by DOD agencies, laboratories, and contractors. Section IV looks at the maintenance technician's work from the "job design" standpoint, and explores his job satisfaction and motivation. The final section lists some research recommendations, including nineteen specific projects that might be considered by agencies like ONR, AFOSR, and ARI. There are also a few administrative recommendations.

The main conclusion of this report thesis can be quickly imparted. Troubleshooting of very complex systems is difficult for numerous reasons, but the critical factor is that the technician's cognitive map of essential physical relations (electronic, hydraulic, electro-mechanical, and so on) in a complex equipment is often incomplete, vague, or incorrect. As long as this is so, any series of checks and test readings, though apparently well motivated and accomplished, cannot "close in" logically on a faulty unit. All the technician can do in this environment is to keep making checks in the hope of finding some drastic test indication, or to engage in probabilistic or mass replacement of subunits. The conventional approach has been to provide general "theory" training in electronics or hydraulics for the technician. Armed with this theory, and with the assistance of technical manuals, the technician supposedly could generate his own fault-location sequences. But modern prime equipments are so complicated that it is not reasonable to expect an ordinary military technician to know them well enough to originate effective test sequences for himself, after a few months of training. It is, then, not so much the technician's reasoning that is at fault, as it is his information base regarding the meaning of the checks and test readings he makes. Given a sharp map or model of the elimination logic that prevails between observable test symptoms and the set of possible troubles, a technician can usually solve a troubleshooting problem within a reasonable time, even though his logical path through the network is not the optimal or most efficient sequence. If the equipment is extremely large or complex, then some kind of proceduralized or step-by-step insructions will be necessary.

It follows that much of the training and aiding effort should be directed to preparing a special symptom-malfunction model of the prime equipment, and making that model accessible to, and usable by, an ordinary trained person. <u>If there is sufficient top level determination to achieve this, as in the commercial computer industry, then the major technological problems of aiding can be solved, at least for the majority of complex systems</u>. Right now, and for the next few years, the best solution probably is to provide special "aiding" or documentation to the technicians, to have this documentation so effective that it will actually guide troubleshooting down to the appropriate component depth, and to give the technicians intensive practice with these materials. The competent first term technician thus becomes an extremely fluent user of complicated booklets, charts, and software routines. He will not often originate test sequences himself. Rather, he will follow a definite "tree logic" or other algorithm that will guarantee localization of most failures. If the documentation and associated procedures cannot locate certain troubles, then the aiding package must be immediately modified so that it will accomplish that task in the future. In this scenario, we do not lapse into the conception of "trained-ape maintenance," where an untrained person blindly follows a complex test routine, and does what it tells him to do. Our technician will still be a highly skilled person. It will take great care and judgment on his part to carry out the appropriate procedures. The aiding technology to support the troubleshooter is already here, and has been proven in about a dozen demonstration projects (Shiver, 1975; VanHemel, 1979; Foley, 1978). There will always be a need for military maintenance people who can go beyond the proceduralized aids, and can solve the difficult problems. These people will have to possess a deeper understanding of the systems they work on; perhaps a good model here would be the "flying squad" specialists in the computer industry, who are extremely competent in both hardware and software aspects of big computers. Training such people, and providing materials for them, will be a challenge to the military personnel community.

Efficient troubleshooting can be achieved in the military. There are many successful examples from Navy submarines, from the special weapons area, and from certain aircraft systems. Also, many good people in the military system think that they are helping the troubleshooter. Examples of these are the people who originate fault-location schemes, the school instructors, and the manual writers. According to our view, many of their efforts are far less effective than they could be, and this is because they do not stay close to the actual cognitive situation faced by the military technician. One goal of this report, then, is to explicate some of the ways that improvements can be made.

## Bibliographical Note

The troubleshooting literature is widely scattered in about half a dozen major clusters. For behaviorally oriented studies, Rouse's privately-circulated bibliography is the best (Rouse, 1979). In fact, Rouse's list of references in one of his articles constitutes a reasonably good library on the subject (Rouse, 1978). Johnson's (1972) text is the standard reference on the psychology of reasoning. Fault-tree methodology, probabilistic troubleshooting, and the associated mathematics are summarized in the ONR-sponsored report on reliability and fault-tree analysis (Barlow, et al, 1975), and in the Ross (1970) textbook. For maintainability program management, the best general source is still the Blanchard and Lowery (1969) book; although the microcircuitry revolution has dated some of it, this text has thorough treatments of maintainability prediction, tradeoffs, and demonstration procedures. There are several new books on the logic of digital troubleshooting (Gasperini, 1979; Coffron, 1979). The computer-science approach to complex search problems is treated by Raphael (1976). There are many guides which will tell how to design a maintainable device, a good example being the one by Morgan et al., (1963). State-of-the-art in military maintenance aiding and training is well reviewed in the NTEC-Orlando conference proceedings (NTEC, 1975; NTEC, 1979), and in Foley's summary report to the Air Force (Foley, 1978). Foley's summary is especially important, because it lists every experimental evaluation of maintenance aiding up to 1977, and it also provides strong administrative advice for implementing fully-proceduralized aiding systems.

## SECTION II. LOCATING A FAILED COMPONENT

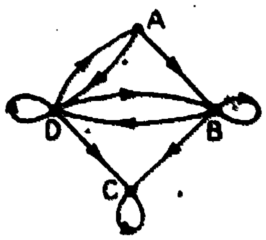
### The Logic of Diagnosis

Much troubleshooting is very simple. When something goes wrong, all or most of the possible causes of the fault are listed, and are then successively eliminated. The process is continued until only one culprit remains. That item is repaired or replaced and the problem is solved. Or maybe one component is known to be likely to fail, and it is therefore summarily replaced, without much of an attempt at fault-tracing. Only if this "obvious" replacement fails to clear the trouble is any further search undertaken. Such troubleshooting is applied in all practical trades and professions, and in daily life. It seems so natural that it may not even be formulated in an explicit way. Technical difficulties arise, of course, when the list of possible causes is incomplete, when it is impossible to eliminate some possible causes, or when there are a great many related "partial causes." But the common-sense conception of trouble-isolation stands up very well, and is especially effective in easily visualized physical systems, such as a plumbing layout.

When systems get more complex and the number of alternatives becomes large, a simple enumerate-and-eliminate strategy will not be practical. It was just barely practical for repairing TV sets in the vacuum-tube era. As a rule of thumb, replacing tubes would repair a malfunctioning set in about eight times out of ten. But a big air-control radar may have thousands of components in it, with many of these linked together in complex ways. Furthermore, there is good reason to think that, if a technician attempted simply to replace every part, he would introduce far more troubles than he would eliminate. Evidently, more systematic and efficient search strategies are needed.

## Deterministic Models

There are several ways to display the relations in a system: flow charts, schematic diagrams, and so on. The essentials often boil down to some kind of logical graph or table. In Figure 1, a graph is shown in 1a; it has four vertices (A, B, C, D) and ten arcs (AB, AD, BB, etc.). The relations in this graph may also be described by the Boolean logic matrix in 1b, or by the dictionary of successors shown in 1c (Kaufmann et al., 1977). The "successor" table reproduces the Boolean matrix row by row. As shown, the vertices and arcs could be anything that is well-defined, and so they could represent nodes and signal flows in an electrical network. Many theorems have been derived for handling the relations in a graph or logical matrix. One of the most important of these is that, for each state of the set of system components, a unique structure function can be defined. Thus, one can calculate the influence of each component state on the overall system (Kaufmann, 1977; Barlow, Fussell, & Singpurwala, 1975). As another and more surprising example, if a set of K "links" of a monotone function are known, an equivalent network can be obtained by placing in parallel K subnetworks, each formed of the components of a link placed in series. The networks obtained in this manner can also be "reduced" to their simplest form. As far as we know, such transformations are only employed in theoretical analysis of systems, and are never utilized by working technicians. even though such analyses do express all the logic in a system.



(a)

|   | A | B | C | D |
|---|---|---|---|---|
| A | 0 | 1 | 0 | 1 |
| B | 0 | 1 | 1 | 1 |
| C | 0 | 0 | 1 | 0 |
| D | 1 | 1 | 1 | 1 |

(b)

|   |   |
|---|---|
| A | B,D |
| B | B,C, D |
| C | C |
| D | A, B, C, D |

(c)

Figure 1. (a) Graphical representation; (b) Boolean matrix; (c) dictionary of successors.

The Boolean-table idea has been extended to handle pseudo-verbal content, and to print out "sentence solutions" to computerized search problems. Findler's Universal Verbal Puzzle Solver for example, solves any well-formed verbal membership puzzle which can be expressed in terms of logical inclusion, exclusion, and conditionality. If a string of problem sentences is inserted the logical relations from the sentences are stored as a long list of inclusions and exclusions. When all are entered in the computer, the program does a brute-force recursive search until a suitable solution is found (Findler et al., 1973). The search loop really operates upon the equivalent of a Boolean matrix. Though it has apparently never been used in the troubleshooting domain, the Findler program would certainly find troubles if enough logic from trouble-test relations were entered in a pseudo-verbal format. The technician would enter test results in a constrained-English format, until isolation was attained. Another kind of "logical machine" is the theorem-prover concept, as developed by Wang and others. A theorem-prover program accepts a list of logical premises or conditions. Then, to search for an answer to a puzzle (or a trouble-shooting problem), one asks the program whether a given "theorem" (logical statement) is valid. An ingenious reduction routine collapses the premises in such a way as to permit a validity check on any well-formed proposition involving the premises. For a verbal puzzle, a test theorem might be "the butler murdered the viscount", but as far as logic is concerned, a theorem could be "operational amplifier #16 is malfunctioning" (Raphael, 1976). To be useful, both the Findler and Wang concepts have to be "full of data", otherwise no solution will be attained, or else the logic is so loose that a number of pseudo-solutions will be printed out, with the machine unable to discriminate among them.

In practical maintenance work, a useful format is often some kind of a symptom-malfunction (S-M) matrix. Many projects have discovered, rediscovered, and formatted the basic idea, which is nothing more than a table showing the dependencies among symptoms and components. An early realization of this was in the BAMAGAT project at Hughes Aircraft in the 1950's. The charts used there, called maintenance dependency charts (MDC), showed an ordered list of procedures, a rather complete listing of test points and measurements, and also all functional units that generate inputs to a given test. If a test failed, then (hopefully) only a limited set of hardware signal sources had to be checked further. That basic concept has survived several renamings as SIMM (Symbolic Integrated Maintenance Manual) and FOMM (Functionally Oriented Maintenance Manual). Roeder and Ranc (1975) believe that FOMM is most successful with straight-line analog functions, and that logic diagrams, state tables, or trees are preferred for digital circuitry. In the simplest non-sequential format of S-M matrix, tests are often listed as rows, with components or subunits in the many columns. As the trouble search proceeds, parts of the table are logically eliminated, and when one or a few units are left, those are repaired or replaced. If the chart is correct and inclusive, and if the readings are correctly made and interpreted, then trouble isolation proceeds steadily. The logic in such charts is generally easy to follow, but in the practical case there is often ambiguity about the normality of a complex signal or waveform, and so if a mistake is made the search may not converge (Joyce, 1975). Almost always, though, some trouble isolation will be achieved. Most research people, we believe, who work closely with maintenance people in the field have come to favor aiding the technician with some kind of S-M matrix approach. The basic idea of maintenance dependency also can be enhanced by following good display and presentation features, as Inaba (1979) and others have demonstrated with the PIMO format. If the system is extremely large, then almost any format becomes unwieldy. Roeder and Rano (1975) estimated that for one system, some 733 sheets of FOMM function block diagrams would be required to describe the system!

It is best to provide good S-M information to the field technician, and not make him generate it for himself. The general rationale for this is that when working under time and operational stresses, the technician is not in a good position to be discovering logical relations. At that time, he should be using effective relations already discovered by himself and by others. For large digital systems, there is a further rationale. Many IC chips are delivered to the system designer with data sheets which describe chip operation in terms of gate equivalents. But the data sheet may not be complete, or when it is encapsulated into a system the unit can experience logical ambiguities caused by timing, noise, stray capacitance, or threshold problems. Often the only way to separate all these causes of logical failure is to do high-speed test runs via automatic test equipment (ATE). So in some cases the technician could not possibly use logical-status derivations from a simple consideration of the gating logic.

Probabilistic Models

Many aspects of systems are probabilistic in character. Life and failure expectations for components, for subsystems, and for the whole system can be expressed in terms of probability distributions. There are also distributions for the time it takes to set up and make different test readings, for the likelihood that a particular failure will be detected when it occurs, for the chance that a troubleshooter will introduce a new trouble as he works on the prime equipment, and so on. As all these distributions can change during the course of a search, analysts have studied ways of structuring and optimizing the process. Powerful solution techniques such as linear programming and dynamic programming can be brought to bear.

A simple probabilistic example will give some of the flavor. Consider each test or check reading as a means of reducing uncertainty concerning the location of a fault. In the language of information theory (Guiasu, 1977), the amount of uncertainty resolved by a test t is given by

$$W(\tau) = -\Sigma p(s_i) \log_2 p(s_i), \quad i \in Z_i$$

which is the sum, over all sets of modules into which the test divides the system Z (τ), of the probability of the fault being within the set, $p(s_i)$, times the logarithm to base two of this probability. Each test is then conceived as dividing the system into two subsets (the fault being in one or the other). The probabilities in the above expression are conditional upon all test information obtained up to any point in a given test sequence.

