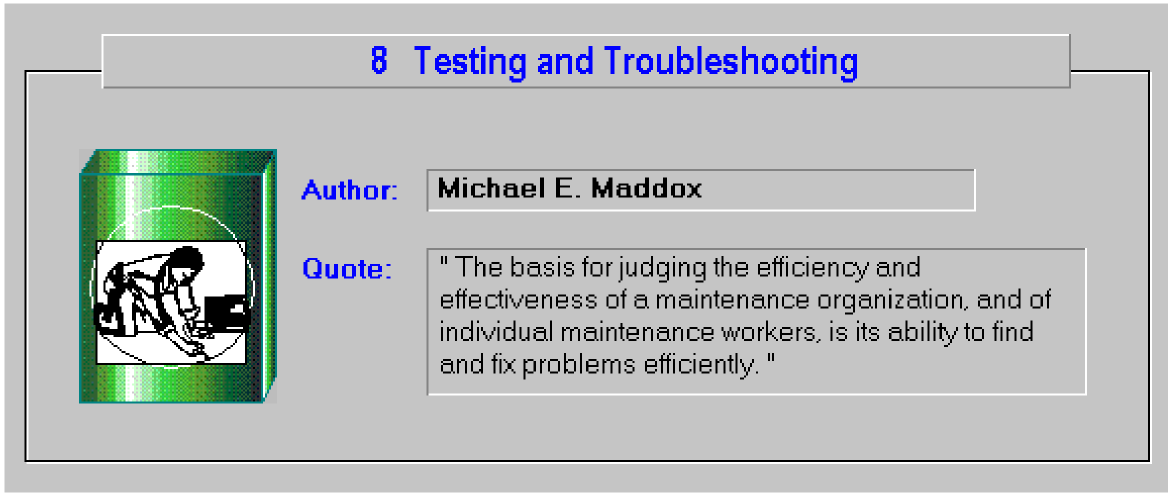
Chapter 8
TESTING AND TROUBLESHOOTING



INTRODUCTION

Aviation maintenance consists of many separate tasks. For example, AMTs are expected to perform routine preventative maintenance (PM) activities, which normally consist of inspecting, adjusting, lubricating, replacing, etc. They may or may not find anything broken during PM. In fact, the intent of PM is to keep things from breaking. Technicians are occasionally expected to upgrade or overhaul existing systems or components -- even though these systems appear to be functioning properly. Such tasks are commonly done in response to regulatory requirements or to take advantage of technological advances. There are also a number of routine administrative tasks that include AMTs.

Every aviation maintenance organization is responsible for performing the full range of maintenance tasks. However, these tasks do not count equally in determining whether or not an organization is doing a good job. The basis for judging the efficiency and effectiveness of a maintenance organization, and of individual maintenance workers, is the ability to find and fix problems efficiently. Especially in today's competitive air carrier business environment, maintenance groups are judged on their ability to keep aircraft safely in the air -- not on the ramp or in the hangar.

Maintenance workers must possess both the knowledge and skills to find and fix problems efficiently. These requirements are essentially no different than those for medical doctors, automobile mechanics, appliance repair people, or any other profession or craft that involves both diagnostic and manual skills. As one might expect, the most valued maintenance abilities are also the most difficult to acquire and practice. Many years of research, on-the-job observations, and common experience have demonstrated that it is much easier to teach and learn manual skills than diagnostic (or troubleshooting) skills.

In this chapter, we discuss some fundamental human factors concepts related to testing and troubleshooting. Many research findings are no doubt familiar to AMTs. Other findings may appear counter to experience. Testing and troubleshooting are complex topics, and our discussion merely scratches the surface. Clearly, sound human factors principles can be applied to aviation testing and troubleshooting tasks.

BACKGROUND


CABIN BCP

Figure 8-1. Typical aviation maintenance troubleshooting scene (Courtesy of United Airlines)

We could treat testing and troubleshooting as two topics. Troubleshooting almost always involves some type of testing. However, *troubleshooting* implies that we suspect some "trouble" to exist. Testing can be done for reasons entirely unrelated to finding a suspected problem. For example, we might perform a test to make certain that an electrical component is within its calibration tolerances. For the purposes of this *Guide*, it is reasonable to discuss testing and troubleshooting as closely linked elements of aviation maintenance. An image of this process is that of aviation maintainers huddled over a piece of test equipment, trying to figure out what the problem is, if anything (Figure 8-1).

Research History

Issues related to troubleshooting have been actively researched since the 1950's. The impetus for much early work in this area was the burgeoning electronics industry developing after World War II. With increased availability of electronic products, it became apparent that added complexity caused a number of maintenance-related problems. As is common with new technology, the military became early users of electronic components and were the first to examine issues related to troubleshooting.[1,2,3]

Much research in this area has attempted to identify characteristics making individuals good troubleshooters.[4,5] As with other tasks involving complex skills, there appear to be large individual differences in the ability to troubleshoot efficiently. Some people just do a better job on complex maintenance tasks, such as manually rebuilding certain components. In most job domains, certain individuals stand out from their peers on specific tasks or on particular systems. (See "Individual Differences" in the CONCEPTS section.)

Since the late 1970's, much troubleshooting research has involved the aviation maintenance domain.[6,7,8] Most aviation-specific troubleshooting research has attempted to identify the most important diagnostic tasks AMTs perform. The purpose of such research was to develop tools that would help teach troubleshooting skills.[9] A number of recent studies have examined troubleshooting issues not directly related to training. Some of these are described below.

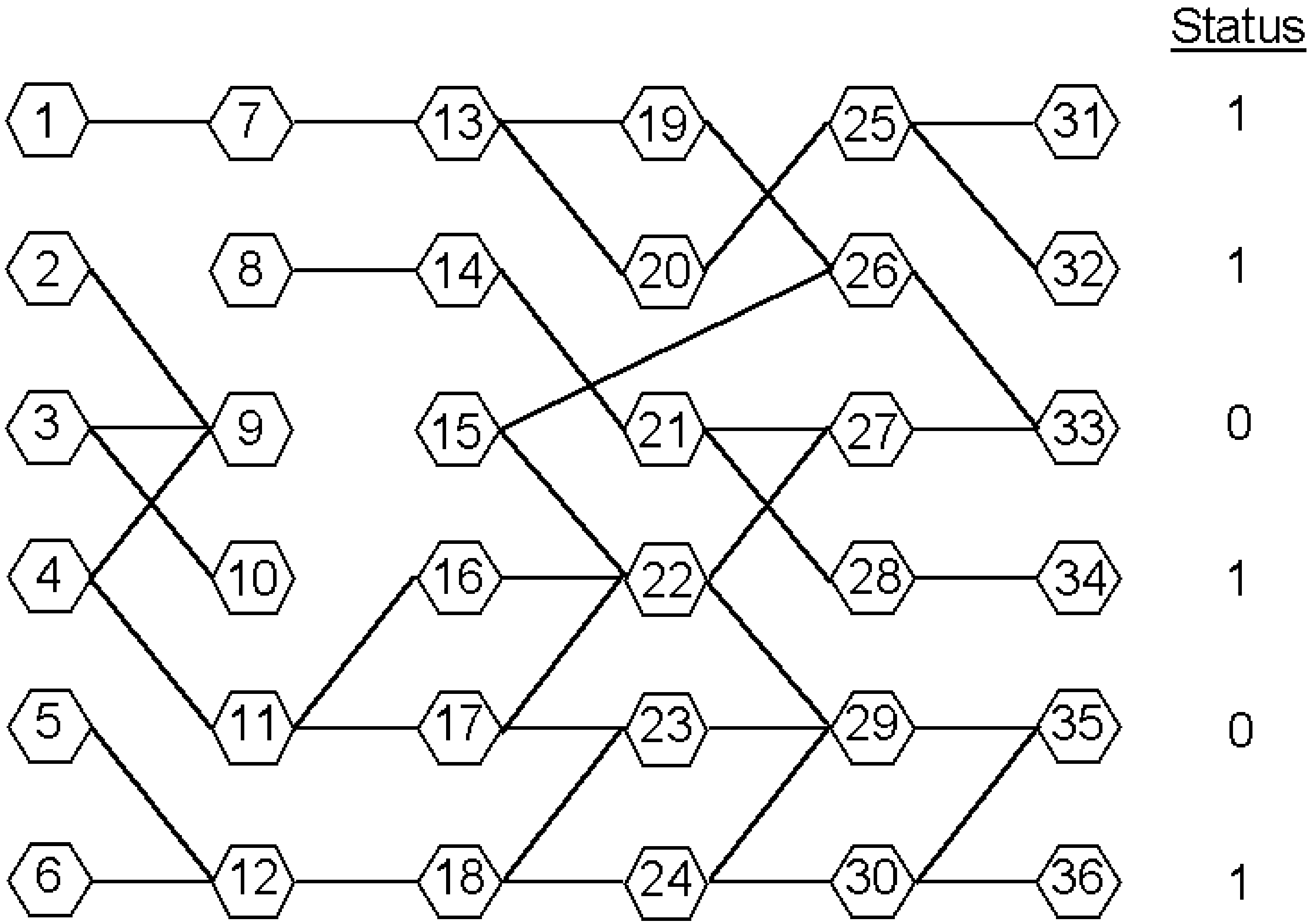


Figure 8-2. Example of a system used to study general troubleshooting strategies

General vs. Domain-Specific

Research on troubleshooting can be categorized as general or domain-specific. General troubleshooting research is concerned with knowledge, skills, and other characteristics of abstract systems.[10,11] For instance, a common general research task is to find the fault(s) in a system of interconnected boxes or nodes. The interconnected nodes don't represent any particular components; they are simple logical connections such as AND gates. This type of research aims to identify diagnostic strategies troubleshooters use. An example of a generalized (purely logical) system is shown in Figure 8-2.

Domain-specific research uses representations of real systems; it asks people to find faults that might really occur. Much of this research is training-related. A typical domain-specific study might attempt to train maintainers to troubleshoot an automobile engine using a computer representation of the subsystems and components of a real engine (Figure 8-3). Many domain-specific studies have been conducted, including systems such as diesel generators,[12] aircraft engines,[13] gas turbine electrical generators,[14] and, recently, the environmental control system of a commercial aircraft.[15]

Troubleshooting Skills

Research related to troubleshooting has greatly increased our understanding of factors affecting performance. An extensive analysis of previous research published in the mid-1980's[16] identified three general skills that appear to produce good troubleshooting performance:

- Ability to repair or replace system components
- Ability to make tests to eliminate components from further consideration
- Ability to employ a strategy to search for failed components.

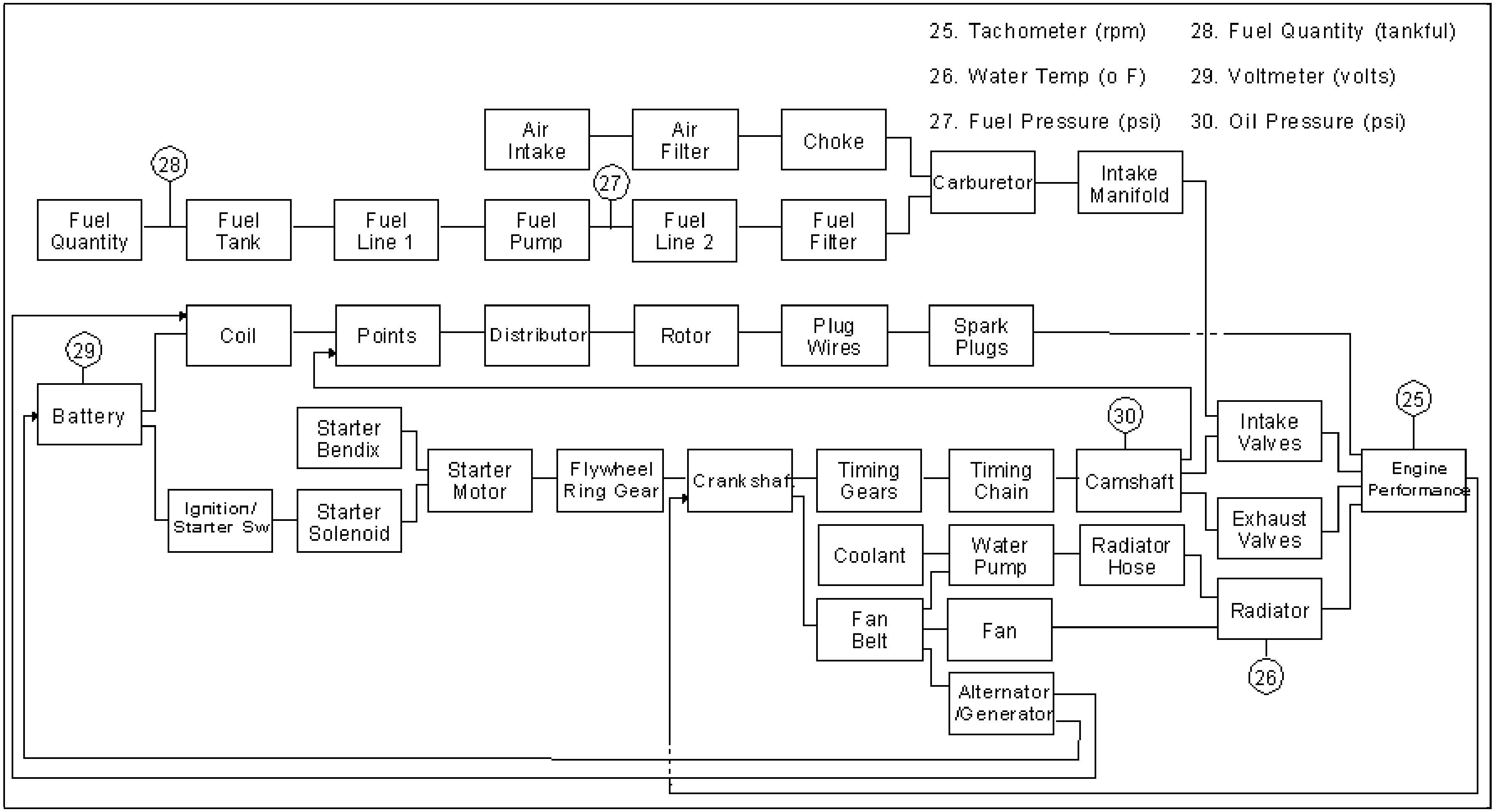


Figure 8-3. A logical troubleshooting diagram for an automobile engine

Most researchers focus on the ability to employ an efficient strategy as the most important and the most difficult to teach and learn.

Factors Affecting Performance

Researchers have identified many factors that affect troubleshooting performance. In this section, we briefly describe factors that seem to apply to the aviation maintenance environment.

Training

Of all factors affecting troubleshooting performance, training seems to have been the focus of the most research over the past 10-15 years. Studies have examined both the content and type of troubleshooting training. The following two findings have been confirmed repeatedly:

1. Teaching the theory of system operation does not enhance troubleshooting performance.[17] Training must address specific troubleshooting procedures.
2. Training must provide significant opportunities for students to ***practice*** troubleshooting on specific systems and components.[18]

Since the teaching and learning of troubleshooting skills is so difficult, much research has compared computer-based training regimens with traditional, i.e., classroom, instruction. Well-developed computer-based training including practice opportunities produces troubleshooting performance equal to or better than traditional training methods.[19] Computer-based training is generally more efficient than classroom instruction, so it remains an attractive alternative.

Complexity

Obviously, performance degrades as the complexity of the system being diagnosed increases.[20] While this is an expected finding, it is not good news for AMTs. Many of the systems they maintain are extremely complex. The types of complexity that have been studied include the following variables:

- number of individual components that can fail[6,10]
- number of failures actually present[21]
- presence of feedback among components[22]
- presence of multiple paths through components.[11,23]

Aircraft systems exhibit all these types of complexity. The use of Line-Replaceable Units (LRUs) and procedures is an attempt to reduce the complexity of such systems.

Environment

Most troubleshooting tasks are conducted in work settings that include noise, heat or cold (or both), less-than-optimal lighting, cramped physical spaces, work during nighttime hours, etc. Many tasks are also performed under time pressure. These environmental factors have all been found to affect troubleshooting performance, albeit sometimes unpredictably.

Time pressure degrades both novices' and experts' troubleshooting performance. This degrading effect is present even for troubleshooting tasks performed in laboratory settings with abstract "systems."[24]

Other environmental characteristics affect troubleshooting performance predictably. We know from other research that work in very hot or very cold environments causes people to lose their ability to concentrate and to perform logical operations such as inductive reasoning.[25] This degradation is directly related to the forming and testing of hypotheses, so it is no surprise that troubleshooting suffers in such environments.

Noise affects novice and expert troubleshooters differently. A study of the effects of noise on troubleshooting performance found that high noise levels degraded experts' performance, but *enhanced* novices'.[26] Possibly, the high noise levels caused novices to stay alert and pay more attention to problems, whereas the noise simply distracted experts. Evidence for the hypothesized "arousal" effect is that noise improved both novices' and experts' performance at night -- when one might expect that the ability to concentrate would be lower.

Individual Differences

People differ both physically and psychologically. Researchers have been fascinated by individual differences for many years.[27] In the troubleshooting domain, a number of individual differences have been studied. These include experience, general ability and aptitude, and cognitive style.

While cognitive style has been shown to affect troubleshooting performance, the link between troubleshooting performance and general ability and aptitude is rather tenuous. Levels of ability and aptitude are generally inferred from scores on qualification tests such as those administered to individuals joining the armed forces. These measures have a fairly strong relationship with the time required to complete instructional modules and to the ability to use certain job aids.[28] However, troubleshooting skills tend to be acquired over long periods. As individuals have an opportunity to work on actual systems, small performance differences related to initial abilities and aptitudes tend to disappear.

Cognitive style is a general term used to classify people into categories related to a particular psychological variable. For example, common "scales" used in cognitive style research include "reflective-impulsive," "field dependent-field independent," "passive-aggressive," etc. If it could be shown that people with particular cognitive styles make better troubleshooters, this could be applied profitably to the personnel selection process. Unfortunately or fortunately, depending on one's point of view, no strong link has been identified between cognitive style and overall troubleshooting performance, with certain exceptions. In at least one study, impulsive people made more troubleshooting errors than reflective people; the effect did not diminish with practice.[29]

Except for experience, links between specific individual characteristics and troubleshooting performance are few and weak.

Experience

Experience is an area of individual difference research where findings support the common-sense view that more experience leads to better troubleshooting performance. As with other skills acquired over time, experience enhances one's ability to learn from new troubleshooting experiences.[6] Much research in this area has been conducted in the aviation maintenance domain; this fact alone should make the research results directly applicable to the guidance we provide.

While experience contributes to troubleshooting performance, its advantages do not hold under all conditions. When certain job aids or specific troubleshooting procedures are employed, performance differences between experienced and novice troubleshooters tend to disappear (see Proceduralization). The research in this area doesn't address advantages of the qualitative effects of experience, such as judgment.[30]

Proceduralization

The structure imposed on troubleshooting activities varies widely among organizations. In some cases, maintenance personnel are allowed to develop their own diagnostic strategies. In others, diagnostic procedures are tightly controlled by procedures or step-by-step job aids. Even within the same maintenance organization, the flexibility of troubleshooting strategies may vary considerably. A number of research studies consistently have shown that proceduralization improves most measures of troubleshooting performance.[31]

Two aspects of proceduralization are most salient for aviation maintenance. First, when procedures are simple and apply to the specific system on which work is being performed, they lead to the most pronounced improvements. Second, proceduralization can reduce, can in fact eliminate, differences in troubleshooting performance between experts and novices. Elliot and Joyce[32] made a dramatic demonstration of the second point. In their study, high school students using troubleshooting guides performed as well as trained Air Force technicians using traditional technical manuals.

ISSUES AND PROBLEMS

Many issues and problems are associated with testing and troubleshooting. In this *Guide*, we examine three troubleshooting issues that seem to pervade maintenance domains, including aviation. We chose these issues because we can provide specific guidance for related tasks. Also, these issues cause many troubleshooting-related problems in maintenance organizations.

Training

Maintenance researchers and practitioners have long recognized that one of the most difficult aspects of troubleshooting is teaching and learning it. The questions researchers have attempted to answer, with variable success, include the following:

- What content should be taught?
- How should it be taught?
- What part should on-the-job experience play in training?
- Are simulators appropriate for troubleshooting training?
- Should troubleshooting training be equipment-specific or general?
- Do troubleshooting skills deteriorate with time?
- Is refresher training required?

Some of these issues were discussed in the BACKGROUND section. We provide some general guidance later in this chapter. As a practical matter, each training program must be addressed individually.

Incorrectly Diagnosed Failures

In the CONCEPTS section, we note that a large proportion of failures causing LRUs to be pulled during line maintenance turn out to be non-reproducible. However, it would be wrong to conclude that all CNDs are caused by line technicians' improper diagnosis. Built-in test algorithms in LRUs often leave line technicians with no choice but to replace the module. In other instances, incorrect diagnoses are caused by a number of conditions that have nothing to do with technicians' ability to test and diagnose.

Failures are sometimes reported by flight crew members or other third parties. The initial reports often incorrectly attribute cause. Regardless of the cause, incorrect diagnoses are a common and repeating problem for aviation maintenance organizations, increasing repair time and making the maintenance process inefficient.

Inefficient Troubleshooting

Aviation maintenance organizations are judged by their ability to find and fix problems efficiently. Improper diagnoses, as discussed above, cause inefficiency in the maintenance process. However, improper diagnoses are not as potentially degrading to efficiency as inefficient troubleshooting strategies. AMTs tend to apply the same strategies to nearly every problem they address. Thus, an inefficient strategy's effects are multiplied across every troubleshooting task a maintainer performs.