A rational or optimal technician might then perform next that test which resolves the greatest amount of uncertainty, per time spent testing. Thus, he should maximize

$$D(\tau) = \frac{W(\tau)}{t(\tau)},$$ where t (τ) is the

time required to perform the test, starting at whatever system and test condition prevails just then.

Towne's dynamic programming (DP) formulation (Rigney and Towne, 1977) utilzes the structure of the system to yield deterministic relationships between indicators (including test points) and the elements which they monitor. Time costs for extracting information from each indicator are then either estimated or computed. These might include times for test equipment setup, partial disassembly, or even walking to another location. Finally, reliabilities are associated with each hardware element. The DP algorithm then successively computes the optimum next "indicator" to sample, in order to minimize expected (time) cost. This technique would be considered probabilistic, since the reliability data are probabilistic.

Guiasu (1977) gives a similar model of classifying a system (in our domain, classifying a system would identify the trouble state, i.e., locate the trouble). His model calculates the entropy of each test, weights it by the cost of a test (again, this could be the time or inconvenience required to perform it), and then selects the test that has the maximum weighted entropy. This scheme always leads to the trouble, with the smallest expected cost. If checks involve extraordinary amounts of time or risk to set up, such an analysis might be quite practical. One application used the model to select which of the 27 possible clinical tests should be made next on a human patient, to diagnose any of 13 renal diseases. Using the model, an average of about eight tests are required, to complete the diagnosis, instead of doing the full set of 27 tests.

Models like these are certainly elegant rationales for test selection, which can be valuable for judging the effectiveness of a particular strategy and for developing procedural guides. It is unlikely, however, that a technician could employ these techniques to generate his own search process. There may be some rough heuristics that can be applied by technicians, which come out of such models. The information theory approach suggests, for example, that if all tests are reasonably close to splitting the remaining sets of candidates into even halves, the next test should be the one that takes the shortest time. Also, if all tests are long shots (less than 5 percent chance of finding the fault), then the test that takes the least time often should be selected. Such rules might already be known fairly well by the working technician.

## Human Search Behavior

As mentioned earlier, it has been known for twenty-five years that a symbolic format can capture much of troubleshooting behavior, and can get at the crux of the search task. This was shown with various kinds of devices: tab tests, masonite boards with little windows, punchboards, and special paper formats (Grings, 1953; Glaser et al., 1952; Fattu, 1956). To be sure, the synthetic format leaves out such key behaviors as locating test points, connecting meters, and being generally careful and safe around dangerous hardware. Unless the technician can troubleshoot effectively at the symbolic level, however, it would be of little avail to be skilled in these other aspects of troubleshooting. Most investigators have therefore used some kind of synthetic format for their troubleshooting studies.

Nearly every study of troubleshooting behavior has noticed great variation in the search sequences taken by technicians. Even for rather simple electronics circuits, exact replications of paths are rarely found. When detailed records of performances are examined no more than about half of the moves "make sense" in retrospect (Bryan et al., 1956). Why do we see there such marked individual differences, so much uninterpretable behavior, and so much apparent "wandering?" The best answer, we believe, is that ordinary technicians differ in their knowledge about the normal system and in the significance they attach to readings in the abnormal system. They simply do not share the same information bases, despite similarities of training and experience. This can be quickly demonstrated at any military installation by presenting a few technicians with a standard transistor amplifier schematic, and asking them separately what changes in the currents and voltages would result from parametric changes in one of the parts, such as a resistor that increased in value. There will not be much agreement, and many mistakes will be noted.

It is likely, then, that most technicians simply do not remember much of the electronics theory that has been presented to them in schools and books. One study done in the early 1960's at a Navy repair facility presented simple test items involving the "fifteen basic vacuum-tube circuits" to a sample of civilian shipyard technicians, along with some elementary electronics theory such as Kirchhoff's Laws. The goal was to find out which circuit principles were most difficult for the men, and how these correlated with knowledge of basic theory. All the scores were so low that the research planned on those subjects could not proceed. In fact, it was unclear how these men could understand, or could repair, the complex radars and radios they worked on. One possibility is that, although they could not manage detailed circuit analysis, they could perform a rather cut-and-dried overhaul and checkout procedure. When discussing these results, the supervisors explained that detailed circuit-analyzing skills were useful for designers, but not necessarily required for maintenance shop people. A supervisor would often say, "I don't know that kind of stuff myself, now." Twenty years ago, Williams and Whitmore (1959) showed that, whereas knowledge of electronics theory about the Nike-Ajax missiles system was highest at the end of the training school, ability to find faults was poor. Then, fault-finding ability improved with field experience, but knowledge of theory declined. Shepherd et al, (1977) think that it is possible that technicians may develop rough and effective search rules during the field work (and may attempt to use theory while appreciating these rules), but once the rules are in hand, theory can be forgotten. Foley's (1974) review suggested that the correlation between theory test scores and performance is low, as is the relation between school marks and job performance. Thus, "teaching theory" is doubly ineffective. People do not learn or retain it well, and even if they did, such knowledge is not strongly tied to maintenance effectiveness.

Perhaps the most famous behavioral analsyis of troubleshooting was Miller's investigation of the "half-split" technique (Miller et al, 1953). The half-split procedure recommends that a chain of system elements be checked first in the middle of the chain, or in such a way that the two groups of elements on both sides are equally likely to contain the faulty element. The half-split idea has been extended and generalized in various ways, to permit inclusion of parallel paths, probability-of-failure data, and cost figures. While people can learn the half-split idea (Hannom et al., 1967), it is difficult to employ except in the most crude and obvious decision situations, such as a string of lights. In difficult real-world problems, units and subsystems of widely different reliabilities are arranged in complex and non-linear chains, with obscure barriers and feedbacks between links in the chain. Otherwise, troubleshooting would be rapid and conclusive by any reasonable method, and the slight increases in efficiency caused by half-splitting would be negligible.

Other optimal search models can also be formulated, and their troubleshooting effectiveness can be compared with actual human behavior. As an example of this, a computerized Bayesian search policy was defined for a certain symptom-malfunction matrix (Bond & Rigney, 1966). The computer program operated on the conditionals that obtained between test symptoms and component parts. When a malfunction was introduced, the program would always find the trouble in the smallest number of steps or checks (if the trouble could be found from the data given). By updating the failure-likelihood estimates for each component after each test, the program acted as a good statistician would, if confronted with a fault-location problem. When a human technician's search record is compared to the performance of such a program, it is always found that the human is not an optimal troubleshooter. He makes redundant checks, forgets things he has already done, replaces components which logically cannot be faulty, and often seems to mill around the prime equipment in a near-aimless way. One study estimated human search efficiency at about thiry percent of the optimal (Rigney, 1968). Such observations might suggest that technicians are illogical or feckless in their work, which is not so. The situation resembles that which is found in the psychology of reasoning. When intelligent people are given syllogistic problems to solve, many errors and incorrect inferences will be found. On close examination, however, many of these mistakes are largely due to the artificiality of the syllogism, and to the subject's unfamiliarity with the way that English terms like "or" and "some" are used in logic (Johnson, 1972). When corrected and practiced, and especially when syllogisms are cast in a familiar or "real" context, subjects are indeed quite logical. Going back to the troubleshooting context, the frequent near randomness of a search pattern is largely due to a vague and incomplete conception of the basic system, and of the measurements made upon that system. An additional bit of evidence on this point comes from the Bayesian fault-locator study mentioned above (Rigney, 1968). In an extension of that research, technicians were required to construct their own subjective symptom-malfunction matrices. To do this, they entered their estimates of the relationship between a reading at a test point and a possible malfunction in each component cell. Then, taking these subjective estimates as probabilities, the Bayesian comparison routine was run again. It was learned that while most technicians are not "good Bayesians," even on their own subjective matrices, their search does proceed rather well, if inefficiently, and would locate troubles eventually, <u>if the matrices were correct enough</u>. Again the conclusion is rather strong: It is the information base, rather than the search algorithm, or search efficiency, that best predicts success.

For an overall picture of technician activities, Table 1 gives a breakdown from one set of experimental observations (Rigney et al., 1968). The table is fairly discouraging. Most of the time (58.7%), these troubleshooters did not have the malfunctioning unit included in their set of "possibles." About 10 per cent of the time, the equipment was classified as fully operational, even though the malfunction persisted; and about 13 percent of the time the trouble already had been repaired, but the technicians didn't recognize that fact.

Table 1

| Technician's State | TotalTime (min.) | % of Total Time |
|---|---|---|
| Perfect hypothesis set | 52.3 | 1.3 |
| Malfunction properly suspected, but hypotheses imperfect | 666.3 | 16.5 |
| Malfunction not included in hypotheses | 2,278.8 | 58.7 |
| Equipment judged all right despite malfunction | 405.0 | 10.0 |
| Malfunction actually repaired but not known | 546.0 | 13.5 |

A recent program of research by Rouse (1978) has been directed to human search behavior in digital networks. The subject faces an arrangement of AND gates, some of which are good, and some of which are not operating. As in the Bayesian search comparison mentioned previously, subjects did not perform optimally, but they were superior to a brute-force searching scheme, and they could be aided by special software. When network size was increased, performance deviated further from optimal. Two incidental results from Rouse's work are intriguing to the psychologist. One of these findings was that self-paced initial training can transfer positively to a forced-paced test situation. Another discovery was that the unaided subjects did not seem to appreciate the diagnostic value of a "good" test at a node (node not failed). This observation is similar to Wason & Laird's evidence on the modus tollens fallacy in human reasoning, wherein subjects also did not realize the meaning of information that did not directly support the hypothesis under review (Wason & Laird, 1968), Thus,

> "In our fault diagnostic context, this idea means that humans have difficulty in effectively utilizing a test that indicates some component has not failed (Rouse, 1978).

This is one instance where a troubleshooting experiment can be integrated nicely with cognitive psychology.

Rasmussen and Jensen (1974) watched Danish technicians working on real equipment in atomic power plants. They noticed that technicians had a tendency to "do something," rather than to "reason it out," hence troubleshooting performances often look busy but inefficient, when gauged by optimal-test standards. As many other researchers have noted, there were frequent "....rapid sequences of good-bad checks on actual signals against normal signals." Most of the observed performances could be classified as being either topographic, functional search, or evaluation of a fault. In a topographic troubleshooting attempt, the technician may "lose" a good signal in, say, an amplifier. The amplifier itself, and the paths in and out of it, would then be explored. Functional search proceeds on a "failed function" basis. Thus, if a TV picture is low, one might consider first the circuits that control the vertical deflection plates. A person who evaluates a fault derives information from the fault itself, without explicit localization. A "fuzzy" video signal is often due to ripple in the main supply, and so the voltage regulators may not be doing their job, when this symptom appears.

If one of Rasmussen's technicians was stumped, he might pause, and then during the break in performance have some fresh ideas about things to do. At several places in the analyses, the disparity between "engineering thinking" and technician work methods was evident. The engineer often wants an intellectual understanding of the trouble, and a rationale for its associated parametric changes throughout the hardware. On the other hand, the technician's goal is to find <u>this</u> trouble, and considerations of the logic or elegance of the solution are secondary. This is not to say that technicians cannot admire an ingenious search scheme, but their focus is usually quite practical, and redundancy does not bother them at all.

Wescourt and Hemphill (1978) studied computer program debugging in both expert and novice programmers. The expert may indeed have a better general strategy than the novice, but his most important capability is specialized memory for certain program behavior characteristics, that is, he has a large "library" of experience which often enables him to bypass the usual deductive processes. A novel feature of the Wescourt investigation was the explicit recognition that advanced programmers often knowingly write incorrect programs, finding it easier to debug than to perform the logical analysis necessary for correct coding.

A great limitation of much behavioral research in the electronics troubleshooting area is that very simple circuits and equipment are employed as the performance vehicles. With the exception of the Rasmussen study and a few others, the academic researchers have stayed with simple DC circuits, Ohm's Law, and similar engineering rudiments that are easily analyzed. The people who have really faced up to the big prime-equipment problems are those who were under contract to produce a specific aid or training system, and to demonstrate it on an item of operational complexity. Actually, major troubles may require a very lengthy analysis. Anyone who does not believe this should consult Coffron's account of an advanced troubleshooting problem in a system made up of standard IC chips. Some thirty pages of technical discussion are required to explicate the test rationale (Coffron, 1979). Even a procedural guide to this task would take several pieces of paper.