REGULATORY REQUIREMENTS

The source of most aviation maintenance regulations is the Federal Aviation Regulations (FARs) administered by the Federal Aviation Administration. While the FARs give statutory weight to certain requirements, other mechanisms carry de facto regulatory implications. In this section, we briefly describe both statutory and pseudo-regulatory mechanisms.

Federal Aviation Administration (FAA)

The Federal Aviation Administration (FAA) is responsible for ensuring the safety of the flying public. In this role, it has rather broad powers to ensure the competence of aviation maintenance personnel and the airworthiness of aircraft.

FARs

The statutory powers of the FAA are derived from those parts of the Code of Federal Regulations known as the Federal Aviation Regulations (FARs). The FAA essentially uses four mechanisms to ensure that maintainers' actions, including testing and troubleshooting, comply with the FARs:

- Advisory Circulars
- Airworthiness Directives
- Review of Maintenance Procedures
- Inspections of Maintenance Work.

The FAA also sets minimum training standards for all licensed aviation mechanics. These training issues are addressed in Chapter 7.

Advisory Circulars

The FAA issues Advisory Circulars (ACs) to provide non-time-critical information to maintenance personnel. ACs are distinguished from Airworthiness Directives (ADs) by the fact that ACs usually contain neither specific action requirements nor deadlines. A typical AC might alert maintainers that a certain troubleshooting or repair procedure has been found to work well (or not to work well) on a specific aircraft model.

Airworthiness Directives

Airworthiness Directives (ADs) communicate information directly pertinent to the airworthiness of certain aircraft. ADs are the mechanism the FAA uses to tell maintenance personnel that they must take some specific action by a particular date. The two distinguishing features of ADs are the following:

- specific action(s)
- deadline for performance.

An example of a maintenance-related AD is the directive to inspect B-747 engine fuse pins, issued after the El Al 747 crash in Holland.[33]

Maintenance Procedures

The FAA does not write maintenance procedures, except for explicit actions Airworthiness Directives require. However, the FAA has a statutory requirement to *approve* the maintenance procedures of all organizations it regulates. The FAA must evaluate and approve all maintenance manuals, troubleshooting and repair guides, and workcards prior to their use. This aspect of regulation is the most far-reaching regulatory power the FAA has; it covers every maintenance procedure licensed organizations perform.

Inspections

FAA Airworthiness Inspectors essentially form the "front-line" of regulation. FAA inspectors have the statutory authority to inspect any and all aircraft inspections, tests, and repairs. Some repairs, such as sheet metal repairs made on the ramp, require FAA inspection before being released. Although the FAA obviously has neither the time nor inspectors to evaluate every repair, a typical AMT's most frequent contact with the FAA's regulatory authority comes in the form of an FAA Inspector.

Manufacturers

Aircraft and component manufacturers have no statutory authority regarding maintenance or operation. In the instance of the Designated Engineering Representative (DER), the FAA ceded some regulatory authority to manufacturers. Even though they have no statutory authority, manufacturers hold the most expertise related to their products. The FAA often relies on manufacturers to identify problems, to develop procedures to find and fix problems, and to notify maintenance personnel of actual or potential problems.

Designated Engineering Representative

The FAA recognizes that certain manufacturers' employees possess a great deal of expertise regarding their products and that it is in manufacturers' best interests to ensure the airworthiness of their products. Thus, the FAA has appointed certain individuals as Designated Engineering Representatives (DERs).

DERs are employees of manufacturers, not FAA employees, but a DER's role is to be an on-site FAA representative. DERs have authority to inspect certain products, repairs, and procedures and to determine whether they comply with FAA rules and regulations.

Service Letters

Manufacturers use Service Letters to transmit non-critical information to maintenance personnel and operators. A Service Letter is usually general, although it typically applies only to certain aircraft models. As with Advisory Circulars, Service Letters do not *require* any action, nor do they contain any time deadline.

Service Instructions

Like Service Letters, Service Instructions are informational. However, Service Instructions usually contain detailed procedures for performing one or more specific tasks. A Service Letter might call attention to the fact that an airline has an efficient method to perform a particular inspection. A related Service Instruction might detail the procedure for performing that inspection efficiently.

Service Bulletins

Manufacturers use Service Bulletins to notify maintenance personnel and operators of airworthiness-critical information. This is the most urgent form of communication between manufacturers and those who need the information. If the information is immediately safety-critical, the FAA often issues an Airworthiness Directive that simply invokes the Manufacturer's Service Bulletin.

CONCEPTS

The concepts described below, while not exhaustive, are common to most maintenance environments, including aviation.

After-Maintenance Verification

We normally think of testing as an activity aimed at identifying problems and their causes. From this perspective, we expect testing to reveal a symptom or a cause for an observed symptom. However, there is one type of test in which we expect to find nothing wrong. After we perform maintenance on a component or system, we expect it to be fully functional. To verify that we have, indeed, left the system in a functional state, we normally perform some type of post-maintenance verification test. Such tests are sometimes called quality assurance tests.

An interesting aspect of both preventative maintenance (PM) and after-maintenance testing is that it is quite possible to test a component or system until it breaks. We are never really sure whether or not a particular test has left the system in a functional state. For example, a component could pass an electronic test, but the test itself could degrade the component's operation. Thus, there is a tradeoff between the amount of testing we should perform and the ultimate reliability of the components we are maintaining.

Algorithm

Algorithm is a fancy term for a method or a procedure used to solve a problem. In aviation maintenance, the "problem" is some type of failure in a system or a component. Troubleshooting algorithms are usually based on logic, although they don't have to be.

Automated Test Equipment (ATE)

In the early days of aviation, aircraft were relatively simple and maintenance was straightforward. As aircraft and their components became more sophisticated, diagnosis and repair became more complex. As part of this evolution, automated test capabilities became part of the maintenance technicians "toolbox." *Automated test equipment* (ATE) describes a broad range of partially- or fully-automated test capabilities.

There is no universally-accepted definition of ATE. The equipment spans the range from extremely sophisticated and expensive test consoles to simple equipment that performs programmed checks on a single avionics module's output. All ATE is either set up to perform a series of tests without requiring human intervention, or can be programmed to do so (see BITE).

Built-In Test Equipment (BITE)

As with ATE, Built-In Test Equipment (BITE) has evolved with the increased sophistication of aircraft subsystems. BITE is included in the design of a component, module, or subsystem. Except for that common thread, however, BITE describes an extremely broad range of equipment complexity and sophistication.

The simplest BITE might allow a technician or flight crew member to perform a "go/no-go" self-test on a specific module. A more-sophisticated module might allow a technician to perform tests with built-in switches and indicators on a module. The most-sophisticated BITE retains performance information over a number of flight legs, diagnosing failures and displaying specific instructions to technicians (see ATE and Figure 8-4).

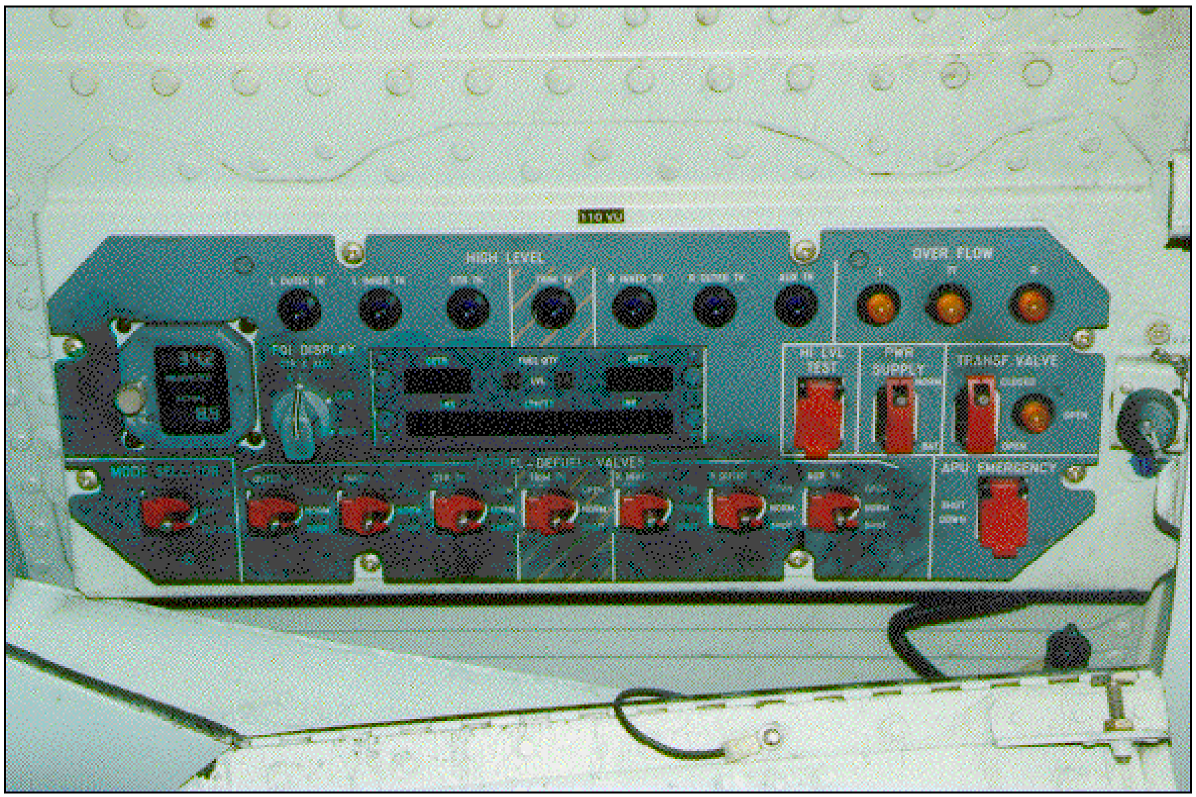


Figure 8-4. Example of a readout unit for built-in test equipment (Courtesy of Delta Air Lines)

Certain BITE is capable of reconfiguring systems to maintain functional capabilities despite component failures. A good example is the control system on the General Motors Northstar engine which can change valve timing and cylinder firing order to compensate for a complete loss of coolant. This BITE capability has been discussed as a way to allow combat aircraft to "self-repair" in battle.[34]

Cannot Duplicate (CND)

Cannot Duplicate (CND) commonly describes a situation in which AMTs cannot cause equipment to exhibit the same failure symptoms other AMTs or flight crew members reported. CNDs are a concern in aviation maintenance because of the high proportion of LRUs classified as "CND" during depot repair. Between 30 and 60 percent of all LRUs pulled from aircraft and sent to depots for repair are eventually tagged as CND.[8]

The inability to reproduce failure symptoms does not necessarily mean that reports of those symptoms were spurious. Complex equipment such as inertial navigation modules often exhibits intermittent failures, i.e., glitches. However, CNDs cause repair processes to be inefficient. If 50 percent of the LRUs returned to a depot are CNDs, approximately half of the technicians' time is spent working on modules that will not be repaired.

Consistent Fault Set (CFS)

Consistent Fault Set is one of the names given to the group of all possible failures that can reasonably explain a given set of trouble symptoms.[35] The name comes from the fact that the group contains faults "consistent" with the symptoms. For example, when an automobile won't start, the CFS could contain an ignition failure, but would not contain a failed seat back adjustment control.

Decision Tree

One type of maintenance job performance aid (JPA) is called a "decision tree". A decision tree is a printed or computerized chart that directs the maintenance technician along a logical testing and diagnosis path for a particular system or product. After each test or observation, the decision tree branches to another test (or conclusion) based on the test results. An easy characterization of a decision tree is a series of "if-then" statements, e.g. "If the voltage is below 'x,' then do this."

Depot Maintenance

LRUs thought to be non-functional are sent to a depot for repair. Depots are shops set up to perform extensive diagnosis on particular types of LRUs. For example, avionics modules are typically sent to a depot set up to handle them. Depot technicians typically have available various types of test and calibration equipment, as well as spare parts for the modules they work on.

Since depot technicians work on the same types of modules each day, they develop significant expertise related to these modules. Their experience and the availability of sophisticated test equipment tends to make depot maintenance very efficient (see Line Maintenance).

Easter Egging

One method of troubleshooting is to replace various LRUs until the symptoms of trouble disappear. This method is known as "Easter Egging" because a technician never really knows where he or she will find the failed part. Easter Egging is an extremely inefficient, expensive way to find a problem.

Einstellung (Psychic Blindness)

Einstellung describes a phenomenon discovered in the early 1940's[36] and since shown to exist in different domains. Researchers have found that when people have spent time solving one particular type of troubleshooting problem, it is virtually impossible for them immediately to diagnose a different type of problem. This phenomenon holds even when people are told that they will see a new and different type of malfunction.[37]

Expert System

Expert systems are diagnostic decision-making aids used in a number of different domains, including medicine, geological exploration, and maintenance. Expert systems are usually computer-based. They are generally developed by embedding a system of rules acquired from human experts. For example, if we were developing an expert system for diagnosing problems in aircraft braking systems, we would first try to determine how human experts do such diagnosis and then put these "rules" into our expert system.

Expert systems in aviation maintenance are commonly embedded in computer-based training systems[38] or diagnostic equipment.[39] Students using such training systems can ask an embedded expert for advice at any point in their troubleshooting practice.

Fidelity

Fidelity describes how closely a reproduction resembles the actual (or original) item. For example, musical recordings are often rated in terms of how much they sound like the original performance. In maintenance, *fidelity* describes how closely a simulator or mockup resembles the real item. There are several types of fidelity, e.g., physical, functional, operational, and psychological. Moving-base cockpit simulators are examples of full-fidelity reproductions because they are essentially indistinguishable from the real thing.

Many studies have shown that full physical fidelity is not necessary for training troubleshooting skills.[40,41] The operational, or psychological, fidelity of simulators used to teach troubleshooting is more important. It is not necessary to move a physical switch if the simulation depicts that switch and allows the student to alter its position.

Half-Split Test

Theoretically, the most efficient test a maintenance technician can perform is the one that provides the most information. Early troubleshooting research involving electronic circuits found that the "best" test is the one eliminating roughly half the items from a set of possibly failed components. Such a test is called a "half-split" test.

Heuristic

Many strategies can be used to troubleshoot. There are written, step-by-step procedures, half-split algorithms, etc. One category of troubleshooting strategies consists of *heuristics*. Heuristics are simply rules-of-thumb useful for problem-solving. A typical heuristic might be to test a particular component first, since it is known to fail often.

Hypothesis

A hypothesis is an assumption presumed to be true, but that must be proven or disproven by objective testing. In the course of troubleshooting, a maintenance technician needs to adopt one, or more, hypothesis as to what is causing the symptoms.

Researchers have identified three relevant aspects of hypotheses.[42] First, troubleshooters tend to give more weight to information found early in the diagnostic process, i.e., we make up our minds pretty quickly about what is causing a problem. Second, maintainers tend to adopt only a few hypotheses, even when a much broader range of hypotheses is consistent with the observed problem. Third, once a maintainer adopts a hypothesis, he or she tends to look for evidence supporting it while discounting evidence that refutes it (see Tunnel Vision).

Individual Differences

Individual differences are those physical and psychological characteristics that make people different. Human factors researchers try to relate individual differences to variations in performance. For example, if we found that people with extroverted personalities were generally better troubleshooters (which isn't actually true), we could select extroverts as technicians. In the BACKGROUND section, we discuss the research findings related to certain individual differences and troubleshooting performance.

Line Maintenance

In many operational settings, maintenance is categorized as either "line" or "depot." Line maintenance emphasizes keeping equipment operational. Line maintenance technicians must quickly diagnose problems to the LRU level and replace any non-functioning LRUs. "Broken" LRUs are then sent to a depot for further diagnosis and repair.

Line maintenance is sometimes characterized as "replacement" maintenance because line technicians don't actually fix broken modules. While this is accurate to a point, it is a false distinction. Depot technicians might also simply replace a lower level subassembly in the LRU. The real distinction between line and depot maintenance is that line maintenance occurs in the operational environment, i.e., on the flight line or in the hangar, whereas most depot maintenance is done in a shop environment (see Depot Maintenance).

Line-Replaceable Unit (LRU)

Line-Replaceable Unit (LRU) is a common term in both maintenance and system design. An LRU is simply the smallest assembly line maintenance technicians can replace. A system is typically tested until one, or more, LRU is thought to be causing the problem. This LRU is then replaced with a "good" LRU, and the "faulty" LRU is sent to a depot for more detailed diagnosis (see Depot Maintenance).

Proceduralization

Specific steps for a troubleshooting task can be left to a technician's judgment or can be carefully scripted in a procedure. A pre-landing checklist provides an example of a strict procedure in the aviation domain. The flight crew uses the checklist to ensure that they have completed all the necessary steps before they land the aircraft.

Maintenance procedures take many forms. The most common troubleshooting procedure is probably in the form of a troubleshooting "guide" providing suggested tests based on the observed operational symptoms.

A decision tree is a more sophisticated troubleshooting procedure; it directs a technician to perform specific tests and then branches to different actions based on the tests' outcomes. Procedures can be in the form of printed checklists, guides, etc., or part of an automated job performance aids such as an expert system.

Test-Induced Failure

When a technician performs a functional test on a system or component, there is some probability that the test will *cause* a failure. Because all systems and components have non-zero failure rates over time, a technician must balance the need for functional testing against the likelihood of a test-induced failure. Test-induced failures are safety risks only when they remain undetected. That is, a technician can test a subsystem, find it functioning properly and turn it off. If there is a test-induced failure, the component will be left in a failed state and will not work the next time it is needed.

Tunnel Vision

Tunnel vision describes viewing a situation as though through a tunnel, i.e., seeing in only one direction and being blocked from seeing information coming from other directions. In the maintenance domain, tunnel vision is a well-known occupational hazard. Once a troubleshooter thinks he or she knows what is causing a problem, information that might disprove the hypothesis tends to be given less weight than information confirming it.

One of the most common causes of tunnel vision in aviation maintenance is technicians' use of problem reporting information that goes beyond describing symptoms to suggest a cause[43] (see Hypothesis).

METHODS

Since testing and troubleshooting are so pervasive in aviation maintenance, they are potentially a part of almost any maintenance task. For purposes of this *Guide*, we have concentrated on methods that seem most applicable to the reader tasks described later in this chapter.

Aiding

Aiding means helping human workers perform their job tasks. In any sufficiently complex system, it is possible for humans to become overwhelmed by their job requirements. Once humans approach their mental or manual limits, performance begins to degrade. Common causes of task overload in the maintenance environment include extreme time pressure, attempting to interpret very complex information, or diagnosing multiple failures in complicated aircraft subsystems.

Aiding is common for complex manual control tasks such as piloting an aircraft. In maintenance, aiding usually takes one of two forms:

1. Expert advice in computer-based training or testing systems
2. Automated interpretation of complex test results.

Successful implementation of aiding requires a thorough understanding of the information requirements of each task.44 Specific design of aiding must be preceded by some form of task or job analysis (see Chapters 1 and 6).

Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is typically used as a safety analysis technique, using a diagrammatic representation of a particular system as its base. Each system component is presumed to fail in one of a number of modes. The effects of that failure are then determined by analyzing the connections between the failed component and other parts of the system. FMEA is a "bottom up" analysis technique; first we choose a component and then we determine what happens when it fails. Fault tree analysis is the opposite of FMEA.

For testing and troubleshooting, FMEA is most useful for generating and testing hypotheses concerning failure symptoms. For example, if we think a failed avionics module might be causing certain symptoms, we can use FMEA to determine what effects a failure of that module would have on the overall system. In other words, we want to know if the symptoms are consistent with a specific failure mode for a particular component?

Fault Tree Analysis

Fault tree analysis (FTA) is opposite of FMEA. It shares with FMEA its use of a diagrammatic representation of a system, but FTA is much more an exercise in logic. For FTA, we first specify a particular set of symptoms then logically determine every component failure that could cause those symptoms. FTA-like methods in aviation (and other) maintenance are typically used as troubleshooting guides. A troubleshooting guide generally lists a series of symptoms, e.g., landing gear green light will not illuminate, then directs the troubleshooter to a number of possible causes for the symptoms.

FTA's biggest shortcoming is that it must include *every* possible cause of the observed symptoms. Logically, being all-inclusive is quite difficult. However, when FTA is used in conjunction with FMEA, it quickly narrows the search for a consistent fault set (CFS -- see Consistent Fault Set in the CONCEPTS section).

Probabilistic Risk Assessment (PRA)

The essence of troubleshooting is identifying the failure(s) causing a particular set of symptoms. In nearly all physical systems, some failures are more likely than others. Manufacturers often test their products to determine the failure rates of particular components. When component failure rates are known, or can be reasonably estimated, they can also be mathematically combined to predict the probability of various types of system failures. This process is known as Probabilistic Risk Assessment (PRA).

PRA is commonly used to assess safety risks associated with complex systems, such as nuclear power plants, or of potentially dangerous operations, such as extended twin-engine operations over water (ETOPS). In the maintenance domain, PRA can determine the most likely failure modes for a particular system, and the information can then be factored into troubleshooting guides or expert systems.

Proceduralization

As we noted in the BACKGROUND section, proceduralization can improve troubleshooting performance. When troubleshooting is properly proceduralized, performance differences between expert and novice troubleshooters can be virtually eliminated. As with any other endeavor, however, there are good and bad procedures. More accurately, there are procedures improving performance and procedures with either little effect or that actually degrade performance.

Proceduralization must be preceded by a thorough analysis of relevant troubleshooting tasks to determine what each troubleshooting step tries to accomplish, what information is required and produced, and what tests or tools should be used. As with certain aspects of automation, it is possible to proceduralize to the extent that human technicians are left with an essentially mechanical role. We should also note that troubleshooting procedures exist in an overall organizational and work environment. Good procedures are worthless if they are used improperly or ignored.