Another big gap in behavioral research on troubleshooting is the near-absence of data on just how the technician codes, remembers, and retrieves information about the prime equipment. Researchers often focus too much on the outcome of the performance, such as the time to solution, or success or failure in finding a trouble, when they should be watching the process. Electronics material is abstract, and that is one reason why it is so difficult to learn. What imagery and analogies can be used in visualizing the relationships in an AC circuit? There are some hints from mnemonics, and we know that making abstract material meaningful, or coding items into a story line can facilitate memory, but do subjects use such techniques? And could they easily learn to use them? We know that years of intensive practice, say in engineering school, can produce great fluency in certain basic circuit relations, but we have few tricks to facilitate or to short-cut such long exposure. There are learning difficulties, too, in going from qualitative to quantitative appreciation of relations. Suppose you are displaying the several currents and voltages in an amplifier stage. Each little current can be shown in a different color, and these currents can then be discussed separately under the operating conditions of the circuit, as in the remarkable Adams series of textbooks (Adams, 1966). If a component has changed slightly in value, though, the troubleshooter eventually may have to perform quantitative analysis, perhaps *via* sets of equations. How does this bridging from the qualitative to the quantitative come about? Again, what imagery can support the performer? In other settings, Bruner (1965) has shown how ingenious and concrete imagery schemes can make abstract and difficult concepts accessible to children. For instance, children can appreciate the concept of the energy quantum. We need some of this ingenuity to support troubleshooter cognition. There is some evidence that the ability to bring up vivid voluntary images can aid in problem solving, through its association with "independence of judgement" (Richardson, 1969). A related cognitive hint comes from Rowan (1965), who tested a programmatic approach to solving algebra word problems:

> "...The program 'translates' the word problems, step by step into algebraic equations. A number of algebra students do the same. But other youngsters first translate the English prose into a 'picture' of the physical situation and then translate this representation into equations. And those who perform this indirect rather than direct translation prove to be more powerful problem solvers."

This conclusion might apply directly to the circuit analysis domain;

good circuit analysts should be those who can originate a clear picture of circuit actions.

When subjects are presented with a logically simple troubleshooting problem, and can approach it from either a "work saving" or "probability" standpoint, they initially perform easy stage checks, gradually shifting to the more likely but more difficult kinds of testing. At least they did so in the Detambel and Stolurow (1957) experiment, when work was represented by the number of screws in the lid of each component, and probability was the likelihood of a malfunction. As in the other work cited, there were few optimal troubleshooters. A similar setup, but with more units, was used by Dale (1959). His display had nineteen electric sockets, one of which was defective. As far as the subjects knew, there was no particular arrangement between the sockets. About a third searched randomly, but some used a stepwise pattern. When the subjects were told that the current was flowing through the nineteen stages, and that the malfunction could interrupt the current flow at any point, subjects were more systematic. As expected, the more informed subjects were more efficient.

Neimark (1967) used a problem board equipped with shutters which could control viewing of test information. The optimal half-split strategy showed up again here, although few people applied it strictly. Some subjects uncovered good information on the first look, and therefore tended to become "gamblers." These people would eventually shift to a more systematic and conservative scheme, however, if their gambling did not pay off. The results again indicate a general rationality, but not optimality, in search behavior.

For some complex tasks, knowledge hiearachies can be defined. Gagne et al., (1961) took as the terminal behavior the capability of finding formulas for the sum of n terms in a number series. This terminal behavior was broken down into prerequisite behaviors, and these were then arranged in an ascending series, which were taught one level at a time. The final or highest level was not attempted until all the prerequisite behaviors were mastered. Most of the empirical studies of this learning-hierarchy approach use "clean" mathematical tasks, and in those cases the data are predicted well from the stratified-skill arrangement (Gagne et al., (1961). While most training courses do assume prerequisites and cumulative knowledges, a logically engineered hiearachy does not guarantee learning efficiency, and may even hold up progress (Merrill, 1965; Johnson, 1972). Subjects can learn "from the top down," and can master lower-level skills while working on the higher levels. It is still true, of course, that at some point the lower-level capabilities will have to be developed. The learning hierarchy idea has not been fully been evaluated in troubleshooting of real equipment, though hierarchies were defined for a fairly involved DC circuit problem (Wollmer & Bond, 1975).

Cognitive styles can sometimes predict aspects of intellectual performance that cannot be explained by aptitude and experience. One style feature is the way that a problem solver gathers information about his problem. In Gaier's (1955) Air Force study, trainees who preferred to seek principles rather than facts performed better in a mechanics course. Gardner & Schoen (1962) found a stable style of cognitive control in their free-sorting test situation. Some subjects made sharp and genuine cognitive differentiations when arranging a set of items, while others merely listed concrete features, and did little "real thinking." Interestingly, this "differentiating" cognitive style was independent of general intelligence. Perhaps it could be confirmed in a troubleshooting domain, and could help to explain the wide individual differences in eventual performance, among technicians who are all selected on general intelligence. Similar expectations might apply to the Witkin "field independence" concept, since people scoring high on that variable tend to achieve figure concepts readily, and to perform well on the classical problems of Duncker and Maier (Davis & Klausmeier, 1970). Nearly all of the cognitive style variables proposed so far are of questionable utility, insofar as reliability and generalizability are concerned, but they offer some intriguing research possibilities.

As mentioned earlier, negative information is not employed in the same way as positive information. Wason's (1960) research is a good illustration. In asking college students to generate a rule from a number series, he instructed ...."You will be given three numbers which conform to a simple rule that I have in mind....Your aim is to discover this rule by writing down sets of three numbers, together with reasons for your choice." A significant finding was that the subjects seemed to avoid negative or disconfirming examples that could eliminate a given hypothesis. Campbell's (1965) experiment was along the same line. It presented word problems wherein the letters of the words were replaced by other letters. If the letter substitution had to be done indirectly, by elimination, then the problems were more difficult. Johnson (1972) interprets such results in terms of information load:

> "....There is an upper limit to the amount of information that the individual can handle, and that as he approaches this limit he makes errors. Presumably, he retains the information that first comes to him while taking in new information to be related to it. If he can relate the new information directly to what is being retained, solution is easy. But if he must transform the new information, as from negative to affirmative, or reverse the order, or change the subject, the total load may approach his capacity and errors may occur."

The positive-negative logical disparity in human processing can also be demonstrated by timing the performance on specially-constructed items. The statement "seventy-eight is an odd number" can be answered quicker than the negative counterpart "fifty-seven is not an even number." As Johnson (1972) observes, such items can be written in completion form, and again the positive statement is evaluated sooner. Jones (1966) showed that subjects can mark "3, 4, 7, 8" faster that they can mark "all numbers except 1, 2, 5, 6." Perhaps the ultimate in timing technology in this domain was achieved by Trabasso (1967). He gave one subject 32 selection rules about two-part-figures that were systematically varied in size (large or small) and color (orange or green). A rule was phrased in terms of logical "and" (conjunctive) or logical "or" (disjunctive). A rule like "orange and orange" was verified faster (.634 secs.) than "orange and not-green" (.736 secs.), and "not green and not green" took .824 seconds. Trabasso then assumed that these time differences were due to a basic transformation time. Thus, "orange and not-green," though logically equivalent to "orange and orange," took about a tenth of a second longer because one transformation was required for the not-green term. Two transformations ("not green and not-green") would add another tenth of a second. Perhaps such transformation times are basic parameters of human information processing capability. As far as we know, nobody has measured them in troubleshooters.

Conditional reasoning involves some kind of if-then contingency. Here again, many logical errors are observed when people are asked to process conditional statements. The format structure can be expressed in P Q form, as follows (Johnson, 1972):

| | |
|---|---|
| If X is a fish, then X can swim | $P \rightarrow Q$ |
| X is a fish | $P$ |
| Therefore, X can swim | $\therefore Q$ |

Nearly everybody perceives this as a valid argument. But the following fallacy is also perceived as valid:

| | |
|---|---|
| If X is a fish, then X can swim | $P \rightarrow Q$ |
| X can swim | $Q$ |
| Therefore, X is a fish | $\therefore P$ |

One trouble with the conditional is that the subject may put temporal or causal meaning into a structure which is supposed to be strictly logical. English words like if and then have a distinct time and order flavor about them. Also, the same difficulty with handling negation in ordinary logic is found with conditional falsity. Wason's (1968) demonstration involves only four simple cards, but it shows the logical and psychological skeleton of the conditional. The four cards have D, 3, B, and 7 on their respective faces, and the subject is asked to evaluate the validity of the rule: if there is a D on one side of any card, there is a 3 on the other side. Which cards should be turned over? The correct answer is D and 7. In the event, everybody selected D, because if there was a 3 on the other side the rule would be violated, but it was much more difficult for people to see that 7 was the only other choice that could invalidate the rule. Many people turn over the 3 card, and even after hearing the answer and having it explained, some subjects do not feel right about it. Johnson-Laird and Wason (1970) think that the difficulty stems from the incomplete "truth tables" which are held by most people, and from their set for truth rather than for falsity. If the arguments are presented in a "practical setting," say with real objects, then the logical errors decrease sharply. As far as we know, there have been no systematic studies of the "negative logic" in human troubleshooting.

This review, brief as it is, has given a glimpse of behavioral research that is relevant to troubleshooting. Taken together, people who work on troubleshooting programs and devices seem never to refer to it. Humrro's conclusion from over twenty years ago still holds: "....the study of human problem solving, concept formation, probability learning, and so forth, has provided little data of immediate use to the researcher in electronic troubleshooting, but has provided certain limits as to important variables...." (Czeh, 1957). Rather little of this work has influenced the practical design of equipments, courses, and troubleshooting procedures. Occasionally one will find an engineer who has heard of the half-split notion, and some conception of a learning hierarchy is discernible in many lesson plans. But such items as "mnemonics for electronics," "story coding" for memory, cognitive sytle, and human processing of conditionality and falsification, are apparently not recognized outside of psychology. This could be due simply to interdisciplinary ignorance, but then it is very difficult to take a conception such as cognitive style, or "imagery-supported electronics," and to develop it into something useful for the real troubleshooting domain. Suppose one wished to match a military troubleshooting aid or training device to an individual's cognitive style. There would have to be a lot of psychometric work, difficult field trials, and long-term commitment from operational commands. Instead of going through all this, the practical operator might ask his technologists to set up the troubleshooting task so as to reduce the impact of cognitive style on the search task. That is exactly what the aiders have done. If the aids and supports are effective, then individual variance in processing skill will be minimized, or at least reduced. We have already noted that "concretizing" the P's and Q's of logic problems will tend to reduce the logical errors, to improve performance generally, and to make the task more routine for everybody. The practical training and operational executive wants this kind of aiding, rather than an academic explication of the factors underlying the performance when the aiding is not present.

Digital systems bring special problems and opportunities to the behavior analyst. A large digital system is an assembly of many copies of a few standard units. There are only about a dozen basic logic functions such as AND, OR, NOR, or NAND. Each of these functions has a logical truth table, and can be realized in hardware by means of various technologies. Usually an item such as an OR gate is encapsulated as a small integrated circuit. Operating sections of a system can then be put together by an array of the simple functions. For instance, information which is coded in four binary digits as 0's and 1's can be converted to decimal form by means of 8 inverters and 8 NAND gates, and the whole converter can be smaller than a letter, or even a dot, on this page (Coffron, 1979).

Understanding a digital system seems to be a psychological challenge for many people. It takes some time to get used to the many logical 0's and 1's that are processed and transferred about. Since transistors, resistors, and diodes are often employed in the circuits, the student also must know enough electronics to follow the current states in a bistable device or an operational amplifier. Often, there is not much imagery to assist human memory in holding the big logic arrays in mind. The digital system with its abstract design may seem to be austere and counter-intuitive.

Digital components such as counters and shift registers are driven by special clocks, and so the timing is extremely critical. The clean and definite nature of the signals, and of the flip-flop circuits, means that a timing diagram of signals and events in a circuit can be very precise. A timing layout may show free-running clock pulses running along a top line, with real time going to the right. Below this there could be many other event lines, which show preset, clear, and output-synchronous events. Such diagrams seem not to be very memorable, however, and the meaning of all the time intervals can quickly be forgotten. Furthermore, unless every event is understood at some physical action level, the diagram may be useless in a real trouble search, and the technician can get lost in a jumble of microsecond-duration events. The cognitive problem in digital electronics seems to be somewhat similar to that of the computer programmer (or debugger) who must at once understand a complex program at a global level, yet be able to deal with the most minute aspect of one or more individual instructions.

There is another type of intellectual effort that is required of any electronic technician, and particularly so of one working on a digital system. A quote from an engineering text will give the flavor:

> "....When we look at the overall system....we see feed-back loops, DAC's, LED displays, and digital counters.... The troubleshooter must develop the ability to separate in his thinking the individual subcircuits from the complete circuit or system. This is a mental separation at first for the purpose of understanding the small circuit and large system operation. The second step will be to apply the mental separation to the physical hardware to accomplish the task of troubleshooting." (Coffron 1979).

Again, this "mental separation" depends on a detailed appreciation of circuit functions and inter-relations, at some level. In fact, someone who could troubleshoot each little subcircuit would probably not need much further capability to do the whole thing. There is a big picture, of course, but working inside the big picture depends on many little perceptions which are accurate. One training strategy, which is often used in the computer industry, is to teach just enough electronic theory for the technician to understand the dozen basic logic funtions in digital processors, or perhaps only that set that he "has to know about," in order to use the aids furnished to him.

There are special problems in the location of intermittent faults, and the process of finding them is just beginning to be modeled (Varshney, 1978). Many such faults emerge only under certain conditions of age, timing, and adverse operation. The necessity for finding intermittents is one of the most challenging problems the technician faces now, and this will probably continue into the future. From theoretical considerations, the "memory" required for intermittent troubles will be found partly in the technician's head, and partly in his aids. No behavioral research has been done in this area.