Simulation-Oriented Computer-Based Instruction

We noted earlier in the chapter that teaching testing and troubleshooting skills has traditionally been problematic for maintenance organizations. Traditional training methods such as classroom lectures tend to be expensive and inefficient. Simulation-Oriented Computer-Based Instruction (SOCBI)45 has a number of advantages for the effort to teach troubleshooting skills. SOCBI capitalizes on two findings cited in the BACKGROUND section of this chapter:

1. Troubleshooting training most efficiently addresses specific tasks related to the actual equipment that students encounter on the job.
2. Developing troubleshooting skills requires a great deal of practice, preferably on a representation of actual equipment.

SOCBI meets both requirements by exposing students to realistic failures on a computer simulation of the actual systems they will see on the job. SOCBI's focus is on high psychological and visual fidelity: students perform tests and acquire information much as they would with real equipment. In a number of studies, SOCBI has been shown to produce troubleshooting performance equal to, or better than, more traditional, less efficient methods.

READER TASKS

Testing and troubleshooting are pervasive elements in aviation maintenance. The number of tasks directly involving testing and troubleshooting is so large that the entire range of these tasks is far beyond the scope of this *Guide*. From a human factors perspective, general tasks, when properly supported, can significantly improve troubleshooting performance. In this section, we describe three general troubleshooting-related tasks that readers can undertake. We recommend that readers seek professional help for certain task elements.

Developing Diagnostic Training

The assertion that it is difficult to teach and learn troubleshooting skills is supported by a long research history and by everyday experience. Perhaps because the ability to diagnose problems efficiently is so difficult and complex, it is highly valued. Readers of this *Guide* are likely to be asked to develop or at least to evaluate training aimed at teaching diagnostic skills.

Most maintenance managers and supervisors probably have neither the desire nor the abilities to develop and implement a diagnostic training program. However, since initial and recurrent training is a prominent feature of the aviation maintenance workplace, it seems appropriate to focus training resources in the most difficult or problematic areas such as troubleshooting. To assess the potential benefits of such training, supervisors should understand the principles forming the basis of good diagnostic training. There are also a number of existing diagnostic training programs for the aviation domain.

We will describe the desirable features of diagnostic training, and provide guidelines that apply to developing and selecting good diagnostic training products and programs. For a more detailed discussion of training, see Chapter 7.

Evaluating Automation Alternatives

As aircraft systems become more complex, automated troubleshooting assumes a more prominent role in the maintenance process. Automation commonly takes one of two forms:

1. Automated data recording and diagnostic functions manufacturers build into their aircraft
2. Test equipment with some degree of automation.

There are a number of human factors issues related to automated testing and troubleshooting equipment. Maintenance supervisors have almost total control over the selection and use of stand-alone test equipment. On the other hand, maintenance organizations have very little control over aircraft manufacturers' design of automated troubleshooting systems. However, even for automation built into aircraft, there is often an external component or system that is part of the troubleshooting process. In the GUIDELINES section, we describe the salient human factors issues related to such equipment.

For a more detailed discussion of automation and its affects, see Chapter 9.

Reducing Troubleshooting Errors

Troubleshooting errors are the bane of most aviation maintenance organizations. In fact, troubleshooting is notoriously error-prone. The fundamental complexity of many aircraft systems contributes to the number and type of errors observed in actual troubleshooting tasks. There are also human traits that contribute to relatively poor troubleshooting performance. We previously noted the high proportion of non-duplicated failures cited in line maintenance. These errors contribute to overall inefficiencies in the maintenance process and eventually appear on the bottom-line.

Various strategies can be used to reduce troubleshooting errors. From both organizational and human factors perspectives, each technique has its advantages and disadvantages. In the GUIDELINES section, we provide an overview of techniques that appear to hold the most promise for error-reduction. We also provide guidance for developing and implementing each error-reduction technique.

GUIDELINES

Table 8-1. Training approaches that *do not* work well for teaching troubleshooting skills

- Teaching the theory of operation for systems and components, without also teaching how to use that knowledge to troubleshoot.
- Observing examples of specific troubleshooting experiences.
- Teaching non-specific troubleshooting techniques.
- Classroom instruction, in general.
- Non-interactive (canned) computer-based instruction.
- Teaching from technical manuals.

In this section, we provide practical guidance related to the tasks described above. These guidelines have been developed from a human factors perspective, so they do not include certain other considerations, such as cost, that might weigh heavily when management considers these issues. Since human factors deals with the capabilities and limitations of human users, these guidelines can directly affect how well or poorly AMTs perform testing and troubleshooting tasks.

Developing Diagnostic Training

The general topic of maintenance training is addressed in Chapter 7. In this section, we examine training techniques related only to testing and troubleshooting. Testing and troubleshooting are but two components of the overall job of Aviation Maintenance Technicians (AMTs). As we pointed out earlier in this chapter, testing and troubleshooting constitute a large proportion of maintainers' core competencies. We also noted that it is particularly difficult to teach people how to troubleshoot.

Table 8-2. Training approaches that improve troubleshooting performance

- Using simulators and mockups
- Simulation-Oriented Computer-Based Instruction
- Almost any training method that allows meaningful practice
- Providing heuristics (rules-of-thumb)
- Teaching context-specific troubleshooting procedures
- Teaching how to analyze failure symptoms
- Teaching troubleshooting algorithms, such as half-splitting, when combined with training in how to generate possible failure hypotheses

Applied research has identified certain training considerations related directly to testing troubleshooting skills. We have extracted the guidelines that appear most applicable to training testing and troubleshooting.

What Doesn't Work

For troubleshooting, many common training practices have been shown to be quite ineffective. Because so many approaches have been shown ***not*** to work, we begin these guidelines with a partial list of these elements. Table 8-1 lists some "tried and failed" techniques for teaching troubleshooting skills.

What Works

While it is difficult to teach troubleshooting skills, it is certainly possible. There are a number of worthwhile approaches to troubleshooting; many of these were developed in the aviation maintenance environment.[19,46] Table 8-2 lists some training methods and elements that have been shown to improve troubleshooting performance.

At least one research study has identified each of these elements as improving troubleshooting performance. The elements can be incorporated into a number of different training methods: classroom instruction, on-the-job training (OJT), and intelligent computer-based instruction (see Chapter 7 for more detail).

Simulation-Oriented Computer-Based Instruction. Simulation-Oriented Computer-Based Instruction (SOCBI) is one of the most diligently-studied training methods that combines many elements for success in troubleshooting training. Work in SOCBI began in the aviation maintenance domain in the late 1970's. SOCBI provides students with a two-dimensional, interactive depiction of the particular system or component that they are learning to troubleshoot. If the component is small enough, an SOCBI module can actually show a picture of its controls and displays, for example, the environmental control system (ECS) panel shown in Figure 8-6.[47]

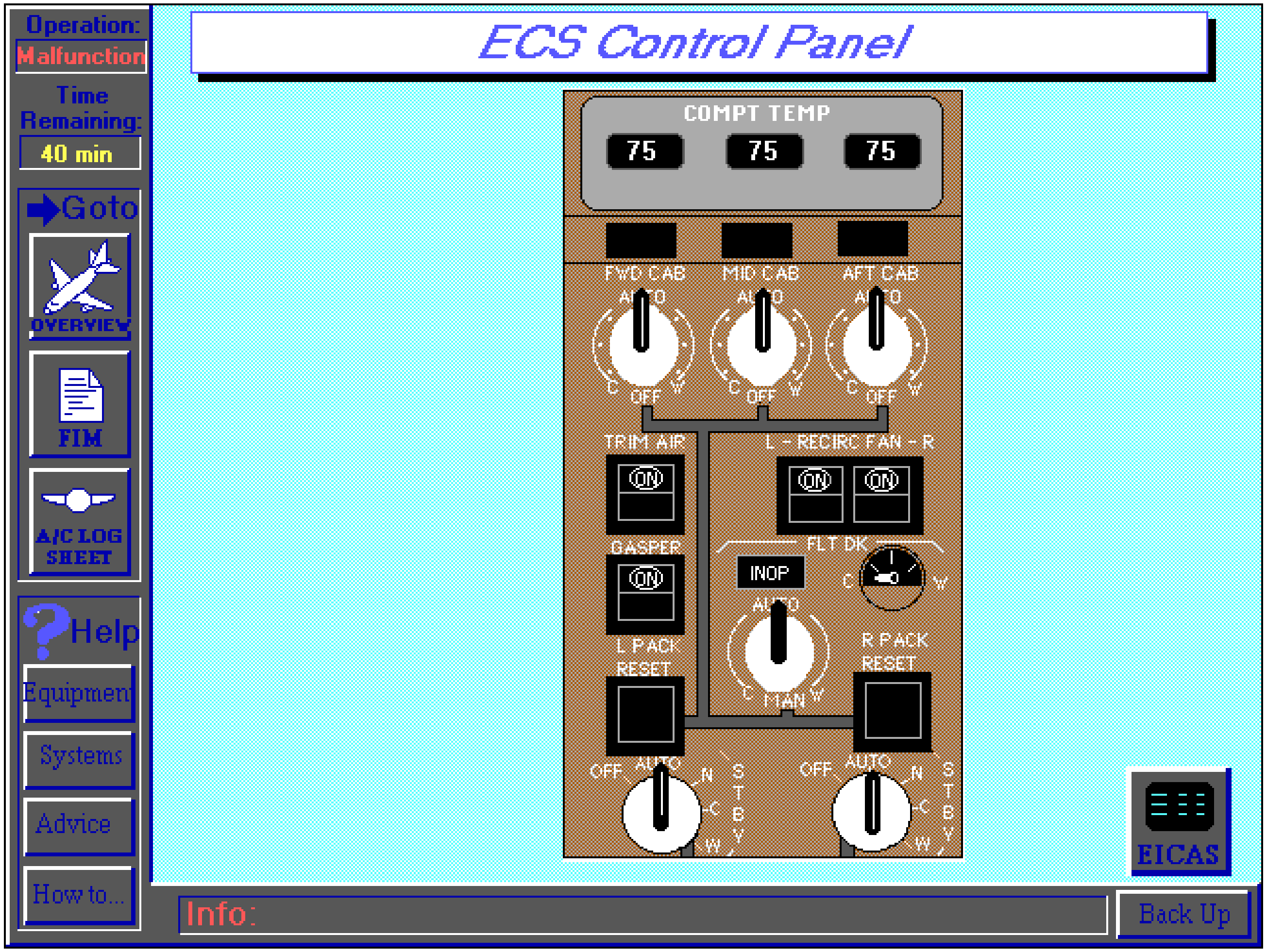


Figure 8-5. SOCBI depiction of an ECS control panel

Students use the working controls and displays to practice diagnosing a number of (usually randomly occurring) faults built into the simulation. SOCBI modules also contain diagrammatic, i.e., logical, representations of the system being taught. An example of these diagrams is shown in Figure 8-6. These functional/logical diagrams teach students how a system is functionally connected and allow them to use logical troubleshooting algorithms such as half-splits.

Effective SOCBI allows students to acquire diagnostic information from the same sources available in the work environment. Students must be able to observe indications, such as lights and gauges; to perform specific tests on the system; to receive verbal reports from flight crew members, etc.