If the troubleshooter of the immediate future will indeed be primarily a highly-skilled user of complex procedures and aids, then information about the way that <u>procedures</u> are learned should be useful in preparing such people. Again, there are promising ideas and hints from academic research, but not much that is easily applied. Norman (1978), for example, says that the common sense notion of repeated practice as the key to learning may be largely erroneous. Instead of endless repetition, learning often proceeds better if a story line is mapped onto the new material, or if mnemonics and visualization can be utilized. A well-learned complex procedure can give the performer a play-like experience of "flow," which can be intensely satisfying (Csikszentmihalyi, 1975). Norman believes that a student should know more about his own psychology of learning, and about the way he responds to practice schedules, feedback, and the arrangement of materials. White (1959) points out that being able to do things well gives one a feeling of "effectance," of being in control of one's actions. Since White's effectance idea requires that the performer have some opportunity for originating parts of a task sequence, the designers of future trouble-shooting aids might well program certain possibilities for individual choice into their complex test routines. The best troubleshooting aid might be one which has just the right amount of cognitive novelty for the person using it!

It is well known that there are ways to memorize very large quantities of data by utilizing "peg-word hooks" as in the Furst memory system (Logan, 1956). Even if a large table of symptom-function relationships were memorized, however, the problem of correctly exploiting thoe data would remain. Considering the ease of substituting paper or microcircuitry for human memory, the pursuit of memory enhancement, without understanding, seems unattractive.

## Engineering A Maintainable System

People who have worked on human factors problems in complex equipment often have disparate views of the world, but on one issue they are almost universally agreed: almost never is sufficient attention given to "people problems" in the design of a new prime equipment. A little reflection and observation will suggest why this is so. In the standard R & D scenario, a scientist or engineer has a bright idea, for a new hardware item. After some company-funded preliminary work a proposal is made to NASA, FAA, or a military service. Contracts are let, and the development cycle begins. In the early stages, nearly the total emphasis is on engineering feasibility, and such matters as packaging, logistics, and ease of maintenance always "can be taken care of later." Since the equipment is complex and is challenging the technical limits, there will be many problems in getting out a working prototype, and by then there probably will be time and cost overruns. If the hardware conception is basically valid, then a short time before delivery some attention will be given to support functions, and the maintainability specialist and other support people will be allowed to look at the project. By then, though, radical design changes may be expensive or impossible, and quick fixes may be attempted. Once more, an incomplete system goes into service.

Of course, there can be strong persons along the development trail who insist on maintenance considerations all the way. At military procurement desks these are often people who have had to use new equipment in the field, and who are sensitive to the problems.

But the persons with the technological ideas are usually engineers and scientists who perceive the main challenge as one of innovative design. They get their satisfactions, and their reputations, from the design activities. The program managers, on the other hand, have budget and delivery schedules in mind, as well as acceptance tests and field trials. A lot of money and prestige is riding on the basic project feasibility. In these circumstances, maintainability is just another secondary support irritation to worry about.

There is a "design side" to maintainability analysis, and there is a "system availability" side. Availability is often expressed as a joint measure of reliability and maintainability. Thus, if reliability is denoted by Mean Time Between Failure (MTBF) and if maintainability is measured as Mean Time To Repair (MMTR), then Availability (A) can be expressed as a simple ratio:

$$A = \frac{MTBF}{MTBF + MTTR}$$

Formulas like this can be computed, graphed, and extended mathematically in many ways. As just one example, MTTR is often assumed to follow a log-normal distribution, and under this assumption the likelihoods of certain availability levels may be computed. Equations like this can show clearly the tradeoff between reliability and maintainability, and it is no doubt interesting to work out graphs relating availability to various numbers of R & D dollars. But such formulas are rather empty, because they do not tell *what to do* in order to achieve a given level of availability. Hence we do not pursue the availability question here, except to say that we have almost never seen a military service hold a manufacturer to the availability promised in the original proposal.

The design side of maintainability engineering is a much richer and more useful discipline. It encourages the formulation of an explicit maintenance policy, it gives specific design rules which are (sometimes) behaviorally based, and it can stay close to the work that must be performed. When fully implemented, a maintainability effort starts with the maintenance concept for a given prime equipment. The concept defines levels of maintenance, the arrangements for support by mobile and depot facilities, the number of operational and maintenance installations, spare parts facilities, and other system requirements. There will also be a repair policy. A system can be designed to be nonmaintainable, partially repairable, or fully repairable (a nonmaintainable item is not repaired, but simply replaced by a spare). A partially repairable system will have some assemblies which are throwaway items, while others will be fixed when they fail. Ideally the maintenance concept will be complete, that is, actual behavior constraints required at the different levels will be fully designated.

Subsequent steps in a good maintainability program will go on to tradeoffs, design assistance and review, and the demonstration of a maintenance capability (Blanchard & Lowery, 1969). Check-lists and hardware evaluation sheets are used to score each equipment item. In a large project, there will be much paper related to design recommendations, and regular maintainability meetings. The final demonstration is often two-phased. The first one takes place at the contractor's facility and uses contractor personnel; the second is held in the user's environment such as a Navy ship, with the user's people in charge.

It is surprisingly difficult to prove the utility of a maintainability program. There are many case studies and illustrations of the presumed benefits of redesigning an equipment for ease of maintenance. A favorite textbook example is an Army field radio, which had many arbitrarily designed and located switches and dials and controls on its front panel. To operate or check the original radio, a technician had to explore the entire panel. The task sequence was made more regular, allowing the operator to start at the top and work clockwise around the front panel. Readout dials and test points were made more legible, and the switches were enlarged and shaped so they could be discriminated by a gloved hand in the dark. Inside the box, a partial rearrangement of wires and parts was done, so that the electronic states were more clear-cut to the repairman, and use of clips and clamps hastened the removal of parts. Yet, nobody ever really proved these improvements resulted in better field usefulness of that radio.

Maintainability design and planning effort should be considered as a necessary but insufficient condition for good troubleshooting. The cognitive load on the technician is the key thing. It does not help the technician much to have an accessible test point if the meaning of the voltage at that place is obscure, or if he does not know which voltage to look at. We would argue for a basic behavioral reference for many of the design proposals made by maintainability people.

Maintainability programs rarely admit a fact which is obvious to others: sometimes the corrective maintenance technician has an impossible task. One Navy air-search radar, for example, could not be maintained by typical technicians. The system was extremely complicated. Designed just before the integrated-circuit technological revolution, it had several cabinets jammed full of subsystems. Some of the test sets accompanying it were novel, and difficult to use. The manuals were beautifully bound but impenetrable to the average technician. Spares were often very expensive, which made a throwaway policy untenable. A graduate electrical engineer might have kept the radar going with months of specific training on it, no other duties to perform, and a big parts budget. Here was a total operational failure, yet the maintainability documents and field advisories kept coming in a steady flow, both from the manufacturer and the Washington bureaus. Nobody ever said, out loud, that the system was not maintainable. The point is obvious: real troubleshooting in the services is often done by people who have a year or less in a military technical school and some months in the field, and there are many items they simply cannot service. When the maintainability and planning documents do deal with human capabilities, the reference is often to formal school levels or ratings, with assumptions of capability in the higher enlisted ranks. The assumptions are often wrong; many first class ET's are not first class troubleshooters.

Why is so much equipment plainly unsatisfactory from an elementary design standpoint? Do the engineers not know of our maintainability design guides and review procedures? What about the design suggestions we have catalogued—are they seriously inadequate or incomplete? Maybe the best answer is that while maintainability guides and directives are often known by and available to the designer, there is not a sufficiently clear payoff to be had from consulting them in a systematic way. After all, much of the advice is rather obvious: Keep it simple, label things clearly, organize check sequences in a natural order, write the manuals so users can understand them, encase fragile parts in plastic. Glancing through a set of homilies like those, a professional engineer might think he was not getting anything novel. Perhaps an even more basic answer, and a major key to eventual utlization of the advice we do have, is that maintainability people are staff people, and seldom have the power to impose their arts onto a design. This situation can change when equipment <u>must</u> be maintainable, as in a submarine or a NASA space labboratory. Fortunately, human factors courses appear more frequently in engineering curricula, and are also popular in middle-management military courses. The most critical pressure for application will come from the users. Unless that pressure is applied, good maintainability engineering will continue to be very rare.

## SECTION III. AIDING AND TRAINING THE TROUBLESHOOTER

### <u>Aiding Concepts and Devices</u>

#### <u>Manuals</u>

The tech manual is the original aid. It has always been provided as a part of the prime equipment package. Much effort always goes into it, and yet the tech manuals have usually been unsatisfactory to the user. Maybe this is because there are many users—maintenance technicians, installers, operators, parts suppliers, field engineers, field change people, curriculum planners, and so on.

While the information in a manual may be correct, it may be impossible for a typical user to find out just what he wants to know. The troubleshooting section of the manual was, and often still is, not arranged well for a military technician who is trying to find and replace a faulty unit in the middle of the night.

Things are better when special troubleshooting manuals are produced, on the basis of behavioral considerations such as these (Rigney, 1970):

1. Content organization should follow the sequence of events in the job. The first things in the book should be the first things the technician does as the search proceeds. The technician works through the book, which becomes more detailed.
2. The information presented should be relevant to the job. Thus, a troubleshooter's manual should include only the items that the individual needs.
3. The level of discourse should be appropriate to the user's technical knowledge. A trained technician probably does not know much electronics theory, and he cannot use an engineer's course on theory of operation of the particular system he is working on now.
4. The information should be accurate. An idealized waveform in a manual may not be a good basis for comparison with a real wave shape at a test point. It is often surprisingly difficult, or impossible, to obtain the good "normal" parameters as shown in a manual. Failure to obtain the reference indications can cause considerable confusion for the technician.

5. The format should be convenient to use, in the user's environment. Manuals should be easy to carry, to read, and to prop up in cramped spaces. Sometimes a "manual" could be something like a pack of plastic cards riveted together at the corners, or a small device with slides and wheels.

There are military specifications calling for such improvements, of course, but the manuals still are produced by much the same process, and the same people, that produced the older inadequate ones. DOD has devoted large sums to manual-improvement projects in recent years, such as "new concept" projects in manual writing and production (Klesch, 1979). These efforts are beginning to have an impact. A most convincing demonstration by Potter (1976) compared a fully-proceduralized (FPTA) manual and a logic-tree manual (LTTA) with a regular Technical Order (TO). Both new formats produced better troubleshooting, less wasted parts, and positive acceptance by the field people. This study used Air Force operational radar and computer gear, and presented realistic fault-location problems. About the only disadvantages of the new formats were the higher preparation costs, and the extreme necessity for avoiding errors in the documentation (if a man following FPTA instructions is told to go to page 37 when he should go to page 73, he may be irretrievably lost.) Shriver's analysis of the new presentation formats indicates that they are all based on a single assumption:

> '....experts can analyze the equipment, figure out what should be done to it in every possible situation, and record this in Technical Manuals that even a novice can use correctly" (Shriver, 1975).

Shriver goes on to state that this concept is realized by means of four techniques for producing content (task analysis, behavioral cues at each step, etc.); and the appreciation of this content is then enhanced by employing good readability and display considerations. Shriver also observes that the technician may only need system understanding at a block level, and not at an electron level. This accords well with the evidence that electron-level knowledge is not well retained following academic training.

Hand-held Aids

In this category, we think of items like the flow diagram for the "B-7 fire control" (Morgan, et al., 1963), and the Experimental Fault Locator (XFL) troubleshooting wheel, developed by Rigney and Fromer at BTL (Rigney, et al., 1965). Morgan's diagram offered a clear functional layout of test points and line replaceable units, and also furnished a sequence of checks to follow. Rough but effective test tolerances were also provided. For example, the guide says that at a testpoint the "wave shape is not critical;" but the absence of a signal, or the presence of spurious oscillations, does indicate a malfunction. This is just the kind of information that a technician needs, and can use.

The XFL wheel is a circular plastic device, similar to a circular slide rule; it contains a symptom-malfunction matrix for a Navy transceiver, along with an algorithm for selecting the next front panel test to perform until the fault is localized. The device thus unburdens the technician in two respects: memory for the malfunction-significant symptoms, and the formulation of a logical search plan for narrowing down the fault. Radio operators, who had no training in maintenance work, were able to use the XFL in a few hours, and could localize faults inserted in the equipment. This finding not only indicated the value of the aid, but also confirmed our general thesis that, if an adequate next-step selection aid is available to a technician, good troubleshooting behavior can be expected.

Many other hand-held devices like these two have been invented, and some have reached the field. The original research studies almost always show the effectiveness of such items, but somehow the aids themselves rarely become widely distributed and utilized. One thing is certain: One cannot simply develop a device, send it to a Navy or Army field unit, and assume it will be employed. The field people have to be prepared for the device, they have to be trained in its application, and most important of all, they have to feel a need for the things that the device can do.

Perhaps one reason that aiding devices are not widely seen on the job is that they have been somewhat resistant to updating. The aid may, for instance, not take account of field changes in the particular prime equipment. If the technician tries to use it, and encounters an error or omission, he may (wisely) discard the whole thing, when actually it would work most of the time. We have often heard technicians say that a new tech manual or other job aid is "no good," but subsequently close questioning indicated that the item had never been given a fair trial. Sometimes an outside observer gets the idea that technicians in the field are too suspicious of schemes and devices which are provided to them. It is hard to say how much of this rejection is due to previous experience with really inadequate materials, and how much is due to the field person's need to maintain his own discretion and control over his work. What cannot be ignored is that something about the field environment presents serious difficulties to the successful introduction of a job aid.