A number of SOCBI systems have been compared with more traditional training methods such as classroom instruction and demonstrations of actual equipment. In these studies, SOCBI produces troubleshooting performance as good as, or better than, that produced by less-efficient techniques.[19]

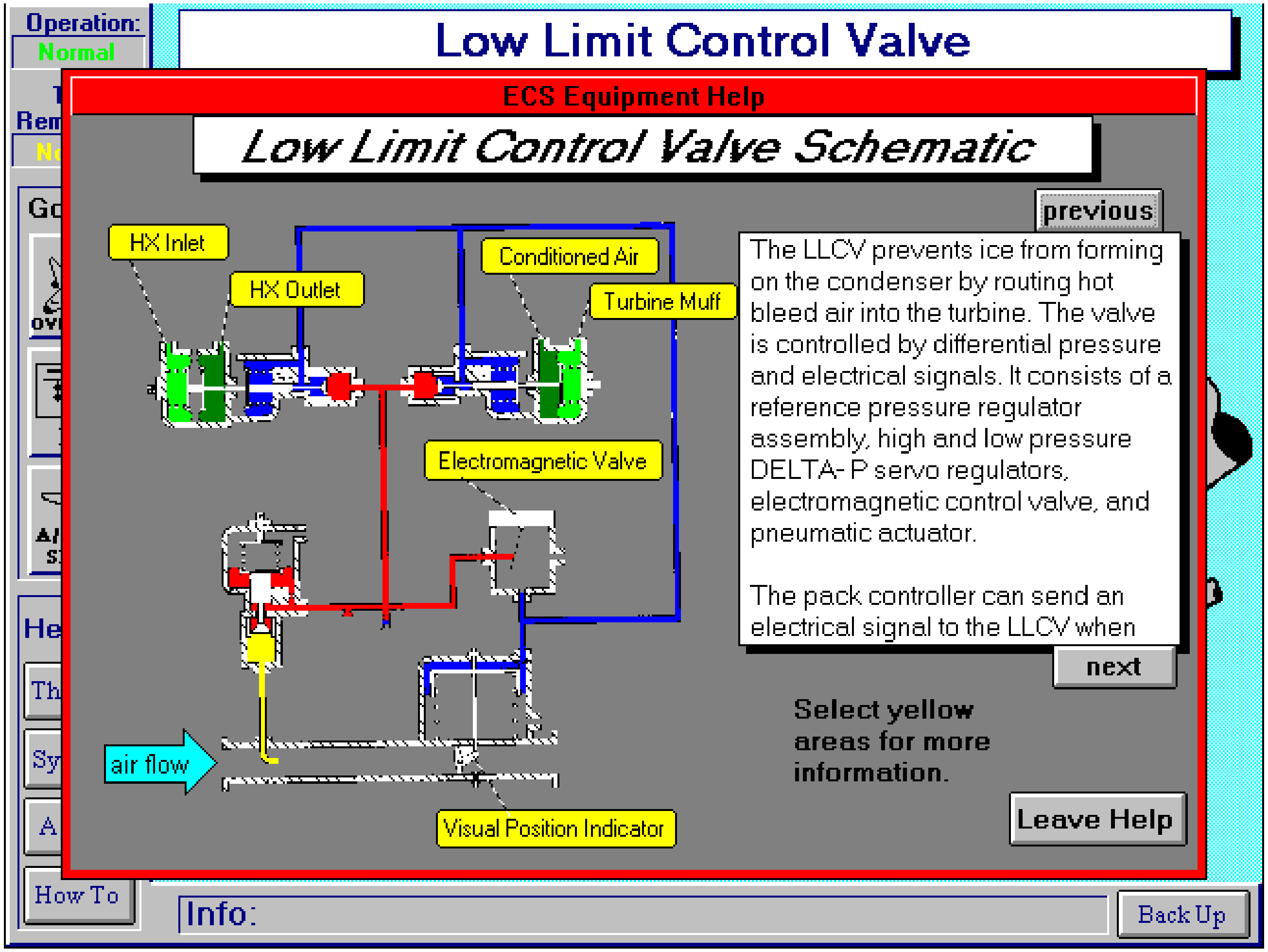


Figure 8-6. Example of a functional/logic diagram from an SOCBI module

Practice. Regardless of which training method, or combination of methods, one uses to teach troubleshooting skills, students must be given an opportunity for practice. In Table 8-3, we have explicitly specified that troubleshooting practice must be ***meaningful*** and listed the most important components of meaningful practice.

Table 8-3. Components of meaningful troubleshooting practice

To be meaningful, troubleshooting practice should:

- pertain to the equipment that will actually be maintained on the job
- be done using mockups that provide the same types of information as the real system
- allow students to gather information from the same sources as in the actual work environment

- provide feedback regarding the outcome of various tests and other actions
- allow students to know how long their actions would take in the actual work environment

Context-specific knowledge. Many maintenance skills are generalizable from one domain to another. For example, skill in the use of tools for repairing automobile engines is directly applicable to using tools to repair turbine engines. However, troubleshooting skills tend to be context-specific. The ability to diagnose problems with a television set does not directly transfer to troubleshooting avionics modules. When teaching troubleshooting knowledge, it is important to provide specific information. Table 8-4 lists some elements of context-specific troubleshooting knowledge.

Table 8-4. Elements of context-specific troubleshooting knowledge

Troubleshooting knowledge should be:

- **Explicit** - Tell students how you expect them to use the information you are providing. Don't rely on them to guess how it should be used.
- **Specific** - Relate troubleshooting steps to the component(s) on which students will be working. For example, don't tell students how to perform a general half-split test. Tell them how to do a half-split on the antiskid controller.
- **Simple** - Students will not be able to remember long, involved troubleshooting procedures. Break these procedures into simple, serial steps. If there is no easy way to decompose a troubleshooting process, then supply a written procedure.
- **Heuristic** - There are almost always rules-of-thumb for troubleshooting specific components or subsystems. Describe them for the students.

Evaluating Automation Alternatives

Automation is discussed in Chapter 9. Most issues that generally apply to maintenance automation are relevant to testing and troubleshooting. As aircraft systems become more sophisticated, we can expect more emphasis on automated testing and diagnosis. Newer systems and even individual components depend on software for their functional capabilities. This general trend affects many maintenance domains.[48]

One non-aviation example of the emphasis on software is found in network communication components. Until recently, hubs, routers, switchers, and other network components were essentially hardware-based. Since newer components rely instead on built-in software, the old methods of troubleshooting and repairing these components are inappropriate. While aircraft manufacturers and system vendors have until recently resisted the general movement to software, the trend is clear.

Many modern aircraft components contain sophisticated built-in automated test and diagnostic capabilities. Line maintenance for these modules often consists of reading diagnostic information from a cockpit control-display unit (CDU). One example of such an automated module is the inertial navigation unit on the DC-10 aircraft.

Probably the biggest issue related to maintenance automation, including testing and troubleshooting, is that it is possible to become too dependent on automated equipment. Studies of cockpit automation have consistently shown that, rather than eliminating operational problems, automation is the source of an entire new set of errors.[49,50]

We can't provide a set of guidelines that apply to every testing and troubleshooting situation, but there are common automation "rules." Table 8-5 lists and describes guidelines that apply to troubleshooting automation.

Reducing Troubleshooting Errors

The goal of every maintenance organization is 100% error-free performance. While this is a worthwhile goal, expecting 100% *anything* is unrealistic. In fact, one of the few rules on which human factors professionals agree is that people make mistakes. Most testing and troubleshooting in the aviation industry includes a human element, so we can expect errors to occur.[51] A more realistic goal is to *reduce* troubleshooting errors as much as possible. An adjunct goal should be to make errors, when they occur, as obvious and benign as feasible.

Past research and experience have shown a number of ways to reduce testing and troubleshooting errors. Common error-reduction methods include the following:

- Automate
- Instruct in algorithms or heuristics
- Proceduralize
- Practice
- Reduce Complexity
- Relax time pressure
- Select technicians
- Work in teams.

We discuss guidelines for each method in the remainder of this section.

Table 8-5. Guidelines for selecting testing and troubleshooting automation

Automation for testing and troubleshooting should include the following characteristics:

- **Very few "modes"** - The number of different operating modes should be kept to a minimum, i.e., no more than 3 or 4.

- **Clearly displayed mode** - The current operating mode of the automated equipment should be clearly displayed to technicians.

- **Explicit actions** - The automated equipment should inform technicians regarding what it is doing (and why, if the reason is not obvious).

- **Common terminology** - The terminology used in the technician-equipment interface should be compatible with the terminology used for non-automated troubleshooting tasks.

- **Consistent interface** - The technician/equipment interface should be consistent for all automated troubleshooting equipment.

- **No computer babble** - Understanding the information, instructions, labels, etc., should require no software expertise on the part of the operating technician.

- **No *bit tweaking*** - Technicians should not have to examine individual bits or bytes of data to acquire troubleshooting information. The user interface should display information in an easily interpretable format.

- **Operator override** - Allow users to override automated testing or troubleshooting functions at any time.

Automate

Table 8-6. Steps in automating testing and troubleshooting tasks

Step	Activity
1	Analyze errors
2	Analyze high-error tasks
3	Determine automation candidates
4	Assign manual/automated steps
5	Identify automation alternatives
6	Select automation alternatives
7	Integrate manual and automated steps

Automation does not eliminate all errors during testing and troubleshooting. We have made this point in our discussions of automation in this chapter and in Chapter 9. Improper automation can actually *introduce* errors that do not typically occur in manual troubleshooting. However, when automation is used properly, it can reduce certain types of maintenance errors. The trick is in knowing where, how, and how much to automate.

The specific steps to take when introducing automation for testing and troubleshooting tasks are summarized in Table 8-6. They are similar to the steps for introducing any type of automation (see Chapter 9). The most important step is to analyze the errors and tasks for which automation is anticipated. For automation or any other error-reduction method to work, we must first know relevant information like the following:

- What types of errors are occurring?
- What is the frequency of each error type?
- In which tasks do errors occur?
- Who is committing each type of error?
- What are the working conditions in which errors occur?
- Is there a connection among errors and time of day, time of year, etc.?

After completing the error and task analysis, emphasize properly allocating steps either to human technicians or to automated equipment. Improper allocation does not reduce (and might increase) the number or type of errors. For example, suppose we identify the following two errors:

1. Replacing test leads on the incorrect connector pins
2. Incorrectly interpreting the display on an eddy current tester.

In this example, automation, perhaps in the form of an expert system should help with the second problem. For the first problem, automation probably would not help. This task requires complex cognitive ability coupled with manual dexterity.

Instruct in Algorithms and Heuristics

Teaching certain theoretical information, such as a theory of operation, doesn't necessarily improve troubleshooting or testing performance. However, teaching heuristics (rules-of-thumb) and particular troubleshooting algorithms can improve the efficiency of testing and troubleshooting, including reducing errors.