Right now, the most exciting hand-held aid possibilities are those involving micro-computers, especially those termed programmable calculators. In 1979 technology, a small memory cube (read-only memory or ROM) about a half-inch on each side, holding nearly a thousand program instructions, plugs into the side of a small hand-held computer. If desired, a light printer can be attached. The whole thing weighs only a few pounds, is ultra-reliable, and costs less than 400 dollars. Special-purpose ROM's approximately the size of sugar cubes, can be produced economically in quantities over a few hundred. Thus, we envision a proliferation of this technology which transforms a general-purpose processor into a special-purpose machine.

In addition to commercial applications of this technology, Towne (1977) has implemented a detailed troubleshooting strategy for the URC-32 tranceiver, to demonstrate the potential of guiding the troubleshooter with a hand-held processor. The services have also begun to employ this technology both in the schools and the fleet. The latest development in programmable calculators, the Hewlett Packard 41-C, provides non-volatile memory, eliminating the need to load a program each day. And there is a full alphanumeric display. This latter capability allows a truly interactive program in which user inputs are cued by natural English words and phrases. While not yet built into a programmable calculator, voice synthesizers and generators have been sufficiently miniaturized and mass-produced to be incorporatd in the next generation of hand-held devices.

## Human-Oriented Computer Aids

The term "human-oriented" is used here to differentiate such systems from automatic test equipment, which is usually strictly hardware-oriented. Until a few years ago, "computer assisted" usually meant that an aid was driven by its own prime equipment. When timeshare technology became cheap and reliable, it became convenient to store maintenance charts and sequence information in a master program which could advise the technician about the best next test to perform. A complete system like this becomes a more or less sophisticated page turner, which is based on a large network of contingent action-choices. Though the concept seems simple enough, setting up a practical program is a considerable task. A good example is a special logic-tree program written in the IBM Coursewriter language using the IBM 1440-1410 computer and a 1050 student terminal for storage and display (Rigney et al., 1966). After only an hour or so of computer-aided practice, a Chief Radioman who had never operated the URC-32 transceiver was able to work through five trouble sequences on the real equipment, which was standing next to the computer terminal. All except one of these problems were "deep", in the sense that they required correct sequencing and interpretation of at least ten or more tests.

This demonstration showed that special languages like Coursewriter can be utilized quickly by electronics instructors who are not trained programmers, and that even a few hours of computer-guided practice can show interesting behavioral results. For each troubleshooting problem, however, a special program had to be written in order to provide a "trace" through the symptom-malfunction tree. To generalize this guidance function, and to make it less problem dependent, Towne and King of BTL produced the AIDE configuration. AIDE accepts troubleshooting tree data from any prime equipment in a standardized format, and furnishes analyses of "next best check," detailed task specifications, procedure lists, exercises in symptom interpretation, exercises in equipment set-up, or simulated maintenance problems. The unique goal of AIDE was to serve as a performance aid, a training system, or some mix of those two functions, as determined from a particular user's needs and experience. At the moment, the AIDE demonstration data base stores 125 color micrographic images and thousands of words of appropriate fault-locating software. This is enough information for a significant part of a large radar system. For the complete radar system perhaps 1000 images would be needed, but there would be no additional software or computer memory.

Another advanced computerized aid is the LOGMOD Diagnostic Test Set, which was designed by DePaul and his associates, as a means of meeting sixteen desirable attributes of a performance aid (DePaul, 1979). The LOGMOD hardware is about the same size as a 15-inch portable TV set. It can provide test sequences, repair parts listings, reliability data, interpretation of test readings, and so forth. The equivalent of 500 pages of manual information can be stored on one 5-1/2-inch floppy disk, which can be accessed in numerous ways.

There is surely reason for optimism, then, on the technology side of the aiding question. The utilization of the hand-held computer, with a special memory cube for maintenance, is on the way. And slightly larger systems like AIDE and LOGMOD can store and deliver an immense amount of information, and can operate in several aiding and training modes. These approaches can realize all the behavioral efficiencies promised by the fully-proceduralized manuals, in a more responsive format.

Certain problems in getting all this to the user will persist, however. Over the near term, success or failure of the aiding technology may depend heavily on the military's reaction to softer problems of implementation, which are intrinsic to all large organizations. Suppose a new aiding idea is developed, tested, and ready to be put into the field. Nobody greets it with open arms. The military field commander has long since adapted to marginal performance as the standard, and he knows that he will be gone before any perceptible benefits will come from this new idea. There are large and unwieldy support bureaus who might be threatened by the new idea. The training planners, lesson-writers, and school managers usually will not be eager to help; they may fear that the aid will make their schools apear to be outmoded or unnecessary. These are conservative, entrenched, and powerful agencies; they have their own departments for research and development, which it is in their interest to preserve and expand. They will say, "Well, we're already doing that." They will think the idea is intruding upon their domain, or they will want it to be implemented, if at all, by a section of their present organization, at a time convenient for them. Or, they may attempt to offer a "watered down" version (Foley, 1978). They may claim that introduction of the new idea will cause budget difficulties, or they may prevent access to research subjects in training schools, because "....we have personnel quotas to deliver."

Given such a conservative system, what can be done by the research community? One thing we can do is to stay closer to the real operational needs, and to make our demonstrations sharper, so that the value of new methods is clearly cost-effective. Training establishments and manual writers often concentrate on delivering manpower quotas and staying within budgets. They are not necessarily reinforced for solving the field problems. Inaba (1979) put it plainly enough:

> "Little attention is given to the usability of the manuals or the performance capabilities of the students....If a change is made and the technicians become more productive, the publications and/or training manager do not share in the benefits—except possibly for a compliment."

But this means that somebody who <u>does</u> concentrate on the real operational problems may find that he can make an impact outside the usual bureaucracy. A strong project office, for example, is often able to implement quickly a new aiding notion, as part of a hardware procurement package. The maintenance concept for at least one Navy shipboard computer system was implemented in this way.

## Automatic Test Equipment (ATE).

Probably no single maintenance development has been so powerful, and yet so ineffective, as has ATE. A sophisticated ATE routine can sample hundreds of measurements in a short time, and can race through a whole pre-launch sequence before a technician could get a meter out of its case. Often the ATE system really can locate faults; some programs even print out an English statement of just what needs to be done, and then "thank you" for doing the corrective work. Such marvelous capabilities lead to a trap, however, by suggesting that since ATE can do so much, it can do everything, and skilled human troubleshooters will be unnecessary. This supposition is false. Recent history proves that ATE is extremely vulnerable to programming snarls, prime equipment inaccessibility, the software difficulties of writing fault location routines, the incompatibility between automatic and manual test procedures, and so forth.

Many good analyses of ATE development issues have been published (e.g., Myles, 1978; Van Hemel, 1978; SETE, 1965). The overselling of ATE capabilties still goes on, however. A recent example is the Versatile Avionics Shop Test (VAST) concept. This is an expensive and complex general-purpose test system for avionics. The system is an engineering <u>tour de force</u> which really can help the technician.

But consider the following quote about the training of people who use VAST (Van Hemel, 1979):

> "The original concept of VAST envisioned the use of an operator with minimal training....This concept has been shown lacking because it anticipates a situation in which the program will be perfect. The machine will always operate properly, and documentation associated with the testing process will always be up-to-date and correct. Experience has shown that all of these factors seldom prevail in spite of the most stringent efforts....The assumptions originally made concerning the VAST maintenance technician also suffered from the same inac-

> curacies as with the operator....this technician required more training and experience to effectively troubleshoot the complex VAST system."

With enough money and effort, systems like VAST can be made to operate. But they seldom achieve their expectations, and they can be just another source of frustration to the field people because they do not begin from a behavioral-requirement base. Indeed, an interesting research project might be an attempt to apply human factors and technician-behavior requirements to a complex ATE system, during the design phases. As far as we know, this has not yet been done on a systematic scale.

## Training

### Conventional School Training

Readers of this report will be familiar with the ordinary sequence of technical schooling in the Services, and with the staggering numbers of courses, schools, and students. The DOD is probably the biggest schoolhouse in the world (Shriver, 1975). A recent Defense Sciences Board (Alluisi, 1976) concluded that technical training in the U.S. military was usually effective, and one can accept that judgment. From a research standpoint, there are surprisingly few thorough evaluations of the training system. There are indeed many body counts, and schools often send out questionnaires to the using commands, asking for data on the proficiencies and deficiencies of school graduates. Such information is presumably used in modifying courses. When genuine experimental evaluations are carried out, though, they are often done in a context of a special training item, such as an aircraft simulator. Since realistic simulators are very expensive, it makes sense to find out whether they really save time in the aircraft. In this particular case, acceptable criterion measures can be defined, and the utility, and even the cost-effectiveness, of a training device can be estimated (Orlansky and String, 1976).

But with no criterion to guide most technical training courses, the usual curricular approach is to furnish general "theory" information, with the expectation that this information will be the basis for on-the-job specialization later (Shriver, 1975). It is hoped the technician can then figure out what to do, regardless of conditions. Certainly it works this way sometimes, but often it does not. The theory which is learned, and most likely quickly forgotten, may be so indirectly related to later activities as to be irrelevant, and there may be no direct training at all in the tasks that must be performed. The present training system is beginning to respond to such circumstances, although rather slowly. Inaba (1979) notes, for instance, that the Navy has started to teach the manuals:

> "....the course essentially leads the students through the manuals (but) the emphasis on using manuals in training has not really helped much because the manuals are not usable. Once the student leaves the training environment, the manuals are put back on the shelf again."

The two main scientific difficulties with conventional training courses seem to be (1) the lack of a criterion to assess the adequacy of the teaching, so that the system is not self-correcting; and (2) the lack of a clear-cut behavioral requirement underlying the training plan. Instead, training plans begin with a set of assumptions about background information that a person needs, to be able to learn on the job.

These two difficulties conceivably could be alleviated, by research or by fiat. But there are administrative difficulties as well. To repeat an earlier point, the military training system is essentially a monopoly, with its own power and autonomy. It does not respond quickly to a new method or a new requirement, because it does not have to. Also, a training unit may not easily accept inputs from, say, the aiding people or the manual writers, in defining course content or practice schedules. The trainer may think that these other people want to eliminate training (Inaba, 1979), and so he may go ahead with his "general technical information" approach. After all, that was the way he was taught, and the way he knows best. Despite such conservatism, we should be slow to disparage conventional training. It is often surprisingly difficult, for instance, to improve upon conventional training with advanced educational technology, as is shown in the next section.

### CAI-CMI Courses

Computers have been used as a practical school aid for nearly fifteen years. The first successful application of Computer Aided Instruction (CAI) was the Suppes-Atkinson project at Stanford, which gave arithmetic and spelling lessons to young children, starting in 1965. The Palo Alto classroom had 18 student stations, each one equipped with its own terminal. In military training, there have been about 30 studies of CAI-CMI (Computer Managed Instruction) effectiveness, and these have been collected and exhaustively analyzed by Orlansky and String (1979). Among their findings are the following:

a. Effectiveness has been measured only by testing student achievement at school, and <u>not</u> by performance on the job.

b. Student achievement in CAI-CMI courses is about the same as that observed under conventional instruction.

c. CAI-CMI courses save about 30 percent (median value) of the time required to finish the same course given under conventional instruction; the time savings vary across courses and situations.

d. Cost-effectivness of CAI-CMI has not been conclusively demonstrated, though some impressive "avoided cost" dollar savings can be claimed for the Navy CMI system.

These results, which are well documented in the Orlansky-String report, should temper any excessive enthusiasm for CAI-CMI courses as the key to technical training efficiency. Of course, the course trials that have been reported may not represent the most advanced technology available. Truly radical CAI-CMI improvements may await better psychological information about the way students visualize and absorb complex physical and mathematical relations, or the way they learn a sequential procedure. Clever scheduling of lessons or real-time monitoring of performance cannot substitute for process information about the learner.

Two intriguing minor results came out in the Orlansky-String survey of military CAI-CMI. One of these was that CMI was about as effective as CAI, in the saving of student training time. However. CMI assistance costs only five to seven cents per student hour, whereas CAI costs a dollar or more per hour. On the basis of this crude comparison, CMI is some thirty times as cost-effective as CAI! Of course, there are difficulties with such a simple-minded argument, but it is still surprising that CAI should not do better than CMI.

The other finding was that instructors were often unfavorable to both CAI and CMI. Many people who work in the computer-aiding field think they are helping the instructors. For example, the claim is often made that by taking the drill-and-practice burden off the instructor's shoulders, the computer makes his job easier, and allows him to concentrate on more difficult conceptual teaching. Why, then, are the instructors unfavorable, and are their negative attitudes due to something specific about the computer-aiding part of it, to unfamiliarity with the system, or to perceived loss of course control? The matter deserves careful study. Regardless of how computerized a course is, there always must be human instructors around to load and run it, and to serve as consultants.

Simulator Trainers

Maintenance trainers and simulators are "poor sisters" in the simulator business. Kinkade (1979) points up the differences between the way training simulators are obtained for a new aircraft, and the way they come about for maintainers of a new electronic device. In the aircraft case, simulator development is initiated early in procurement, and is often budgeted and evaluated at the same time as the aircraft. The DOD aircraft community also has become accustomed to complex and expensive aircraft simulators, with the average cost running over a million dollars (Orlansky & String, 1977). Of course, such devices are often worth their high cost because of the great expense and trouble of operating real aircraft. As a result of these circumstances, the NTEC Directory of Naval Training Devices shows over 70% devoted to aircrew, 25% supporting other operator training, and with less than 5% dedicated exclusively to maintenance technicians. Furthermore, of those devices that are designated as technician trainers,

> "....most are two-dimensional displays of system schematics, or 'cutaway' models of system equipments. Very few provide for 'hands-on' practice of technician tasks and these almost exclusively involve simulation of actual system equipments."

Studies have indicated that maintenance trainer simulators can result in high savings, compared to using the prime equipment (Daniels & Cronin, 1975; Miller & Rockway, 1975). Also, use of real prime equipment has obvious limitations. The hardware will require "peaking up" between training sessions; it is difficult to observe and score performances; the training model which is available may not reflect the realities of field installation, and so forth. Several projects have designed complex maintenance simulator trainers, and conducted some preliminary evaluations. Among these is the Fault Identification Simulator (FIS) used in an experimental course for automatic boiler control technicians. The device can show, in graphic fashion, the symptoms of 23 different fault conditions. In fact, all possible fault conditions resulting from a single component failure in the actual system can be simulated in the FIS (Kinkade, 1979). This trainer also advises the students of incorrect repair decisions about a non-faulty element. Since the simulator is driven by a small computer, it can be programmed to reflect changes in the prime equipment. When tried out as part of an experimental course, the class finished training in two or three weeks, as compared to a regular course duration of five weeks (the experimental class covered the same material as the usual course, and even had more troubleshooting practice than in the old system).

Shepherd et al., (1977) simulated the control panel layout of a chemical plant, and taught trainees how to recognize faults in three different ways: (1) a theory approach, based on conventional instruction; (2) a rules model, wherein subjects were given rules that would help them infer failures from the panel array and (3) a "no story" or control group who received no theoretical training. The "rules" groups was better able to diagnose unfamiliar faults (80% accuracy, vs. 65% and 49% for theory and control). One conclusion is worth quoting here, for its reiteration of a previous point:

> "....there is little to be gained by teaching 'theory' alone. Although trainees in the 'theory' group initially performed well on unfamiliar faults, their score, by the final test, had deteriorated to a level not significantly different from the 'no story' group."

The AIDE and LOGMOD systems, and other advanced aiding devices with large memory, also can be used as simulator trainers. In fact, pure (exclusive) training and pure performance aiding are rare occurrences. Most training experiences involve some degree of job support, and most supported performances rely on some degreee of previous training.

Another training concept is the Generalized Maintenance Trainer Simulator (GMTS), (Rigney et al., 1978). This system was designed to give students intensive troubleshooting practice in a simulated hands-on training environment. Its "simulational bandwidth" is confined to conditions and operations necessary for practicing fault localization, either from front panel information or from data at test-points behind the front panel. GMTS adapts readily to simulate different kinds of equipment, by accepting data bases that describe functional and structural architecture. As a trainer, the GMTS functions automatically. Once a student signs on, he gets instructions, his progress is tracked, and a detailed performance record is kept. In a trial with 16 Navy technicians, practice with the GMTS reduced average times to locate UHF malfunctions from 20 minutes to less than 10 minutes. Most subjects rated it favorably as a learning aid (Rigney, et al., 1978).

The SOPHIE training system is one of the most "reactive" of the present simulator configurations. Subjects can change component values in the circuit under study, can propose hypotheses to an "articulate expert", and can play a "troubleshooting game" by predicting the effects of inserted faults. Students respond very positively to this learning environment (Brown, et al., 1975). The simulated tutor usually provides explanations of student mistakes. Some tutors even proceed in a Socratic fashion, by challenging the student so that he corrects himself (Stevens & Collins, 1977).

These several recent experiences with complex maintenance trainers are most encouraging. Apparently, special maintenance simulators are able to teach technicians efficiently about malfunctions. We believe they work as well as they do because of the clear explication of symptom-fault patterns, and because of the intelligibility appeal mentioned by Shriver (1975). Thus, they meet Duncan's suggestion that, for teaching trouble diagnosis, training simulators should preserve the panel layout and also the "logical layout" of the indicators (Duncan et al., 1975b).

On-the-Job Training (OJT)

The leading research on OJT is probably being done at the Rand Corporation, where Carpenter-Huffman (1979) and others have been surveying field units, instructors, and trainees. Many deficiencies in present OJT practices are rather to be expected: The training is secondary to operational needs of the moment, an adequate instructor may not be present, there is a lack of supplies for training purposes. There is also concern over the instructor-type skills of the trainers (Carpenter-Huffman, 1979);

> "The most common single complaint about OJT on the TAC questionnaire was that those assigned as trainer were inadequate teachers."

Underlying these rather inevitable deficiencies are some administrative causes. Military commanders,

> "....are not immediately rewarded for the quality of their maintenance activities, let alone their maintenance OJT programs. Instead, they and those they command are penalized if documentation of progress in OJT does not conform to the schedule set for it....pressures to come in as Categorty 1 on the Operational Readiness report often destroy the validity and usefulness of vehicle preventive maintenance and operational readines records.... On the other hand, since progress in OJT is tied to the promotion system, supervisors are under pressure to certify a person's competence whether or not the certification is warranted."

The Rand approach to OJT involves a more formal, explicit, and reinforcable conception of OJT within operating units. Several successful applications appear to follow this approach, including the Navy FRAMP and the TOT (Task-Oriented Training) projects in the Air Force Tactical Air Command. Though this area is perhaps not as exciting as some of the new aiding concepts, it is receiving some attention, and the main requirements have been identified. Administrative decisions will be the key factors, since the military can have effective OJT if it really wants it.

## SECTION IV. JOB DESIGN FOR THE TROUBLESHOOTER

Job design is "....the organization of a job to satisfy the technical-organization requirements of the work to be accomplished and the human requirements of the person performing the work" (Davis & Kanter, 1955). The second part of this definition is the key one, as it directs attention to the fit between the work and the needs of the worker. Many proposals have been offered for improving the fit. For example, Davis listed twenty-three techniques which might simultaneously increase worker satisfaction and lead to more effective output (Davis 1957). Many of his proposals have to do with increasing worker autonomy, discretion, achievement, growth, and the meaningfulness and variety of tasks. It is surprising how modern these ideas sound after more than twenty years.

Despite the absence of definitive survey data, it may be worthwhile to speculate about the present job-design status of the maintenance technician's work. For this purpose, we consider the three job characteristics that Hackman and Lawler (1971) identify as contributing to worker need satisfaction and to organizational goals. Their first attribute is that the worker must feel personally responsible for his work. On this dimension, the high-technology troubleshooter should score fairly high. Take the computer maintenance man. He often works alone, and he may not turn to other people for help, because they cannot help. At the same time, however, he certainly must know that he is primarily a skilled user of materials which were originated and validated by others, and that he is not ordinarily free to vary the procedures very much. Computer technicians, for example, are not allowed to change maintenance software, though we have heard of some doing so. On Gulowsen's (1979) scale of work-group autonomy, these technicians would come out near the middle of the range.

The second Hackman-Lawler job requirement is that a work outcome is perceived as meaningful and worthwhile to the individual. According to Turner and Lawrence (1965), meaningful job processes have clear beginning and ending of the work, they utilize skills and abilities which the worker personally values, and they require considerable variety. On these grounds, military troubleshooters certainly should perceive their work as meaningful. They often have command pressure on them, and this accentuates the value of the work being performed.

Feedback is a third job-design criterion. A person who is having higher-order needs satisfied wants to know how he or she is doing. Superficially, the troubleshooter gets almost perfect objective feedback, because the failed machine either is restored or it is not, and the technician usually knows which state prevails (but not always, as we indicated earlier). This immediate task feedback, of course, is not necessarily identical with the performer's own perception of his effectiveness, since he may be evaluating himself against some other standard.

On these three criteria, then, the technician should be rather highly motivated in his work, and from superficial indications he may indeed be quite satisfied, compared to other military people. Comparative personnel statistics are difficult to find, but one large computer company reported that turnover and absence rates for commercial maintenance men are very low, lower than for design engineers or programmers. This is especially so for medium-size cities in America. A few on-site interviews with roving commercial computer technicians did reveal a couple of common sources of dissatisfaction. One of these was the technician's non-professional status, which was related to what the person does. Though the work is technical and demanding, experience in restoring computers results in a person's learning more and more about one particular company's computers, manuals, and fault-isolation procedures. But it does not result in general engineering knowledge. Thus, many technicians perceive that they are regarded as "less than engineers," and that they can never attain engineer status, regardless of how expert they become at their work. The military services may be missing an opportunity to satisfy these growth needs of their technicians. A similar growth-need situation was observed in the U.S. aerospace industry. Engineers in that industry perceived that their real worth depended in their state-of-the-art design capabilities. As a result, when design work was to be done, they tended to design all-new items, and to reject existing and off-the-shelf hardware. They did this to improve themselves and to keep up-to-date, but it was very costly to the company. A solution was for the firm to consider both the engineer's perceived need to sharpen intellectual skills, and the demands of the routine design work which had to be done. Management guaranteed that an individual would have career-advancing assignments often, though at any one time he might be doing a routine job (Davis & Taylor, 1979). A similar job design strategy could be used with military maintenance people.

A more subtle negative factor which was frequently noted in the industrial setting was the psychological distance between the maintenance technicians, and other people in the computer centers.

The roving maintenance person may have few close relationships with other workers, as he is always moving from one place to another, and the other technicians back at maintenance headquarters are also usually on the move. Some respondents even confided that the work leads to a general sense of isolation and non-sociability.

As a final job-design variable, we mention the "flow" experience, which can be a profound dynamic state (Csikszentmihalyi, 1975):

> "....the holistic sensation that people feel when they act with total involvement....(the person) experiences it as a unified flowing from one moment to the next, in which he is in control of his actions, and in which there is little distinction between self and environment, between stimulus and response, or between past, present, and future....People seek flow primarily for itself, not for the incidental extrinsic rewards that may occur from it."

Could a technician's search task be so arranged that this autotelic flow state could occur with some regularity? If so, the motivational advantages should be enormous. From all accounts, flow activities are avidly sought by the people who have experienced them. A beginning could be made by analyzing the flow potential in certain maintenance activities.

## SECTION V. REPRISE AND RECOMMENDATIONS

The military troubleshooter is a fairly good searcher and reasoner. What he needs most is a clear model of the functional relations among symptoms he can observe and malfunctions in the prime equipment, perhaps accompanied by a sequencing model for ordering test actions. Often it is impracticable for him to learn or remember enough theory to generate this model for himself, and so the model will have to be furnished to him. The best procedure for doing this so far is to have the prime equipment analyzed in such a way that all, or nearly all, malfunctioning states of the equipment can be correlated with observable symptoms. The states and symptoms are then stored in some way that can be systematically searched via a predetermined sequence. The main job of the technician then becomes the highly skilled task of searching via complex instructions and diagnostic aids.

"New look" formats for aiding and training these skills have been tried out in the laboratory and in the field, and they are clearly more effective than conventional training plus OJT. The critical requirement is the accuracy and usefulness of the information presented, rather than the particular display medium. Present computer technology can store and distribute, in either hand-held or larger portable units, all the information that is ordinarily included in book-size manuals, along with test sequencing and evaluating data. This technology can, then, alleviate maintenance problems on most complex systems, if it is designed and applied with the behavioral requirements in mind.

The military should not be satisfied with procedurally aided troubleshooting, regardless of how effective a good aiding system may be. Many maintenance specialists will have to possess real insight into the complicated devices of modern warfare, in order to attack the unforeseeable problems. The provision of these more advanced people will be a continuing challenge to the research and training communities, but there is reason for optimism. We know much more about the interaction of men and machines than we did in the vacuum-tube era.

Since effective technology (psychological, aiding and maintainability) is indeed available, and we still have serious problems, then there must be administrative or other reasons why the knowledge has not been more fully utilized (Bond, 1970). We believe that it is not cost that prevents application. Some "new look" aiding and training materials do require significant preparation and debugging effort, but these are one-time expenses, and they are insignificant compared to present wasted manpower and downtime losses. The administrative key is this: To develop and to implement effective aiding and training systems, many separate efforts have to be coordinated and directed through a central "corrective maintenance control" concept. This has been done in the commercial computer world and in other domains, but it cannot be done easily in the military, because no single command or agency is really responsible for it and can insist that a valid maintenance concept be realized. The procuring, designing, and aiding and training have to be planned together and accomplished together, and this infrequently happens in the present military system.

In a report addressed to the research community, most of our "recommendations" come in the form of projects that might be undertaken. A few of these have to do with basic research into human appreciation of complex devices. Others attempt to further the production of arrangements which will facilitate performance, and thus bypass the psychological problems. No doubt some of these ideas are already being pursued. The projects are not listed in order of importance. For <u>immediate practical importance</u> to military effectiveness, numbers 4, 5, 10, 17, and 19 would be near the top of the order. As far as <u>psychological significance</u> numbers 7, 12, 13, 14, and 16 are most interesting.