Rules-of-thumb vary, depending on the specific component or system. An example of a rule-of-thumb is: "If the symptoms include a low pressure indication, then always check the pressure sender unit first." Rules-of-thumb represent the distilled wisdom of expert technicians who have diagnosed problems over a long period. Embedded expert systems depend on a rule base developed by consulting expert troubleshooters.

Algorithms are usually unwritten procedures telling troubleshooters generally how to proceed. Some research studies show that troubleshooting performance improves when technicians are reminded, in general terms, what they should do first, second, etc.17 For example, a general algorithm might require a technician to gather information related to failure symptoms, to generate as many hypotheses consistent with the symptoms as possible, to prioritize the hypothesis set, etc. Such general algorithms seem to have the effect of dissuading technicians from deciding on a specific failure being the cause of the symptom before they have enough information.

Proceduralize

As we noted in the BACKGROUND section, troubleshooting and testing errors can be reduced by proceduralizing a task. Previous studies have shown that procedures are more effective for reducing errors in complex than in simple systems. The notion of using maintenance procedures is certainly not new.52 Within the aviation maintenance industry, various types of procedures are commonly used. In fact, workcards constitute the most common type of procedure.

A number of issues related to procedures are beyond the scope of this *Guide*. We do not give detailed guidelines related to procedural format, typography, placement of warnings, and other aspects.

Maintenance procedures serve various purposes. Reducing errors is certainly an implicit goal of all such procedures. However, error reduction may not be the only, or even the main, focus of procedures. Other valid reasons to develop procedures include to comply with FAA requirements, to reduce the required experience level of technicians, to reduce the performance variability inherent in certain tasks, etc. Procedures aimed at reducing errors should be developed, stored, and used according to the guidelines listed in Table 8-7.

Table 8-7. Guidelines for procedures aimed at reducing testing and troubleshooting errors

Procedures aimed at reducing errors should be:

- **Specific** - Procedures should be written for a specific component, system, or piece of test equipment.
- **Clear** - The terminology should be consistent with the language commonly used by the people who will complete the procedure.
- **Explicit** - Tell users what they are supposed to do. Do not depend on technicians to read between the lines.
- **Detailed** - Include all required steps in the procedure. Don't assume that technicians will know all of the substeps required to achieve a specific system state.
- **Accessible** - Procedures must be stored in a place and manner so they are easy to obtain.

· **Usable** - Procedures must exist in a format and on media that make them easy to use while technicians perform the tasks they describe.

Practice

That "practice makes perfect" has been proven for troubleshooting tasks. The major factor distinguishing expert troubleshooters from novices is experience, i.e., practice. Troubleshooting is a complex skill with cognitive (mental) and manual elements. As is true of all such skills, troubleshooting proficiency cannot be attained simply by reading books or by listening to someone explain what to do. Providing opportunities for meaningful practice is a valid, relatively inexpensive method to reduce troubleshooting errors. Table 8-3 lists guidelines for meaningful practice.

In addition to the elements listed in Table 8-3, we include two other practice-related issues -- fidelity and availability. Troubleshooting practice does not have to be on real equipment; in fact, real equipment is often an inefficient practice medium with the following drawbacks:

- It is difficult to know the precise nature of failures embedded in real equipment
- Experts often disagree as to the appropriate troubleshooting path(s) for failures in real equipment
- Using real equipment as practice aids prevents the equipment from being used to support operations
- Errors made while troubleshooting real equipment can have safety implications
- For failures to be intentionally embedded in real equipment, someone has to embed the failures, check the equipment when practice troubleshooting is complete, and ensure that only controlled failures are present.

The other issue related to practice regards timing and accessibility. Although failures are relatively rare, across an entire fleet of aircraft various failures occur each day. A line or depot technician sees a number of failures over a week or month. Troubleshooting errors tend to occur when technicians see unusual, infrequent problems. Effective practice is conducted on a recurring basis over a long time and is available when a technician's schedule allows.

Use simulation. All these considerations lead to our recommendation that practice aimed at reducing errors be conducted using some type of *computer-based simulation* as described in the Training section of this chapter. Such simulations now exist on laptop computers.[53] Table 8-8 lists some major advantages of computer-based simulation for error-reduction practice.

Reduce Complexity

Our BACKGROUND discussion indicates that testing and troubleshooting errors tend to increase with the complexity of the system or component being maintained. One simple approach to reducing such errors is to reduce the complexity of the systems being maintained. This approach seems ludicrous on its face, i.e., how does one reduce the complexity of a system that already exists? Also, most maintenance organizations don't actually *design* the systems they maintain. A system's complexity is normally determined during its design.

Table 8-8. Advantages of using computer-based simulation for error-reduction practice

· It can be placed in convenient locations so it is accessible to technicians in or near their workplace.

· It can have a game-like quality that appeals to younger technicians (who are likely to be the most in need of practice).

- It can present complex failure scenarios in a non-threatening environment. That is, there is no actual cost for errors.

- There are no safety implications associated with troubleshooting errors.

- It provides distributed practice over long periods of time.

- It provides immediate feedback regarding errors, costs, efficiency, etc.

- The user interface can be made consistent among all simulated systems and between this simulation and that used for training.

There are two approaches to reducing complexity that can improve testing and troubleshooting performance, i.e., reduce errors:

1. Simplify the testing and troubleshooting *equipment* and *procedures.*
2. Break complex testing and troubleshooting tasks into simpler pieces.

Both approaches are probably being used to some extent within most maintenance organizations.

Simplify equipment and procedures. There is no direct link between aircraft components' and systems' complexity and the complexity of related testing and troubleshooting equipment and procedures. Much line maintenance consists of simply reading and following instructions on a control-display unit (CDU). Testing and troubleshooting a complex, sophisticated avionics module might be nothing more difficult than following the instruction, "Remove unit. Replace with new unit."

Maintenance supervisors usually have direct control over the selection and development of equipment and procedures. As the complexity of these elements decreases, testing and troubleshooting errors also decrease.

Decompose complex tasks. In Chapter 7, we describe *part-task* training. Various studies have shown that complex tasks and skills are learned more efficiently when broken down into simpler components. This reasoning can be carried into actual work tasks so that procedures decompose complex tasks into a series of simple individual steps. The effect of such decomposition on performance depends on the resultant steps' complexity.

The drawback of task decomposition is that resultant tasks might be so detailed that technicians loose track of what they are trying to accomplish. For example, we can accomplish the same purpose by telling a technician either to "remove an access cover" or to "remove screw #1, then remove screw #2." The key to success, of course, is to simplify a complex task without losing context and intent.

Relax Time Pressure

Time pressure degrades troubleshooting and testing performance, and nearly all aviation maintenance tasks are subjected to some form of time pressure. Line maintenance technicians are consistently exposed to time pressure because of their need to have aircraft ready for operation. Depot technicians' time constraints are usually measured in days or weeks, instead of line technicians' hours or minutes. Technicians and mechanics working on major structural checks and aircraft re-configurations are also expected to meet time constraints, but their time pressure is similar to that of construction crews, i.e., such projects have milestones and a due date.

There is a limit for relaxing time pressure on troubleshooting tasks in a line maintenance organization. Many line tasks involve unplanned work. When a flight crew reports that a certain component appears to be malfunctioning, technicians must work within the aircraft's planned ground time to diagnose and repair the problem. Maintenance organizations often deal with time constraints by practicing replacement maintenance for unplanned work. They make no attempt at in-depth diagnosis or repair; instead, they identify LRUs that might contribute to the problem and replace them as quickly as possible.

Table 8-9. Time pressure reduction procedure for line technicians

Step 1 - Perform an analysis to determine the most likely causes for certain functional symptoms. This analysis can be composed of different elements, including, PRA, FMEA, Fault Tree, etc.

Step 2 - Build a troubleshooting decision tree based upon this analysis. The decision tree should specify which tests to perform and which modules to remove or repair given particular time constraints. For example, if 15 minutes until departure, remove and replace modules A, B, and C. If 30 minutes until departure, test module A, if bad, then do this. If good, then do that.

Step 3 - Develop a tagging procedure for modules removed in Step 2. It is possible that modules will be removed without testing them. Others may have been only partially tested.

Step 4 - Develop a depot screening process for incoming modules. Depot technicians should be able to look at the tags and tell what level of testing was done on the flight line. This will allow them to perform an initial screening to determine whether modules actually exhibit any failure symptoms.

This practice of rapid diagnosis and replacement undoubtedly contributes to most organizations' high rate of CNDs. Such false positive findings should be expected. In fact, as more time pressure is brought to bear on line organizations, depot technicians likely find a higher proportion of CNDs. This is not necessarily bad, but the tradeoff is more depot technician time or unplanned operational delays.

In reality, there appears to be only one viable way to reduce time pressure on line technicians. This procedure is outlined in Table 8-9.

Select Technicians

As noted in the BACKGROUND section, certain individual personality traits, such as cognitive style, have been correlated with testing and troubleshooting performance. Theoretically, if we select technicians based on these traits, we improve testing and troubleshooting performance. However, it is difficult to know whether traits such as introversion are practically significant for aviation-related testing and troubleshooting tasks. Much stronger links appear among performance and training, experience, proceduralization, etc.

Even if one were to select technicians based on individual traits, it's not clear that the traits can be measured with enough reliability for them to be valid predictors of performance. What is clear is that some people are better troubleshooters than others. A viable selection criterion that *could* reduce testing and troubleshooting errors might be to select people who have demonstrated exceptional troubleshooting performance on the job. This strategy would establish an elite class of technicians recognized for their troubleshooting ability.

However, using personnel selection as a method for reducing errors is fraught with problems, including its depressing effect on employee morale and its repercussions on union work agreements. By forming an elite group of troubleshooters, what message are we giving people not selected? By selecting technicians solely on troubleshooting performance, regardless of other skills and experience, how are we affecting seniority, pay grades, etc.?

Based on these considerations, we ***do not*** recommend personnel selection as an error-reduction technique, although other selection criteria can be used to enhance maintenance productivity.54 A natural selection process occurs in the workplace so that technicians tend to consult the best troubleshooters on particular systems or modules -- especially for complex failures where troubleshooting errors are more likely.

Work in Teams

To quote an old expression, "Two heads are better than one." Intuition suggests that two or three technicians working together commit fewer testing and troubleshooting errors than a single person working alone. Even if individual team members commit the same number of errors, the chances of detecting and correcting those errors seem greater for a team than an individual.

There certainly are ample precedents for using teams of technicians. In manufacturing, the use of workgroups, quality circles, and other worker teams has proven to be successful in increasing product quality, i.e., reducing manufacturing errors. In maintenance, the use of multiple technicians has had mixed results.

A classic example of having more than one technician perform a task is the *double-checkoff* procedure. Double checkoff procedures require one individual to perform a task and initial each completed step. A second person takes the procedure, ensures that each step has been completed and initials it a second time. NASA, the commercial nuclear industry, and the military use such procedures for safety-critical tasks.

Experience with such team concepts has proved them to be fallible. For double-checkoff procedures, workers tend to become complacent, i.e., the second person often assumes that the first did everything properly. The second checkoff becomes nothing more than an exercise in writing initials. Teams that work to reduce errors have the following characteristics:

1. Each member maintains a perspective that allows him or her to question other team members' work.
2. Each member must have the temperament to accept other members' observations without becoming defensive.