Research Recommendations: Possible Projects in Troubleshooting

1. Investigate the use of pseudo-verbal software routines (e.g., Findler's Puzzle-Solver, Wang's Theorem-Prover) for fault-location or aiding, to determine if the pseudo-English format is suitable for practical search tasks.
2. Explicate the basic relations between such methodologically similar concepts such as Cohn-Ott optimal testing, Fano coding, Huffman coding, switching theory diagnosis of logical networks, and so forth. (Some of the identities among these methods have already been proven, but nobody has put them all together for the psychological research community.)
3. Explore the extent to which small handheld aids, such as troubleshooting sequence cards or wheels, are now applied by military technicians.
4. Find out how to best utilize hand-held computer technology for troubleshooting. This would include consideration of the sizes of proceduralized logic trees that could be stored, the best ways to utilize display and recording techniques, acceptability of the device to field people, and development costs.

5. Compare the effectiveness of "new look" proceduralized maintenance manuals, as presented via a LOGMOD or AIDE computerized configuration, with the same information given in a series of booklets.
6. Study the feasibility of a strong "Maintenance Applications Group" in the laboratories for each service, and see what rewards could be given for high-quality applications research, within civil-service constraints.
7. Determine suitable methods for measuring cognitive style in technical work, and study the possibilities for exploiting individual differences on this variable, in the maintenance domain.
8. Review a suitable sample of Automatic Test Equipment (ATE) routines, and delineate the usefulness, and the limitations, of these routines to ordinary military technicians.
9. According to Orlansky and String (1979), there are about 30 studies of CAI and CMI effectiveness. Determine how closely the CAI and CMI technology there reviewed is "up to the best present state-of-the-art".
10. Discover the reasons for unfavorable ratings of CAI-CMI programs by the instructors.
11. Study the process by which good ideas are "stopped" in the maintenance world. Suppose somebody proves that a sequential or logic-tree troubleshooting scheme is better on a military radar or computer (in fact, Potter's group did this). Determine why the technology was not exploited more fully.
12. Determine the extent to which electronics or electromechanical

theory is remembered, after schooling. A project could test at several intervals, say, 3, 6, and 24 months after schooling is finished.

13. Collect all the means for helping students to visualize circuit and electro-mechanical relations, and evaluate experimentally the most promising of these methods. There are many ingenious proposals from mathematics and physics teachers, and from summer science workshops. Some of these are worth experimental investigation, and could be correlated to the literature in cognitive psychology.
14. Investigate the utility of "mnemonics for electronics," in memorizing difficult material such as circuit algebraic laws.
15. Find out if the time it takes a technician to do a basic digital-logic operation (via Trabasso or Posner timing techniques) is a reliable information-processing indicant, and if so, whether it is correlated with troubleshooting performance.
16. Explore the "flow" and "play" aspects of troubleshooting performance, according to the Csikszentmihalyi paradigm, and see if aids can be constructed that could enhance the likelihood of these flow effects in troubleshooting.
17. Do an extensive comparison of military troubleshooting with that performed by commercial computer service companies, with special attention to "what the military can learn" from the commercial experience.
18. See if special training in branch matrix reasoning, can transfer positively to logical (troubleshooting) search in realistic S-M

tables.

19. Determine the effectiveness curves of intensive training (more than 100 troubleshooting problems, perhaps) in using a complex diagnostic aid on subsequent troubleshooting performance.
20. Originate "story line" interpretations of complex physical events, say in AC circuit theory, and evaluate these for their enhancement of learning.

### Administrative Recommendations

1. Conduct an unbiased survey of present prime-equipment capabilities. To prevent the usual "softening" or blurring of lack of capability, this survey probably should be done by an outside engineering group. Sampling techniques would permit strong inferences about true capabilities.
2. Discover and remove non-maintainable equipment items. This action would be an obvious sequel to the capability survey. It should relieve operating commands from the burden of carrying non-usable major equipments.
3. Concentrate first-enlistment technician activities on the expert use of fully-proceduralized troubleshooting aids, and drastically reduce or eliminate the present theory-oriented courses. Foley (1978) shows how this personnel decision alone would save millions of dollars in "effective technician" work time. Hard data supports the idea; in addition to the small evaluation studies, the services should undertake massive trials of proceduralized aids, and this probably should be done outside the present training community.

4. Develop a "flying squad" troubleshooting concept, made up of truly expert technicians. Unlike the first-enlistment people, these second-term people would receive extensive theoretical training. The squad would handle the tough field problems, that is, the remaining troubles that cannot be readily located by proceduralized aids. We do not refer here to simple seniority, such as a cadre of first class ETs with conventional training; we have many of those now who cannot solve maintenance problems. As in the fully proceduralized concept for first-termers, the squad concept would be oriented to effective performance, in much the same way as commercial computer trouble squads are managed. The prospects of qualifying for this kind of work should be motivating to the best career technicians, and could lead to professional-level training in the second and later enlistments.
5. Plan for high-level military administrative "fixers" who support a maintenance program, and continuously guide it through the financial and administrative difficulties faced by every change. A fixer might be an admiral or general. He would develop a maintenance constituency for supporting the use of special troubleshooting aids, for example. He would also intervene with agency officials on special problems that arise, such as finding money to debug a training concept or hand-held computer aid, or pursuing implementation plans in difficult environments. He would be able to move across departments and agencies, and would be able to influence and control activities so that the present technology is utilized.

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Navy

1 Dr. Ed Aiken
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Robert Blanchard
Navy Personnel R&D Center
Managment Support Department
San Diego, CA 92151

1 Dr. Jack R. Borsting
Provost & Academic Dean
U.S. Naval Postgraduate School
Monterey, CA 93940

1 Dr. Robert Breaux
Code N-711
NAVTRAEQUIPCEN
Orlando, FL 32813

1 Deputy Assistant Secretary of the Navy
(Manpower)
Office of the Assistant Secretary of
the Navy (Manpower, Reserve Affairs,
and Logistics)
Washington, DC 20350

1 Dr. Richard Elster
Department of Administrative Sciences
Naval Postgraduate School
Monterey, CA 93940

1 DR. PAT FEDERICO
NAVY PERSONNEL R&D CENTER
SAN DIEGO, CA 92152

1 Dr. John Ford
Navy Personnel R&D Center
San Diego, CA 92152

1 LT Steven D. Harris, MSC, USN
Code 6021
Naval Air Development Center
Warminster, Pennsylvania 18974

1 LCDR Wade Helm
Psychology Department
University of South Dakota
Vermillion, SD 57069

Navy

1 Dr. Lloyd Hitchcock
Human Factors Engineering
Division (6022)
Naval Air Development Center
Warminster, PA 18974

1 CDR Charles W. Hutchins
Naval Air Systems Command Hq
AIR-340F
Navy Department
Washington, DC 20361

1 Dr. Norman J. Kerr
Chief of Naval Technical Training
Naval Air Station Memphis (75)
Millington, TN 38054

1 Dr. William L. Maloy
Principal Civilian Advisor for
Education and Training
Naval Training Command, Code 00A
Pensacola, FL 32508

1 Dr. Kneale Marshall
Scientific Advisor to DCNO(MPT)
OP01T
Washington DC 20370

1 CAPT Richard L. Martin, USN
Prospective Commanding Officer
USS Carl Vinson (CVN-70)
Newport News Shipbuilding and Drydock Co
Newport News, VA 23607

1 Dr. George Moeller
Head, Human Factors Dept.
Naval Submarine Medical Research Lab
Groton, CN 06340

1 Dr William Montague
Navy Personnel R&D Center
San Diego, CA 92152

1 LCDR W. Moroney
Code 55MP
Naval Postgraduate School
Monterey, CA 93940

Navy

1 Commanding Officer
U.S. Naval Amphibious School
Coronado, CA 92155

1 Library
Naval Health Research Center
P. O. Box 85122
San Diego, CA 92138

1 Naval Medical R&D Command
Code 44
National Naval Medical Center
Bethesda, MD 20014

1 Ted M. I. Yellen
Technical Information Office, Code 201
NAVY PERSONNEL R&D CENTER
SAN DIEGO, CA 92152

1 Library, Code P201L
Navy Personnel R&D Center
San Diego, CA 92152

1 Technical Director
Navy Personnel R&D Center
San Diego, CA 92152

1 Director, Navy Personnel R&D Center
Washington Liason Office
Building 200, 2N
Washington Navy Yard, DC 20374

6 Commanding Officer
Naval Research Laboratory
Code 2627
Washington, DC 20390

1 Psychologist
ONR Branch Office
Bldg 114, Section D
666 Summer Street
Boston, MA 02210

1 Psychologist
ONR Branch Office
536 S. Clark Street
Chicago, IL 60605

Navy

1 Office of Naval Research
Code 437
800 N. Quincy SStreet
Arlington, VA 22217

1 Director
Engineering Psychology Programs
Code 455
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

5 Personnel & Training Research Programs
(Code 458)
Office of Naval Research
Arlington, VA 22217

1 Psychologist
ONR Branch Office
1030 East Green Street
Pasadena, CA 91101

1 Special Asst. for Education and
Training (OP-01E)
Rm. 2705 Arlington Annex
Washington, DC 20370

1 Office of the Chief of Naval Operations
Research, Development, and Studies Branc
(OP-102)
Washington, DC 20350

1 Long-Range Manpower, Personnel, and
Training Planning Branch (OP-110)
Room G828
Arlington Annex
Washington, DC 20350

1 Head, Manpower Training and Reserves
Section (Op-964D)
Room 4A478, The Pentagon
Washington, DC 20350

1 Captain Donald F. Parker, USN
Commanding Officer
Navy Personnel R&D Center
San Diego, CA 92152

Navy

1 LT Frank C. Petho, MSC, USN (Ph.D)
Code L51
Naval Aerospace Medical Research Laborat
Pensacola, FL 32508

1 DR. RICHARD A. POLLAK
ACADEMIC COMPUTING CENTER
U.S. NAVAL ACADEMY
ANNAPOLIS, MD 21402

1 Dr. Gary Poock
Operations Research Department
Code 55PK
Naval Postgraduate School
Monterey, CA 93940

1 The Principal Deputy Assistant
Secretary of the Navy (MRA&L)
4E780, The Pentagon
Washington, DC 20350

1 Roger W. Remington, Ph.D
Code L52
NAMRL
Pensacola, FL 32508

1 Mr. Arnold Rubenstein
Naval Personnel Support Technology
Naval Material Command (08T244)
Room 1044, Crystal Plaza #5
2221 Jefferson Davis Highway
Arlington, VA 20360

1 Dr. Worth Scanland
Chief of Naval Education and Training
Code N-5
NAS, Pensacola, FL 32508

1 Dr. Sam Schiflett, SY 721
Systems Engineering Test Directorate
U.S. Naval Air Test Center
Patuxent River, MD 20670

1 Dr. Robert G. Smith
Office of Chief of Naval Operations
OP-987H
Washington, DC 20350

Navy

1 Dr. Alfred F. Smode
Training Analysis & Evaluation Group
(TAEG)
Dept. of the Navy
Orlando, FL 32813

1 Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152

1 DR. H.M. WEST III (OP-01)
Head, Program Development Branch (OP-12C)
ARLINGTON ANNEX
WASHINGTON, DC 20350

1 Dr. Robert Wisher
Code 309
Navy Personnel R&D Center
San Diego, CA 92152

Army

1 Technical Director
U. S. Army Research Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 HQ USAREUE & 7th Army
ODCSOPS
USAAREUE Director of GED
APO New York 09403

1 Col. Gary W. Bloedorn
US Army TRADOC Systems Analysis Activity
Attn: ATAA-TH
WSMR, NM 88002

1 DR. RALPH DUSEK
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 DR. FRANK J. HARRIS
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 Col Frank Hart
Army Research Institute for the
Behavioral & Social Sciences
5001 Eisenhower Blvd.
Alexandria, VA 22333

1 Dr. Ed Johnson
Army Research Institute
5001 Eisenhower Blvd.
Alexandria, VA 22333

1 Dr. Michael Kaplan
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 Dr. Milton S. Katz
Training Technical Area
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Army

1 Director
U.S. Army Human Engineering Labs
Attn: DRXHE-DB
Aberdeen Proving Ground, MD 21005

1 COL F. A. Nerone, Director
Training Developments Institute
Bldg. 10
Ft. Monroe, VA 23651

1 Dr. Harold F. O'Neil, Jr.
Attn: PERI-OK
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Robert Sasmor
U. S. Army Research Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Joseph Ward
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Air Force

1 U.S. Air Force Office of Scientific Research
Life Sciences Directorate, NL
Bolling Air Force Base
Washington, DC 20332

1 Dr. Earl A. Alluisi
HQ, AFHRL (AFSC)
Brooks AFB, TX 78235

1 Dr. Philip De Leo
AFHRL/TT
Lowry AFB, CO 80230

1 Dr. Genevieve Haddad
Program Manager
Life Sciences Directorate
AFOSR
Bolling AFB, DC 20332

1 Dr. Sylvia R. Mayer (TO1T)
HQ Electronic Systems Div.
Hanscom AFB
Bedford, MA 01731

1 Dr. Ross L. Morgan (AFHRL/LR)
Wright -Patterson AFB
Ohio 45433

1 Research and Measurment Division
Research Branch, AFMPC/MPCYPR
Randolph AFB, TX 78148

1 Dr. Marty Rockway (AFHRL/TT)
Lowry AFB
Colorado 80230

1 Dr. Frank Schufletowski
U.S. Air Force
ATC/XPTD
Randolph AFB, TX 78148

2 3700 TCHTW/TTGH Stop 32
Sheppard AFB, TX 76311

1 Jack A. Thorpe, Maj., USAF
Naval War College
Providence, RI 02846

Air Force

1 Brian K. Waters, Lt Col, USAF
Air War College (EDV)
Maxwell AFB, AL 36112

Marines

1 H. William Greenup
Education Advisor (E031)
Education Center, MCDEC
Quantico, VA 22134

1 Headquarters, U. S. Marine Corps
Code MPI-20
Washington, DC 20380

1 Special Assistant for Marine
Corps Matters
Code 100M
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

1 DR. A.L. SLAFKOSKY
SCIENTIFIC ADVISOR (CODE RD-1)
HQ, U.S. MARINE CORPS
WASHINGTON, DC 20380

Other DoD

12 Defense Documentation Center
Cameron Station, Bldg. 5
Alexandria, VA 22314
Attn: TC

1 Dr. Craig I. Fields
Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

1 Dr. Dexter Fletcher
ADVANCED RESEARCH PROJECTS AGENCY
1400 WILSON BLVD.
ARLINGTON, VA 22209

1 Director, Research and Data
OASD(MRA&L)
3B919, The Pentagon
Washington, DC 20301

1 Military Assistant for Training and
Personnel Technology
Office of the Under Secretary of Defense
for Research & Engineering
Room 3D129, The Pentagon
Washington, DC 20301

1 HEAD, SECTION ON MEDICAL EDUCATION
UNIFORMED SERVICES UNIV. OF THE
HEALTH SCIENCES
6917 ARLINGTON ROAD
BETHESDA, MD 20014

Civil Govt

1 Dr. Susan Chipman
Learning and Development
National Institute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Joseph I. Lipson
SEDR W-638
National Science Foundation
Washington, DC 20550

1 Dr. John Mays
National Institute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Arthur Melmed
National Intitute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Andrew R. Molnar
Science Education Dev.
and Research
National Science Foundation
Washington, DC 20550

1 Dr. H. Wallace Sinaiko
Program Director
Manpower Research and Advisory Services
Smithsonian Institution
801 North Pitt Street
Alexandria, VA 22314

1 Dr. Frank Withrow
U. S. Office of Education
400 Maryland Ave. SW
Washington, DC 20202

1 Dr. Joseph L. Young, Director
Memory & Cognitive Processes
National Science Foundation
Washington, DC 20550

Non Govt

1 Dr. John R. Anderson
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Anderson, Thomas H., Ph.D.
Center for the Study of Reading
174 Children's Research Center
51 Gerty Drive
Champiagn, IL 61820

1 Dr. John Annett
Department of Psychology
University of Warwick
Coventry CV4 7AL
ENGLAND

1 DR. MICHAEL ATWOOD
SCIENCE APPLICATIONS INSTITUTE
40 DENVER TECH. CENTER WEST
7935 E. PRENTICE AVENUE
ENGLEWOOD, CO 80110

1 1 psychological research unit
Dept. of Defense (Army Office)
Campbell Park Offices
Canberra, ACT 2600, Australia

1 Dr. Alan Baddeley
Medical Research Council
Applied Psychology Unit
15 Chaucer Road
Cambridge CB2 2EF
ENGLAND

1 Dr. Patricia Baggett
Department of Psychology
University of Denver
University Park
Denver, CO 80208

1 Mr Avron Barr
Department of Computer Science
Stanford University
Stanford, CA 94305

Non Govt

1 Dr. John Bergan
School of Education
University of Arizona
Tuscon AZ 85721

1 Dr. Lyle Bourne
Department of Psychology
University of Colorado
Boulder, CO 80309

1 Dr. Kenneth Bowles
Institute for Information Sciences
University of California at San Diego
La Jolla, CA 92037

1 DR. JOHN F. BROCK
Honeywell Systems & Research Center
(MN 17-2318)
2600 Ridgeway Parkway
Minneapolis, MN 55413

1 Dr. John S. Brown
XEROX Palo Alto Research Center
3333 Coyote Road
Palo Alto, CA 94304

1 Dr. Anthony Cancelli
School of Education
University of Arizona
Tuscon, AZ 85721

1 Dr. William Chase
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 152[illegible]3

1 Dr. Micheline Chi
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

1 Dr. William Clancey
Department of Computer Science
Stanford University
Stanford, CA 94305

Non Govt

1 Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, Ma 02138

1 Dr. Meredith P. Crawford
American Psychological Association
1200 17th Street, N.W.
Washington, DC 20036

1 Dr. Kenneth B. Cross
Anacapa Sciences, Inc.
P.O. Drawer Q
Santa Barbara, CA 93102

1 Director
Behavioural Sciences Division
Defence & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsview, Ontario M3M 3B9
CANADA

1 ERIC Facility-Acquisitions
4833 Rugby Avenue
Bethesda, MD 20014

1 Dr. Ed Feigenbaum
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Mr. Wallace Feurzeig
Bolt Beranek & Newman, Inc.
50 Moulton St.
Cambridge, MA 02138

1 Dr. Victor Fields
Dept. of Psychology
Montgomery College
Rockville, MD 20850

1 Dr. Edwin A. Fleishman
Advanced Research Resources Organ.
Suite 900
4330 East West Highway
Washington, DC 20014

Non Govt

1 DR. JOHN D. FOLLEY JR.
APPLIED SCIENCES ASSOCIATES INC
VALENCIA, PA 16059

1 Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

1 Dr. Alinda Friedman
Department of Psychology
University of Alberta
Edmonton, Alberta
CANADA T6G 2E9

1 DR. ROBERT GLASER
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

1 Dr. Marvin D. Glock
217 Stone Hall
Cornell University
Ithaca, NY 14853

1 Dr. Frank E. Gomer
McDonnell Douglas Astronautics Co.
P. O. Box 516
St. Louis, MO 63166

1 Dr. Daniel Gopher
Industrial & Management Engineering
Technion-Israel Institute of Technology
Haifa
ISRAEL

1 DR. JAMES G. GREENO
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

1 Dr. Harold Hawkins
Department of Psychology
University of Oregon
Eugene OR 97403

Non Govt

1 Dr. Barbara Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. Frederick Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. James R. Hoffman
Department of Psychology
University of Delaware
Newark, DE 19711

1 Dr. Earl Hunt
Dept. of Psychology
University of Washington
Seattle, WA 98105

1 DR. KAY INABA
21116 VANOWEN ST
CANOGA PARK, CA 91303

3 Journal Supplement Abstract Service
American Psychological Association
1200 17th Street N.W.
Washington, DC 20036

1 Dr. Wilson A. Judd
McDonnell-Douglas
Astronautics Co.-St. Louis
P.O. Box 30204
Lowry AFB, CO 80230

1 Dr. Steven W. Keele
Dept. of Psychology
University of Oregon
Eugene, OR 97403

1 Dr. Walter Kintsch
Department of Psychology
University of Colorado
Boulder, CO 80302

1 Dr. David Kieras
Department of Psychology
University of Arizona
Tuscon, AZ 85721

Non Govt

1 Dr. Mazie Knerr
Litton-Mellonics
Box 1286
Springfield, VA 22151

1 Dr. Stephen Kosslyn
Harvard University
Department of Psychology
33 Kirkland Street
Cambridge, MA 02138

1 Mr. Marlin Kroger
1117 Via Goleta
Palos Verdes Estates, CA 90274

1 Dr. Jill Larkin
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. Alan Lesgold
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

1 Dr. Michael Levine
210 Education Building
University of Illinois
Champaign, IL 61820

1 Dr. Robert A. Levit
Director, Behavioral Sciences
The BDM Corporation
7915 Jones Branch Drive
McClean, VA 22101

1 Dr. Charles Lewis
Faculteit Sociale Wetenschappen
Rijksuniversiteit Groningen
Oude Boteringestraat
Groningen
NETHERLANDS

1 Dr. Mark Miller
Computer Science Laboratory
Texas Instruments, Inc.
Mail Station 371, P.O. Box 225936
Dallas, TX 75265

Non Govt

1 Dr. Allen Munro
Behavioral Technology Laboratories
1845 Elena Ave., Fourth Floor
Redondo Beach, CA 90277

1 Dr. Donald A Norman
Dept. of Psychology C-009
Univ. of California, San Diego
La Jolla, CA 92093

1 Dr. Melvin R. Novick
356 Lindquist Center for Measurment
University of Iowa
Iowa City, IA 52242

1 Dr. Jesse Orlansky
Institute for Defense Analyses
400 Army Navy Drive
Arlington, VA 22202

1 Dr. Seymour A. Papert
Massachusetts Institute of Technology
Artificial Intelligence Lab
545 Technology Square
Cambridge, MA 02139

1 DR. PETER POLSON
DEPT. OF PSYCHOLOGY
UNIVERSITY OF COLORADO
BOULDER, CO 80309

1 Dr. Mark D. Reckase
Educational Psychology Dept.
University of Missouri-Columbia
4 Hill Hall
Columbia, MO 65211

1 Dr. Fred Reif
SESAME
c/o Physics Department
University of California
Berkely, CA 94720

1 Dr. Andrew M. Rose
American Institutes for Research
1055 Thomas Jefferson St. NW
Washington, DC 20007

Non Govt

1 Dr. Ernst Z. Rothkopf
Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

1 PROF. FUMIKO SAMEJIMA
DEPT. OF PSYCHOLOGY
UNIVERSITY OF TENNESSEE
KNOXVILLE, TN 37916

1 DR. WALTER SCHNEIDER
DEPT. OF PSYCHOLOGY
UNIVERSITY OF ILLINOIS
CHAMPAIGN, IL 61820

1 Dr. Alan Schoenfeld
Department of Mathematics
Hamilton College
Clinton, NY 13323

1 DR. ROBERT J. SEIDEL
INSTRUCTIONAL TECHNOLOGY GROUP
HUMRRO
300 N. WASHINGTON ST.
ALEXANDRIA, VA 22314

1 Committee on Cognitive Research
% Dr. Lonnie R. Sherrod
Social Science Research Council
605 Third Avenue
New York, NY 10016

1 Dr. Robert Smith
Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

1 Dr. Richard Snow
School of Education
Stanford University
Stanford, CA. 94305

1 Dr. Kathryn T. Spoehr
Department of Psychology
Brown University
Providence, RI 02912

Non Govt.

1 Dr. Robert Sternberg
Dept. of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

1 DR. ALBERT STEVENS
BOLT BERANEK & NEWMAN, INC.
50 MOULTON STREET
CAMBRIDGE, MA 02138

1 Dr. David Stone
ED 236
SUNY, Albany
Albany, NY 12222

1 DR. PATRICK SUPPES
INSTITUTE FOR MATHEMATICAL STUDIES IN
THE SOCIAL SCIENCES
STANFORD UNIVERSITY
STANFORD, CA 94305

1 Dr. Kikumi Tatsuoka
Computer Based Education Research
Laboratory
252 Engineering Research Laboratory
University of Illinois
Urbana, IL 61801

1 Dr. John Thomas
IBM Thomas J. Watson Research Center
P.O. Box [illegible]
Yorktown Heights, NY 10598

1 DR. PERRY THORNDYKE
THE RAND CORPORATION
1700 MAIN STREET
SANTA MONICA, CA 90406

1 Dr. J. Uhlaner
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

1 Dr. Phyllis Weaver
Graduate School of Education
Harvard University
200 Larsen Hall, Appian Way
Cambridge, MA 02138

Non Govt

1 Dr. David J. Weiss
N660 Elliott Hall
University of Minnesota
75 E. River Road
Minneapolis, MN 55455

1 DR. GERSHON WELTMAN
PERCEPTRONICS INC.
6271 VARIEL AVE.
WOODLAND HILLS, CA 91367

1 Dr. Keith T. Wescourt
Information Sciences Dept.
The Rand Corporation
1700 Main St.
Santa Monica, CA 90406

1 Dr. J. Arthur Woodward
Department of Psychology
University of California

1 Commanding Officer
ONR Branch Office
ATTN: Mr. R. Lawson
1030 East Green Street
Pasadena, CA 91106

1 Mr. Phillip Andrews
Naval Sea Systems Command
NAVSEA 0341
Washington, D.C. 20362

1 Mr. Warren Lewis
Human Engineering Branch
Code 8231
Naval Ocean Systems Center
San Diego, CA 92152

1 CDR P.M. Curran
Code 604
Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974

1 Mr. Ronald A. Erickson
Human Facotrs Branch
Code 3175
Naval Weapons Center
China Lake, CA 93555

1 Human Factors Department
Code N215
Naval Training Equipment Center
Orlando, FL 32813

1 Commanding Officer
MCTSSA
Marine Corps Base
Camp Pendleton, CA 92055

1 Dr. Jerry C. Lamb
Display Branch
Code TD112
Naval Underqater Systems Center
New London, CT 06320

1 LT. COL. Joseph A. Birt
Human Engineering Division
USAF AMRL
Wright Patterson AFB, Ohio 45433