In the aviation maintenance environment, including technicians and inspectors on the same team might work to reduce errors, depending on individual personalities. Workers' acceptance of a team as a viable working unit seems largely to depend on their perception of how much their management demonstrates its support. One way to ensure failure of the team concept is to treat the team as a mechanism for catching inept workers. Once employees have the idea that the purpose of the team is punitive, any performance-enhancing effects are lost.

The use of teamwork to reduce maintenance errors is embodied in the concept and practice of Maintenance Resource Management (MRM). Chapter 16 discusses MRM in detail and provides guidelines for developing an MRM training program for AMTs.

WHERE TO GET HELP

If you feel that you need help related to troubleshooting, there are a number of organizations that can provide various levels of assistance. We have listed some of these sources below.

The Air Transport Association is a consortium composed of domestic aviation companies, including airlines and maintenance organizations. The Engineering Department of the ATA is usually a good contact point for any type of technical question related to aviation. It would certainly be a good starting point for troubleshooting questions related to commonly-used test equipment or aircraft modules or components.

Air Transport Association of America
Engineering Department
1301 Pennsylvania Ave., NW
Washington, DC 20004
Phone: (202) 626-4000
Fax: (202) 626-4081
E-mail: ata@air-transport.com
Web site: http://www.air-transport.org

The Human Factors and Ergonomics Society (HFES) is a good starting point for obtaining assistance in any human-factors-related area. The HFES maintains two lists of human factors consultants. They publish an annual Directory of Consultants. The Directory lists consultants by their self-proclaimed specialties. The Membership Directory includes a notation next to each individual member who has expressed a willingness to consult. Obtain either source by contacting the Society.

Human Factors and Ergonomics Society
PO Box 1369
Santa Monica, CA 90406
Phone: (310) 394-1811

Fax: (310) 394-2410
E-mail: HFEA@compuserve.com
Web: http://hfes.org

The International Air Transport Association (IATA) is an international aviation consortium with headquarters in Montreal, Canada. IATA manages much of the infrastructure for its airline members, including acting as a clearing house for ticket exchanges. However it is also known for its extensive list of consultants and training courses. IATA conducts a number of training courses related to troubleshooting various components and using specific types of test equipment.

International Air Transport Association
IATA Building
2000 Peel Street
Montreal, Quebec
Canada H3A 2R4
Phone: (514) 844-6311
Fax: (514) 844-5286
Web: http://www.iata.org

FURTHER READING

The documents listed below contain information pertaining to the testing and troubleshooting topics discussed in this chapter and may or may not have been specifically cited in the chapter. These citations are grouped under general topics to make finding particular information easier. Within each topic area, all references are arranged alphabetically.

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EXAMPLE SCENARIOS

The scenarios presented below represent some of the typical kinds of testing- and troubleshooting-related tasks one expects to encounter in the workplace. The purpose of these scenarios is to demonstrate how the authors foresee the document being used. For each scenario, we describe how the issues raised in the scenario can be resolved. There is usually more than one way to approach these issues, so the responses given below represent only one path that users of the *Guide* might take.

As a general rule, always start to look for information by using the Search function. There will be instances that you already know where required information is located. However, unless you frequently use specific sections of the Guide, you might miss information pertaining to the same issue located in more than one chapter. The Search will allow you to quickly search all chapters simultaneously.

Scenario 1 - Finding Rare Failures

You're the Manager of Avionics Bench Testing. The RF (radio frequency) section seems to do a good job of finding common problems, but they seem to take an inordinately long time to find infrequent failures.

Issues

1. Is this an expected state of affairs? Why or why not?
2. Does this sound like a problem you could fix by buying some new automated test equipment?
4. Is there a training approach that might help your technicians do a better job with infrequent failures?

Responses

1. From the general discussion in the chapter, it should be fairly obvious that experience is a major factor in determining troubleshooting performance. Technicians have more practice diagnosing failures that occur frequently. Conversely, they have little opportunity to work with infrequent failures. The net result of this is that infrequent failures are more difficult to diagnose.

Another factor here is the "Einstellung" effect described in the CONCEPTS section. This effect, which applies to a broad range of troubleshooting domains, causes technicians to have difficulty shifting from one type of failure to another.

2. We could resolve this issue with a resounding "Maybe"! Whether automated test equipment will address the problem of diagnosing infrequently occurring problems depends on the nature of the problem. In the GUIDELINES section, we provide a procedure for automating testing and troubleshooting tasks (Table 8-6). The first step is to analyze errors we are trying to eliminate. It is possible that the infrequent failures described in this scenario are good candidates for automation.

3. Throughout the "Developing Troubleshooting Training" subsection of the GUIDELINES section, we emphasize the importance of exposing technicians to the types of failures they will be diagnosing on the job. Tables 8-2 and 8-3 list a number of training methods and practice elements appropriate for improving troubleshooting performance. Because the problems in this scenario are due to infrequent failures, a training method that provides more practice with these failures should improve performance. Specifically, Simulation-Oriented, Computer-Based Instruction (SOCBI) will probably be effective.

Scenario 2 - Effects of Time Pressure

Maintenance-related flight delays are going to be counted in your company's "on-time" statistics. Your depot CND rate is already running over 50%, and your avionics supervisor thinks the added time pressure will drastically increase the CND rate.

Issues

1. Is the avionics supervisor right? Will the CND rate go up?
2. Can you reduce the CND rate by adding more automated test equipment (ATE)?
3. What steps can you take to accommodate the added time pressure of the new "on-time" requirements?

Responses

1. The chapter provides two pieces of information related to this issue. First, a CND rate of over 50% isn't unusual. In the discussion of CNDs in the CONCEPTS section, we note that researchers report CND rates of between 30 and 60%. Second, we describe several environmental variables that affect troubleshooting performance, including time pressure. Time pressure invariably degrades troubleshooting performance. Yes, the avionics supervisor is correct. Your CND rate will probably go up.

2. CNDs are normally associated with LRU's pulled on the flight line and sent to a depot for further maintenance. Automated test equipment (ATE) is usually located at the depot. By the time LRU's reach the depot, it's already too late to affect whether a failure can be duplicated or not. Thus, adding ATE is unlikely to have any affect on the CND rate. There is the possibility of adding a screening step so that LRU's are tested before they're sent to the depot. In this scenario, adding ATE for the screening process could be quite effective.

3. Increased time pressure degrades troubleshooting performance, and line maintenance technicians routinely experience more time pressure than depot workers. Table 8-9 provides a series of steps that can be implemented to reduce the time pressure on line technicians by tailoring line maintenance actions such as removing LRU's to the time window available for troubleshooting.

Scenario 3 - Troubleshooting Training

The Training Department is trying to reduce its instructor staff. They want to replace a few troubleshooting modules with videotape-based courses. These modules show the basic testing and troubleshooting steps for specific aircraft systems.

Issues

1. Is this training approach likely to train technicians to the proficiency needed to troubleshoot these systems? Why or why not?
2. If not, what would you tell the Training Department to change?
3. Are there any advantages of keeping instructors in these training modules?

Responses

1. In Table 8-1, we provide a list of training techniques that do not seem to work well for teaching troubleshooting skills: neither classroom-only instruction nor any non-interactive technique are likely produce proficient troubleshooters. The videotape method described in this scenario has the same general characteristics of both classroom and non-interactive CBI. First, videotape instruction is passive, i.e., students don't actually participate in the training-they passively watch a video monitor. Second, the trainees have no opportunity to practice the techniques they watch on the videotape.

2. There are a number of elements that should probably be added to this videotape course. However, the one element that must be added is the opportunity to practice with some facsimile of real equipment and real failures. Table 8-2 notes that almost any training that allows meaningful practice will improve troubleshooting performance.

3. Live instructors provide an element very difficult to duplicate with automated instruction. Human instructors can *adapt* their presentation to their students' changing requirements. While certain types of computer-based instruction are capable of adaptation, within limits, human instructors can provide real-life examples of troubleshooting, rules-of-thumb for diagnosing certain systems, and a professional role model for novice technicians.

Scenario 4 - Automated Test Equipment

An automated test equipment (ATE) vendor has been trying to convince you to buy their latest "do all" product. The vendor claims that it will test every type of avionics module in your fleet, and its biggest selling point is that the technician interface is consistent for every type of test.

Issues

1. Is this vendor's selling point of interface consistency valid from a human factors perspective?
2. What other characteristics should you look for when evaluating this product?

3. Would you expect to experience any cost savings due to a consistent test interface? If so, what would be the source of these savings?

Responses

1. Yes! User interface consistency is one of the most fundamental human factors requirements for any type of equipment. Even if a user interface isn't particularly well thought-out, people can learn to use it if it is consistent. Table 8-5 provides a list of automation features that should be evaluated prior to implementing new ATE, including a consistent interface.

2. Table 8-5 provides a list of the characteristics that should be evaluated.

3. The chapter doesn't directly address this issue. However, it is probably easier to learn to use simple, consistent interfaces than complex, idiosyncratic interfaces. Most of the immediate cost savings from using human factors design principles are the result of *decreased training time*. Since training and retraining are such a large component of aviation maintenance costs, savings in this area can be significant. In the longer term, we should realize further cost savings from reduced troubleshooting errors. A direct result of a simple, consistent user interface is that users commit fewer errors. Fewer errors mean higher efficiency and lower cost.

Scenario 5 - Proceduralization

The VP-Maintenance has had it with our error rate. From now on, he insists that every safety-related testing and troubleshooting task be proceduralized and each step be checked by two technicians.

Issues

1. Would you expect proceduralization to reduce errors?
2. Is the double-checkoff process likely to reduce errors over the long term?
3. If implemented, is this policy likely to have any effects on the maintenance organization other than an effect on error rates?

Responses

1. As in the first scenario, we can answer the first question here with a resounding "Probably"! From the discussion of proceduralization in both the BACKGROUND and GUIDELINES sections, it should be clear that, *at least for some processes*, proceduralization can reduce errors. The error-reducing potential of procedures increases with system complexity and decreases with the technicians' expertise. Procedures should have the most effect for complex tasks done by less-experienced technicians.

2. Earlier, we discuss the idea of reducing troubleshooting errors by working in teams, including the concept of double-checkoff procedures. These procedures have the potential to reduce errors, but a number of factors can cause the double-checkoff scenario to fail. The short response to the issue in this scenario is that double-checkoff procedures *might* reduce errors, but we can't really be sure until we evaluate how they must be implemented.

3. We don't address this issue in the chapter. However, it should be relatively easy to see some of the difficulties that implementing double-checkoff procedures could cause. First, well-trained, skilled, and experienced technicians are not likely to embrace the idea that they can't be trusted to complete procedures on their own. Second, such procedures can be viewed as pitting the judgment of one technician against another's and is likely to cause at least a bit of social tension. Finally, since technicians who work together tend to trust one another, the second procedural "check" is likely to become a superficial paper exercise.

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